Fig. 35

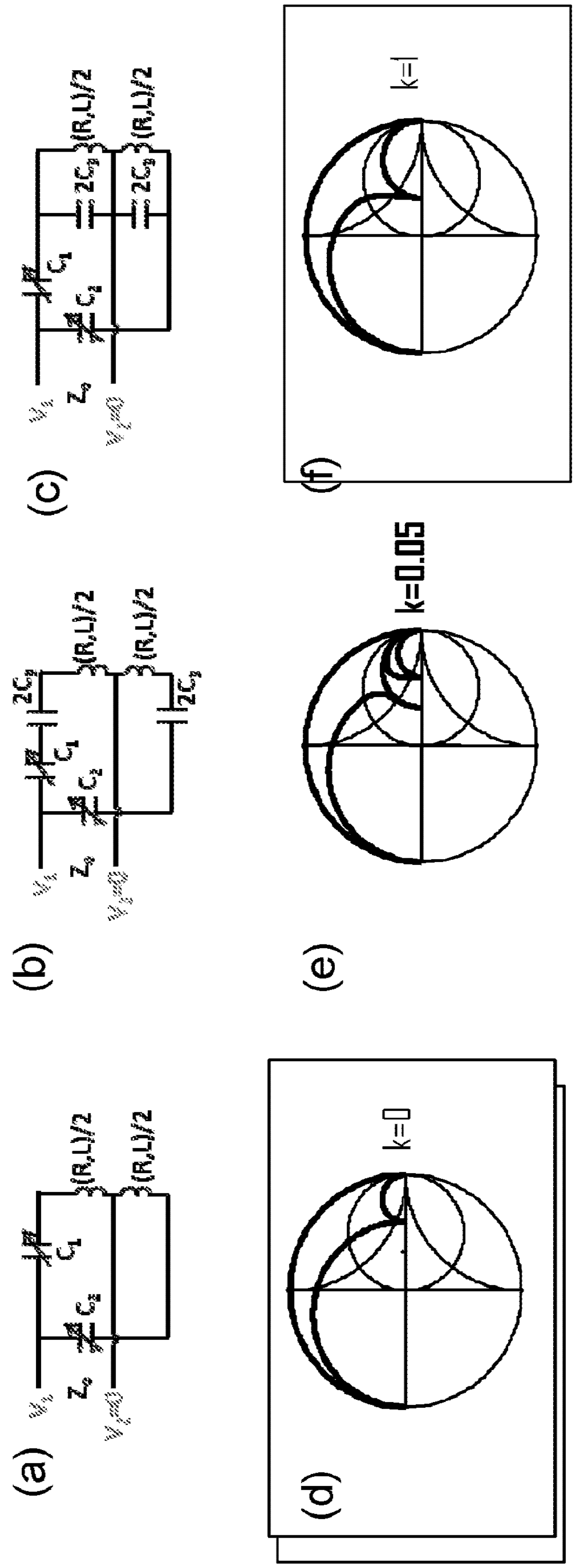

Fig. 36

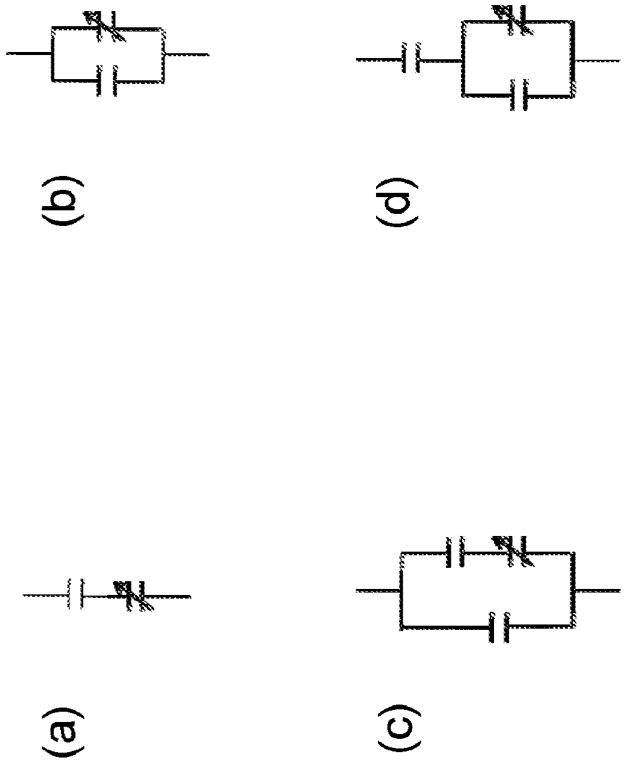

Fig. 37

(b)

(a)

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Fig. 38

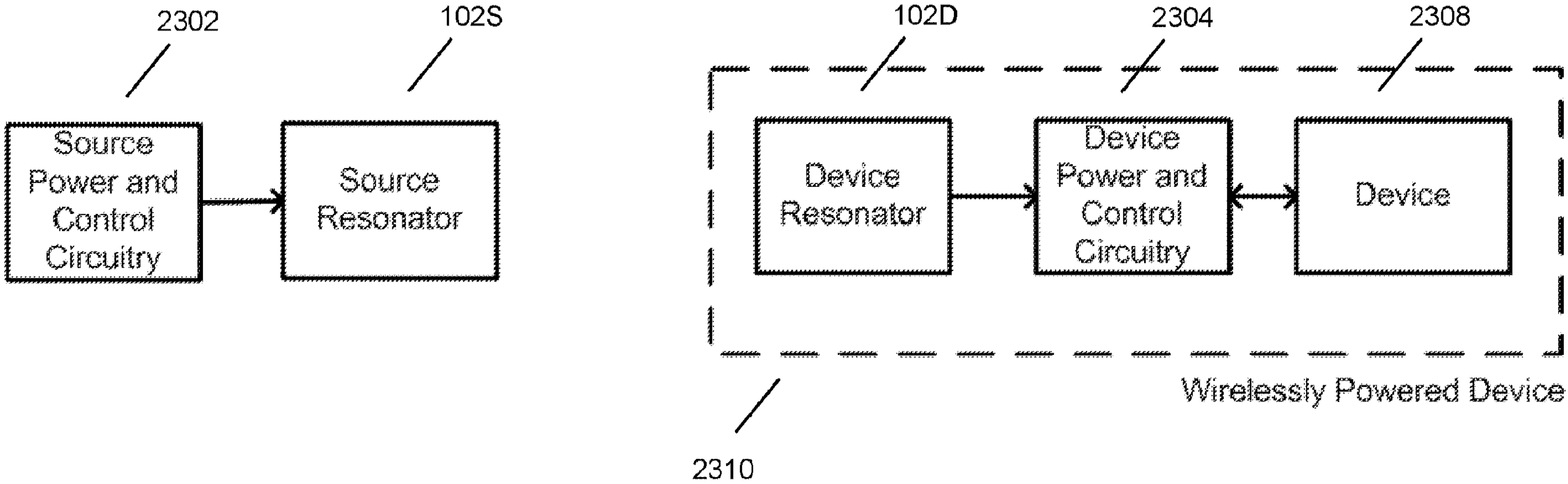
2302
102S
Source Power and Control Circuitry
Source Resonator
102D
2304
2308
Device Resonator
Device Power and Control Circuitry
Device
Wirelessly Powered Device
2310

Fig. 39

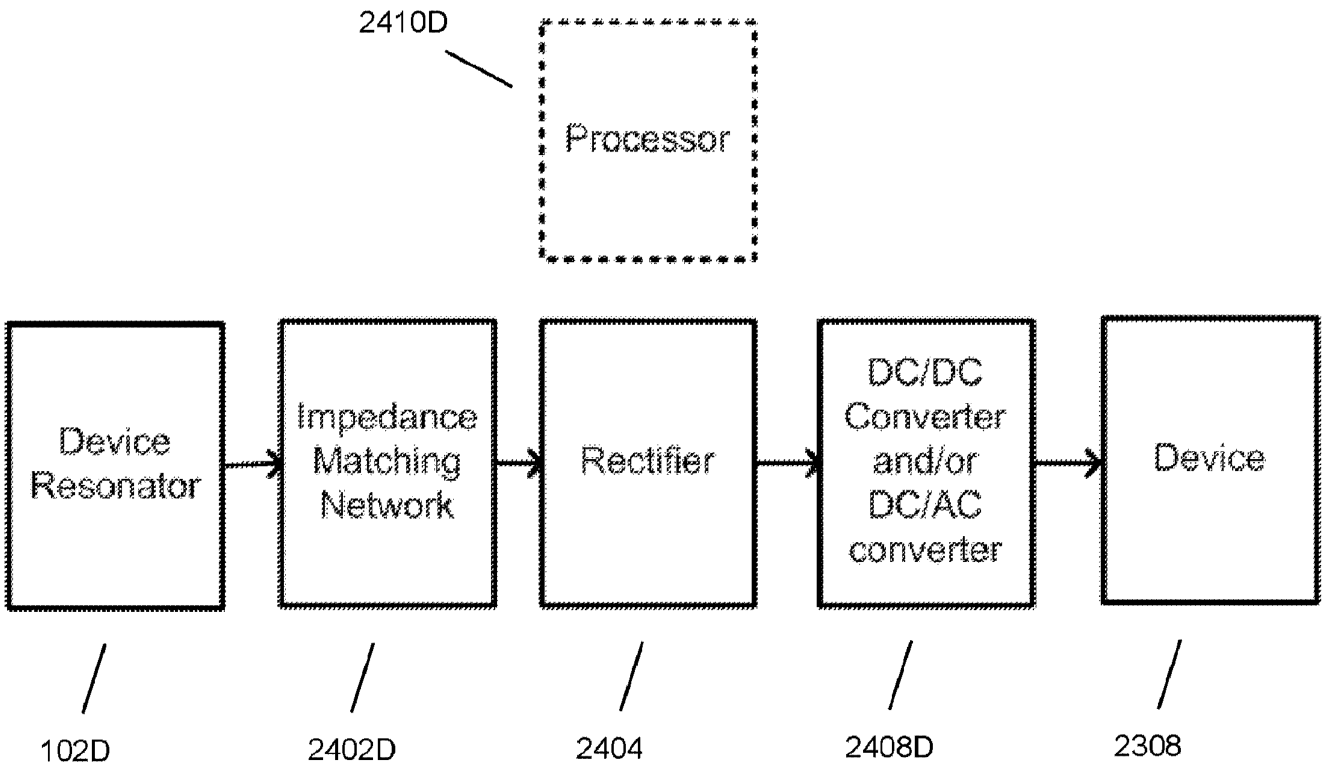
2410D
Processor
Device Resonator
Impedance Matching Network
Rectifier
DC/DC Converter and/or DC/AC converter
Device
102D
2402D
2404
2408D
2308

Fig. 40

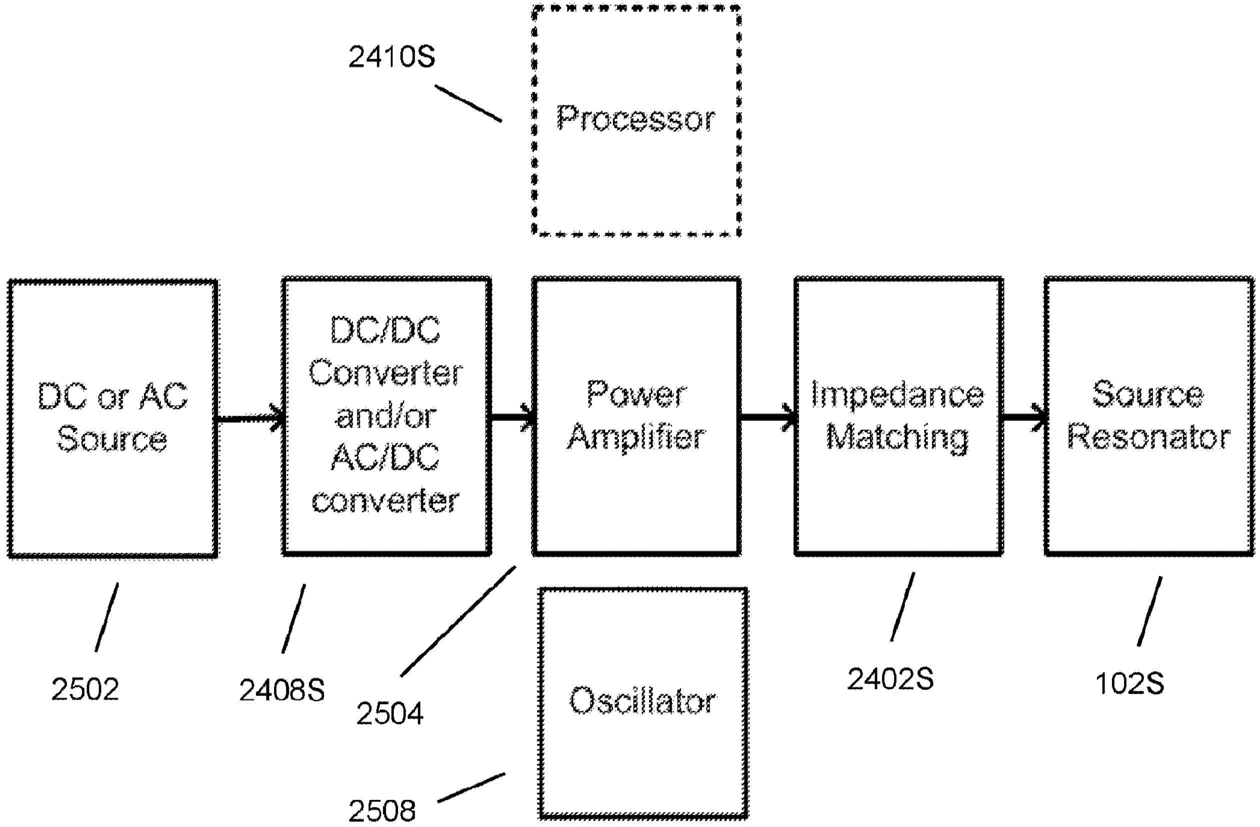
2410S
Processor
DC or AC Source
DC/DC Converter and/or AC/DC converter
Power Amplifier
Impedance Matching
Source Resonator
2502
2408S
2504
Oscillator
2402S
102S
2508

Fig. 41

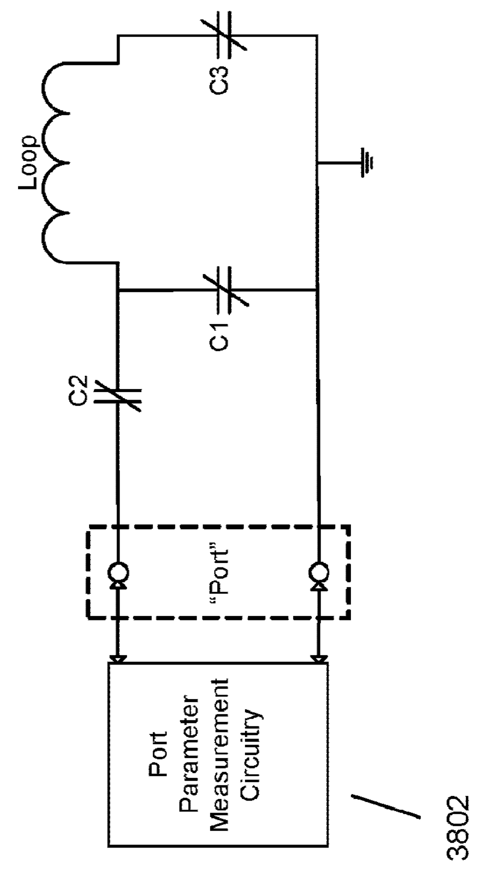
Loop
C3
C1
C2
"Port"
Port Parameter Measurement Circuitry
3802

Fig. 42

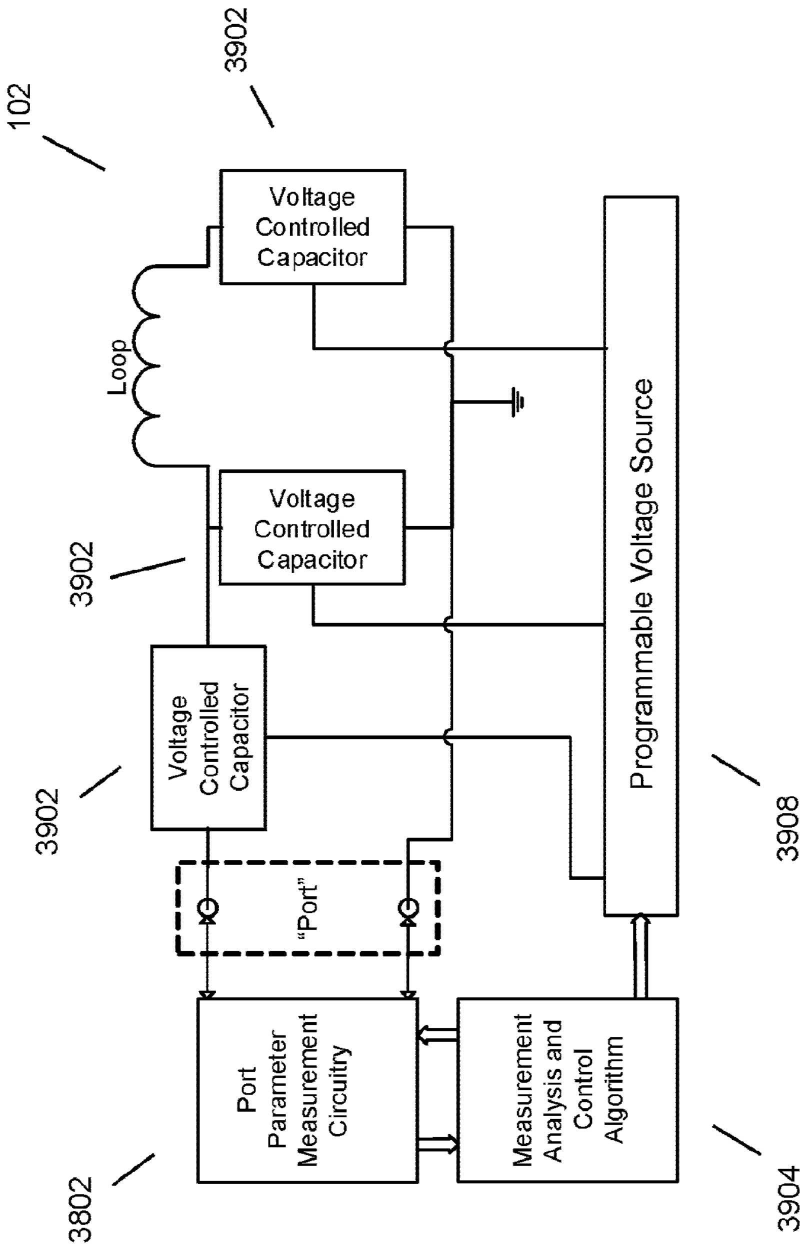

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Fig. 43

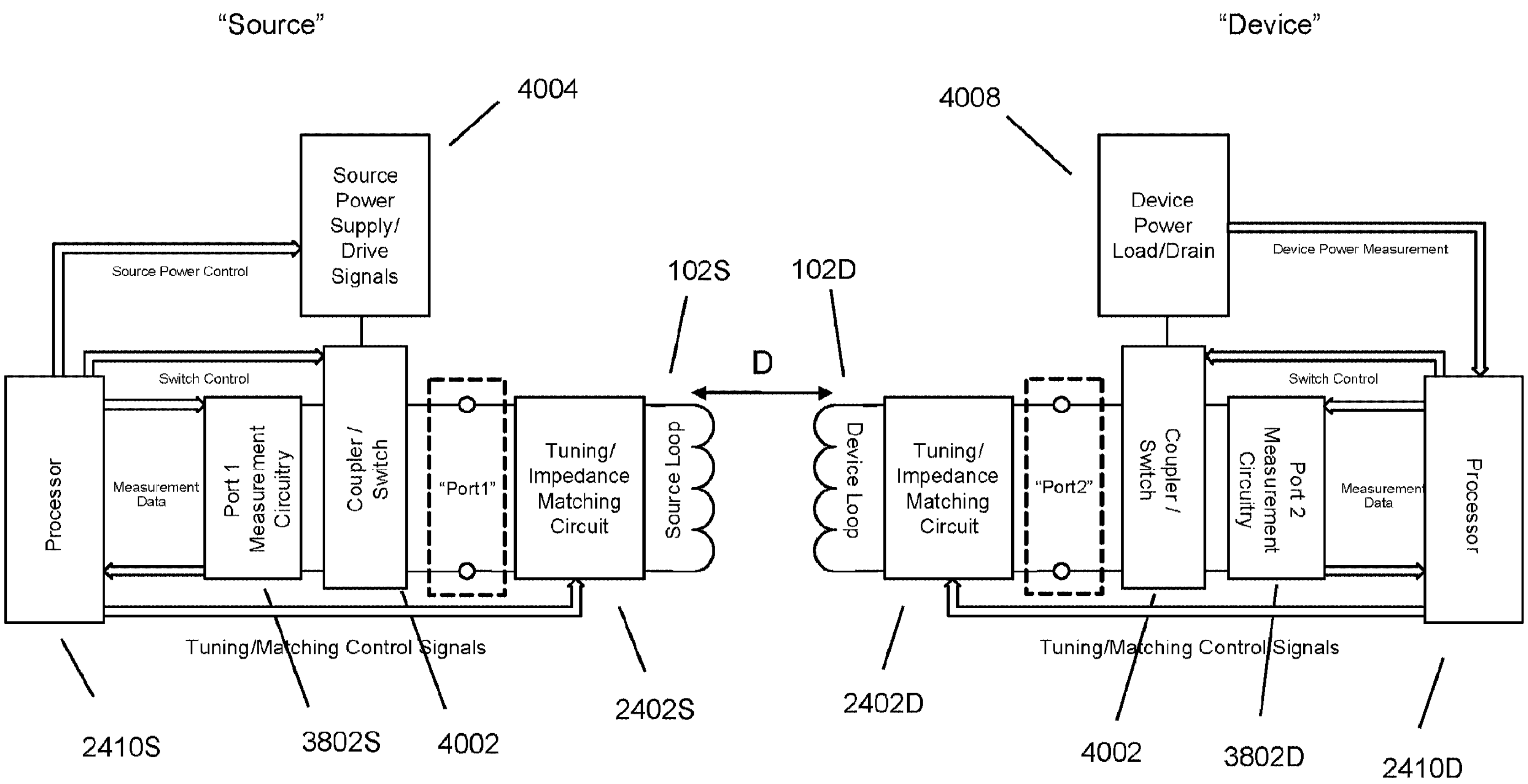

"Source"
"Device"
4004
4008
Source Power Supply/ Drive Signals
Device Power Load/Drain
Source Power Control
Device Power Measurement
102S
102D
D
Switch Control
Switch Control
Processor
Measurement Data
Port 1 Measurement Circuitry
Coupler / Switch
"Port1"
Tuning/ Impedance Matching Circuit
Source Loop
Device Loop
Tuning/ Impedance Matching Circuit
"Port2"
Coupler / Switch
Port 2 Measurement Circuitry
Measurement Data
Processor
Tuning/Matching Control Signals
Tuning/Matching Control Signals
2410S
3802S
4002
2402S
2402D
4002
3802D
2410D

Fig. 44

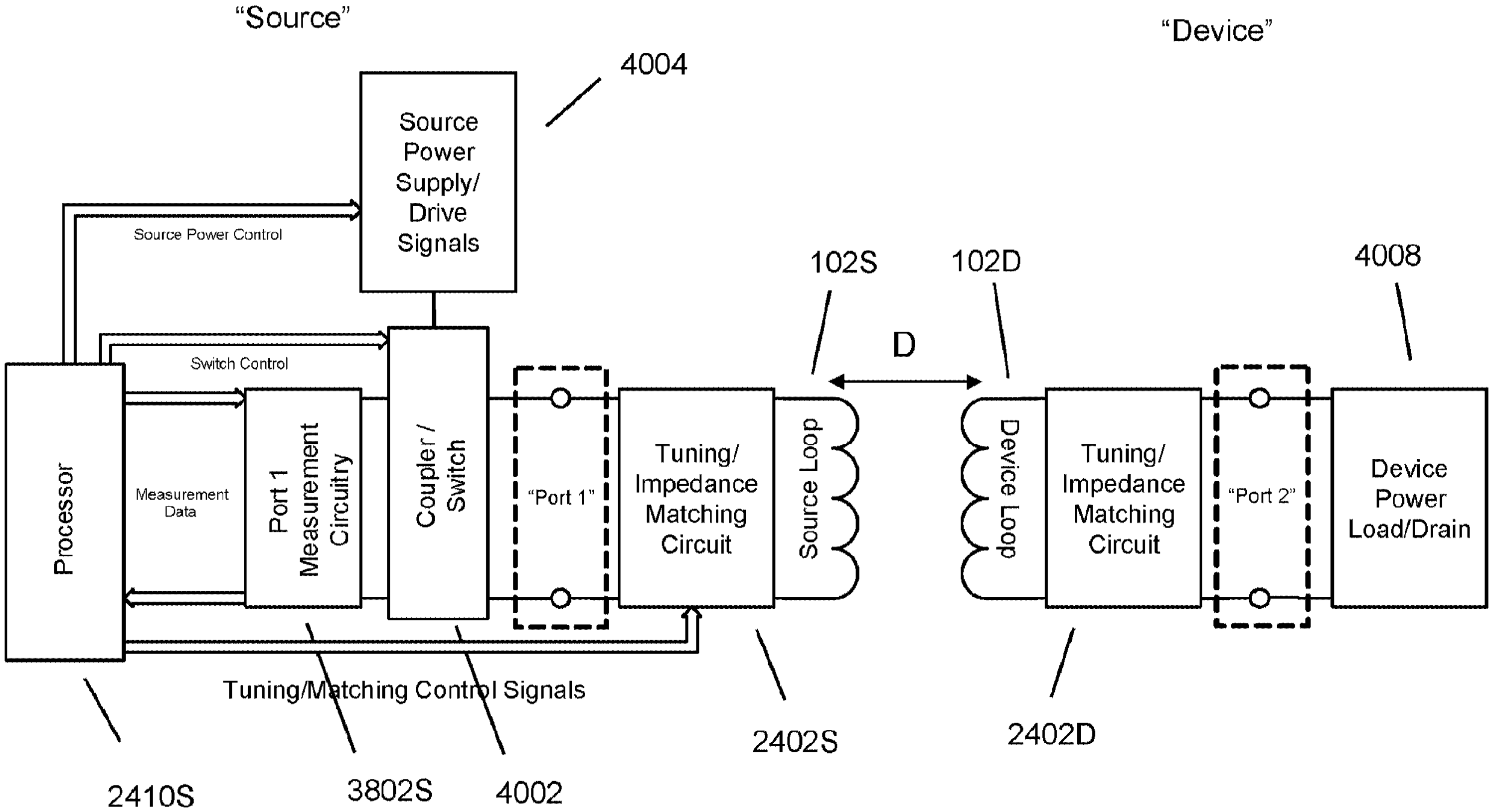

"Source"
"Device"
Source Power Supply/ Drive Signals
4004
Source Power Control
Switch Control
Processor
Measurement Data
Port 1 Measurement Circuitry
Coupler / Switch
"Port 1"
Tuning/ Impedance Matching Circuit
Source Loop
102S
102D
D
Device Loop
Tuning/ Impedance Matching Circuit
"Port 2"
Device Power Load/Drain
4008
Tuning/Matching Control Signals
2410S
3802S
4002
2402S
2402D

Fig. 45

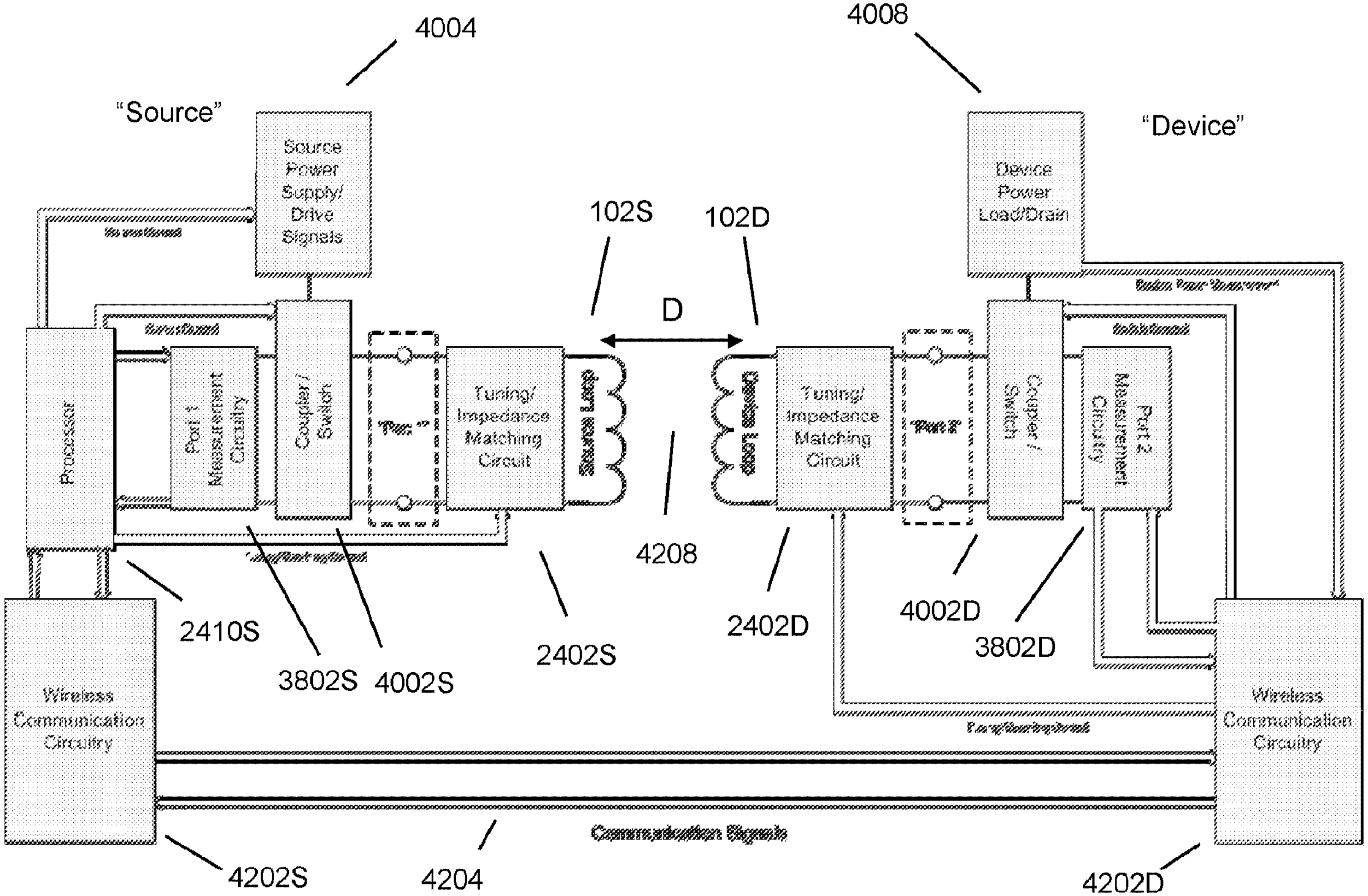
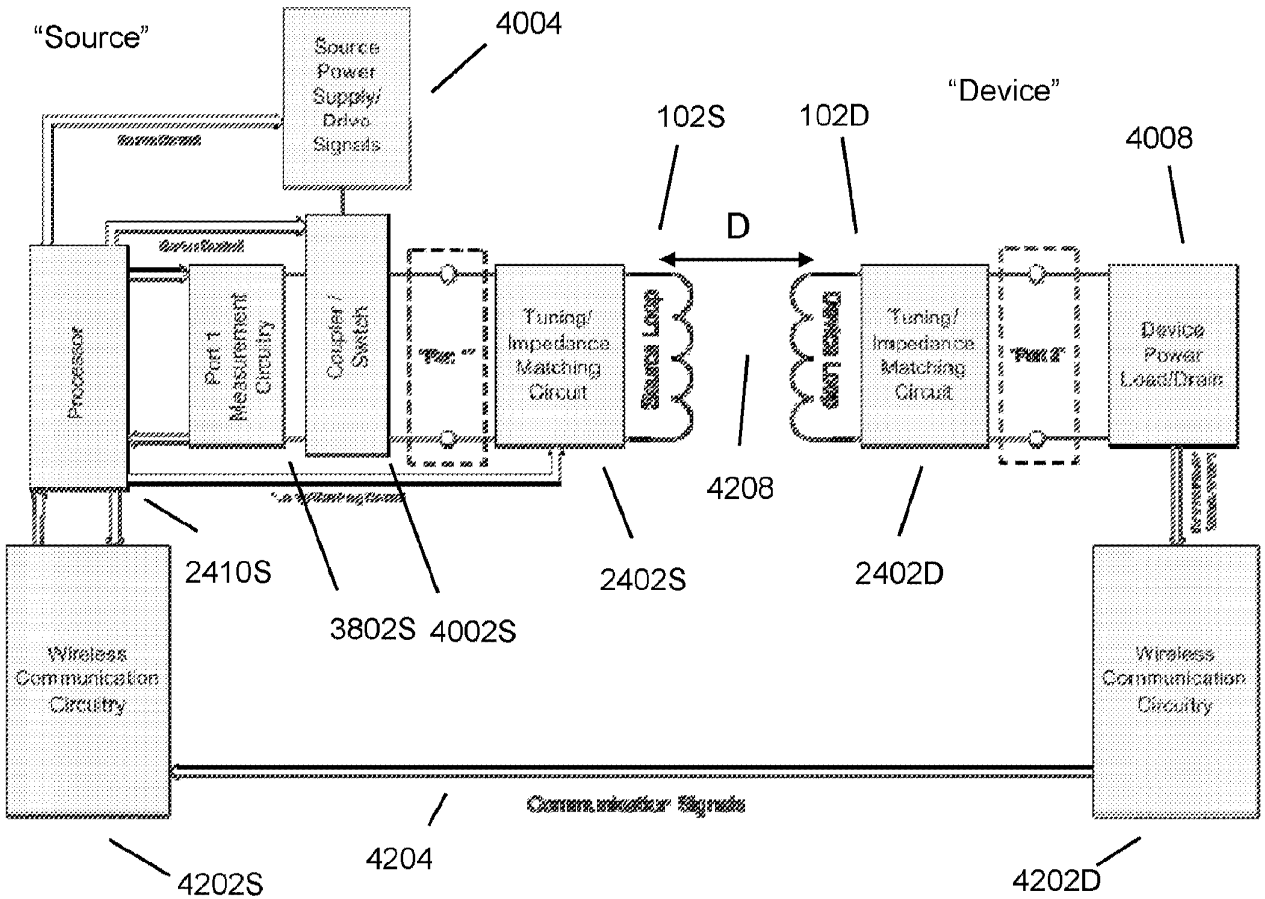

"Source"
4004
Source Power Supply/ Drive Signals
4008
"Device"
Device Power Load/Drain
102S
102D
D
Processor
Port 1 Measurement Circuitry
Coupler / Switch
Tuning/ Impedance Matching Circuit
Source Loop
Device Loop
Tuning/ Impedance Matching Circuit
Coupler / Switch
Port 2 Measurement Circuitry
4208
2410S
3802S
4002S
2402S
2402D
4002D
3802D
Wireless Communication Circuitry
Wireless Communication Circuitry
Communication Signals
4202S
4204
4202D

Fig. 46



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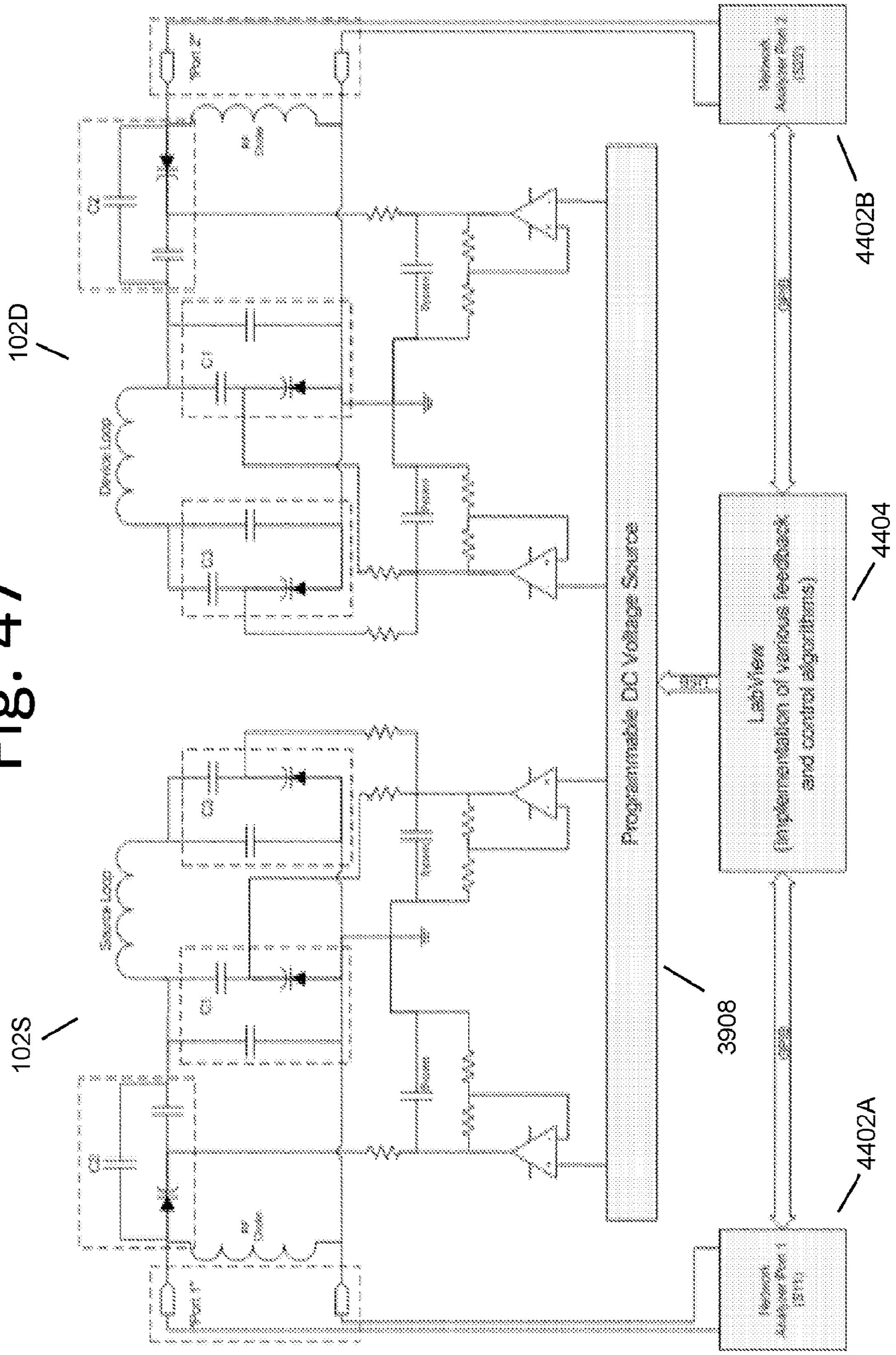
102D
102S
Programmable DC Voltage Source
3908
LabView
(Implementation of various feedback
and control algorithms)
4404
4402A
4402B

Fig. 47

Fig. 48

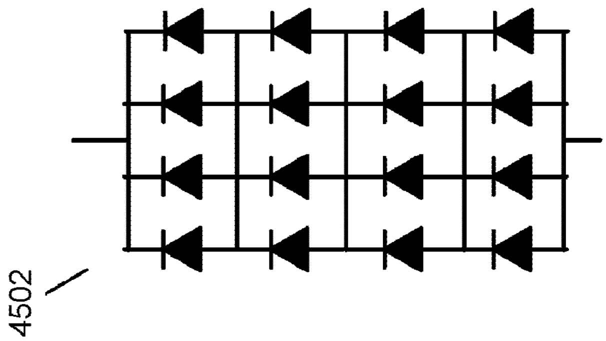

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Fig. 49

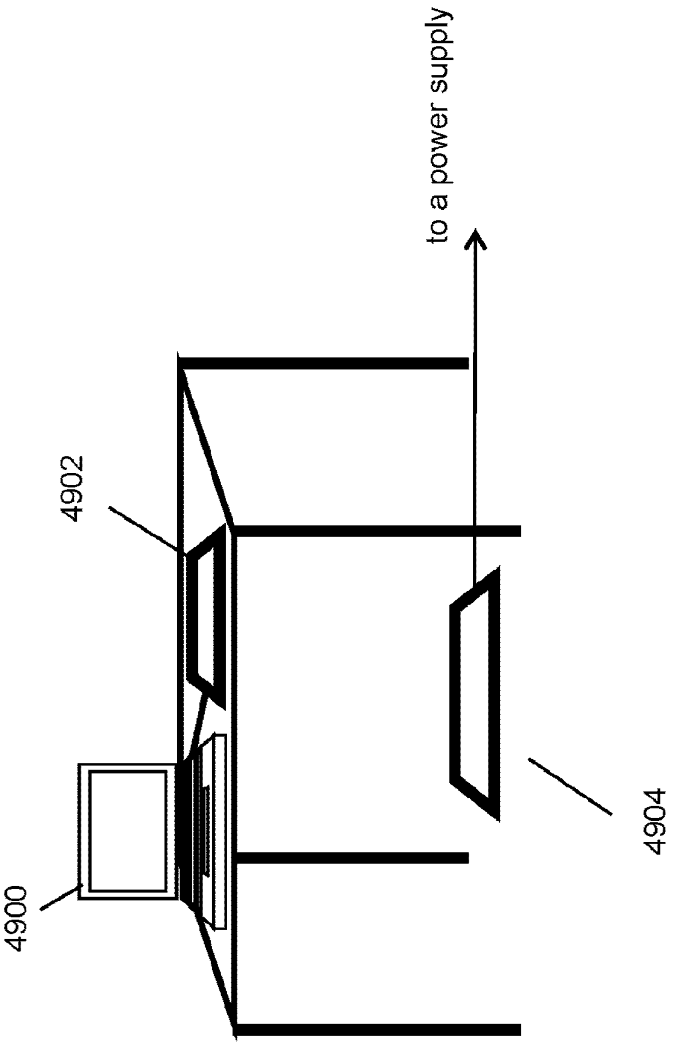

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Fig. 50

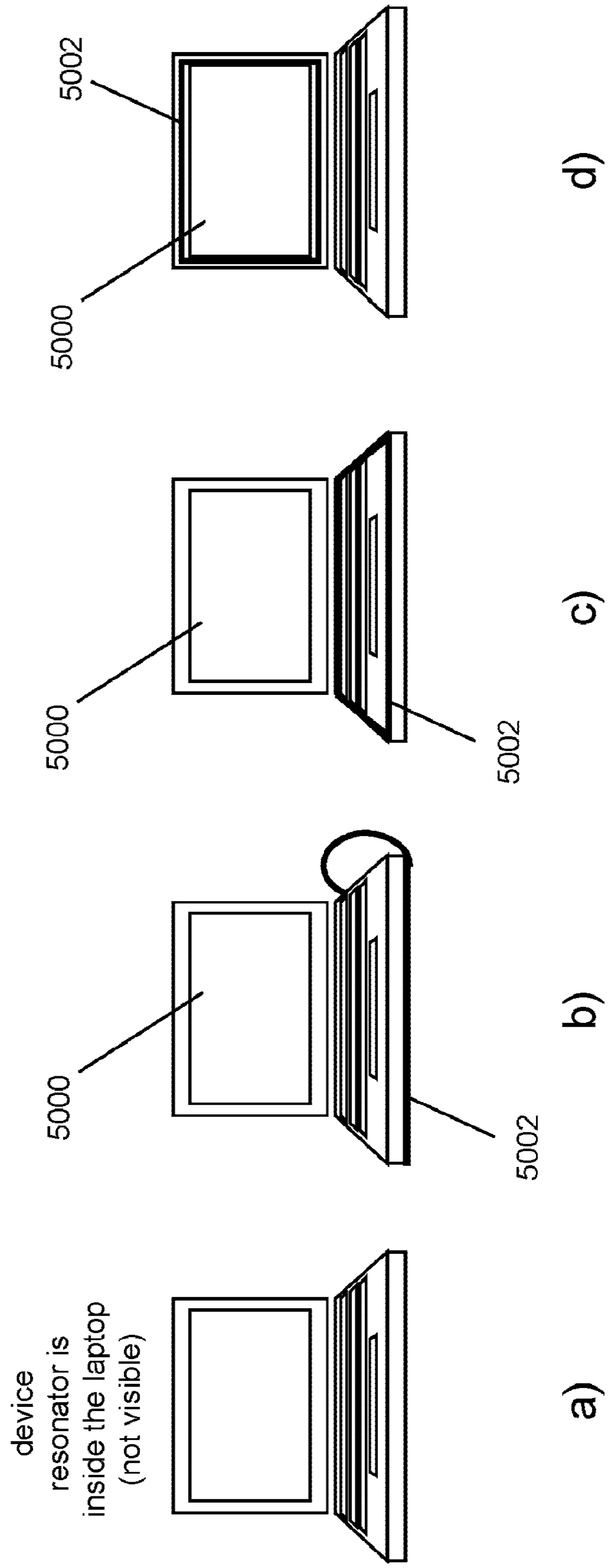
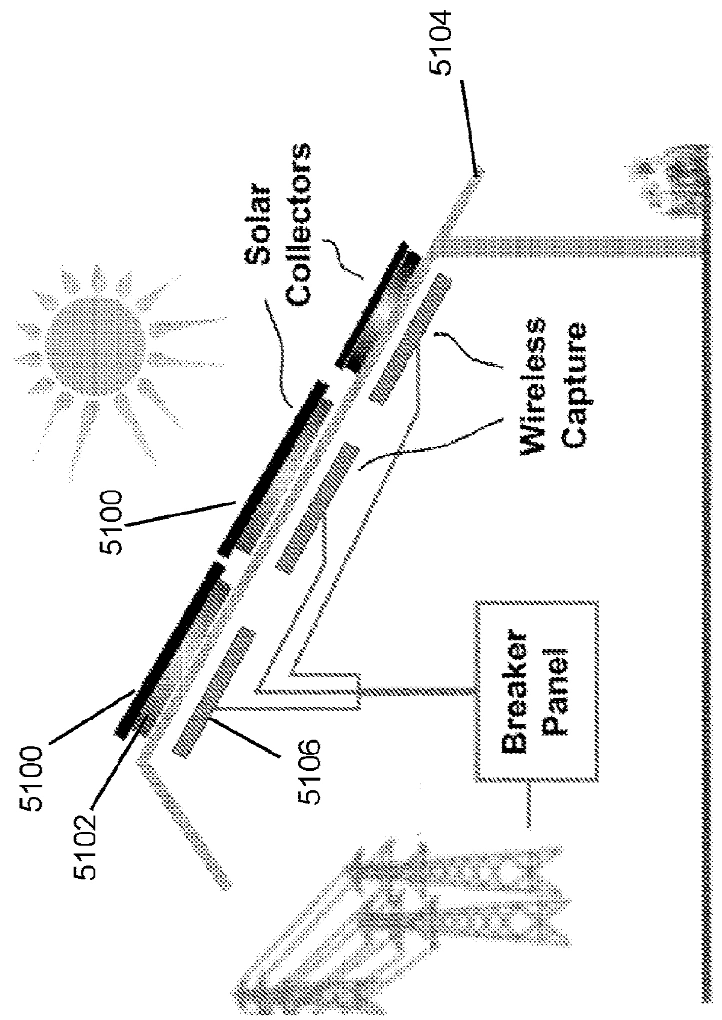

5002
5000
d)
5000
5002
c)
5000
5002
b)
device
resonator is
inside the laptop
(not visible)
a)

Fig. 51


5104
Solar Collectors
Wireless Capture
5100
Breaker Panel
5100
5106
5102

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 09/58499

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H03B 19/00 (2009.01)
USPC - 327/113
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC: 327/113

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 327/113, 306, 530, 555; 375/323; 307/134 (keyword limited - see terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST (PGPB, USPT, USOC, EPAB, JPAB); GOOGLE
Search Terms: energy, power, power generator, generator, wireless, resonator, first resonator, second resonator, third resonator, Q-factor, distance, tunable, oscillating, impedance, capacitance, load

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/0222542 A1 (Joannopoulos et al.) 27 September 2007 (27.09.2007), entire document, especially; abstract, para. [0004], [0005], [0013], [0014], [0019], [0023], [0025], [0029], [0033]	1 - 26
Y	US 6,452,465 B1 (Brown et al.) 17 September 2002 (17.09.2002), entire document, especially; abstract, col. 2, ln 4-6, col. 3, ln 7-12, 66-67	1 - 26

☐ Further documents are listed in the continuation of Box C. ☐

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Date of the actual completion of the international search	Date of mailing of the international search report
24 November 2009 (24.11.2009)	10 DEC 2009

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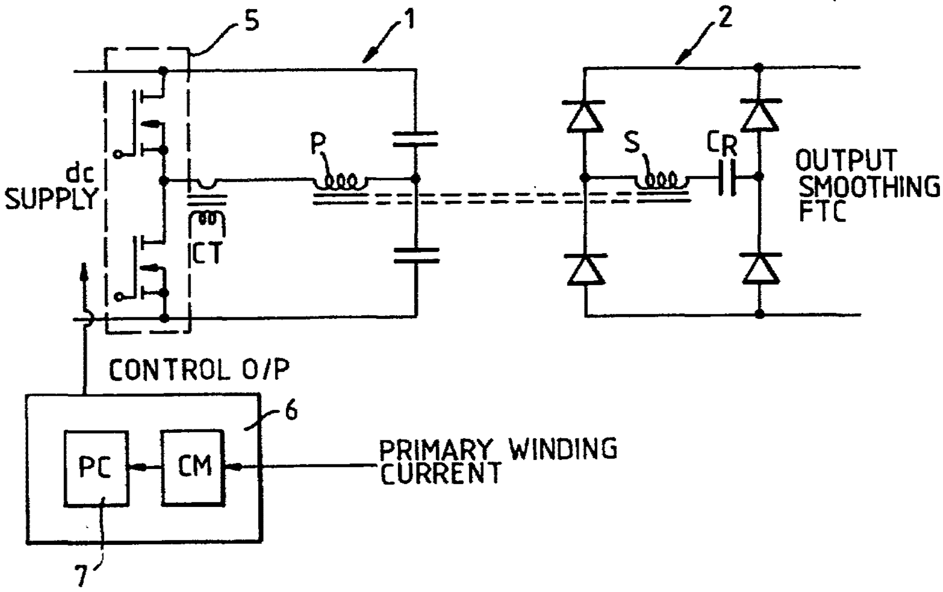
Published
With international search report.

(54) Title: POWER COUPLING



(57) Abstract

A power coupling system includes a source unit (1) which is to be connected to a power supply. The source unit (1) includes a first winding (P). A load unit (2) includes a second winding (S). Power is inductively coupled from the first winding to the second winding. The source unit (1) and load unit (2) are readily separable. The second winding (S) is connected in a resonant circuit. An AC voltage applied to the first winding (P) is tuned to the resonant frequency of the load circuit including the secondary winding leakage inductance. The source unit may be tuned automatically to the resonant frequency and may include a phase-locked loop responsive to voltages and currents in the source and the load.

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POWER COUPLING

BACKGROUND TO THE INVENTION

The present invention relates to a system for coupling electrical power from a source to a load.

Commonly, electrical equipment is connected to a power source by means of a plug and socket or by other arrangements involving direct physical contact between conductors, as in, for example, a domestic light fitting.

There are a number of situations in which the use of these conventional power coupling systems is inappropriate. In medical electronics, the need to ensure the safety of patients connected to the equipment often makes it undesirable that there should be a direct connection from equipment to the mains. In hazardous areas such as mines, oil refineries and chemical plants, there are considerable risks associated with the possibility of sparks occurring as contact is made. Even in domestic settings such as the kitchen or bathroom, the presence of water makes the use of conventional plugs and sockets potentially hazardous.

SUMMARY OF THE INVENTION

According to a first aspect of the present invention, there is provided a power coupling system comprising a source unit arranged to be connected to a power supply and including a first winding and a load unit including a second winding, in use power being inductively coupled from the first winding to the second winding, and

the source unit and load unit being readily separable, characterised in that the second winding is connected in a resonant circuit, and in that an AC voltage applied to the first winding is tuned to the resonant frequency of the load circuit including the secondary winding leakage inductance.

Preferably the system includes a variable tuning circuit arranged to control the frequency of the voltage applied to the first winding in dependence upon the said resonant frequency of the load circuit.

The power supply system of the present invention replaces conventional direct conduction of current from the source to the load by inductive coupling between a primary winding connected to the source, and a secondary winding connected to the load. The primary and secondary windings are not formed around a common core as in a conventional transformer, but are located in physically separable units and power is inductively coupled across an air-gap. Since there is no requirement for a direct physical connection, the different units can be entirely encapsulated, making the system safe for use in hazardous environments such as those discussed above.

It has previously been suggested, in a few specialised fields of application, to use inductive coupling of a power source to a load. For example, it has been proposed to provide a charger for an electric vehicle in which a primary winding in the charging unit is brought into the proximity of a secondary winding of a circuit connected to the vehicle batteries. The system operates at the mains frequency of 50 Hz. However, such systems suffer a number of serious limitations and so hitherto have not found wide acceptance. By comparison with conventional transformers in which the two windings are formed on a common core, the amount of flux leakage is greatly increased and so the efficiency with which power is coupled across the system is very poor. In practice, therefore, such systems have only been used where the power requirement of the load is small.

The present invention overcomes these disadvantages to provide a power coupling system of sufficiently high efficiency to be of use in a wide range of applications. This achieved by providing in the source unit a control circuit arranged to drive the primary winding at a frequency substantially matched to the resonant frequency of the load circuit including the secondary winding leakage inductance. Operation in this manner provides power coupling with high efficiency despite the presence of significant leakage inductances. At the same time, the relatively high frequencies involved makes it possible to reduce the size of the windings to the extent that a load unit can readily be accommodated within many otherwise conventional items of electrical equipment. Because it relies upon tuning to a resonant frequency within a certain range, a system embodying the present invention will not in general couple power, e.g., to a metal object which accidentally comes into contact with the source. The system therefore offers improved safety.

Preferably the control means include a detector responsive to the phase difference between voltage and current in the source circuit or between the source unit voltage and the load unit current as referred to the source unit and arranged to produce a control output dependent on that difference.

Preferably the source unit includes an inverter switched at a frequency determined by the control means.

Using the system of the preferred aspects of the present invention, as the load unit is brought nearer the source unit the load impedance is reflected into the source circuit, reducing the phase difference between voltage and current in that circuit. A phase comparator detects this change and in response to it changes the operating frequency of the inverter so that it becomes closer to the load circuit resonant frequency. As a result, the load circuit driving impedance is reduced, as the frequency of the inverter approaches the resonant frequency of the load circuit.

Preferably the control circuit is arranged to drive the primary circuit at a high frequency in the absence of a load, and to reduce the operating frequency of the inverter as the load approaches. With no load present operating at high frequency, the primary reactance is high resulting in low primary current and low resultant magnetic field strength.

This control arrangement can adjust the operation of the inverter to suit a wide range of load impedances and air gaps. When the source unit has "acquired" the load unit it will operate with air gaps of 0 to about 10% of the total magnetic path length. Circuit efficiency is high when operating in this resonant mode, and with appropriate design of the magnetic core components, stray magnetic fields can be reduced to acceptable levels both when the load unit is present and absent. When no load is present the primary current is small.

Preferably the load winding is formed on a core having a re-entrant portion and the source winding is formed on a core having at least a portion which in use locates in the re-entrant portion of the load core as the load and source are brought together.

Possible applications for the power transfer system include emergency lighting in hazardous areas, plug-in lighting systems for such areas, rechargeable lanterns and torches for marine and industrial use and lanterns or emergency lamps for domestic use, and ultra low leakage power supplies for electronic equipment in, e.g., medical applications. In the case of lighting, luminaries incorporating a non-contact power supply system can be re-lamped without it being necessary for the entire power system to be shut down. The power transfer system is also of particular value in enabling isolation from the effects of large supply transients and common-mode effects which are common, for example, in electric railways.

The systems embodying the present invention are particularly useful in enabling the coupling of both power and data between units which move with respect to each other. Such a system may be used, for example, with a button or other equipment mounted on a sliding door. Another important field is in the use of transducers mounted in a rotating wheel or a rotating turbine. Systems embodying the present invention facilitate the transmission of electrical power from a fixed power supply to the load unit which is mounted with the rotating transducer inside the wheel or turbine.

As will be described in further detail below, power coupling systems embodying the present invention can readily be adapted for the transmission of data using frequency-shift keying techniques without disturbing the transmission of power.

According to a second aspect of the present invention, there is provided a method of coupling power inductively from a source to a load characterised by bringing separable respective source and load units into proximity, the load unit including a winding connected in a resonant circuit, and driving the source at a frequency substantially matched to the resonance frequency of the load, including the load winding leakage inductance.

BRIEF DESCRIPTION OF THE DRAWINGS

A system in accordance with the present invention will now be described in further detail with reference to the accompanying drawings, in which:

Figure 1 is a simplified circuit diagram;

Figure 2 is a diagram showing a rechargeable lantern incorporating the circuit of Figure 1;

Figure 3 is a diagram showing a lumped-circuit model of the transformer;

Figure 4 shows the control characteristic in a first embodiment;

Figure 5i and 5ii shows a current monitoring circuit for a third embodiment;

Figure 6 shows current waveforms for the circuit of Figure 5i and 5ii;

Figure 7 shows the control characteristics of a second embodiment; and

Figure 8a is a schematic a bridge inverter for use in a source unit and Figures 8bi,8bii and 8ci-8civ are detailed circuit diagrams;

Figures 9a to 9d show different alternative configurations for the cores and windings in the source and load units;

Figure 10 is a circuit diagram of a load unit adapted for transmitting a simple logic signal;

Figure 11 is a circuit diagram of a load unit adapted for a continuous data transmission;

Figure 12 is a diagram showing schematically a power coupling system for use underwater; and

Figure 13 is a diagram showing schematically a source and load unit used to provide a power connection to a wheelchair battery charger.

DESCRIPTION OF EXAMPLES

A power coupling system comprises a source unit 1 and a load unit 2, each of which is normally contained within a separate housing. The load unit may, for example, be incorporated in the base of a housing of a rechargeable electric lantern L. The source unit 1 in this case is located in the housing of a charging unit for the lantern.

The source unit comprises a primary winding 3 formed on an associated core 4. The winding is driven via a half-bridge inverter 5. Alternatively, for circuits handling higher power levels, a full bridge inverter may be used. A control circuit 6 including a current monitor CM and phase comparator 7 controls the frequency of switching of the inverter 5. The phase comparator employs exclusive-OR logic devices to provide an output which, after filtering, increases linearly from 0 as the phase difference between the input signals arises. Phase comparison might alternatively be carried out using other logic devices in an equivalent circuit, or integrated circuits such as phase-lock loops. An appropriate device of this latter sort is device 74HC4046A from the standard 74 Series Logic family. The control circuit may be constructed using conventional discrete logic and linear components, or alternatively may be formed as an ASIC, or a thick film hybrid assembly.

The load unit 2 includes a secondary winding 8 on an associated core 9, together with a rectifier and any further smoothing and regulating circuitry required by the particular load. A series resonating capacitor CR is connected between the secondary winding and the output circuitry.

As will be described in further detail below, the reactance of the resonating capacitor, in conjunction with the leakage inductance and any load inductances associated with the secondary winding creates a resonant circuit. The control circuit 5 in the source unit is effective to control the frequency of the source so that it generally corresponds to the resonant frequency of the load circuit. The frequency of operation of the source will typically be within 10% of the resonance frequency and may match the resonance frequency to within 1%. Typical frequencies of operation are from around 100 kHz to 1 or 2 MHz, according to the power requirements of a particular load.

Figure 8a shows in further detail the half bridge inverter 5 of the source unit 1. Parasitic transistor elements are shown in broken lines. The transistor switches in the two arms of the bridge are both power MOSFETs. Suitable devices for a 200 W load are available as model no. IRF 840 manufactured by International Rectifier. Such devices offer high switching speeds but in conventional use suffer the disadvantage of significant power dissipation in the switches.

As conventionally operated, Mosfet switches Q1 and Q2 are driven by anti-phase square wave signals so that the switches conduct alternately. Capacitors C1a and C1b are relatively large so that the voltage at point X remains sensibly constant at Vd/2. This implies that

$$IL/(4fC1) << Vd$$

where IL is the load current as shown on the diagram, f is the switching frequency and C1 = C1a = C1b.

Suppose that switch Q1 is conducting and load current is flowing as shown in the diagram.

The parasitic capacitance CQ1 of switch Q1 will be uncharged (voltage across switch effectively = 0) while CQ2 will be charged to Vd.

Now let Q1 be turned off and Q2 be turned on. The voltage at point Y must fall from Vd to effectively zero. CQ1 must charge to voltage Vd while CQ2 must discharge to zero. The charge and discharge currents must flow via Q2 and power dissipation can be high.

When, at the end of the next half cycle of operation, Q2 turns off and Q1 turns on, a similar action occurs but with energy being dissipated by Q1.

In contrast with the mode of operation described above, if the load is highly inductive then, when Q1 is turned off the load current will continue to flow, the driving force being provided by the energy stored in the magnetic field associated with the inductive load. Current transfers from switch Q1 to capacitors CQ1 and CQ2, charging Q1 and discharging Q2. When the voltage at Y falls to just below zero, diode D2 conducts "catching" the voltage at Y and preventing further fall in voltage. Transistor Q2 can now be turned on without power loss since the switching action will occur with diode D2 conducting and, therefore, almost zero voltage across the transistor. The current through the load will then fall to zero at a rate set by the circuit parameters and then reverse in polarity, flowing via Q2.

In systems embodying the present invention, by using a load coupling transformer with low magnetising inductance the magnetising current is made high and operation in the mode just described can be ensured. The circuit therefore operates with near-zero switching losses in Q1 and Q2. The increased magnetising current leads to increased on-state losses in the switches and in the transformer primary winding resistance but this is offset by the reduction in switching loses, especially at high switching frequencies as are used in NCET.

Figure 2 shows one construction for the transformer cores, and the location of the cores in relation to the housing for the source unit and load unit. The use of a shape having a re-entrant portion for one of the cores and a complementary projecting shape for the other of the cores serves to reduce the stray flux as the load and source unit are brought together. This increases the efficiency of the system, and also serves to reduce radio-frequency interference.

Figures 9a to 9c show further alternative constructions for the transformer cores. Again the shape and configuration of the cores is chosen to maximise the efficiency with which the flux is coupled across the air gap. In Figure 9a, the ferrite core 91 is U-shaped with a winding, indicated by the hatching, formed around the base of the U. The second core 92 is also generally U-shaped but with smaller dimensions than the first core so that it fits within the re-entrant portion of the first core. The tips of the arms of the smaller U-shaped core 92 are cut away as shown in the Figure so that the surface of the arm is closer to the winding on the first core 91 in the region towards the edge of that winding. This serves to increase the uniformity of the field and reduce the flux leakage in that region towards the edge of the winding. Either of the cores may be used as the primary, that is to say for the source unit, but it is preferred to use the smaller core 92 for the source because the source magnetic assembly is then contained by the load assembly and stray field leakage is reduced.

Figure 9b shows another arrangement for the cores. In this example, the cores are generally cylindrical. The first larger core 93 again has a re-entrant portion which receives the second smaller core 94. The arms of the core

93 bounding the re-entrant portion are generally annular in plan. The outer edges of the smaller core 94 and the opposing portions of the larger core 93 are cut away as shown.

In the core structure shown in Figure 9c, a dual E-core structure 95, 96 is used for one of the windings, say the primary, and the other winding 97 on ferrite core 98 is inserted into a slot formed between the two E-cores. This arrangement is particularly suitable for a power coupling systems to be used as a substitute for a conventional plug and socket for users having limited dexterity. The load unit incorporating the secondary winding can then be formed as a simple card or plate which is dropped into the slot provided in the source unit.

If the transformer comprising the primary and secondary winding is considered as a lumped circuit element as shown in Figure 3, the inductance at the secondary output terminals as seen by the secondary-side circuitry is given by:

$$Lout = Ll2 + Lm2 \text{ in parallel with } Ll1 * \left[\frac{Lm2}{Lm1}\right]^{0.5} \qquad (1)$$

The secondary winding open-circuit voltage is given by:

$$V2(oc) = \frac{V1Lm1}{Lm1+Ll1}\sqrt{\left[\frac{Lm2}{Lm1}\right]} \qquad (2)$$

The resonant frequency of the secondary circuit is:

$$f\ RES = \frac{1}{2\pi\sqrt{LoutCR}} \qquad (3)$$

The air-gap between the two parts of the transformer controls the primary and secondary magnetising inductances Lm1 and Lm2 and the leakage inductances Ll1 and Ll2. As the air-gap is changed, the open-circuit secondary voltage, the source impedance presented to the secondary circuit and the resonant frequency of the secondary circuit will all vary.

On the primary side, the low magnetising inductance of the primary winding requires a high magnetising current in phase-quadrature with the applied voltage. If a square-wave drive voltage is employed the current will not only be in quadrature but will be of triangular waveform.

The transformer primary voltage and current are monitored by the source unit control circuitry which includes a phase comparator to provide a signal which is a function of the phase difference between voltage and current. In a first embodiment, this signal is used to modify the operating frequency of the source unit inverter so that the relation is as shown in Figure 4.

The circuit operation is arranged so that if power is applied to the source unit with no load unit present, the inverter operates at a frequency lower than the resonant frequency defined in Equation 3, and with the primary current lagging the applied voltage by, sensibly, 90°. As the load unit is brought near to the source unit, a capacitive impedance is reflected into the primary circuit and the phase difference is reduced. This causes the operating frequency of the inverter to be increased so that it becomes closer to the secondary circuit resonant frequency. In consequence the load circuit driving impedance is reduced. The control circuit adjusts the inverter drive so that operation occurs close to the resonant frequency using an exclusive - OR type phase comparator with the inputs being the sense of the voltage applied to the primary winding (source unit) and the inverse of the sense (polarity) of the primary current. This produces a 50% duty-cycle output when the current lags the voltage by 90° increasing linearly with phase to 100% duty-cycle when the current is in-phase with the voltage. The output of the phase comparator is filtered to produce a dc level which is used as the input to a voltage controlled oscillator (VCO), the output of which controls the power MOSFET switches in the source unit.

In a second embodiment of the control system, operation takes place so that with no load present the frequency at which the primary is driven is higher than the resonant frequency of the load. As before, the magnetising current for square-wave excitation is of triangular wave shape and lags the driving voltage by 90°. The current amplitude required is less than in the first embodiment because of the increased operating frequency. This second embodiment uses an exclusive OR type phase comparator with the inputs being the sense of the voltage applied to the primary winding (source unit) and the sense (polarity) of the primary current. This produces a 50% duty-cycle when the current lags the voltage by 90° decreasing linearly with phase to 0% duty-cycle when the current is in-phase with the voltage. The output of the phase comparator is filtered to produce a dc level to which is used as the input to a voltage controlled oscillator (VCO) the output of which controls the power MOSFET switches in the source unit. The control characteristic for this second embodiment is as shown in Figure 7.

A third embodiment of the control system (Figures 5i and 5ii) includes, in the primary current monitoring circuit, two cascaded differentiator circuits and voltage amplifiers before the phase comparator. Consider with reference to Figure 6 the operation of the circuit with a light load. For the triangular magnetising current component, the first differential will be a square-wave leading the triangular current by 90°. The second differential consists of spikes of alternating polarity leading a further 90° on the current signal. The referred load current signal, being near-sinusoidal, will be unmodified in shape by the differentiators but will undergo phase inversion. The output signal from the differentiator-amplifier system, which will be as shown in Figure 6(H), is fed via a limiting amplifier, Figure 6(I), to the phase comparator together with a signal developed from the drive voltage. The output of the comparator controls the operating frequency of the inverter, moving the frequency towards resonance.

Shown in Figure 8cii is a low cost realisation of the double differentiator circuit which uses CMOS 4069 unbuffered inverters in the linear mode. These devices are taken from the 4000 series of CMOS logic devices. The 4069 used in the linear mode has poor dc performance and requires the output to be ac coupled. The same technique may be used with high performance ac amplifiers/video amplifiers to produce a high frequency (>500 kHz) controller.

The input signal to the cascaded differentiators is taken from winding T1C, (Figure 8ci) which is a current transformer placed in series with the primary winding (see Figure 8b) with auxiliary load current compensation by means of current transformer T3. Resistors R19, R23, R24 and capacitor C25 act as a burden across which a voltage approximately proportional to the primary current is generated. This voltage is used to drive the differentiator circuits. Sketch waveforms are included in Figure 8ci.

The output of the second differentiator (IC2B) is amplified using a voltage comparator and Schmitt-triggered inverter to produce a digital waveform representing the polarity of the secondary (load unit) resonant current. This waveform IRES is applied to the clear direct (CD) input of a D-latch (IC5B) a 4013 device which is gated (Clocked) by the inverted output of the VCO (IC6) of a 4046 CMOS phase-locked-loop. The Q output of IC5B is a pulse train with a duty-cycle dependent upon the phase-lag between the clock (CLK) and Clear Direct (CD) inputs and hence on the phase-lag between the secondary circuit resonant current and the primary voltage. IC5B is used as an edge triggered phase comparator the output of which is zero if the signal applied to the CD input leads that applied to the clock (CLK) input and rises linearly from zero output for in-phase signals to 25% duty-cycle when the signal applied to the CD input lags that applied to the CLK input by 90%.

The D-latch IC5A is used to provide primary side current limiting by forcing the frequency of operation to increase if the sensed primary current exceeds a pre-determined threshold. If this occurs the output of IC3A goes low forcing the $\bar{Q}$ output of IC5A low and the output of IC7A high. The $\bar{Q}$ is set back to a logic 1 synchronously with the resonant circuit once the overcurrent condition has been removed.

The output of IC7A (the phase comparator output if not in an overcurrent condition) is buffered and filtered and compared with a pre-set reference. The difference between the filtered output of the phase comparator and the reference is inverted and amplified by IC30D and used to control the VCO in IC6. The output of IC6 is buffered and used to drive transformer T4 which gates the power MOSFETs M1 and M2 shown in Figure 8bi. This example of the third embodiment uses a closed feedback loop with the phase of the resonant circuit current (with respect to the primary voltage) being maintained close to a pre-set level preferably close to zero to provide a low impedance output.

A second input to the VCO may be included using the OR-ing diode D17 shown in Figure 8ciii. This allows a second control-loop to be included which monitors the output voltage and modifies the frequency of oscillation to achieve output regulation; the phase-controlled loop ensuring that operation below resonance does not occur.

The capacitor C38 shown in Figure 8bii may be included to reduce the operating frequency range required to achieve output V regulation for a given load/supply voltage range. C38 changes the power circuit to a parallel loaded circuit at high operating frequencies, giving better control of the output voltage under light load.

Using this approach, it is possible to detect the phase of the referred load current even when it is small compared with the magnetising current. Very light loads are therefore acquired by the primary circuit so that efficient operation at near-resonant frequency occurs for a very wide range of load and coupling conditions.

The control arrangement can adjust the operation of the inverter to suit a wide range of load impedances and air-gaps. When the source unit has acquired the load unit it will operate with air-gaps of 0 to about 10% of the total magnetic path length. Circuit efficiency is high, producing power outputs ≥ 1kw at efficiencies greater than 90%, with near-unity power factors, e.g. greater than 94% at 2.5kw output, when operating in this resonant mode and stray magnetic fields are reduced to acceptable levels by appropriate design of the magnetic core components. Power efficiency in this context is defined as the ratio of dc power output in the load to dc power input in the source. When no load is present the primary current is small.

The power coupling circuit may also be used for signalling from the source unit to the load unit. Figure 10 shows a load unit which in this example is designed to provide a DC output. This circuit has been modified to allow information about momentary operation of a switch, that is simple transient logic information, to be transmitted from the load unit to the source unit.

In the secondary circuit, capacitor CR resonates with the secondary-side leakage inductance and wiring parasitic inductance. Capacitor C1 acts as an AC short-circuit and isolates the smoothing inductor L1 from the resonant circuit.

Resistor R1 and transistor Q1 (Q1 is a MOSFET) are added to the output circuit to enable transmission of the signal from load unit to source unit. When Q1 is momentarily turned on, current flows via R1 and Q1, increasing the loading as seen by the primary unit. This increase is arranged, by choice of R1 to be substantially greater than the maximum increase resulting from normal load changes. A simple threshold detector in the source unit is used to sense changes in the current demand within that unit, and thereby to recover information about operation of switch Q1 in the load unit.

One possible use for such an arrangement is the transmission of information relating to the operation of a push-button switch mounted, for example, in a sliding door in a railway carriage. Because of the movement of the door conventional wired connections present considerable problems, and these can be overcome by using an inductive connection with the circuit as described above.

Figure 11 shows a further example of a load circuit modified to allow digital data transmission from the load to the source. Additional components are capacitor CR2, transistors Q1 and Q2, and drive transformer TR1. Q1 and Q2 are again Mosfets. All other components are as in the original circuit described above with reference to Figure 10.

Transistors Q1 and Q2 form a bi-directional switch (Bright switch) which is controlled by the data signal via transformer TR1 which provides signal isolation. With the switch undriven and non-conducting, the secondary resonant circuit consists essentially of capacitor CR1 and the coupling transformer secondary leakage inductance. When the switch conducts, capacitor CR2 is connected in parallel with CR1 and the resonant frequency falls.

The primary (source) unit control circuitry contains a phase-locked loop (PLL) which monitors the phase difference between the primary winding voltage and the secondary winding current as referred to the primary. The PLL produces an output voltage proportional to phase difference which controls the frequency of a voltage-controlled oscillator (VCO) so that the primary unit inverter is driven at the resonant frequency of the secondary circuit.

As the secondary (load) side switch, formed by transistors Q1 and Q2, is operated, the resonant frequency of the secondary circuit changes and the PLL output voltage changes in order to move the drive frequency to the required value. The PLL output voltage is passed, via a filter serving to remove system noise, to a logic output stage and the signals controlling Q1 and Q2 in the secondary unit are thereby recovered in the primary unit. With such a circuit, the maximum data transmission rate is approximately 10% of the lower of the two resonant frequencies of the load circuit.

Load and source units embodying the present invention can be used to provide a universal power coupling system enabling a variety of source voltages and load voltages to be handled using standard components. All that is required for such a set is that the load and source units should operate within a defined maximum power level, in a certain frequency range, and at a certain flux density. The control electronics in each source unit can then be designed to sense the presence of a resonant load circuit tuned in the correct frequency range, and then to adjust the drive frequency of the primary unit inverter to the actual resonant frequency. The ratings of the power stage electronic components would be determined primarily from the power output required and the supply voltage to be used.

The physical size of the magnetic coupling components is chosen with reference to the frequency of operation and the maximum power to be transmitted. In any given source unit, the number of turns forming the primary winding is chosen as a function of the supply voltage, frequency of operation and magnetic circuit dimensions and parameters. A number of different primary units may be constructed to operate, for example, one from a 240V 50Hz supply and another from, say, a 50V DC supply. The units operate at the same frequency and the same magnetic flux density and have magnetic assemblies of the same dimensions. The difference in supply is then "transparent" to the load units which receive the same driving conditions from either source unit.

For the secondary (load) units, the dimensions and number of secondary winding turns are functions of the power level, frequency, flux density, and of the structural dimensions of the source unit. The number of turns on the secondary winding is selected to produce a correct desired output voltage when coupled to the standard AC magnetic field of the source units. A range of secondary units can be designed, all of the same physical dimensions and requiring magnetic fields of the same frequency and strength, but providing different output voltages. When secondary-side power processing electronics is added the range of outputs can be very wide, e.g: 5V @ 50A dc; 100V @ 2.5A dc; 5000V @ 50mA dc; 240V, 50Hz ac.... Since for a given frequency of operation, flux density and physical size and form, any secondary "plug" will correctly couple to any primary "socket" a non-contact plug and socket range can be provided which operates from various input voltages and, if the plug is hard wired to the load, always provides the correct drive voltage for the load.

Such a system of universal connectors may be of particular value for use with underwater power tools. Equally any single load unit/source unit system embodying the present invention can offer significant advantages in this context. Conventional so-called wet-mating assemblies used hitherto require complex sealing systems which exclude the water from contact with the power conductors. With such conventional assemblies it is not safe to mate or separate the connectors with the power turned on. In practice often a key interlock system is used, with a diver having in his possession a key necessary to operate a surface power supply while he makes the physical connection between the plug and socket assemblies, and the diver then having to return to the surface to return the key before the power can be turned on.

All these practical problems can be avoided using the non-contact power transfer system of the present invention. With this system true wet-mating is possible: the load unit and source unit can be mated or separated under water and with the power applied. The physical arrangement for the mating can be a simple clip arrangement and there is no need to exclude water.

With a set of universal wet-mating connections, there is the further advantage that a range of different tools having different power supply requirements can be plugged in to a single source unit without the user having to ensure correct matching of a particular tool to a particular power source. Thus, in the example shown schematically in Figure 12, a first tool 121 operating at 12V and a second tool 122 operating at 240V both are wired to a respective secondary unit 123, 124 which generates the correct voltage when mated with the source unit 126. Power to the source unit 126 is supplied from a surface generator 127.

A further example of possible fields of use for systems embodying the present invention, is in the provision of connectors for a power supply for charging the battery of an electrically operated wheelchair. Often a user of the wheelchair will have limited strength or dexterity. Accordingly manipulation of a conventional plug and socket for connecting a charger to the wheelchair battery can present considerable difficulties. These difficulties can be overcome by replacing the conventional plug and socket with a non-contact load unit/source unit constructed in accordance with the present invention. The load unit which is a charging circuit 131 for the battery 132 on the wheelchair 133 may include a slotted double-E coil as discussed with respect to Figure 9c above. This provides the "socket" the source unit 134 is the "plug" used to make the connection. This "plug" containing the source coil is card-shaped and is connected to the mains at its remote end. The user then simply has to drop the card into the socket 135 in the load unit to establish a connection to the mains. Alternatively other non-contact assemblies may be used in different configurations.

The tables below show components for Figure 5 and Figure 8 respectively.

TABLE 1

RESISTORS			
R25	100Ω	2%	0.5W
R26	15KΩ	1%	0.125W
R17	22KΩ	1%	0.125W
R28	22KΩ	1%	0.125W
R37	10KΩ	2%	0.125W
R38	1KΩ	2%	0.125W
R39	1.5MΩ	2%	0.125W
R40	820KΩ	2%	0.125W
R41	1KΩ	2%	0.125W
CAPACITORS			
C36	2n2	10%	CERAMIC
C37	150pF	2%	CERAMIC
C38	8.2pF	0.25P	CERAMIC
C39	47pF	2%	CERAMIC
C40	8.2pF	0.25P	CERAMIC
C45	10pF	2%	CERAMIC
DIODES			
D14, D15, D18, D19		1N4148	
D13, D16		BZX79C6V2	
INTEGRATED CIRCUITS			
IC2	LM6364	IC4	LM311N
IC3	LM6364	IC5	40106

TABLE 2

Ref	*Value*	*Tolerance*	*Limits*
R3	10K	2%	0.125W
R4	100K	5%	1W
R5	100K	5%	1W
R6	47	5%	0.25W
R7	47	5%	0.25W
R18	10K	5%	0.125W
R19	33	2%	0.125W
R20	10K	2%	0.125W
R21	1K5	2%	0.125W
R22	820K	5%	0.125W
R23	33	2%	0.125W
R24	33	2%	0.125W
R25	47K	2%	0.125W
R26	47K	2%	0.125W
R27	10K	1%	0.125W
R28	10K	1%	0.125W
R29	10K	1%	0.125W
R30	10K	5%	0.125W
R31	100K	5%	0.125W
R32	1K	5%	0.25W
R33	10K	5%	0.125W
R34	10K	POT	
R35	10K	2%	0.125W
R36	10K	2%	0.125W
R37	150K	2%	0.125W
R54	10K	2%	0.125W
R55	2K7	2%	0.125W
R56	1K	5%	0.5W
R57	10K	5%	0.125W
R58	15K	2%	0.125W
R59	100K	2%	0.125W
R60	10K	5%	0.125W
R61	18K	2%	0.125W
R62	10K	2%	0.125W

Ref	*Value*	*Tolerance*	*Limits*	*Comments*
R63	10k	2%	0.125W	
R64	10K	2%	0.125W	
R65	15K	2%	0.125W	
R66	1K	5%	0.25W	
R67	1K	5%	0.125W	
R68	330	5%	0.5W	
R69	100	5%	0.5W	
R70	10K	5%	0.125W	
R71	10K	5%	0.125W	
R72	10K	5%	0.125W	
C8	470μF		200V	>1A ripple current
C9	470μF		200V	>1A ripple current
C11	1μF		630V	Siemens MkP
C12	0.22μF		400V	Siemens MkT
C13	0.22μF		400V	Siemens MkT
C14	15nF		2kV	Philips 378 Series
C15	15nF		2kV	Philips 378 Series
C16	15nF		2kV	Philips 378 Series
C17	15nF		2kV	Philips 378 Series
C18	2μ2F		250V	Philips 378 Series
C19	2μ2F		250V	Philips 378 Series
C20	2μ2F		250V	Philips 378 Series
C23	22μF		35V	
C24	10μF		16V	Tantalum
C25	1nF	5%		Ceramic
C26	33pF	2%		Philips 680 Series
C27	2p2F	0.25pF		Philips 680 Series
C28	33pF	2%		Philips 680 Series
C29	2p2F	0.25pF		Philips 680 Series
C30	100nF			
C31	1nF			
C36	100nF	10%		Ceramic
C37	330pF	5%		Ceramic
C38	47nF		1kV	Philips 378 Series
C39	100nF			Ceramic

Ref	Value	Tolerance Limits	Comments
C40	100nF	10%	Ceramic
C41	100nF		Ceramic
C42	33pF		Ceramic
D2			1N4148
D3			1N4148
D4		45V	80SQ045 Fitted for low volt-drop and 175°C junction temperature
D5			80SQ045
D6			80SQ845
D7			80SQ845
D11			UF4001
D12			UF4001
D13			UF4001
D14			UF4001
D15			1N4148
D17			1N4148
D18			1N4148
M1		500V	IRF840
M2		500V	IRF840
M3		20V	ZVP2106A
M4		20V	ZVN2106A
M5		20V	ZVN2106A
M6		20V	ZVN2106A
Q7			BC556

Ref	Comments
IC1	78M150.5A+15V regulator
IC2	4000 Series 4069 inverter
IC3	LM324 op-amp
IC4	4000 Series 40106 inverter
IC5	4000 Series 4013 D-latch
IC6	4000 Series 4046 phase-lock loop
IC7	4000 Series 4093 NAND
IC8	LM311 comparator

L4	50μH differential-mode choke
T1	1:1:30 current transformer wound on Philips 3C85 U10 core using 0.315mm enamelled copper wire
T2	Power transformer
T3	3:20 current transformer wound as T1
T4	48:48:48 gate drive transformer wound on Philips 3C85 U10 core using 0.224mm enamelled copper wire

CLAIMS

1. A power coupling system comprising a source unit (1) arranged to be connected to a power supply and including a first winding (P) and a load unit (2) including a second winding (S), in use power being inductively coupled from the first winding to the second winding, and the source unit (1) and load unit (2) being readily separable,

characterised in that the second winding is connected in a resonant circuit, and in that an AC voltage applied to the first winding (P) is tuned to the resonant frequency of the load circuit including the secondary winding leakage inductance.

2. A system according to claim 1, including a variable tuning circuit arranged to control the frequency of the voltage applied to the first winding in dependence upon the said resonant frequency of the load circuit.

3. A system according to claim 2, in which the tuning circuit (6) includes a phase-locked loop responsive to the phase difference between voltage and current in the source circuit or between the source unit voltage and the load unit current as referred to the source unit and arranged to control the frequency of the AC voltage accordingly.

4. A system according to claim 3, in which the source unit (1) includes an inverter (5) switched at a frequency determined by the tuning circuit.

5. A system according to claim 4, in which each arm of the inverter includes a field-effect transistor (FET) (Q1, Q2, Fig 8), each FET being arranged to be turned on when the voltage across the FET is substantially zero.

6. A system according to any one of claims 2 to 5, in which the tuning circuit (6) is arranged to drive the source unit circuit at a high frequency in the absence of a load,and to reduce the frequency as the load approaches.

7. A system according to any one of the preceding claims, in which one winding (P) is formed on a core (4) having a re-entrant portion and the core (9) for the other winding

has at least one part which is dimensioned to fit within the re-entrant portion of the core as the load and source units are brought together.

8. A system according to claim 7, in which both the source core (4) and the load core (9) are generally U-shaped.

9. A system according to claim 7, in which both the source core (93) and the load core (94) are generally cylindrical, with one of the cores (93) including a generally annular extension defining the re-entrant portion.

10. A system according to any one of the preceding claims, in which one of the source and load windings is positioned around a slot for receiving the other of the source and load windings.

11. A system according to any one of the preceding claims, in which the resonant circuit in the load unit (2) includes a switched component (R1. Fig. 10) which, when connected in the resonant circuit, changes the resonant frequency of the circuit, in use, the source unit (1) detecting the change in resonant frequency of the load unit (2), the switching of the switch component thereby being used to transmit a signal from the load to the source.

12. A system according to claim 11, in which the switch (Q1, Q2, Fig. 11) for the switched component is responsive to a pulsed data stream, the load unit thereby transmitting data to the source unit.

13. A system according to any one of claims 2 to 12, in which the tuning circuit (6) includes a differentiator arranged to detect the phase of a quasi-sinusoidal component of the source unit winding current.

14. A system according to any one of the preceding claims, in which the source unit and load unit are sealed within respective water-tight housings.

15. A power coupling system comprising at least one source unit and a plurality of load units arranged to be coupled individually to the at least one source unit, the at least

one source unit and any one of the load units together forming a system in accordance with any one of the preceding claims, different load units being arranged to provide different respective drive voltages when coupled to the at least one source unit.

16. A system according to claim 15, including a plurality of source units, each source unit being arranged to be coupled to a different respective power supply and to generate a common standard coupling field for the load units.

17. A power coupling system comprising a plurality of source units and at least one load unit arranged to be coupled to any one of the source units, any one of the source units and the at least one load unit together forming a system in accordance with any one of the preceding claims, the plurality of source units being arranged to be connected to different respective power supplies, and to generate a common standard coupling field for the load unit.

18. A method of coupling power inductively from a source to a load characterised by bringing separable respective source and load units into proximity, the load winding being connected in a resonant circuit and driving the source at a frequency substantially matching the resonant frequency of the load including the load winding leakage inductance.

19. A method according to claim 18, further comprising tuning automatically the frequency of operation of the source unit to match the said resonant frequency.

20. A source unit (1) for use in a system according to any one of the claims 1 to 17.

21. A load unit (2) for use in a system according to any one of the claims 1 to 17.

22. A charger for a battery including a load unit according to claim 21 arranged to couple the charger to a source unit connected to a power supply.

23. An electric wheelchair including a charger according to claim 22.

24. A lamp including a load unit according to claim 21 arranged to couple the lamp to a source unit connected to a power supply.

25. An electrically-powered transducer for a rotating member including a power coupling system according to any one of claims 1 to 17.

26. A system according to any one of claims 1 to 17 in which one of the load and source units is mounted for rotation and the other is fixed.

27. A system according to claim 26, in which the load unit is mounted on a wheel or turbine.

28. A system according to any one of claims 25 to 27 in which one of the windings is formed on a bobbin-shaped core which in use rotates about its central axis.

29. A system according to claim 28, in which the other core is generally U-shaped.

30. An inductive non-contact power coupling system having a power efficiency ≥ 90% for output powers ≥ 1kw.

31. A power coupling system comprising a source unit (1) arranged to be connected to a power supply and including a first winding (P) and a load unit (2) including a second winding (5), in use power being inductively coupled from the first winding to the second winding,

characterised in that the first and second windings are separated by an air-gap, the second winding being connected in a resonant circuit, and in that an AC voltage applied to the first winding (P) is tuned to the resonant frequency of the load circuit including the secondary winding leakage inductance.

32. A system according to claim 31, including a variable tuning circuit arranged to control the frequency of the voltage applied to the first winding in dependence upon the said resonant frequency of the load circuit.

Fig.1.

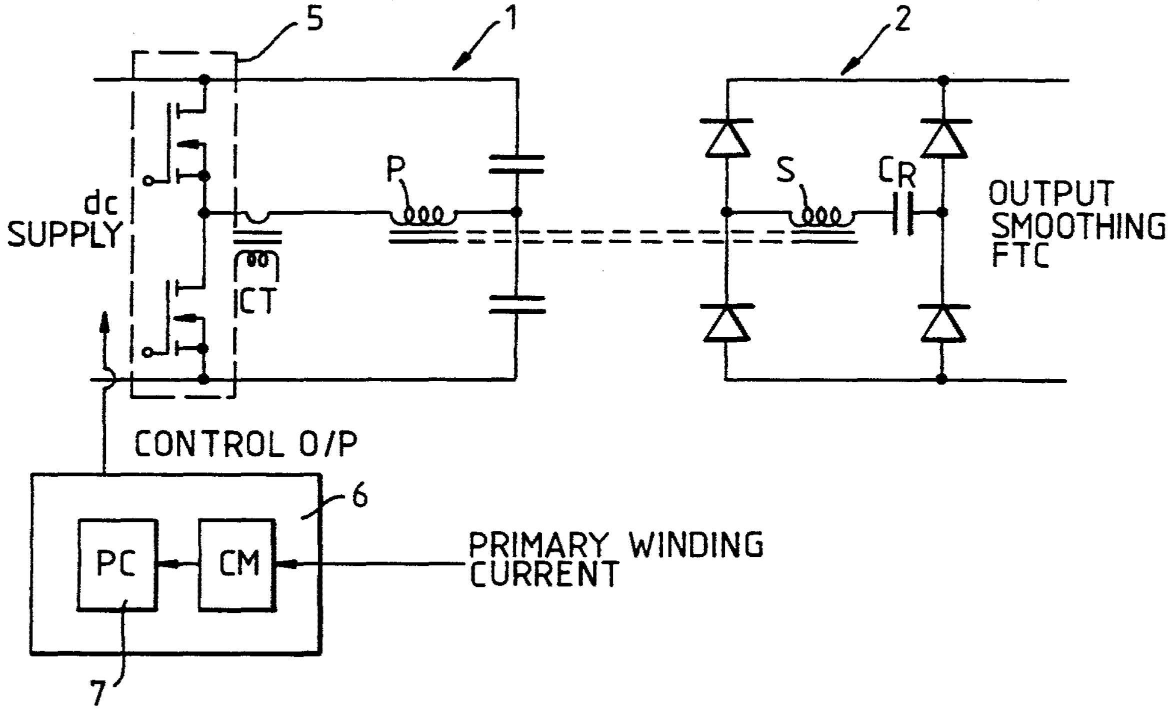

5
1
2
dc
SUPPLY
P
CT
S
CR
OUTPUT
SMOOTHING
FTC
CONTROL O/P
6
PC
CM
PRIMARY WINDING
CURRENT
7

Fig.2.

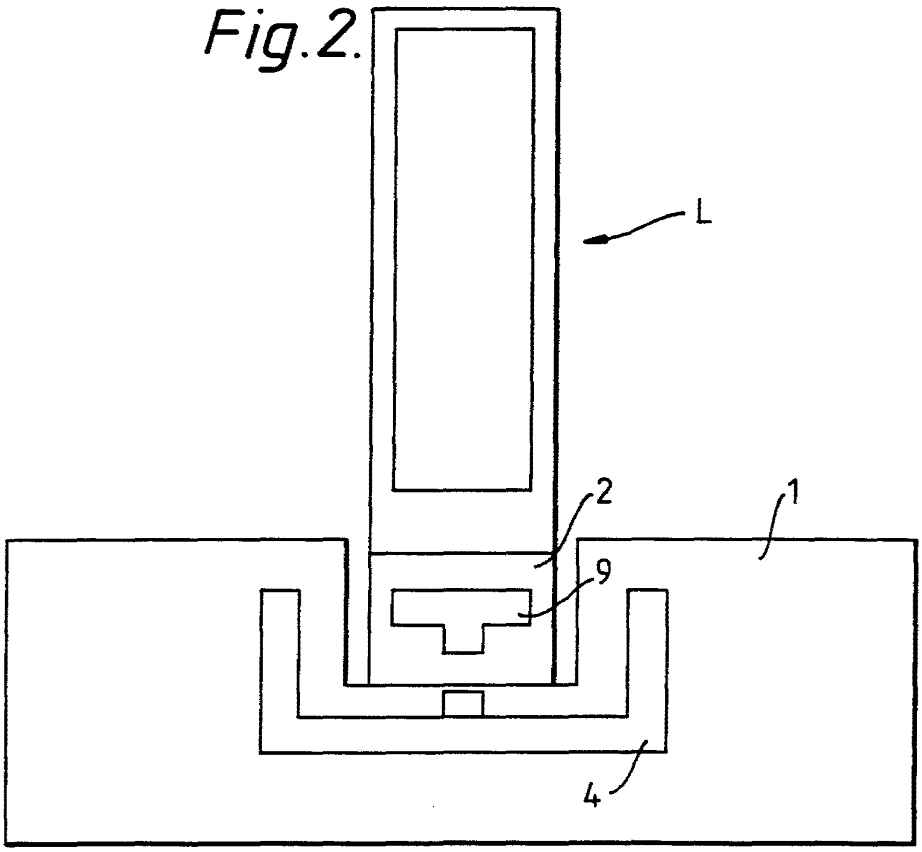

L
2
1
9
4

Fig. 3.

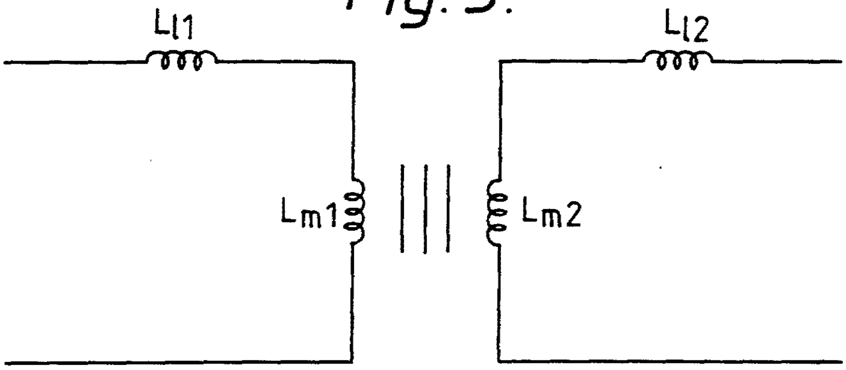


Fig. 4.

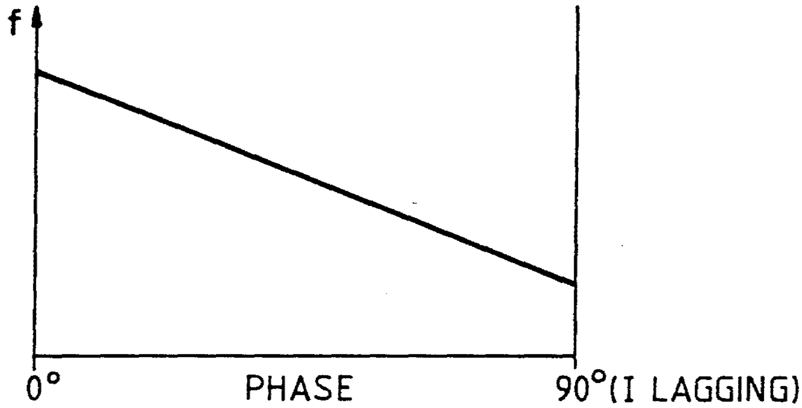
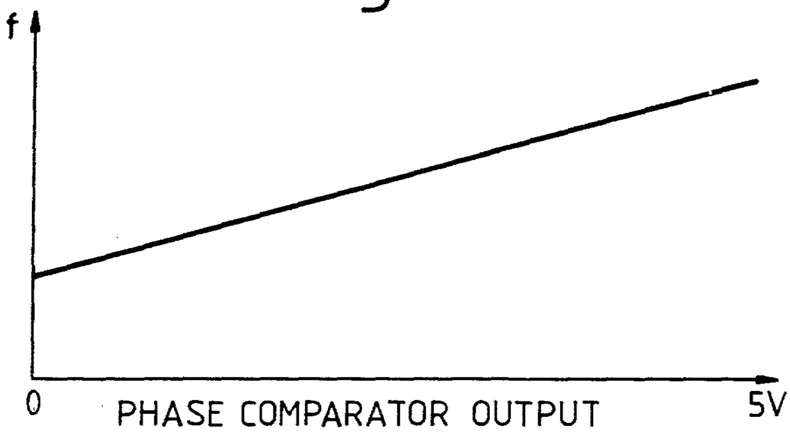


Fig. 7.



SUBSTITUTE SHEET (RULE 26)

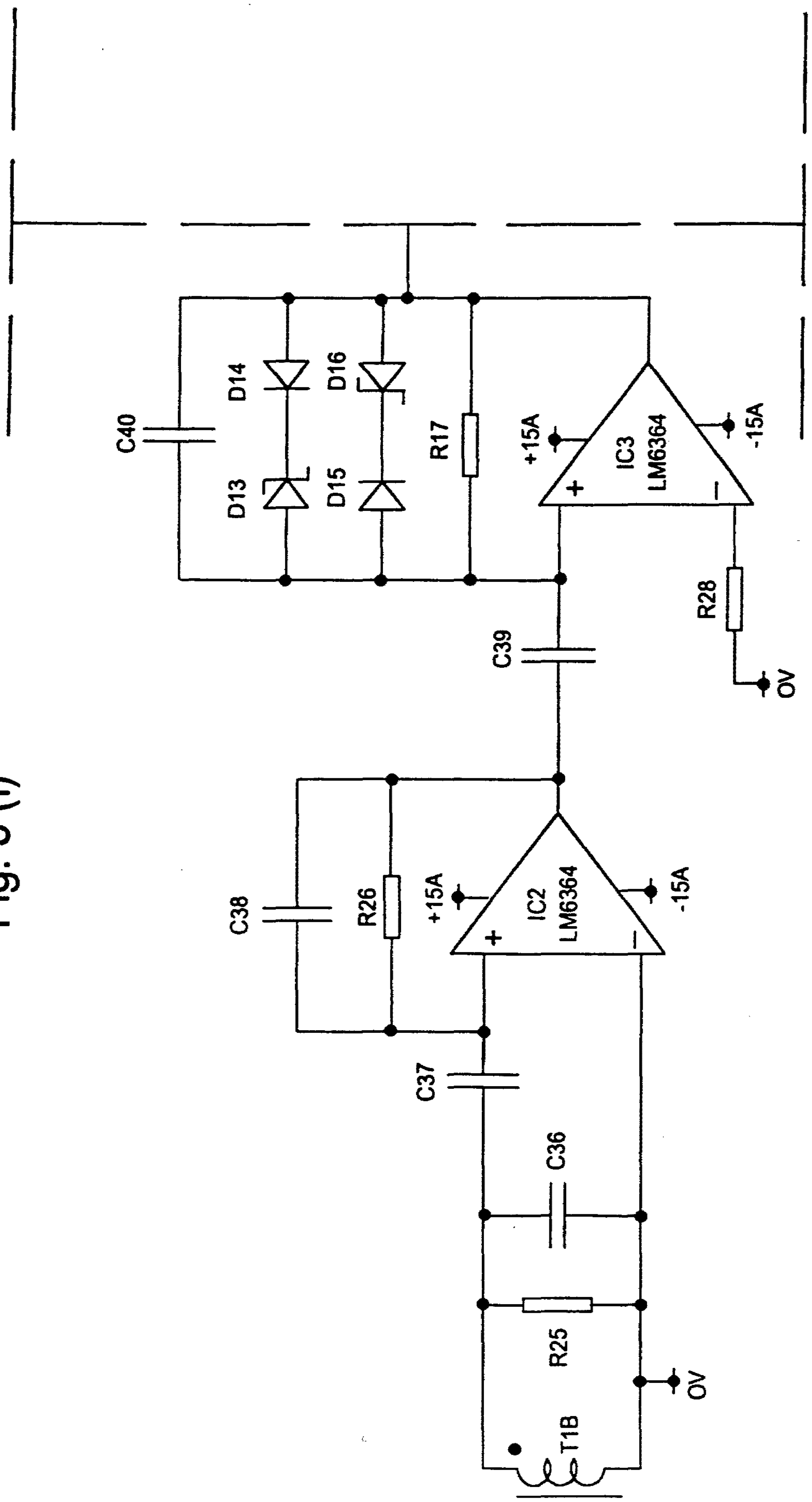
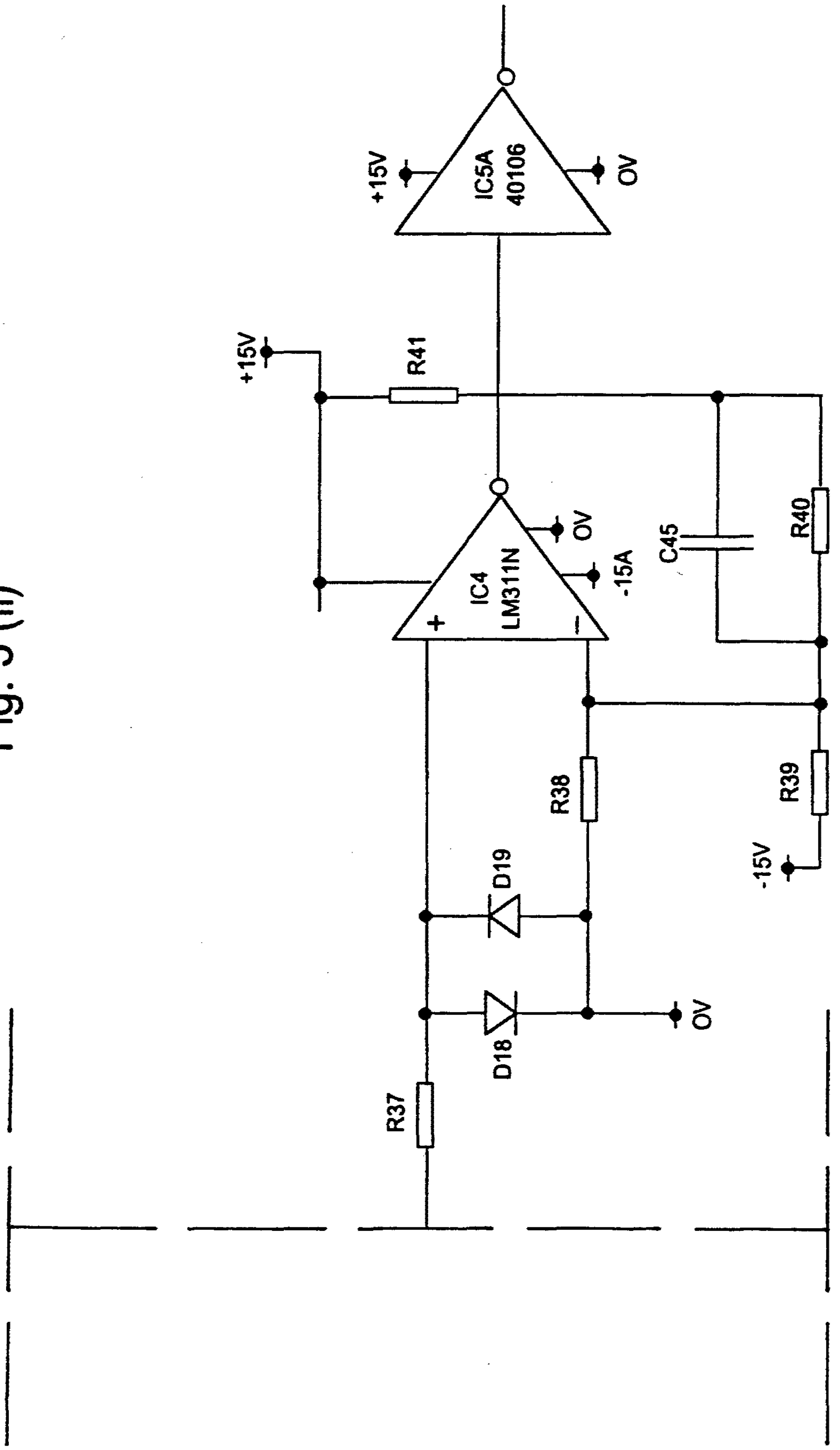


Fig. 5 (i)

SUBSTITUTE SHEET (RULE 26)

Fig. 5 (ii)



SUBSTITUTE SHEET (RULE 26)

Fig. 6.

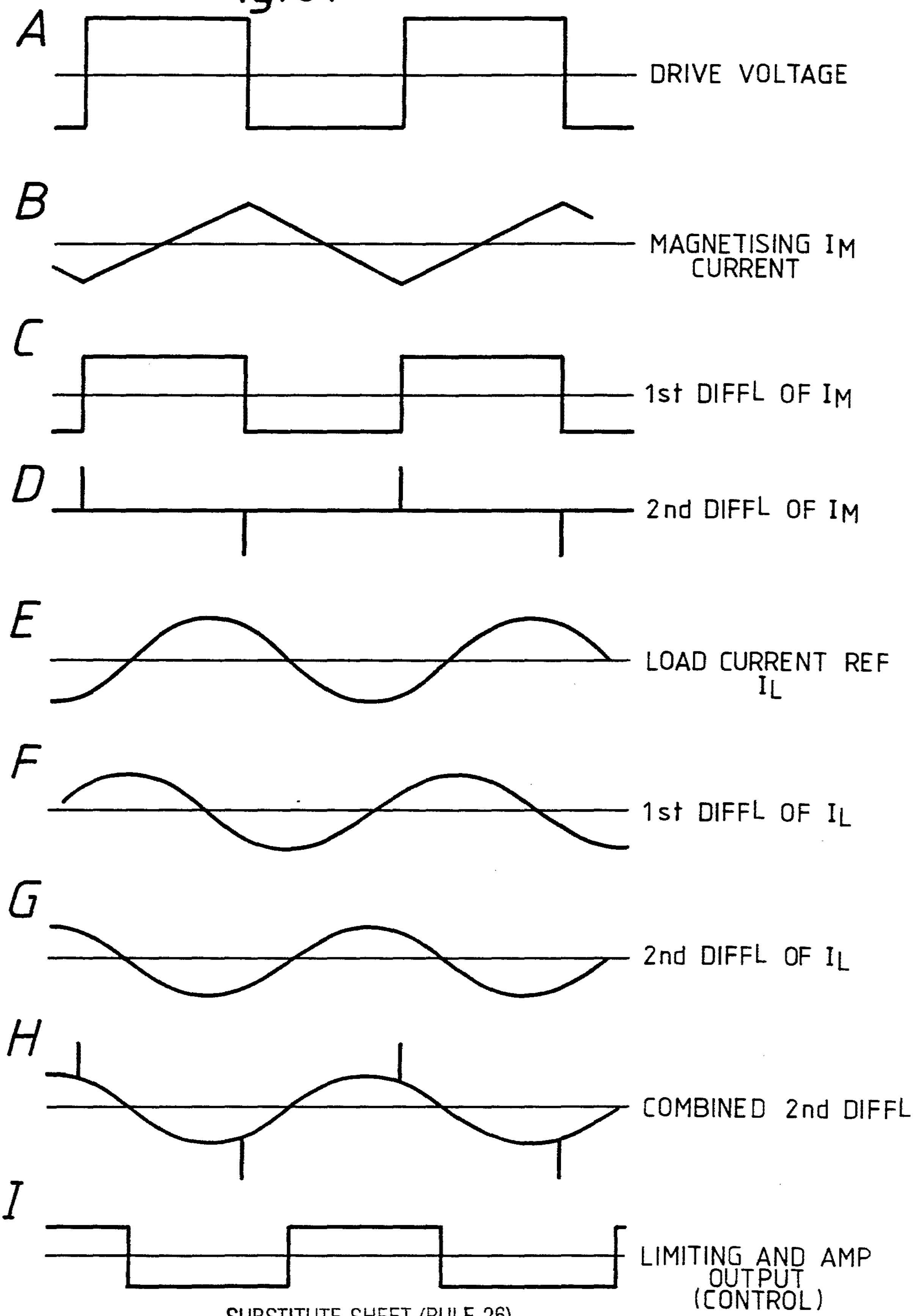
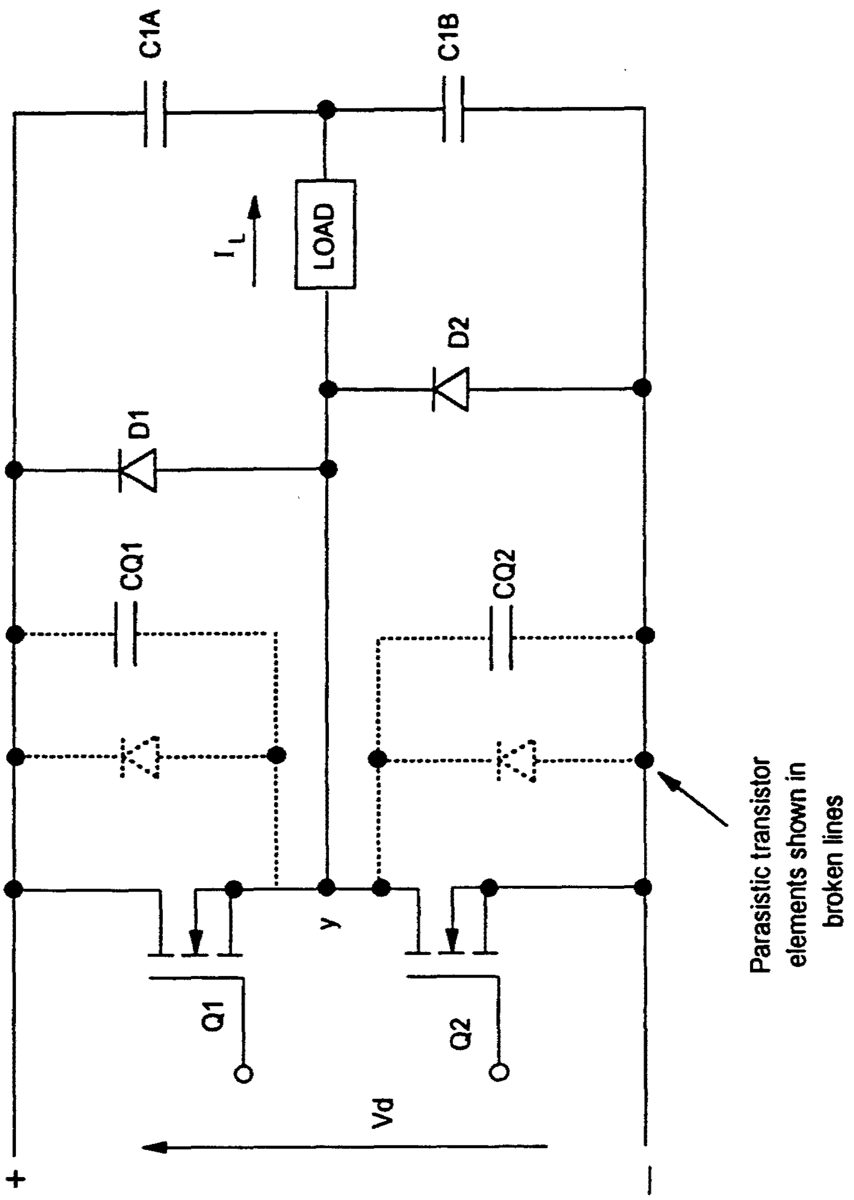

A
DRIVE VOLTAGE
B
MAGNETISING IM CURRENT
C
1st DIFFL OF IM
D
2nd DIFFL OF IM
E
LOAD CURRENT REF IL
F
1st DIFFL OF IL
G
2nd DIFFL OF IL
H
COMBINED 2nd DIFFL
I
LIMITING AND AMP OUTPUT (CONTROL)

Fig. 8a


C1A
C1B
LOAD
I_L
D1
D2
CQ1
CQ2
y
Q1
Q2
Vd
+
–
Parasistic transistor elements shown in broken lines

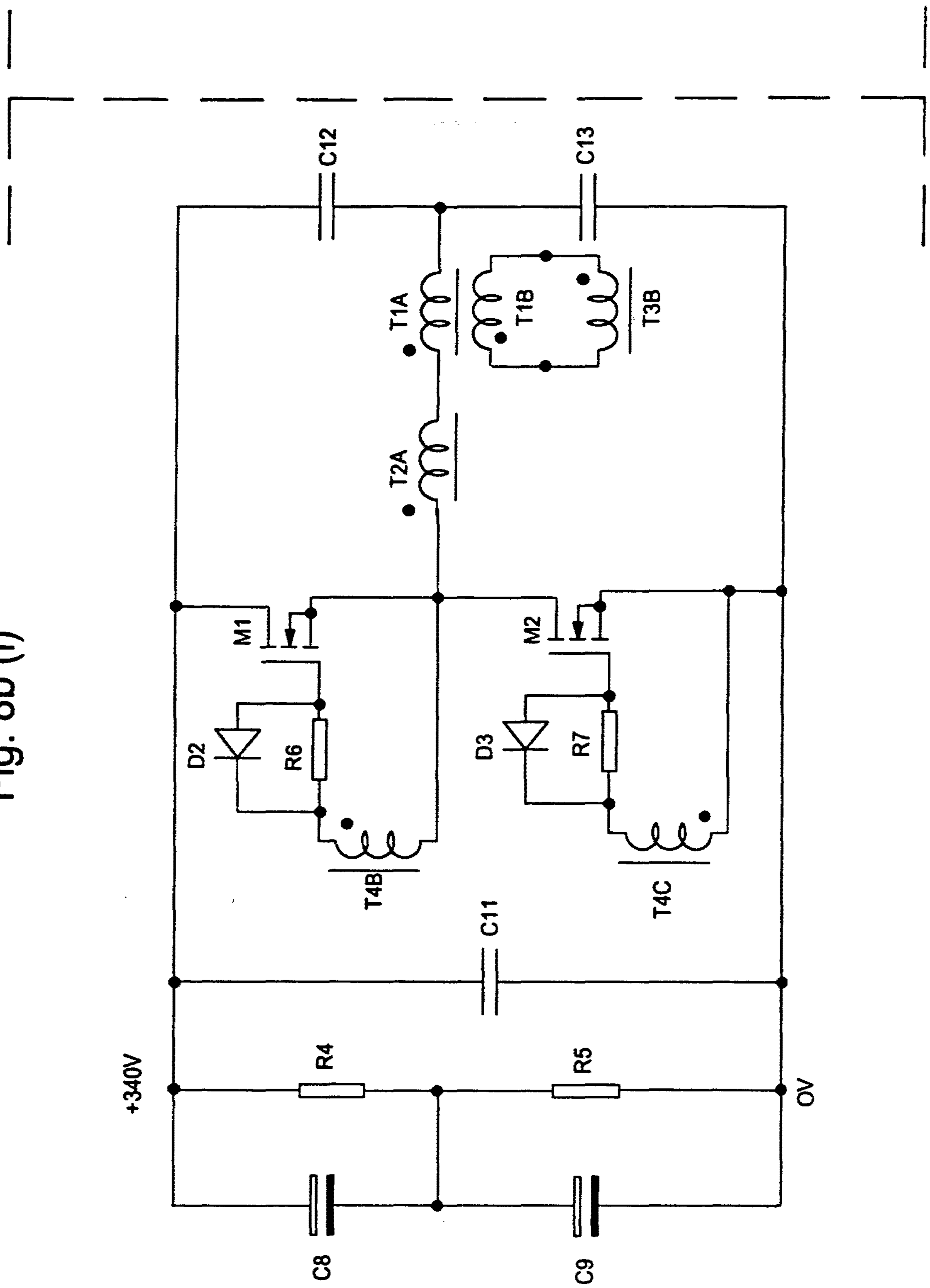
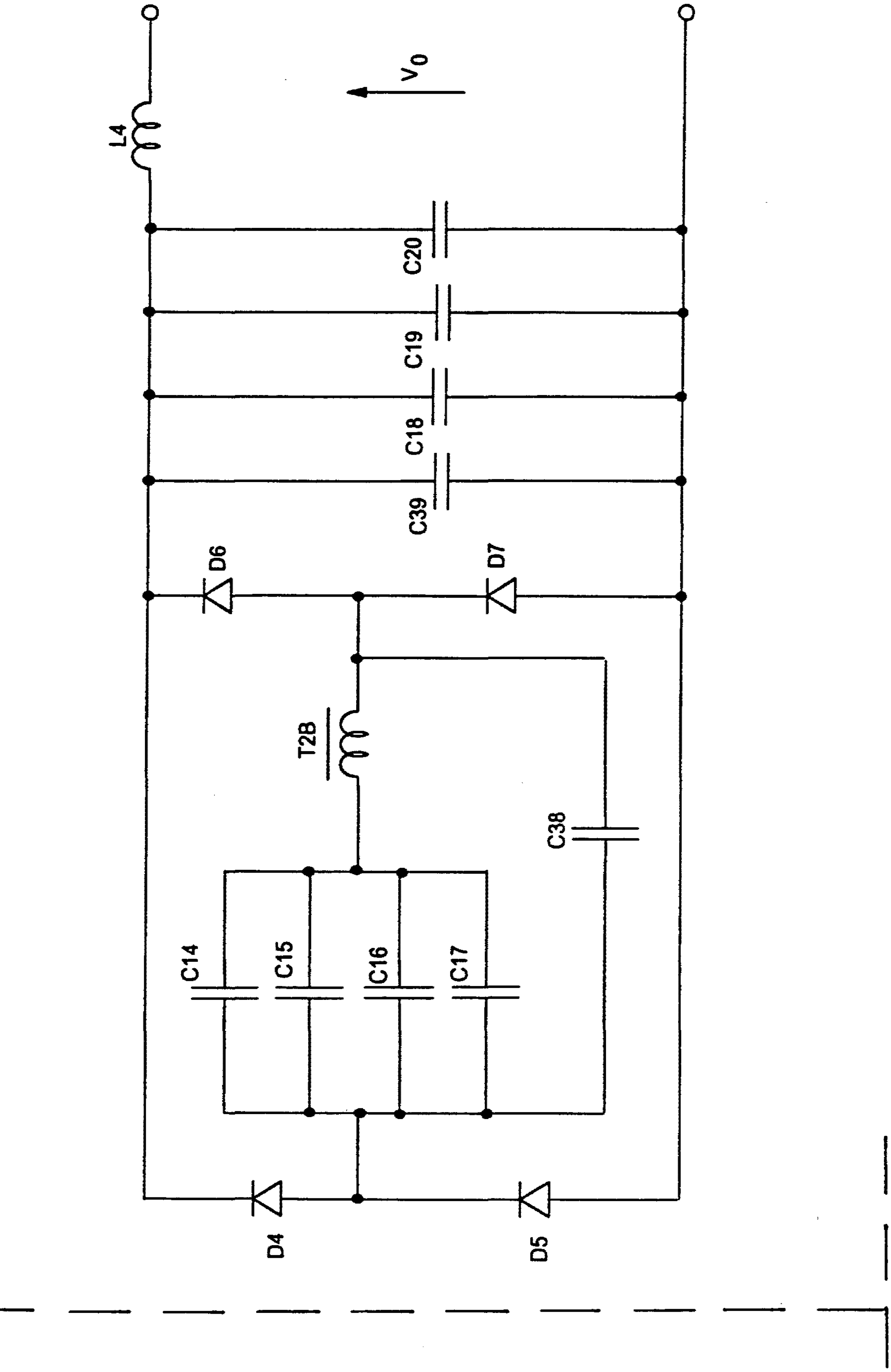

C12
C13
T1A
T1B
T3B
T2A
M1
M2
D2
R6
D3
R7
T4B
T4C
C11
+340V
R4
R5
0V
C8
C9

Fig. 8b (i)

Fig. 8b (ii)



SUBSTITUTE SHEET (RULE 26)

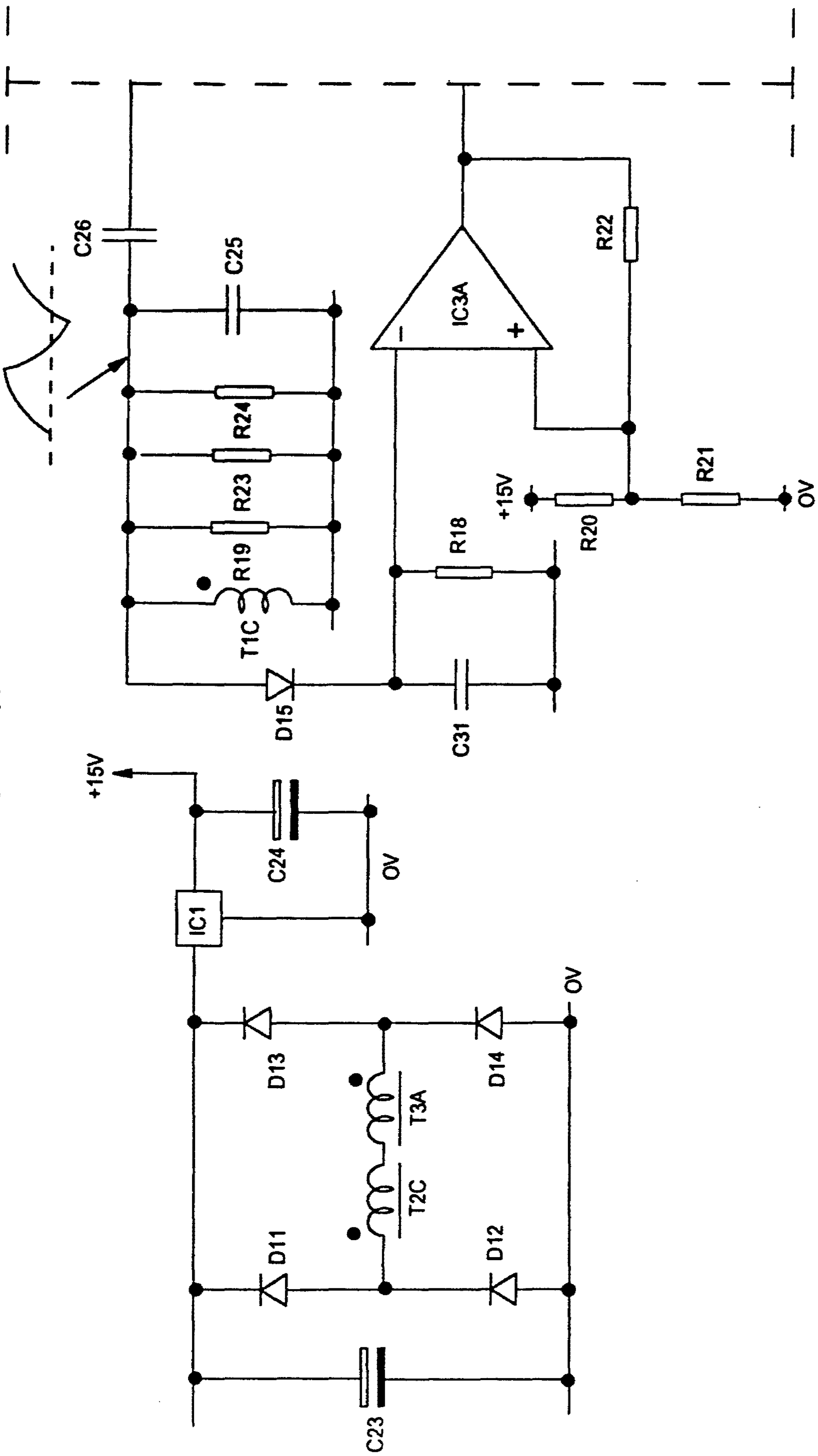
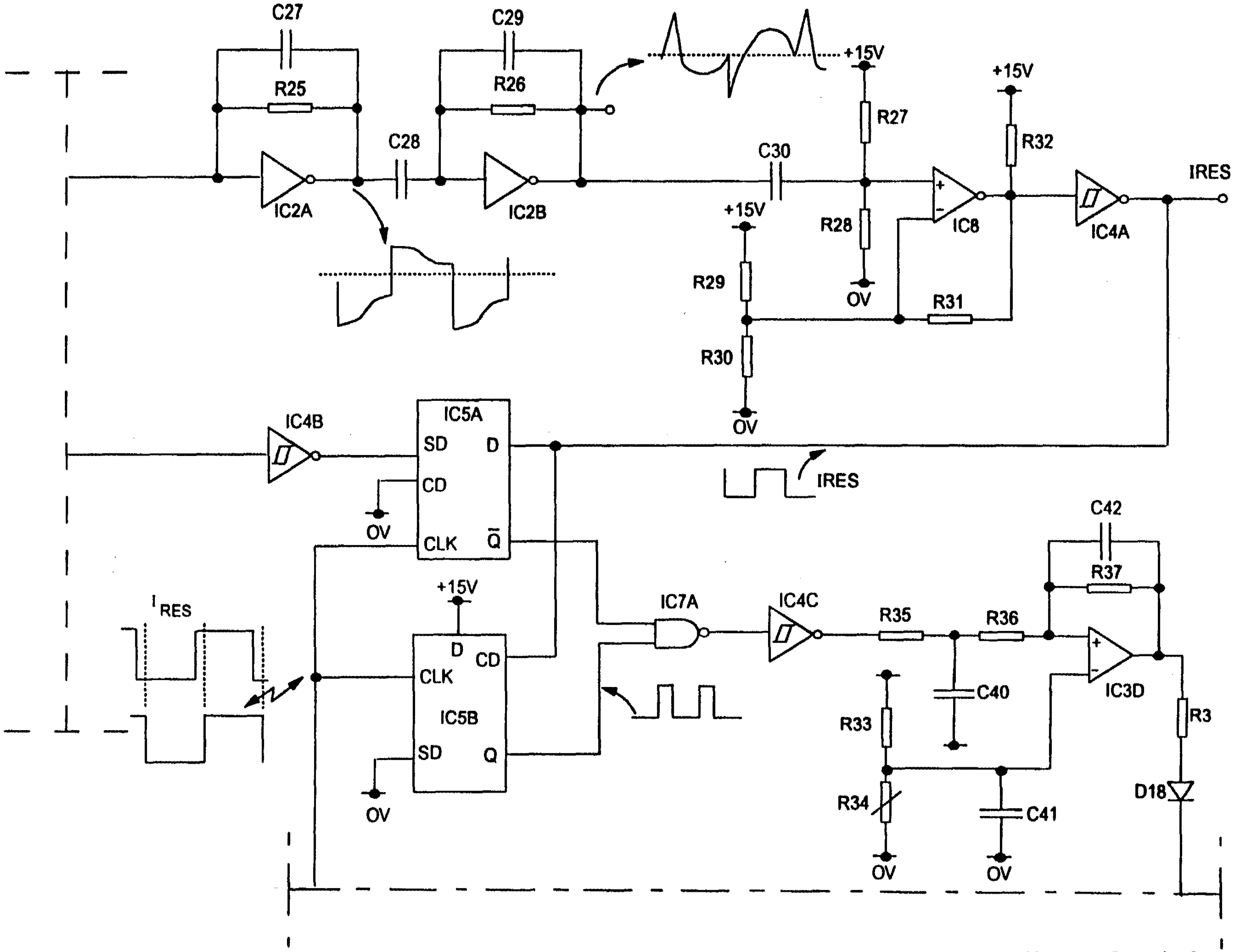


Fig.8c (i)

SUBSTITUTE SHEET (RULE 26)

Fig.8c (ii)



SUBSTITUTE SHEET (RULE 26)

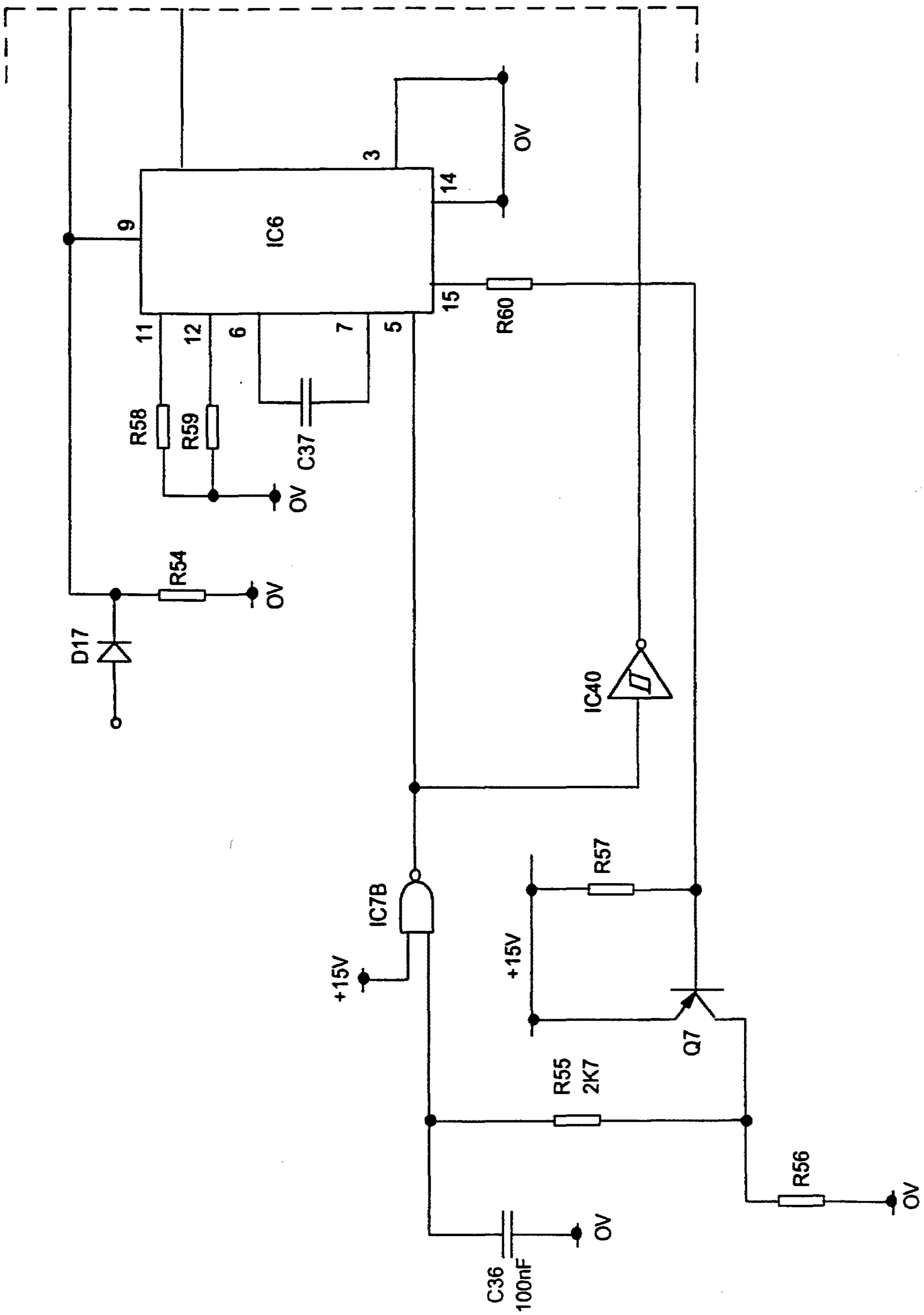

IC6
3
14
9
15
11
12
6
7
5
0V
R60
R58
R59
C37
0V
R54
0V
D17
IC40
IC7B
+15V
R57
+15V
Q7
R55
2K7
R56
0V
C36
100nF
0V

Fig.8c (iii)

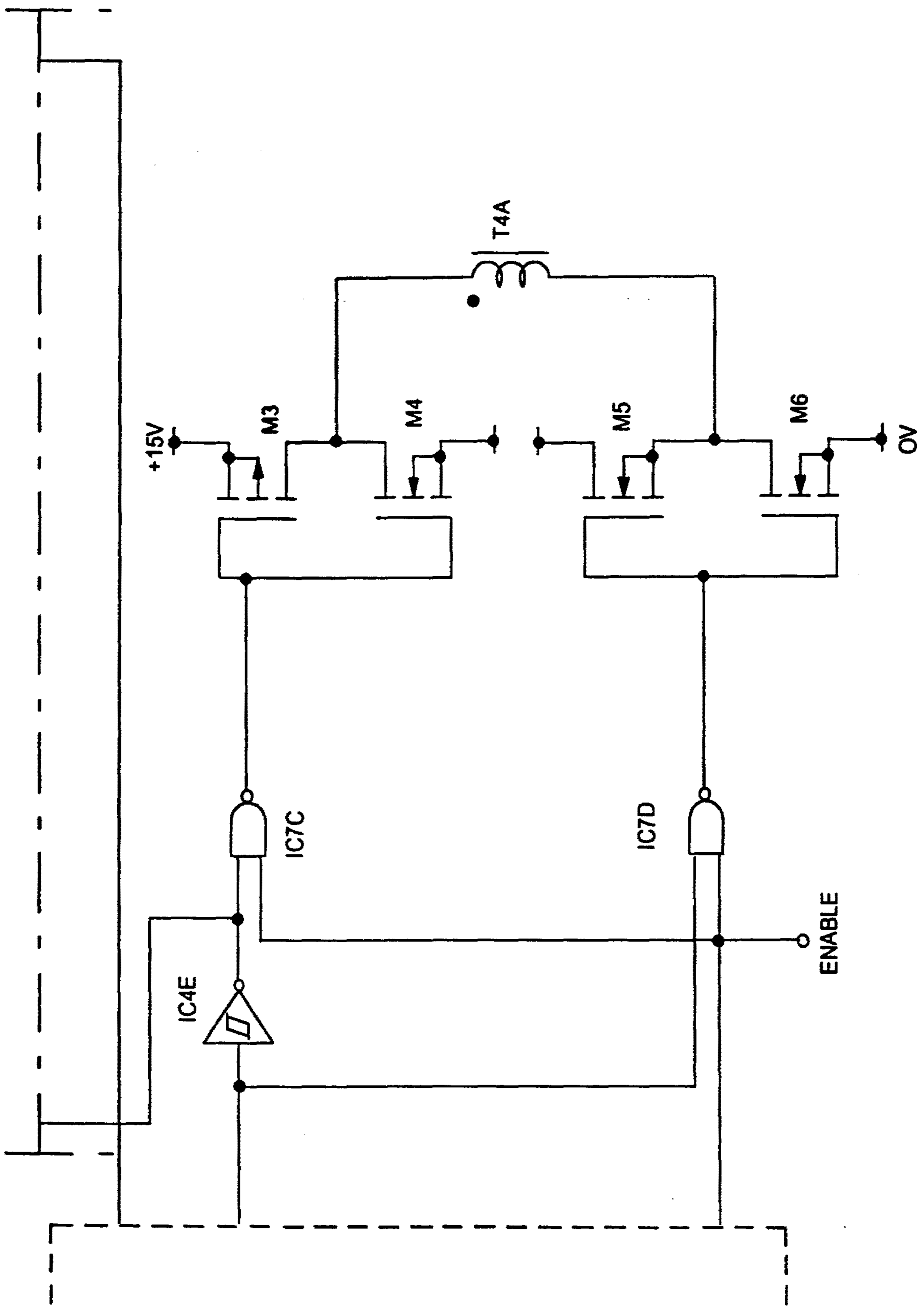


Fig.8c (iv)

Fig. 9a.

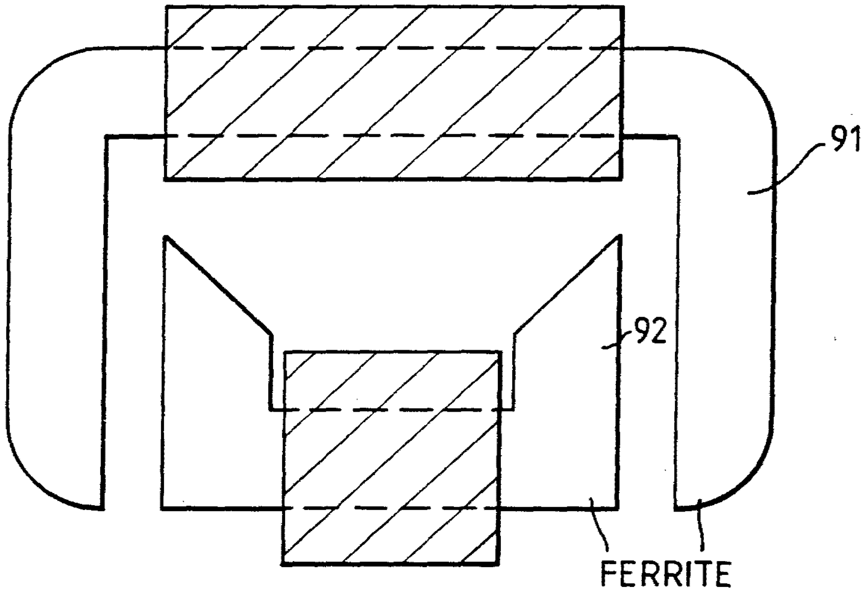
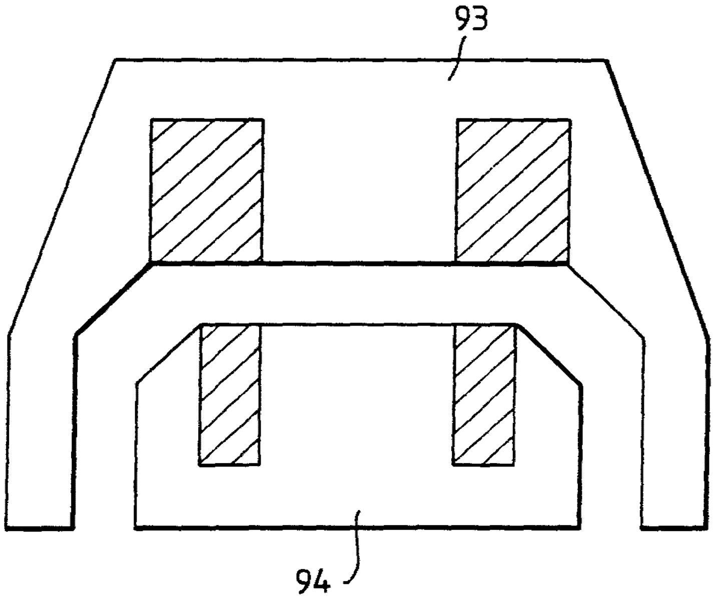


Fig. 9b.



SUBSTITUTE SHEET (RULE 26)

Fig. 9c.

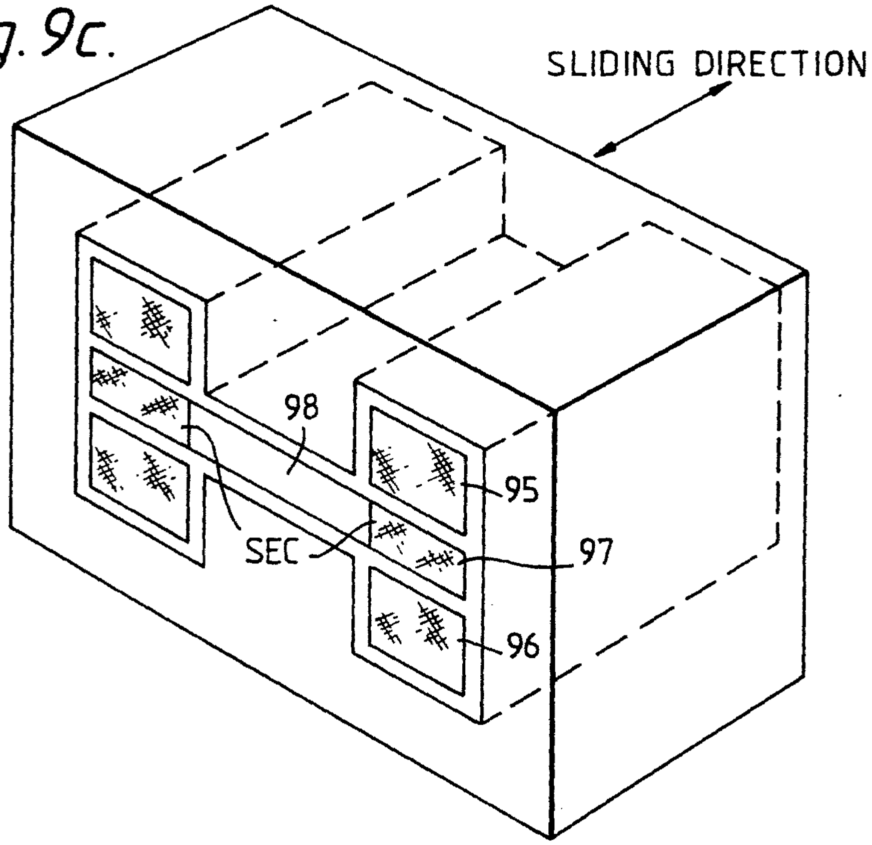
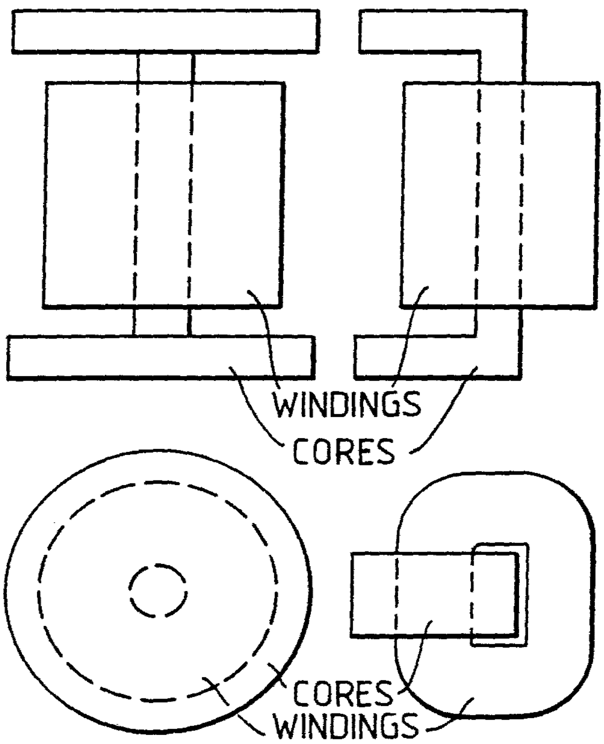


Fig. 9d.



SUBSTITUTE SHEET (RULE 26)

Fig. 10.

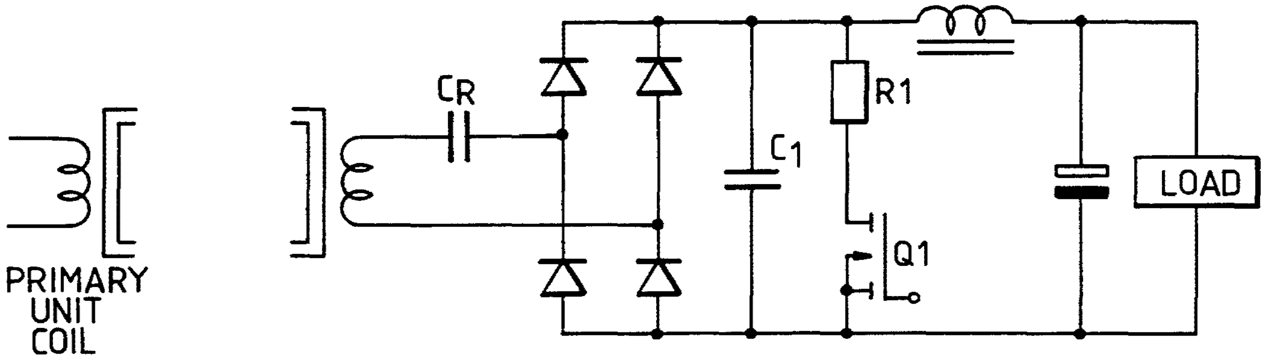

CR
R1
C1
Q1
LOAD
PRIMARY
UNIT
COIL

Fig. 11.

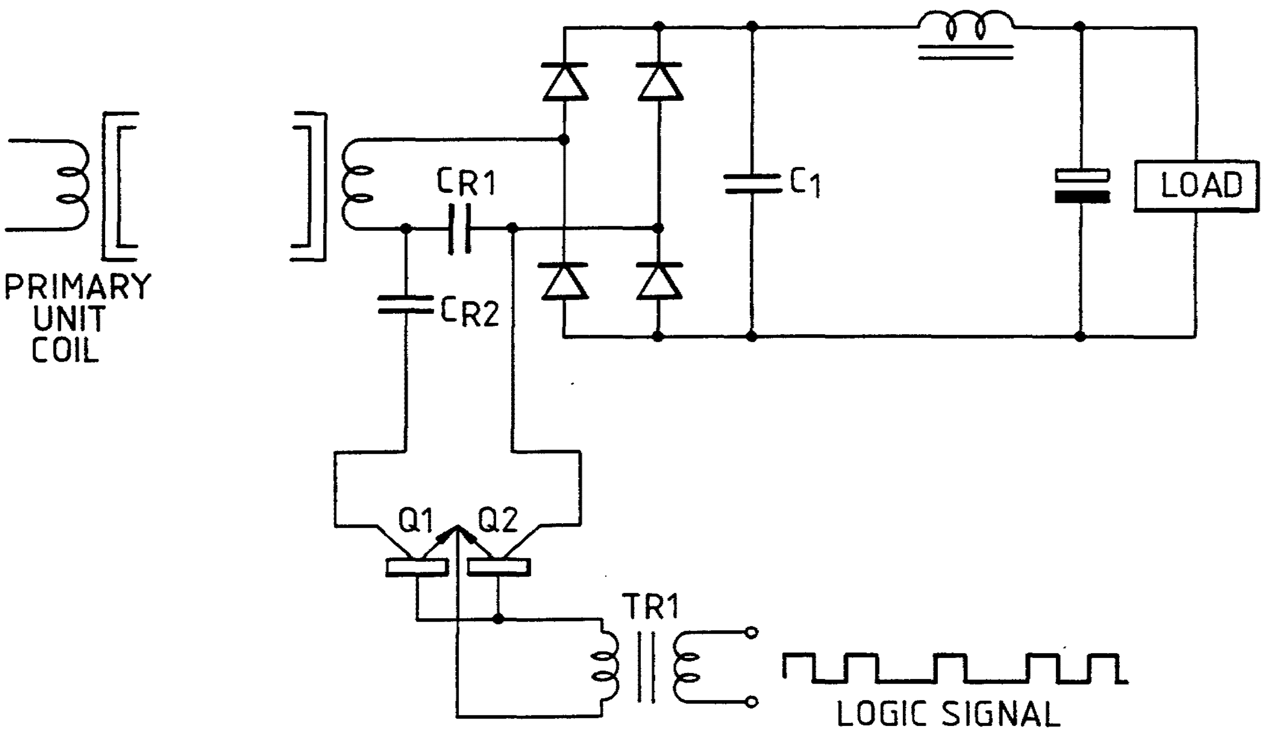

CR1
CR2
C1
LOAD
PRIMARY
UNIT
COIL
Q1
Q2
TR1
LOGIC SIGNAL

Fig.12.

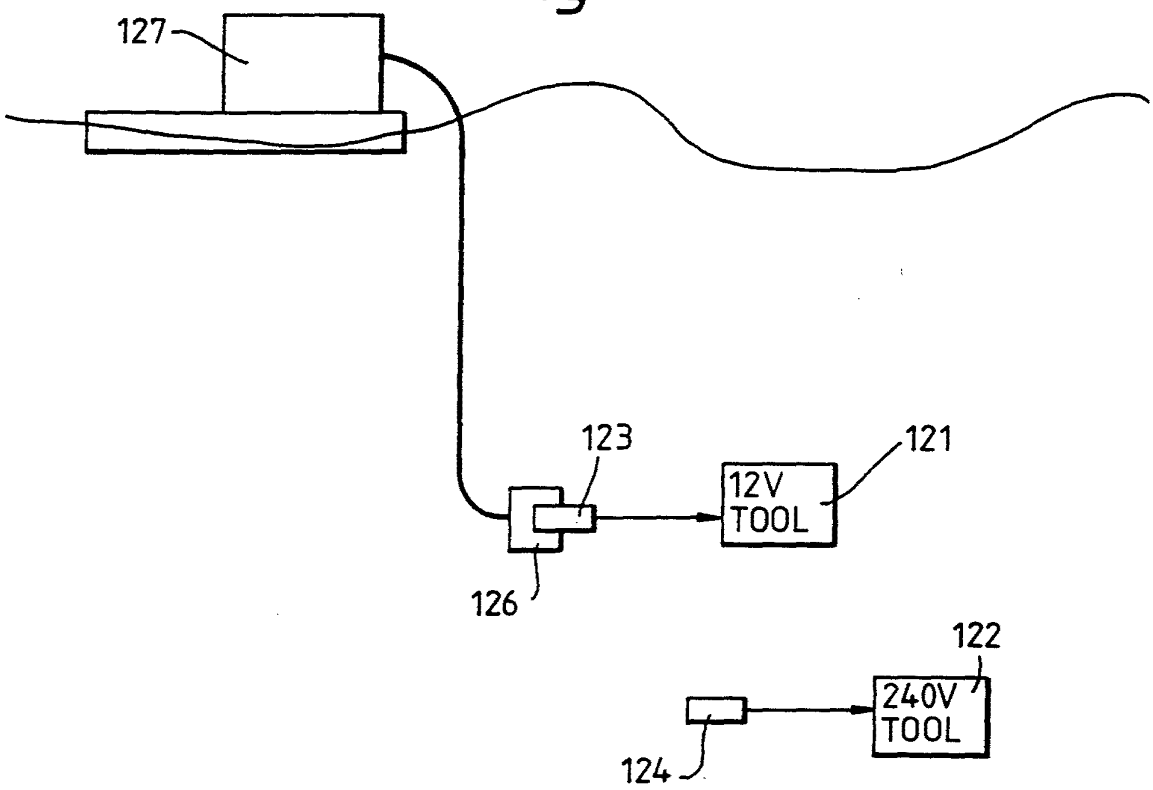
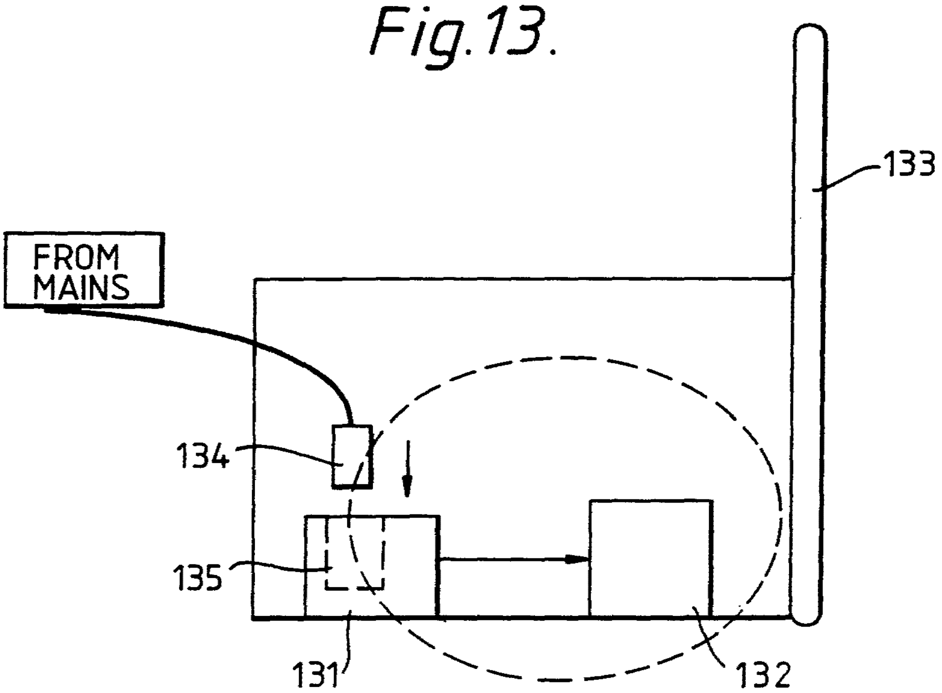

127
123
121
12V TOOL
126
122
240V TOOL
124

Fig.13.


133
FROM MAINS
134
135
131
132

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 94/01068

A. CLASSIFICATION OF SUBJECT MATTER
IPC 5 H01F23/00 H02J5/00 H02J7/02 H02M3/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 5 H01F H02J H02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO,A,92 17929 (PIPER) 15 October 1992 see amended claims 5-7, 17-17 and 22	1-5, 7-10, 18-24, 30-32
Y	FR,A,2 618 618 (RANSBURG-GEMA) 27 January 1989 see page 1, line 22 - line 29; figure 1 see page 6, line 18 - page 7, line 15	1-5, 18-24, 30-32
Y	EP,A,0 540 750 (YASKAVA) 12 May 1993 see abstract; figures 1-5	7-10
A	US,A,5 157 319 (KLONTZ) 20 October 1992 see column 8, line 25 - line 66; figure 7	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
19 August 1994	26.08.94

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+ 31-70) 340-3016	Gentili, L

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 94/01068

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A-9217929	15-10-92	AU-A-	1237392	02-11-92
		CA-A-	2106784	27-09-92
		EP-A-	0577611	12-01-94
		US-A-	5293308	08-03-94
FR-A-2618618	27-01-89	DE-A-	3823557	02-02-89
		US-A-	4916571	10-04-90
EP-A-0540750	12-05-93	JP-A-	4345008	01-12-92
		WO-A-	9221131	26-11-92
		US-A-	5327073	05-07-94
US-A-5157319	20-10-92	NONE		

Form PCT/ISA/210 (patent family annex) (July 1992)

PATENT COOPERATION TREATY

ADVANCE E-MAIL

PCT

NOTIFICATION CONCERNING TRANSMITTAL OF COPY OF INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY (CHAPTER I OF THE PATENT COOPERATION TREATY)

(PCT Rule 44bis.1(c))

From the INTERNATIONAL BUREAU

To:

NORTRUP, John, H.
Strategic Patents, P.C.
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402
ETATS-UNIS D'AMERIQUE

Date of mailing *(day/month/year)* 20 September 2012 (20.09.2012)	
Applicant's or agent's file reference WTCY0053PWO	**IMPORTANT NOTICE**

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US2011/027868	10 March 2011 (10.03.2011)	10 March 2010 (10.03.2010)

Applicant

WITRICITY CORPORATION et al

The International Bureau transmits herewith a copy of the international preliminary report on patentability (Chapter I of the Patent Cooperation Treaty)

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No. +41 22 338 82 70	Authorized officer Simin Baharlou e-mail: pt09.pct@wipo.int

Form PCT/IB/326 (January 2004)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

(Chapter I of the Patent Cooperation Treaty)

(PCT Rule 44*bis*)

Applicant's or agent's file reference WTCY0053PWO	**FOR FURTHER ACTION**	See item 4 below
International application No. PCT/US2011/027868	International filing date *(day/month/year)* 10 March 2011 (10.03.2011)	Priority date *(day/month/year)* 10 March 2010 (10.03.2010)
International Patent Classification (8th edition unless older edition indicated) See relevant information in Form PCT/ISA/237		
Applicant WITRICITY CORPORATION		

1. This international preliminary report on patentability (Chapter I) is issued by the International Bureau on behalf of the International Searching Authority under Rule 44 *bis*.1(a).

2. This REPORT consists of a total of 7 sheets, including this cover sheet.

   In the attached sheets, any reference to the written opinion of the International Searching Authority should be read as a reference to the international preliminary report on patentability (Chapter I) instead.

3. This report contains indications relating to the following items:

☒	Box No. I	Basis of the report
☐	Box No. II	Priority
☐	Box No. III	Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
☐	Box No. IV	Lack of unity of invention
☒	Box No. V	Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
☐	Box No. VI	Certain documents cited
☐	Box No. VII	Certain defects in the international application
☐	Box No. VIII	Certain observations on the international application

4. The International Bureau will communicate this report to designated Offices in accordance with Rules 44*bis*.3(c) and 93*bis*.1 but not, except where the applicant makes an express request under Article 23(2), before the expiration of 30 months from the priority date (Rule 44*bis* .2).

	Date of issuance of this report 11 September 2012 (11.09.2012)
The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No. +41 22 338 82 70	Authorized officer Simin Baharlou e-mail: pt09.pct@wipo.int

Form PCT/IB/373 (January 2004)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To: JOHN NORTRUP
STRATEGIC PATENTS, P.C.
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

Date of mailing (*day/month/year*)	05 JUL 2011

Applicant's or agent's file reference	FOR FURTHER ACTION
WTCY0053PWO	See paragraph 2 below

International application No.	International filing date (*day/month/year*)	Priority date (*day/month/year*)
PCT/US2011/027868	10 March 2011	10 March 2010

International Patent Classification (IPC) or both national classification and IPC
IPC(8) - H04B 5/00 (2011.01)
USPC - 307/104

Applicant WITRICITY CORPORATION

1. This opinion contains indications relating to the following items:

- ☒ Box No. I Basis of the opinion
- ☐ Box No. II Priority
- ☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- ☐ Box No. IV Lack of unity of invention
- ☒ Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
- ☐ Box No. VI Certain documents cited
- ☐ Box No. VII Certain defects in the international application
- ☐ Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

3. For further details, see notes to Form PCT/ISA/220.

Name and mailing address of the ISA/US	Date of completion of this opinion	Authorized officer:
Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	27 June 2011	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (July 2009)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US2011/027868

Box No. I Basis of this opinion

1. With regard to the **language**, this opinion has been established on the basis of:
   - [x] the international application in the language in which it was filed.
   - [ ] a translation of the international application into ______________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).

2. [ ] This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing filed or furnished:

   a. (means)
   - [ ] on paper
   - [ ] in electronic form

   b. (time)
   - [ ] in the international application as filed
   - [ ] together with the international application in electronic form
   - [ ] subsequently to this Authority for the purposes of search

4. [ ] In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

Form PCT/ISA/237 (Box No. I) (July 2009)

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US2011/027868

Box No. V **Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

1. Statement

Novelty (N)	Claims	3, 5-10, 13, 16, 18-19	YES
	Claims	1-2, 4, 11-12, 14-15, 17	NO
Inventive step (IS)	Claims	20-25	YES
	Claims	1-19	NO
Industrial applicability (IA)	Claims	1-25	YES
	Claims	None	NO

2. Citations and explanations:

Claims 1-2, 4, 11-12, 14-15, 17 lack novelty under PCT Article 33(2) as being anticipated by Bruhn.

Regarding claim 1, Bruhn discloses a wireless power converter (apparatus for wireless energy transmission, para 0017, Fig. 9) comprising at least one receiving magnetic resonator 130, 132 configured to capture electrical energy received wirelessly (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) through a first oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) characterized by a first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9); and at least one transferring magnetic resonator 126, 128 (Fig. 9) configured to generate (through resonance, para 0017-0018, Fig. 9) a second oscillating magnetic field (transferred to the secondary winding 20, para 0017-0018, 0031, Fig. 9) characterized by a second plurality of parameters different from the first plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), wherein the electrical energy from the at least one receiving magnetic resonator 130, 132 is used to energize the at least one transferring magnetic resonator 126, 128 (Fig. 9) to generate the second oscillating magnetic field (energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0018, Fig. 9).

Regarding claim 2, Bruhn discloses wherein the first plurality of parameters includes a first frequency (operating at the fundamental frequency, para 0017, 0031, Fig. 9) different from a second frequency of the second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018).

Regarding claim 4, Bruhn discloses wherein the second frequency is approximately an integer multiple of the first frequency (second resonator has twice the resonant frequency of first resonator, para 0018).

Regarding claim 11, Bruhn discloses wherein the at least one receiving magnetic resonator 130, 132 is configurable to capture energy from magnetic fields with different parameters (resonator 130 can receive energies with different frequencies, para 0017-0018, 0040, Fig. 9).

Regarding claim 12, Bruhn discloses wherein the at least one transferring magnetic resonator 126, 128 is configurable to generate magnetic fields with different parameters (resonator 126 can generate and transmit energy with different frequencies, para 0017-0018, 0040, Fig. 9).

Regarding claim 14, Bruhn discloses a system (para 0017, 0043) comprising a source resonator 126, 128 configured to generate a first oscillating magnetic field (transferred to the secondary winding 20, para 0017-0018, 0031, Fig. 9) characterized by a first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9); a device resonator 130, 132 configured to capture electrical energy received wirelessly (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) through a second oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) characterized by a second plurality of parameters different from the first plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018); and a wireless power converter (apparatus for wireless energy transmission, para 0017, Fig. 9) including conversion circuitry (circuits as seen in Fig. 9) configured to capture energy from the second oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) and to energize the source resonator 126, 128 to generate the first oscillating magnetic field (transferred to the secondary winding 20, energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0017-0018, 0031, Fig. 9).

Regarding claim 15, Bruhn discloses wherein the first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9) and the second plurality of parameters are different in at least a frequency (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018).

Form PCT/ISA/237 (Box No. V) (July 2009)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No. PCT/US2011/027868

Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

Regarding claim 17, Bruhn discloses wherein the wireless power converter (apparatus for wireless energy transmission, para 0017, Fig. 9) is powered by electrical energy captured by the device resonator 130, 132 (transferred to the secondary winding 20, energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0017-0018, 0031, Fig. 9).

Claim 3 lacks an inventive step under PCT Article 33(3) as being obvious over Bruhn.

Regarding claim 3, Bruhn discloses the invention above, the invention above, and discloses a first frequency (operating at the fundamental frequency, para 0017, 0031, Fig. 9) and a second frequency (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), but does not disclose wherein the first frequency is approximately an integer multiple of the second frequency. It would have been obvious to one of ordinary skill in the art at the time of the invention to provide a first frequency that is approximately an integer multiple of the second frequency, in order to provide a system that can handle different power levels for providing wireless energy to multiple devices, and because discovering the optimal value of a result effective variable involves only routine skill in the art.

Claims 5, 8-10, 16, 18 lack an inventive step under PCT Article 33(3) as being obvious over Bruhn in view of Cook et al. (hereinafter referred to as Cook).

Regarding claim 5, Bruhn discloses the invention above, but does not specifically disclose wherein the first plurality of parameters includes a first magnitude different from a second magnitude of the second plurality of parameters. Cook is in the field of wireless power systems (para 0044) and teaches wherein the first plurality of parameters includes a first magnitude different from a second magnitude of the second plurality of parameters (transmit power converter unit converts the supply voltage and frequency, such as 110V/60Hz, into another voltage [different voltage] and into another frequency, such as under 50Hz, that is more appropriate for wireless transmission, para 0155-0158). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the different magnitudes as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Regarding claim 8, Bruhn discloses the invention above, and further discloses electrical energy captured by the at least one receiving magnetic resonator 130 (resonator 130 captures energy developed by generator 16 and primary winding 18, Fig. 9, para 0034), but does not specifically disclose a first converter circuit configured to convert the electrical energy into a direct current signal. Cook teaches a first converter circuit 1550 configured to convert the electrical energy into a direct current signal (a DC/DC or DC/AC converter 1550 converts the electrical energy received by resonator antenna into direct current, para 0194-0195, Fig. 15). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the direct current conversion as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Regarding claim 9, Bruhn discloses the invention above, and further discloses wherein the alternating current signal (power source 16 provides AC current signal, Fig. 9, para 0040) is used to energize the at least one transferring magnetic resonator 126, 128 (energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0018, Fig. 9), but does not disclose a second converter circuit configured to convert the direct current signal from the first converter circuit into an alternating current signal. Cook teaches a second converter circuit (two converter circuits for converting current signals, para 0194-0195, as shown in Fig. 15) configured to convert the direct current signal from the first converter circuit into an alternating current signal (a DC/DC or DC/AC converter 1550 can convert the electrical energy received by resonator antenna into alternating current, para 0194-0195, Fig. 15). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the direct current conversion as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Regarding claim 10, Bruhn discloses the invention above, and further discloses at least one receiving magnetic resonator 130, 132 (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) and at least one transferring magnetic resonator 126, 128 (Fig. 9), but does not disclose wherein at least one of the resonators has a quality factor Q>100. Cook teaches a resonator with a quality factor Q>100 (magnetic resonant antennas used in system must provide a Q-factor as high as possible, and can provide Q-factors up to 300, para 0060-0061). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the high quality factor resonator as taught in Cook with the invention of Bruhn in order to provide a very efficient wireless power transmission system with minimal power losses (see Cook, para 0047).

Regarding claim 16, Bruhn discloses the invention above, but does not specifically disclose wherein the first plurality of parameters and the second plurality of parameters of the oscillating magnetic fields are different in at least a magnitude. Cook teaches wherein the first plurality of parameters and the second plurality of parameters of the oscillating magnetic fields are different in at least a magnitude (transmit power converter unit converts the supply voltage and frequency, such as 110V/60Hz, into another voltage [different voltage] and into another frequency, such as under 50Hz, that is more appropriate for wireless transmission, para 0155-0158). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the different magnitudes as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

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PCT/US2011/027868

Supplemental Box

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Regarding claim 18, Bruhn discloses the invention above, and further discloses the source resonator 126, 128 and the device resonator 130, 132 (Fig. 9), but does not disclose wherein at least one of the resonators has a quality factor Q>100. Cook teaches a resonator with a quality factor Q>100 (magnetic resonant antennas used in system must provide a Q-factor as high as possible, and can provide Q-factors up to 300, para 0060-0061). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the high quality factor resonator as taught in Cook with the invention of Bruhn in order to provide a very efficient wireless power transmission system with minimal power losses (see Cook, para 0047).

Claims 6-7 lack an inventive step under PCT Article 33(3) as being obvious over Bruhn in view of Keyes, IV et al. (hereinafter referred to as Keyes).

Regarding claim 6, Bruhn discloses the invention above, and discloses wherein the first plurality of parameters includes a first frequency (operating at the fundamental frequency, para 0017, 0031, Fig. 9) different from a second frequency of the second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), but does not disclose a frequency hopping sequence. Keyes is in the field of wireless energy transfer systems (para 0008-0009, Fig. 43), and teaches a frequency hopping sequence (power transmitted wirelessly using frequency hopping technique, para 0056-0058). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the frequency hopping sequence as taught in Keyes with the invention of Bruhn in order to avoid wireless interference (see Keyes, para 0056).

Regarding claim 7, Bruhn discloses the invention above, and discloses wherein the first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9) includes a sequence different from a second sequence of the second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), but does not disclose an on/off sequence. Keyes teaches an on/off sequence (wireless reception of on or off control commands for wireless base units, para 0094). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the on/off sequence as taught in Keyes with the invention of Bruhn in order to provide a method of wirelessly powering devices on and off (see Keyes, para 0007-0008).

Claims 13, 19 lack an inventive step under PCT Article 33(3) as being obvious over Bruhn in view of Lee.

Regarding claim 13, Bruhn discloses the invention above, and discloses a loop inductor 130 (Fig. 9), but does not disclose wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor. Lee is in the field of wireless power converters (para 0001) and teaches wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor (transmitter and receiver are combined, para 0048, and constructed by winding transmission coil outputting power generated from electromagnetic wave generating source, para 0051, Fig. 10). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the shared loop as taught in Lee with the invention of Bruhn to provide a more efficient wireless power system for transferring power by maximizing generation and reception of electromagnetic waves in the resonance circuit (see Lee, para 0051).

Regarding claim 19, Bruhn discloses the invention above, and discloses a loop inductor 130 (Fig. 9), but does not disclose wherein the source resonator and the device resonator include a shared loop inductor. Lee teaches wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor (transmitter and receiver are combined, para 0048, and constructed by winding transmission coil outputting power generated from electromagnetic wave generating source, para 0051, Fig. 10). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the shared loop as taught in Lee with the invention of Bruhn to provide a more efficient wireless power system for transferring power by maximizing generation and reception of electromagnetic waves in the resonance circuit (see Lee, para 0051).

Claims 20-25 meet the criteria set out in PCT Article 33(2)-(3), because the prior art does not teach or fairly suggest:

Regarding claim 20, a method of wireless power conversion comprising: providing a configurable magnetic resonator; tuning the configurable magnetic resonator to capture a first oscillating magnetic field characterized by a first plurality of parameters; converting the oscillating magnetic field into electrical energy; storing the electrical energy as stored energy in an energy storage element; tuning the configurable magnetic resonator to generate a second oscillating magnetic field characterized by a second plurality of parameters; and energizing the configurable magnetic resonator using the stored energy to produce the second oscillating magnetic field.

Claims 21-25 meet the criteria due to their dependence on novel claim 20.

The prior art, as shown below, details some aspects of the invention, however, none of the prior art teaches all the missing limitations either alone or in combination as specified.

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Bruhn (US 2009/0085408 A1) teaches a method of wireless power conversion (method for wireless energy transmission, para 0017, Fig. 9) comprising providing a configurable magnetic resonator 130, 132 (resonators can be configured for different frequencies, para 0017, Fig. 9); tuning the configurable magnetic resonator 130, 132 to capture (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) a first oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) characterized by a first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9); converting the oscillating magnetic field into electrical energy (magnetic field converted induces voltage to provide current flow, para 0005, 0017-0018); tuning a [different, second] configurable magnetic resonator 126, 128 (Fig. 9) to generate (through resonance, para 0017-0018, Fig. 9) a second oscillating magnetic field (transferred to the secondary winding 20, para 0017-0018, 0031, Fig. 9) characterized by a second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018); and energizing the [different, second] configurable magnetic resonator to produce the second oscillating magnetic field (energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0018, Fig. 9), but does not disclose tuning a magnetic resonator to capture energy, storing the energy, and then tuning the same magnetic resonator to generate energy using the stored energy to wirelessly transfer power.

Cook (US 2009/0243397 A1) teaches a method (para 0249) of wireless power conversion (wireless power system including power converter, para 0153-0158, Fig. 13, Fig. 15) comprising providing a configurable magnetic resonator (resonant magnetic antenna is adjustable to provide different operational parameters and configurations, para 0143-0144, 0210); tuning the configurable magnetic resonator (resonator receives tuning through tuning network, para 0194, Fig. 15) to capture a first oscillating magnetic field (receive antenna unit is a resonant magnetic antenna for receiving energy in form of magnetic field, para 0143-0144, 0191, Fig. 15) characterized by a first plurality of parameters (energy is in form of magnetic field which is oscillating or resonating and characterized by parameters such as frequency, para 0143-0144, 0157); converting the oscillating magnetic field into electrical energy (power converter receives energy in form of magnetic field and converts to DC current to be used by devices, para 0129, 0143-0144); tuning a [different, second] configurable magnetic resonator (resonator receives tuning through tuning network, para 0175, Fig. 13) to generate a second oscillating magnetic field characterized by a second plurality of parameters (energy transmitted is in form of magnetic field and is characterized by parameters such as frequency, para 0143-0144, 0156); and energizing the [different, second] configurable magnetic resonator using the stored energy to produce the second oscillating magnetic field (wireless energy transfer system relays energy from the energy receiver which receives power source supply and sends it to the energy receiver which powers the device, para 0129, 0143-0144), but does not disclose tuning a magnetic resonator to capture energy, storing the energy, and then tuning the same magnetic resonator to generate energy using the stored energy to wirelessly transfer power.

Iverson (US 2008/0036588 A1) teaches storing the electrical energy as stored energy in an energy storage element 302 (energy harvesting unit 302 stores the energy electromagnetically received by antenna coil 106 from master antenna coil 104, para 0005, 0019, Fig. 3), and using the stored energy (stored energy is used to power remote unit 306 and to transmit message wirelessly through antenna 106, para 0005, 0019, Fig. 3), but does not disclose tuning a magnetic resonator to capture energy, storing the energy, and then tuning the same magnetic resonator to generate energy using the stored energy to wirelessly transfer power.

Claims 1-25 meet the criteria set out in PCT Article 33(4), and thus have industrial applicability because the subject matter claimed can be made or used in industry.

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(54) **Title**: EFFICIENT NEAR-FIELD WIRELESS ENERGY TRANSFER USING ADIABATIC SYSTEM VARIATIONS

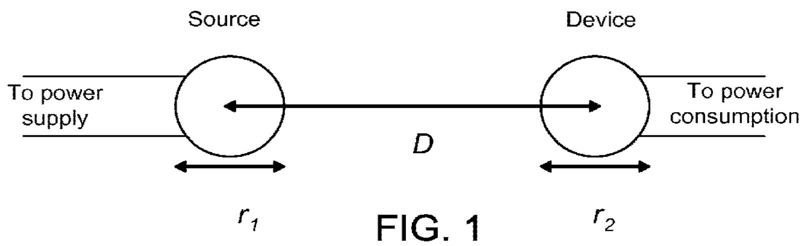

FIG. 1

(57) **Abstract**: Disclosed is a method for transferring energy wirelessly including transferring energy wirelessly from a first resonator structure to an intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B}, transferring energy wirelessly from the intermediate resonator structure to a second resonator structure, wherein the coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2} and during the wireless energy transfers, adjusting at least one of the coupling rates κ_{1B} and κ_{B2} to reduce energy accumulation in the intermediate resonator structure and improve wireless energy transfer from the first resonator structure to the second resonator structure through the intermediate resonator structure.

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MIT Case No 13441 (WiT MIT 4)

Efficient Near-Field Wireless Energy Transfer Using Adiabatic System Variations

CROSS REFERENCE TO RELATED APPLICATIONS

Pursuant to U.S.C. § 119(e), this application claims priority to U.S. Provisional Application Serial No. 61/101,809, filed October 1, 2008. The contents of the prior application is incorporated herein by reference in its entirety.

BACKGROUND

The disclosure relates to wireless energy transfer. Wireless energy transfer can for example, be useful in such applications as providing power to autonomous electrical or electronic devices.

Radiative modes of omni-directional antennas (which work very well for information transfer) are not suitable for such energy transfer, because a vast majority of energy is wasted into free space. Directed radiation modes, using lasers or highly-directional antennas, can be efficiently used for energy transfer, even for long distances (transfer distance $L_{TRANS} \gg L_{DEV}$, where L_{DEV} is the characteristic size of the device and/or the source), but may require existence of an uninterruptible line-of-sight and a complicated tracking system in the case of mobile objects. Some transfer schemes rely on induction, but are typically restricted to very close-range ($L_{TRANS} \ll L_{DEV}$) or low power (~mW) energy transfers.

The rapid development of autonomous electronics of recent years (e.g. laptops, cell-phones, house-hold robots, that all typically rely on chemical energy storage) has led to an increased need for wireless energy transfer.

SUMMARY

Disclosed is a method for transferring energy wirelessly. The method includes i) transferring energy wirelessly from a first resonator structure to an intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B}; ii) transferring energy wirelessly from the intermediate resonator structure to a second resonator structure, wherein the coupling rate

between the intermediate resonator structure and the second resonator structure is κ_{B2}; and iii) during the wireless energy transfers, adjusting at least one of the coupling rates κ_{1B} and κ_{B2} to reduce energy accumulation in the intermediate resonator structure and improve wireless energy transfer from the first resonator structure to the second resonator structure through the intermediate resonator structure.

Embodiments of the method may include one or more of the following features.

The adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can be selected to minimize energy accumulation in the intermediate resonator structure and cause wireless energy transfer from the first resonator structure to the second resonator structure.

The adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can be selected to maintain energy distribution in the field of the three-resonator system in an eigenstate having substantially no energy in the intermediate resonator structure. For example, the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can further cause the eigenstate to evolve substantially adiabatically from an initial state with substantially all energy in the resonator structures in the first resonator structure to a final state with substantially all of the energy in the resonator structures in the second resonator structure.

The adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can be selected to include adjustments of both coupling rates κ_{1B} and κ_{B2} during wireless energy transfer.

The resonator structures can each have a quality factor larger than 10.

The first and second resonator structures can each have a quality factor greater than 50.

The first and second resonator structures can each have a quality factor greater than 100.

The resonant energy in each of the resonator structures can include electromagnetic fields. For example, the maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} for inductive coupling between the intermediate resonator structure and each of the first and second resonator structures can each be larger than twice the loss rate Γ for each of the first and second resonators. Moreover, The maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} for inductive coupling between the intermediate resonator structure and each of the first and second resonator structures can each be larger than four (4) times the loss rate Γ for each of the first and second resonators.

Each resonator structure can have a resonant frequency between 50 KHz and 500 MHz.

The maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} can each be at least five (5) times greater than the coupling rate between the first resonator structure and the second resonator structure.

The intermediate resonator structure can have a rate of radiative energy loss that is at least twenty (20) times greater than that for either the first resonator structure or the second resonator structure.

The first and second resonator structures can be substantially identical.

The adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can be selected to cause peak energy accumulation in the intermediate resonator structure to be less than five percent (5%) of the peak total energy in the three resonator structures.

The adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can be selected to cause peak energy accumulation in the intermediate resonator structure during the wireless energy transfers to be less than ten percent (10%) of the peak total energy in the three resonator structures.

Adjusting at least one of the coupling rates κ_{1B} and κ_{B2} can include adjusting a relative position and/or orientation between one or more pairs of the resonator structures. Moreover, adjusting at least one of the coupling rates κ_{1B} and κ_{B2} can include adjusting a resonator property of one or more of the resonator structures, such as mutual inductance.

The resonator structures can include a capacitively loaded loop or coil of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

The resonator structures can include an inductively loaded rod of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

The wireless energy transfers are non-radiative energy transfers mediated by a coupling of a resonant field evanescent tail of the first resonator structure and a resonant field evanescent tail of the intermediate resonator structure and a coupling of the resonant field evanescent tail of the intermediate resonator structure and a resonant field evanescent tail of the second resonator structure.

The adjustment of the at least one of the coupling rates can define a first mode of operation, wherein the reduction in the energy accumulation in the intermediate resonator structure is relative to energy accumulation in the intermediate resonator structure for a second mode of operation of wireless energy transfer among the three resonator structures having a coupling rate κ'_{1B} for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate κ'_{B2} for wireless energy transfer from the intermediate resonator structure to the second resonator structure with κ'_{1B} and κ'_{B2} each being substantially constant during the second mode of wireless energy transfer, and wherein the adjustment of the coupling rates κ_{1B} and κ_{2B} in the first mode of operation can be selected to $\kappa_{1B}, \kappa_{B2} < \sqrt{\left(\kappa'^{2}_{1B} + \kappa'^{2}_{B2}\right)/2}$. Moreover, the first mode of operation can have a greater efficiency of energy transferred from the first resonator to the second resonator compared to that for the second mode of operation. Further, the first and second resonator structures can be substantially identical and each one can have a loss rate Γ_A, the intermediate resonator structure can have a loss rate Γ_B, and wherein Γ_B/Γ_A can be greater than 50.

Also, a ratio of energy lost to radiation and total energy wirelessly transferred between the first and second resonator structures in the first mode of operation is less than that for the second mode of operation. Moreover, the first and second resonator structures can be substantially identical and each one can have a loss rate Γ_A and a loss rate only due to radiation $\Gamma_{A,rad}$, the intermediate resonator structure can have a loss rate Γ_B and a loss rate only due to radiation $\Gamma_{B,rad}$ and wherein $\Gamma_{B,rad}/\Gamma_B > \Gamma_{A,rad}/\Gamma_A$.

The first mode of operation the intermediate resonator structure interacts less with extraneous objects than it does in the second mode of operation.

During the wireless energy transfer from the first resonator structure to the second resonator structure at least one of the coupling rates can be adjusted so that $\kappa_{1B} << \kappa_{B2}$ at a start of the energy transfer and $\kappa_{1B} >> \kappa_{B2}$ by a time a substantial portion of the energy has been transferred from the first resonator structure to the second resonator structure.

The coupling rate κ_{B2} can be maintained at a fixed value and the coupling rate κ_{1B} is increased during the wireless energy transfer from the first resonator structure to second resonator structure.

The coupling rate κ_{1B} can be maintained at a fixed value and the coupling rate κ_{B2} is decreased during the wireless energy transfer from the first resonator structure to second resonator structure.

During the wireless energy transfer from the first resonator structure to second resonator structure, the coupling rate κ_{1B} can be increased and the coupling rate κ_{B2} is decreased.

The method may further include features corresponding to those listed for one or more of the apparatuses and methods described below.

In another aspect, disclosed is an apparatus including: first, intermediate, and second resonator structures, wherein a coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B} and a coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2}; and means for adjusting at least one of the coupling rates κ_{1B} and κ_{B2} during wireless energy transfers among the resonator structures to reduce energy accumulation in the intermediate resonator structure and improve wireless energy transfer from the first resonator structure to the second resonator structure through the intermediate resonator structure.

Embodiments for the apparatus can include one or more of the following features.

The means for adjusting can include a rotation stage for adjusting the relative orientation of the intermediate resonator structure with respect to the first and second resonator structures.

The means for adjusting can include a translation stage for moving the first and/or second resonator structures relative to the intermediate resonator structure.

The means for adjusting can include a mechanical, electro-mechanical, or electrical staging system for dynamically adjusting the effective size of one or more of the resonator structures.

The apparatus may further include features corresponding to those listed for the method described above, and one or more of the apparatuses and methods described below.

In another aspect, a method for transferring energy wirelessly includes i): transferring energy wirelessly from a first resonator structure to a intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B}; ii) transferring energy wirelessly from the intermediate resonator structure to a second resonator, wherein the coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2}; and iii) during the wireless energy transfers, adjusting at least one of the coupling rates κ_{1B} and κ_{B2} to cause an energy distribution in the field of the three-resonator system to have substantially no energy in the intermediate resonator structure while wirelessly transferring energy from the first resonator structure to the second resonator structure through the intermediate resonator structure.

Embodiments for the method above can include one or more of the following features.

Having substantially no energy in the intermediate resonator structure can mean that peak energy accumulation in the intermediate resonator structure is less than ten percent (10%) of the peak total energy in the three resonator structures throughout the wireless energy transfer.

Having substantially no energy in the intermediate resonator structure can mean that peak energy accumulation in the intermediate resonator structure is less than five percent (5%) of the peak total energy in the three resonator structures throughout the wireless energy transfer.

The adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can be selected to maintain the energy distribution in the field of the three-resonator system in an eigenstate having the substantially no energy in the intermediate resonator structure.

The adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can be selected to further cause the eigenstate to evolve substantially adiabatically from an initial state with substantially all energy in the resonator structures in the first resonator structure to a final state with substantially all of the energy in the resonator structures in the second resonator structure.

The adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can include adjustments of both coupling rates κ_{1B} and κ_{B2} during wireless energy transfers.

The resonant energy in each of the resonator structures comprises electromagnetic fields. For example, the maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} for inductive coupling between the intermediate resonator structure and each of the first and second resonator structures can each be larger than twice the loss rate Γ for each of the first and second resonators. Moreover, the maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} for inductive coupling between the intermediate resonator structure and each of the first and second resonator structures can each be larger than four (4) times the loss rate Γ for each of the first and second resonators.

The resonator structure can have a resonant frequency between 50 KHz and 500 MHz.

The maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} can each be at least five (5) times greater than the coupling rate between the first resonator structure and the second resonator structure.

The intermediate resonator structure can have a rate of radiative energy loss that is at least twenty (20) times greater than that for either the first resonator structure or the second resonator structure.

The first and second resonator structures can be substantially identical.

Adjusting at least one of the coupling rates κ_{1B} and κ_{B2} can include adjusting a relative position and/or orientation between one or more pairs of the resonator structures.

Adjusting at least one of the coupling rates κ_{1B} and κ_{B2} can include adjusting a resonator property of one or more of the resonator structures, such as mutual inductance.

The resonator structures can include a capacitively loaded loop or coil of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

The resonator structures can include an inductively loaded rod of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

The wireless energy transfers can be non-radiative energy transfers mediated by a coupling of a resonant field evanescent tail of the first resonator structure and a resonant field evanescent tail of the intermediate resonator structure and a coupling of the resonant field evanescent tail of the intermediate resonator structure and a resonant field evanescent tail of the second resonator structure.

The first and second resonator structures can each have a quality factor greater than 50.

The first and second resonator structures can each have a quality factor greater than 100.

The adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} can be selected to cause the energy distribution in the field of the three-resonator system to have substantially no energy in the intermediate resonator structure improves wireless energy transfer between the first and second resonator structures.

The adjustment of the at least one of the coupling rates can be selected to define a first mode of operation, wherein energy accumulation in the intermediate resonator structure during the wireless energy transfer from the first resonator structure to second resonator structure is smaller than that for a second mode of operation of wireless energy transfer among the three resonator structures having a coupling rate κ'_{1B} for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate κ'_{B2} for wireless energy transfer from the intermediate resonator structure to the second resonator structure with κ'_{1B} and κ'_{B2} each being substantially constant during the second mode of wireless energy transfer, and wherein the adjustment of the coupling rates κ_{1B} and κ_{B2} in the first mode of operation can be selected to satisfy $\kappa_{1B}, \kappa_{B2} < \sqrt{\left(\kappa'^{2}_{1B} + \kappa'^{2}_{B2}\right)/2}$.

The first mode of operation can have a greater efficiency of energy transferred from the first resonator to the second resonator compared to that for the second mode of operation.

The first and second resonator structures can be substantially identical and each one can have a loss rate Γ_A, the intermediate resonator structure can have a loss rate Γ_B, and wherein Γ_B/Γ_A can be greater than 50.

A ratio of energy lost to radiation and total energy wirelessly transferred between the first and second resonator structures in the first mode of operation can be less than that for the second mode of operation.

The first and second resonator structures can be substantially identical and each one can have a loss rate Γ_A and a loss rate only due to radiation $\Gamma_{A,rad}$, the intermediate resonator structure can have a loss rate Γ_B and a loss rate only due to radiation $\Gamma_{B,rad}$ and wherein $\Gamma_{B,rad}/\Gamma_B > \Gamma_{A,rad}/\Gamma_A$.

The first mode of operation the intermediate resonator structure interacts less with extraneous objects than it does in the second mode of operation.

During the wireless energy transfer from the first resonator structure to the second resonator structure at least one of the coupling rates can be adjusted so that $\kappa_{1B} << \kappa_{B2}$ at a start of the energy transfer and $\kappa_{1B} >> \kappa_{B2}$ by a time a substantial portion of the energy has been transferred from the first resonator structure to the second resonator structure.

The coupling rate κ_{B2} can be maintained at a fixed value and the coupling rate κ_{1B} can be increased during the wireless energy transfer from the first resonator structure to second resonator structure.

The coupling rate κ_{1B} can be maintained at a fixed value and the coupling rate κ_{B2} can be decreased during the wireless energy transfer from the first resonator structure to second resonator structure.

During the wireless energy transfer from the first resonator structure to second resonator structure, the coupling rate κ_{1B} can be increased and the coupling rate κ_{B2} can be decreased.

The method may further include features corresponding to those listed for the apparatus and method described above, and one or more of the apparatuses and methods described below.

In another aspect, disclosed is an apparatus including: first, intermediate, and second resonator structures, wherein a coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B} and a coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2}; and
means for adjusting at least one of the coupling rates κ_{1B} and κ_{B2} during wireless energy transfers among the resonator structures to cause an energy distribution in the field of the three-resonator system to have substantially no energy in the intermediate resonator structure while wirelessly transferring energy from the first resonator structure to the second resonator structure through the intermediate resonator structure.

Embodiments for the apparatus can include one or more of the following features.

Having substantially no energy in the intermediate resonator structure can mean that peak energy accumulation in the intermediate resonator structure is less than ten percent (10%) of the peak total energy in the three resonator structures throughout the wireless energy transfers.

Having substantially no energy in the intermediate resonator structure can mean that peak energy accumulation in the intermediate resonator structure is less than five percent (5%) of the peak total energy in the three resonator structures throughout the wireless energy transfers.

The means for adjusting can be configured to maintain the energy distribution in the field of the three-resonator system in an eigenstate having the substantially no energy in the intermediate resonator structure.

The means for adjusting can include a rotation stage for adjusting the relative orientation of the intermediate resonator structure with respect to the first and second resonator structures.

The means for adjusting can include a translation stage for moving the first and/or second resonator structures relative to the intermediate resonator structure.

The means for adjusting can include a mechanical, electro-mechanical, or electrical staging system for dynamically adjusting the effective size of one or more of the resonator structures.

The resonator structures can include a capacitively loaded loop or coil of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

The resonator structures can include an inductively loaded rod of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

A source can be coupled to the first resonator structure and a load can be coupled to the second resonator structure.

The apparatus may further include features corresponding to those listed for the apparatus and methods described above, and the apparatus and method described below.

In another aspect, disclosed is a method for transferring energy wirelessly that includes: i) transferring energy wirelessly from a first resonator structure to a intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B} ; ii) transferring energy wirelessly from the intermediate resonator structure to a second resonator, wherein the coupling rate between the intermediate resonator structure and the second resonator structure with a coupling rate is κ_{B2} ; and iii) during the wireless energy transfers, adjusting at least one of the coupling rates κ_{1B} and κ_{B2} to define a first mode of operation in which energy accumulation in the intermediate resonator structure is reduced relative to that for a second mode of operation of wireless energy transfer among the three resonator structures having a coupling rate κ'_{1B} for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate κ'_{B2} for wireless energy transfer from the intermediate resonator structure to the second resonator structure with κ'_{1B} and κ'_{B2} each being substantially constant during the second mode of wireless energy transfer, and wherein the adjustment of the coupling rates κ_{1B} and κ_{B2} in the first mode of operation can be selected to satisfy $\kappa_{1B}, \kappa_{B2} < \sqrt{\left(\kappa'^{2}_{1B} + \kappa'^{2}_{B2}\right)/2}$.

The method may further include features corresponding to those listed for the apparatuses and methods described above.

In another aspect, disclosed is an apparatus that includes: first, intermediate, and second resonator structures, wherein a coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B} and a coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2}; and means for adjusting at least one of the coupling rates κ_{1B} and κ_{B2} during wireless energy transfers among the resonator structures to define a first mode of operation in which energy accumulation in the intermediate resonator structure is reduced relative to that for a second mode of operation for wireless energy transfer among the three resonator structures having a coupling rate κ'_{1B} for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate κ'_{B2} for wireless energy transfer from the intermediate resonator structure to the second resonator structure with κ'_{1B} and κ'_{B2} each being substantially constant during the second mode of wireless energy transfer, and wherein the adjustment of the coupling rates κ_{12} and κ_{B2} in the first mode of operation can be selected to satisfy $\kappa_{1B}, \kappa_{B2} < \sqrt{\left(\kappa'^{2}_{1B} + \kappa'^{2}_{B2}\right)/2}$.

The apparatus may further include features corresponding to those listed for the apparatuses and methods described above.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present disclosure, suitable methods and materials are described below. All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

The details of one or more embodiments are set forth in the accompanying drawings and the description below, including the documents appended hereto. Other features and advantages will be apparent from this disclosure and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a schematic of an example wireless energy transfer scheme.

Figs. 2(a)-(b) show the efficiency of power transmission η_P for (a) $U=1$ and (b) $U=3$, as a function of the frequency detuning D_o and for different values of the loading rate U_o.

Fig. 2(c) shows the optimal (for zero detuning and under conditions of impedance matching) efficiency for energy transfer η_{E*} and power transmission η_{P*}, as a function of the coupling-to-loss figure-of-merit U.

Fig. 3 shows an example of a self-resonant conducting-wire coil.

Fig. 4 shows an example of a wireless energy transfer scheme featuring two self-resonant conducting-wire coils.

Fig. 5 is a schematic of an experimental system demonstrating wireless energy transfer.

Fig. 6 shows a comparison between experimental and theoretical results for the coupling rate of the system shown schematically in Fig. 5.

Fig. 7 shows a comparison between experimental and theoretical results for the strong-coupling factor of the system shown schematically in Fig. 5.

Fig. 8 shows a comparison between experimental and theoretical results for the power-transmission efficiency of the system shown schematically in Fig. 5.

Fig. 9 shows an example of a capacitively-loaded conducting-wire coil, and illustrates the surrounding field.

Fig. 10 shows an example wireless energy transfer scheme featuring two capacitively-loaded conducting-wire coils, and illustrates the surrounding field.

Fig. 11 illustrates an example circuit model for wireless energy transfer.

Fig. 12 shows the efficiency, total (loaded) device Q, and source and device currents, voltages and radiated powers (normalized to 1Watt of output power to the load) as functions of the resonant frequency, for a particular choice of source and device loop dimensions, wp and N_s and different choices of N_d=1,2,3,4,5,6,10.

Fig.13 shows the efficiency, total (loaded) device Q, and source and device currents, voltages and radiated powers (normalized to 1Watt of output power to the load) as functions of frequency and wp for a particular choice of source and device loop dimensions, and number of turns N_s and N_d.

Fig. 14 shows an example of an inductively-loaded conducting-wire coil.

Fig. 15 shows (a) an example of a resonant dielectric disk, and illustrates the surrounding field and (b) a wireless energy transfer scheme featuring two resonant dielectric disks, and illustrates the surrounding field.

Fig. 16 shows a schematic of an example wireless energy transfer scheme with one source resonator and one device resonator exchanging energy indirectly through an intermediate resonator.

Fig. 17 shows an example of a wireless energy transfer system: (a) (Left) Schematic of loops configuration in two-object direct transfer. (Right) Time evolution of energies in the two-object direct energy transfer case. (b) (Left) Schematic of three-loops configuration in the constant-κ case. (Right) Dynamics of energy transfer for the configuration in (b. Left). Note that the total energy transferred E_2 is 2 times larger than in (a. Right), but at the price of the total energy radiated being 4 times larger. (c) (Left)

Loop configuration at t=0 in the adiabatic-κ scheme. (Center) Dynamics of energy transfer with adiabatically rotating loops. (Right) Loop configuration at $t=t_{EIT}$. Note that E_2 is comparable to (b. Right), but the radiated energy is now much smaller: In fact, it is comparable to (a. Right).

Fig. 18 shows a schematic of an example wireless energy transfer scheme with one source resonator and one device resonator exchanging energy indirectly through an intermediate resonator, where an adjustment system is used to rotate the resonator structures to dynamically adjust their coupling rates.

Fig. 19 shows an example of a temporal variation of the coupling rates in a wireless energy transfer system as in Fig. 18 to achieve an adiabatic transfer of energy from the source object R_1 to the device object R_2.

Fig. 20 shows the energy distribution in a wireless energy transfer system as in Fig. 18 as a function of time when the coupling rates are time-varying, for $\Gamma_A=0$, $\kappa/\Gamma_B=10$, $\kappa_{1B}=\kappa\sin[\pi t/(2t_{EIT})]$, and $\kappa_{B2}=\kappa\cos[\pi t/(2t_{EIT})]$.

Figs. 21(a)-(f) show a comparison between the adiabatic-κ and constant-κ energy transfer schemes, in the general case: (a) Optimum E_2 (%) in adiabatic-κ transfer, (b) Optimum E_2 (%) in constant-κ transfer, (c) $(E_2)_{adiabatic-\kappa}/(E_2)_{constant-\kappa}$, (d) Energy lost (%) at optimum adiabatic-κ transfer, (e) Energy lost (%) at optimum constant-κ transfer, (f) $(E_{lost})_{constant-\kappa}/(E_{lost})_{adiabatic-\kappa}$.

Fig. 22(a)-(e) show a comparison between radiated energies in the adiabatic-κ and constant-κ energy transfer schemes: (a) E_{rad}(%) in the constant-scheme for $\Gamma_B/\Gamma_A=500$ and $\Gamma_{rad}^A=0$, (b) E_{rad}(%) in the adiabatic-κ scheme for $\Gamma_B/\Gamma_A=500$ and $\Gamma_{rad}^A=0$, (c) $(E_{rad})_{constant-\kappa}/(E_{rad})_{adiabatic-\kappa}$ for $\Gamma_B/\Gamma_A=50$, (d) $(E_{rad})_{constant-\kappa}/(E_{rad})_{adiabatic-\kappa}$ for $\Gamma_B/\Gamma_A=500$, (e) $[(E_{rad})_{constant-\kappa}/(E_{rad})_{adiabatic-\kappa}]$ as function of κ/Γ_B and Γ_B/Γ_A, for $\Gamma_{rad}^A=0$.

Figs. 23(a)-(b) show schematics for frequency control mechanisms.

Figs. 24(a)-(c) illustrate a wireless energy transfer scheme using two dielectric disks in the presence of various extraneous objects.

DETAILED DESCRIPTION

Efficient wireless energy-transfer between two similar-frequency resonant objects can be achieved at mid-range distances, provided these resonant objects are designed to operate in the 'strong-coupling' regime. 'Strong coupling' can be realized for a wide variety of resonant objects, including electromagnetic resonant objects such as inductively-loaded conducting rods and dielectric disks. Recently, we have demonstrated wireless energy transfer between strongly coupled electromagnetic self-resonant conducting coils and capacitively-loaded conducting coils, bearing high-Q electromagnetic resonant modes. See, for example, the following commonly owned U.S. Patent Applications, all of which are incorporated herein by reference: U.S. Application Serial No. 11/481,077, filed on July 5, 2006, and published as U.S. Patent Publication No. US 2007-0222542 A1; U.S. Application Serial No. 12/055,963, filed on March 26, 2008, and published as U.S. Patent Publication No. US 2008-0278264 A1; and U.S. Patent Application Serial No. 12/466,065, filed on May 14, 2009, and published as U.S. Patent Publication No. __________. In general, the energy-transfer efficiency between similar-frequency, strongly coupled resonant objects decreases as the distance between the objects is increased.

In this work, we explore a further scheme of efficient energy transfer between resonant objects that extends the range over which energy may be efficiently transferred. Instead of transferring energy directly between two resonant objects, as has been described in certain embodiments of the cross-referenced patents, in certain embodiments, an intermediate resonant object, with a resonant frequency equal or nearly-equal to that of the two energy-exchanging resonant objects is used to mediate the transfer. The intermediate resonant object may be chosen so that it couples more strongly to each of the resonant objects involved in the energy transfer than those two resonant objects couple to each other. One way to design such an intermediate resonator is to make it larger than either of the resonant objects involved in the energy transfer. However, increasing the size of the intermediate resonant object may lower its quality factor, or Q, by increasing its radiation losses. Surprisingly enough, this new "indirect" energy transfer scheme may be shown to be very efficient and only weakly-radiative by introducing a meticulously chosen time variation of the resonator coupling rates.

The advantage of this method over the prior commonly owned wireless energy transfer techniques is that, in certain embodiments, it can enable energy to be transferred wirelessly between two objects with a larger efficiency and/or with a smaller radiation loss and/or with fewer interactions with extraneous objects.

Accordingly, in certain embodiments, we disclose an efficient wireless energy transfer scheme between two similar resonant objects, strongly coupled to an intermediate resonant object of substantially different properties, but with the same resonance frequency. The transfer mechanism essentially makes use of the adiabatic evolution of an instantaneous (so called 'dark') resonant state of the coupled three-object system. Our analysis is based on temporal coupled mode theory (CMT), and is general. Of particular commercial interest is the application of this technique to strongly-coupled electromagnetic resonators used for mid-range wireless energy transfer applications. We show that in certain parameter regimes of interest, this scheme can be more efficient, and/or less radiative than other wireless energy transfer approaches.

While the technique described herein is primarily directed to tangible resonator structures, the technique shares certain features with a quantum interference phenomenon known in the atomic physics community as Electromagnetically Induced Transparency (EIT). In EIT, three atomic states participate. Two of them, which are non-lossy, are coupled to one that has substantial losses. However, by meticulously controlling the mutual couplings between the states, one can establish a coupled system which is overall non-lossy. This phenomena has been demonstrated using carefully timed optical pulses, referred to as probe laser pulses and Stokes laser pulses, to reduce the opacity of media with the appropriate collection of atomic states. A closely related phenomenon known as Stimulated Raman Adiabatic Passage (STIRAP) may take place in a similar system; namely, the probe and Stokes laser beams may be used to achieve complete coherent population transfer between two molecular states of a medium. Hence, we may refer to the currently proposed scheme as the "EIT-like" energy transfer scheme.

In certain embodiments, we disclose an efficient near-field energy transfer scheme between two similar resonant objects, based on an EIT-like transfer of the energy through a mediating resonant object with the same resonant frequency. In embodiments, this EIT-like energy transfer may be realized using electromagnetic resonators as have been described in the cross-referenced patents, but the scheme is not bound only to wireless energy transfer applications. Rather, this scheme is general and may find applications in various other types of coupling between general resonant objects. In certain embodiments described below, we describe particular examples of electromagnetic resonators, but the nature of the resonators and their coupling mechanisms could be quite different (e.g. acoustic, mechanical, etc.). To the extent that many resonant phenomena can be modeled with nearly identical CMT equations, similar behavior to that described herein would occur.

1. Efficient energy-transfer by two ‘strongly coupled’ resonances

Fig. 1 shows a schematic that generally describes one example of the invention, in which energy is transferred wirelessly between two resonant objects. Referring to Fig. 1, energy is transferred over a distance D, between a resonant source object having a characteristic size r_1 and a resonant device object of characteristic size r_2. Both objects are resonant objects. The wireless near-field energy transfer is performed using the field (e.g. the electromagnetic field or acoustic field) of the system of two resonant objects.

The characteristic size of an object can be regarded as being equal to the radius of the smallest sphere which can fit around the entire object. The characteristic thickness of an object can be regarded as being, when placed on a flat surface in any arbitrary configuration, the smallest possible height of the highest point of the object above a flat surface. The characteristic width of an object can be regarded as being the radius of the smallest possible circle that the object can pass through while traveling in a straight line. For example, the characteristic width of a cylindrical object is the radius of the cylinder.

Initially, we present a theoretical framework for understanding near-field wireless energy transfer. Note however that it is to be understood that the scope of the invention is not bound by theory.

Different temporal schemes can be employed, depending on the application, to transfer energy between two resonant objects. Here we will consider two particularly simple but important schemes: a one-time finite-amount energy-transfer scheme and a continuous finite-rate energy-transfer (power) scheme.

1.1 Finite-amount energy-transfer efficiency

Let the source and device objects be 1, 2 respectively and their resonance modes, which we will use for the energy exchange, have angular frequencies $\omega_{1,2}$, frequency-widths due to intrinsic (absorption, radiation etc.) losses $\Gamma_{1,2}$ and (generally) vector fields $\mathbf{F}_{1,2}(\mathbf{r})$, normalized to unity energy. Once the two resonant objects are brought in proximity, they can interact and an appropriate analytical framework for modeling this resonant interaction is that of the well-known coupled-mode theory (CMT). This model works well, when the resonances are well defined by having large quality factors and their resonant frequencies are relatively close to each other. In this picture, the field of the system of the two resonant objects 1, 2 can be approximated by $\mathbf{F}(\mathbf{r},t)=a_1(t)\mathbf{F}_1(\mathbf{r})+a_2(t)\mathbf{F}_2(\mathbf{r})$, where $a_{1,2}(t)$ are the field amplitudes, with $|a_{1,2}(t)|^2$ equal to the energy stored inside the object 1, 2 respectively, due to the normalization. Then, using $e^{-i\omega t}$ time dependence, the field amplitudes can be shown to satisfy, to lowest order:

$$\begin{aligned}\frac{d}{dt}a_1(t)&=-i(\omega_1-i\Gamma_1)a_1(t)+i\kappa_{11}a_1(t)+i\kappa_{12}a_2(t)\\ \frac{d}{dt}a_2(t)&=-i(\omega_2-i\Gamma_2)a_2(t)+i\kappa_{21}a_1(t)+i\kappa_{22}a_2(t)\end{aligned} \quad (1)$$

where $\kappa_{11,22}$ are the shifts in each object's frequency due to the presence of the other, which are a second-order correction and can be absorbed into the resonant frequencies (eigenfrequencies) by setting $\omega_{1,2}\rightarrow\omega_{1,2}+\kappa_{11,22}$, and $\kappa_{12,21}$ are the coupling coefficients, which from the reciprocity requirement of the system satisfy $\kappa_{21}=\kappa_{12}\equiv\kappa$.

The resonant modes of the combined system are found by substituting $[a_1(t), a_2(t)] = [A_1, A_2]e^{-i\bar{\omega}t}$. They have complex resonant frequencies

$$\bar{\omega}_{\pm} = \omega_{12} \pm \sqrt{(\Delta\omega_{12})^2 + \kappa^2} \tag{2a}$$

where $\omega_{12} = [(\omega_1 + \omega_2) - i(\Gamma_1 + \Gamma_2)]/2$, $\Delta\omega_{12} = [(\omega_1 - \omega_2) - i(\Gamma_1 - \Gamma_2)]/2$ and whose splitting we denote as $\delta_E \equiv \bar{\omega}_+ - \bar{\omega}_-$, and corresponding resonant field amplitudes

$$\vec{V}_{\pm} = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}_{\pm} = \begin{bmatrix} \kappa \\ \Delta\omega_{12} \mp \sqrt{(\Delta\omega_{12})^2 + \kappa^2} \end{bmatrix}. \tag{2b}$$

Note that, at exact resonance $\omega_1 = \omega_2 = \omega_A$ and for $\Gamma_1 = \Gamma_2 = \Gamma_A$, we get $\Delta\omega_{12} = 0$, $\delta_E = 2\kappa$, and then

$$\bar{\omega}_{\pm} = \omega_A \pm \kappa - i\Gamma_A$$

$$\vec{V}_{\pm} = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}_{\pm} = \begin{bmatrix} 1 \\ \mp 1 \end{bmatrix},$$

namely we get the known result that the resonant modes split to a lower frequency even mode and a higher frequency odd mode.

Assume now that at time $t = 0$ the source object 1 has finite energy $|a_1(0)|^2$, while the device object has $|a_2(0)|^2 = 0$. Since the objects are coupled, energy will be transferred from 1 to 2. With these initial conditions, Eqs.(1) can be solved, predicting the evolution of the device field-amplitude to be

$$\frac{a_2(t)}{|a_1(0)|} = \frac{2\kappa}{\delta_E} \sin\left(\frac{\delta_E t}{2}\right) e^{-\frac{\Gamma_1+\Gamma_2}{2}t} e^{-i\frac{\omega_1+\omega_2}{2}t}. \tag{3}$$

The energy-transfer efficiency will be $\eta_E \equiv |a_2(t)|^2/|a_1(0)|^2$. The ratio of energy converted to loss due to a specific loss mechanism in resonators 1 and 2, with respective loss rates $\Gamma_{1,\mathrm{loss}}$ and $\Gamma_{2,\mathrm{loss}}$ will be $\eta_{loss,E} = \int_0^t d\tau\left[2\Gamma_{1,\mathrm{loss}}|a_1(\tau)|^2 + 2\Gamma_{2,\mathrm{loss}}|a_2(\tau)|^2\right]/|a_1(0)|^2$. Note that, at exact resonance $\omega_1 = \omega_2 = \omega_A$ (an optimal condition), Eq.(3) can be written as

$$\frac{a_2(T)}{|a_1(0)|} = \frac{\sin\left(\sqrt{1-\Delta^2}T\right)}{\sqrt{1-\Delta^2}} e^{-T/U} e^{-i\omega_A t} \tag{4}$$

where $\equiv \kappa t$, $\Delta^{-1} = 2\kappa/(\Gamma_2 - \Gamma_1)$ and $U = 2\kappa/(\Gamma_1 + \Gamma_2)$.

In some examples, the system designer can adjust the duration of the coupling t at will. In some examples, the duration t can be adjusted to maximize the device energy (and thus efficiency η_E). Then, it can be inferred from Eq.(4) that η_E is maximized for

$$T_* = \frac{\tan^{-1}\left(U\sqrt{1-\Delta^2}\right)}{\sqrt{1-\Delta^2}} \tag{5}$$

resulting in an optimal energy-transfer efficiency

$$\eta_{E*} \equiv \eta_E(T_*) = \frac{U^2}{1+U^2(1-\Delta^2)} \exp\left(-\frac{2\tan^{-1}\left(U\sqrt{1-\Delta^2}\right)}{U\sqrt{1-\Delta^2}}\right). \tag{6a}$$

which is a monotonically increasing function of the coupling-to-loss ratio $U = 2\kappa/(\Gamma_1 + \Gamma_2)$ and tends to unity when $U \gg 1 \Longrightarrow |\Delta|^{-1} \gg 1$. Therefore, the energy transfer is nearly perfect, when the coupling rate is much faster than all loss rates ($\kappa/\Gamma_{1,2} \gg 1$). In Fig.2(c) we show the optimal energy-transfer efficiency when $\Gamma_1 = \Gamma_2 = \Gamma_A \Leftrightarrow \Delta = 0$:

$$\eta_E(T_*, \Delta=0) = \frac{U^2}{1+U^2} \exp\left(-\frac{2\tan^{-1} U}{U}\right). \tag{6b}$$

In a real wireless energy-transfer system, the source object can be connected to a power generator (not shown in Fig.1), and the device object can be connected to a power consuming load (e.g. a resistor, a battery, an actual device, not shown in Fig.1). The generator will supply the energy to the source object, the energy will be transferred wirelessly and non-radiatively from the source object to the device object, and the load will consume the energy from the device object. To incorporate such supply and consumption mechanisms into this temporal scheme, in some examples, one can imagine that the generator is very briefly but very strongly coupled to the source at time $t = 0$ to almost instantaneously provide the energy, and the load is similarly very briefly but very strongly coupled to the device at the optimal time $t = t_*$ to almost instantaneously drain the energy. For a constant powering mechanism, at time $t = t_*$ also the generator can again be coupled to the source to feed a new amount of energy, and this process can be repeated periodically with a period t_*.

1.2 Finite-rate energy-transfer (power-transmission) efficiency

Let the generator be continuously supplying energy to the source object 1 at a rate κ_1 and the load continuously draining energy from the device object 2 at a rate κ_2. Field amplitudes $s_{\pm 1,2}(t)$ are then defined, so that $|s_{\pm 1,2}(t)|^2$ is equal to the power ingoing to (for the + sign) or outgoing from (for the - sign) the object 1, 2 respectively, and the CMT equations are modified to

$$\begin{aligned}
\frac{d}{dt}a_1(t) &= -i(\omega_1 - i\Gamma_1)a_1(t) + i\kappa_{11}a_1(t) + i\kappa_{12}a_2(t) - \kappa_1 a_1(t) + \sqrt{2\kappa_1}s_{+1}(t) \\
\frac{d}{dt}a_2(t) &= -i(\omega_2 - i\Gamma_2)a_2(t) + i\kappa_{21}a_1(t) + i\kappa_{22}a_2(t) - \kappa_2 a_2(t) \\
s_{-1}(t) &= \sqrt{2\kappa_1}a_1(t) - s_{+1}(t) \\
s_{-2}(t) &= \sqrt{2\kappa_2}a_2(t)
\end{aligned} \tag{7}$$

where again we can set $\omega_{1,2} \rightarrow \omega_{1,2} + \kappa_{11,22}$ and $\kappa_{21} = \kappa_{12} \equiv \kappa$.

Assume now that the excitation is at a fixed frequency ω, namely has the form $s_{+1}(t) = S_{+1}e^{-i\omega t}$. Then the response of the linear system will be at the same frequency, namely $a_{1,2}(t) = A_{1,2}e^{-i\omega t}$ and $s_{-1,2}(t) = S_{-1,2}e^{-i\omega t}$. By substituting these into Eqs.(7), using $\delta_{1,2} \equiv \omega - \omega_{1,2}$, and solving the system, we find the field-amplitude transmitted to the load (S_{21} scattering-matrix element)

$$S_{21} \equiv \frac{S_{-2}}{S_{+1}} = \frac{2i\kappa\sqrt{\kappa_1\kappa_2}}{(\Gamma_1+\kappa_1-i\delta_1)(\Gamma_2+\kappa_2-i\delta_2)+\kappa^2} = \frac{2iU\sqrt{U_1U_2}}{(1+U_1-iD_1)(1+U_2-iD_2)+U^2} \quad (8)$$

and the field-amplitude reflected to the generator (S_{11} scattering-matrix element)

$$S_{11} \equiv \frac{S_{-1}}{S_{+1}} = \frac{(\Gamma_1-\kappa_1-i\delta_1)(\Gamma_2+\kappa_2-i\delta_2)+\kappa^2}{(\Gamma_1+\kappa_1-i\delta_1)(\Gamma_2+\kappa_2-i\delta_2)+\kappa^2} = \frac{(1-U_1-iD_1)(1+U_2-iD_2)+U^2}{(1+U_1-iD_1)(1+U_2-iD_2)+U^2} \quad (9)$$

where $D_{1,2} \equiv \delta_{1,2}/\Gamma_{1,2}$, $U_{1,2} \equiv \kappa_{1,2}/\Gamma_{1,2}$ and $U \equiv \kappa/\sqrt{\Gamma_1\Gamma_2}$. Similarly, the scattering-matrix elementsS_{12}, S_{22} are given by interchanging $1 \leftrightarrow 2$ in Eqs.(8),(9) and, as expected from reciprocity, $S_{21} = S_{12}$. The coefficients for power transmission (efficiency) and reflection and loss are respectively $\eta_P \equiv |S_{21}|^2 = |S_{-2}|^2/|S_{+1}|^2$ and $|S_{11}|^2 = |S_{-1}|^2/|S_{+1}|^2$ and $1 - |S_{21}|^2 - |S_{11}|^2 = (2\Gamma_1|A_1|^2 + 2\Gamma_2|A_2|^2)/|S_{+1}|^2$.

In some implementations, the parameters $D_{1,2}$, $U_{1,2}$ can be designed (engineered), since one can adjust the resonant frequencies $\omega_{1,2}$ (compared to the desired operating frequency ω) and the generator/load supply/drain rates $\kappa_{1,2}$. Their choice can target the optimization of some system performance-characteristic of interest.

In some examples, a goal can be to maximize the power transmission (efficiency) $\eta_P \equiv |S_{21}|^2$ of the system, so one would require

$$\eta_P'(D_{1,2}) = \eta_P'(U_{1,2}) = 0 \quad (10)$$

Since S_{21} (from Eq.(8)) is symmetric upon interchanging $1 \leftrightarrow 2$, the optimal values for $D_{1,2}$ (determined by Eqs.(10)) will be equal, namely $D_1 = D_2 \equiv D_o$, and similarly $U_1 = U_2 \equiv U_o$. Then,

$$S_{21} = \frac{2iUU_o}{(1+U_o-iD_o)^2+U^2} \quad (11)$$

and from the condition $\eta_P'(D_o) = 0$ we get that, for fixed values of U and U_o, the efficiency can be maximized for the following values of the symmetric detuning

$$D_o = \begin{cases} \pm\sqrt{U^2-(1+U_o)^2}, & \text{if } \quad U > 1+U_o \\ 0, & \text{if } \quad U \leq 1+U_o \end{cases}, \tag{12}$$

which, in the case $U > 1 + U_o$, can be rewritten for the two frequencies at which the efficiency peaks as

$$\omega_\pm = \frac{\omega_1\Gamma_2+\omega_2\Gamma_1}{\Gamma_1+\Gamma_2} \pm \frac{2\sqrt{\Gamma_1\Gamma_2}}{\Gamma_1+\Gamma_2}\sqrt{\kappa^2-(\Gamma_1+\kappa_1)(\Gamma_2+\kappa_2)}, \tag{13}$$

whose splitting we denote as $\delta_P \equiv \overline{\omega}_+ - \overline{\omega}_-$. Note that, at exact resonance $\omega_1 = \omega_2$, and for $\Gamma_1 = \Gamma_2 \equiv \Gamma_o$ and $\kappa_1 = \kappa_2 \equiv \kappa_o$, we get $\delta_P = 2\sqrt{\kappa^2 - (\Gamma_o + \kappa_o)^2} < \delta_E$, namely the transmission-peak splitting is smaller than the normal-mode splitting. Then, by substituting D_o into η_P from Eq.(12), from the condition $\eta_P'(U_o) = 0$ we get that, for fixed value of U, the efficiency can be maximized for

$$U_{o*} = \sqrt{1+U^2} \quad \overset{\text{Eq.(12)}}{\Rightarrow} \quad D_{o*} = 0 \tag{14}$$

which is known as 'critical coupling' condition, whereas for $U_o < U_{o*}$ the system is called 'undercoupled' and for $U_o > U_{o*}$ it is called 'overcoupled'. The dependence of the efficiency on the frequency detuning D_o for different values of U_o (including the 'critical-coupling' condition) are shown in Fig. 2(a,b). The overall optimal power efficiency using Eqs.(14) is

$$\eta_{P*} \equiv \eta_P(D_{o*}, U_{o*}) = \frac{U_{o*}-1}{U_{o*}+1} = \left(\frac{U}{1+\sqrt{1+U^2}}\right)^2, \tag{15}$$

which is again only a function of the coupling-to-loss ratio $U = \kappa/\sqrt{\Gamma_1\Gamma_2}$ and tends to unity when $U \gg 1$, as depicted in Fig. 2(c).

In some examples, a goal can be to minimize the power reflection at the side of the generator $|S_{11}|^2$ and the load $|S_{22}|^2$, so one would then need

$$S_{11,22} = 0 \Rightarrow (1 \mp U_1 - iD_1)(1 \pm U_2 - iD_2) + U^2 = 0, \tag{16}$$

The equations above present 'impedance matching' conditions. Again, the set of these conditions is symmetric upon interchanging $1 \leftrightarrow 2$, so, by substituting $D_1 = D_2 \equiv D_o$ and $U_1 = U_2 \equiv U_o$ into Eqs.(16), we get

$$(1 - iD_o)^2 - U_o^2 + U^2 = 0, \tag{17}$$

from which we easily find that the values of D_o and U_o that cancel all reflections are again exactly those in Eqs.(14).

It can be seen that, the two goals and their associated sets of conditions (Eqs.(10) and Eqs.(16)) result in the same optimized values of the intra-source and intra-device parameters $D_{1,2}$, $U_{1,2}$. Note that for a lossless system this would be an immediate consequence of power conservation (Hermiticity of the scattering matrix), but this is not apparent for a lossy system.

Accordingly, for any temporal energy-transfer scheme, once the parameters specific only to the source or to the device (such as their resonant frequencies and their excitation or loading rates respectively) have been optimally designed, the efficiency monotonically increases with the ratio of the source-device coupling-rate to their loss rates. Using the definition of a resonance quality factor $Q = \omega/2\Gamma$ and defining by analogy the coupling factor $k \equiv 1/Q_\kappa \equiv 2\kappa/\sqrt{\omega_1\omega_2}$, it is therefore exactly this ratio

$$U = \frac{\kappa}{\sqrt{\Gamma_1\Gamma_2}} = k\sqrt{Q_1Q_2} \tag{18}$$

that has been set as a figure-of-merit for any system under consideration for wireless energy-transfer, along with the distance over which this ratio can be achieved (clearly, U will be a decreasing function of distance). The operating regime $U > 1$ is sometimes called 'strong-coupling' regime and is a sufficient condition for efficient energy-transfer. In particular, for $U > 1$ we get, from Eq.(15), $\eta_{P*} > 17\%$, large enough for many practical applications. Note that in some applications, U>0.1 may be sufficient. In applications where it is impossible or impractical to run wires to supply power to a device, U<0.1 may be considered sufficient. One skilled in the art will recognize that the sufficient U is application and specification dependent. The figure-of-merit U may be called the strong-coupling factor. We will further show how to design systems with a large strong-coupling factor.

To achieve a large strong-coupling factor U, in some examples, the energy-transfer application preferably uses resonant modes of high quality factors Q, corresponding to low (i.e. slow) intrinsic-loss rates Γ. This condition can be satisfied by designing resonant modes where all loss mechanisms, typically radiation and absorption, are sufficiently suppressed.

This suggests that the coupling be implemented using, not the lossy radiative far-field, which should rather be suppressed, but the evanescent (non-lossy) stationary near-field. To implement an energy-transfer scheme, usually more appropriate are finite objects, namely ones that are topologically surrounded everywhere by air, into where the near field extends to achieve the coupling. Objects of finite extent do not generally support electromagnetic states that are exponentially decaying in *all* directions in air away from the objects, since Maxwell's Equations in free space imply that $\mathbf{k}^2=\omega^2/c^2$, where $\mathbf{k}$ is the wave vector, ω the angular frequency, and c the speed of light, because of which one can show that such finite objects cannot support states of infinite Q, rather there always is some amount of radiation. However, very long-lived (so-called "high-Q") states can be found, whose tails display the needed exponential or exponential-like decay away from the resonant object over long enough distances before they turn oscillatory (radiative). The limiting surface, where this change in the field behavior happens, is called the "radiation caustic", and, for the wireless energy-transfer scheme to be based on the near field rather than the far/radiation field, the distance between the coupled objects must be such that one lies within the radiation caustic of the other. One typical way of achieving a high radiation-Q (Q_{rad}) is to design subwavelength resonant objects. When the size of an object is much smaller than the wavelength of radiation in free space, its electromagnetic field couples to radiation very weakly. Since the extent of the near-field into the area surrounding a finite-sized resonant object is set typically by the wavelength, in some examples, resonant objects of subwavelength size have significantly longer evanescent field-tails. In other words, the radiation caustic is pushed far away from the object, so the electromagnetic mode enters the radiative regime only with a small amplitude.

Moreover, most realistic materials exhibit some nonzero amount of absorption, which can be frequency dependent, and thus cannot support states of infinite Q, rather there always is some amount of absorption. However, very long-lived ("high-Q") states can be found, where electromagnetic modal energy is only weakly dissipated. Some typical ways of achieving a high absorption-Q (Q_{abs}) is to use materials which exhibit very small absorption at the resonant frequency and/or to shape the field to be localized more inside the least lossy materials.

Furthermore, to achieve a large strong-coupling factor U, in some examples, the energy-transfer application may use systems that achieve a high coupling factor k, corresponding to strong (i.e. fast) coupling rate κ, over distances larger than the characteristic sizes of the objects.

Since finite-sized subwavelength resonant objects can often be designed to have high Q, as was discussed above and will be seen in examples later on, such objects may typically be chosen for the resonant device-object. In these cases, the electromagnetic field is, in some examples, of a quasi-static nature and the distance, up to which sufficient coupling can be achieved, is dictated by the decay-law of this quasi-static field.

Note that in some examples, the resonant source-object may be immobile and thus less restricted in its allowed geometry and size. It can be therefore chosen to be large enough that the near-field extent is not limited by the wavelength, and can thus have nearly infinite radiation-Q. Some objects of nearly infinite extent, such as dielectric waveguides, can support guided modes, whose evanescent tails are decaying exponentially in the direction away from the object, slowly if tuned close to cutoff, therefore a good coupling can also be achieved over distances quite a few times larger than a characteristic size of the source- and/or device-object.

2 'Strongly-coupled' resonances at mid-range distances for realistic systems

In the following, examples of systems suitable for energy transfer of the type described above are described. We will demonstrate how to compute the CMT parameters $\omega_{1,2}$, $Q_{1,2}$ and k described above and how to choose or design these parameters for particular examples in order to produce a desirable figure-of-merit $U = \kappa/\sqrt{\Gamma_1\Gamma_2} = k\sqrt{Q_1 Q_2}$ at a desired distance D. In some examples, this figure-of-merit is maximized when $\omega_{1,2}$ are tuned close to a particular angular frequency ω_U.

2.1 Self-resonant conducting coils

In some examples, one or more of the resonant objects are self-resonant conducting coils. Referring to Fig. 3, a conducting wire of length, l, and cross-sectional radius, a, is wound into a helical coil of radius, r, and height, h, (namely with $N = \sqrt{l^2 - h^2}\,/\,2\pi r$ number of turns), surrounded by air. As described below, the wire has distributed inductance and distributed capacitance, and therefore it supports a resonant mode of angular frequency ω. The nature of the resonance lies in the periodic exchange of energy from the electric field within the capacitance of the coil, due to the charge distribution $\rho(\mathbf{x})$ across it, to the magnetic field in free space, due to the current distribution $\mathbf{j}(\mathbf{x})$ in the wire. In particular, the charge conservation equation $\nabla \cdot \mathbf{j} = i\omega\rho$ implies that: (i) this periodic exchange is accompanied by a $\pi/2$ phase-shift between the current and the charge density profiles, namely the energy W contained in the coil is at certain points in time completely due to the current and at other points in time completely due to the charge, and (ii) if $\rho_l(x)$ and $I(x)$ are respectively the linear charge and current densities in the wire, where x runs along the wire, $q_o = \frac{1}{2}\int dx\left|\rho_l(x)\right|$ is the maximum amount of positive charge accumulated in one side of the coil (where an equal amount of negative charge always also accumulates in the other side to make the system neutral) and $I_o = \max\{\left|I(x)\right|\}$ is the maximum positive value of the linear current distribution, then $I_o = \omega q_o$. Then, one can define an effective total inductance L and an effective total capacitance C of the coil through the amount of energy W inside its resonant mode:

$$W \equiv \frac{1}{2} I_o^2 L \Rightarrow L = \frac{\mu_o}{4\pi I_o^2} \iint d\mathbf{x} d\mathbf{x}' \frac{\mathbf{j}(\mathbf{x}) \cdot \mathbf{j}(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}, \quad (19)$$

$$W \equiv \frac{1}{2} q_o^2 \frac{1}{C} \Rightarrow \frac{1}{C} = \frac{1}{4\pi\varepsilon_o q_o^2} \iint d\mathbf{x} d\mathbf{x}' \frac{\rho(\mathbf{x}) \rho(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}, \quad (20)$$

where μ_o and ε_o are the magnetic permeability and electric permittivity of free space.

With these definitions, the resonant angular frequency and the effective impedance can be given by the formulas $\omega = 1/\sqrt{LC}$ and $Z = \sqrt{L/C}$ respectively.

Losses in this resonant system consist of ohmic (material absorption) loss inside the wire and radiative loss into free space. One can again define a total absorption resistance R_{abs} from the amount of power absorbed inside the wire and a total radiation resistance R_{rad} from the amount of power radiated due to electric- and magnetic-dipole radiation:

$$P_{abs} \equiv \tfrac{1}{2} I_o^2 R_{abs} \Rightarrow R_{abs} \approx \zeta_c \frac{l}{2\pi a} \cdot \frac{I_{rms}^2}{I_o^2} \quad (21)$$

$$P_{rad} \equiv \tfrac{1}{2} I_o^2 R_{rad} \Rightarrow R_{rad} \approx \frac{\zeta_o}{6\pi} \left[\left(\frac{\omega |\mathbf{p}|}{c} \right)^2 + \left(\frac{\omega \sqrt{|\mathbf{m}|}}{c} \right)^4 \right], \quad (22)$$

where $c = 1/\sqrt{\mu_o \varepsilon_o}$ and $\zeta_o = \sqrt{\mu_o / \varepsilon_o}$ are the light velocity and light impedance in free space, the impedance ζ_c is $\zeta_c = 1/\sigma\delta = \sqrt{\mu_o \omega / 2\sigma}$ with σ the conductivity of the conductor and δ the skin depth at the frequency ω, $I_{rms}^2 = \frac{1}{l} \int dx |I(x)|^2$, $\mathbf{p} = \int dx\, \mathbf{r} \rho_l(x)$ is the electric-dipole moment of the coil and $\mathbf{m} = \frac{1}{2} \int dx\, \mathbf{r} \times \mathbf{j}(x)$ is the magnetic-dipole moment of the coil. For the radiation resistance formula Eq.(22), the assumption of operation in the quasi-static regime ($h, r \ll \lambda = 2\pi c / \omega$) has been used, which is the desired regime of a subwavelength resonance. With these definitions, the absorption and radiation quality factors of the resonance may be given by $Q_{abs} = Z / R_{abs}$ and $Q_{rad} = Z / R_{rad}$ respectively.

From Eq.(19)-(22) it follows that to determine the resonance parameters one simply needs to know the current distribution $\mathbf{j}$ in the resonant coil. Solving Maxwell's equations to rigorously find the current distribution of the resonant electromagnetic eigenmode of a conducting-wire coil is more involved than, for example, of a standard LC circuit, and we can find no exact solutions in the literature for coils of finite length, making an exact solution difficult. One could in principle write down an elaborate transmission-line-like model, and solve it by brute force. We instead present a model that is (as described below) in good agreement (~5%) with experiment. Observing that the finite extent of the conductor forming each coil imposes the boundary condition that the current has to be zero at the ends of the coil, since no current can leave the wire, we assume that the resonant mode of each coil is well approximated by a sinusoidal current profile along the length of the conducting wire. We shall be interested in the lowest mode, so if we denote by x the coordinate along the conductor, such that it runs from $-l/2$ to $+l/2$, then the current amplitude profile would have the form $I(x)=I_o\cos(\pi x/l)$, where we have assumed that the current does not vary significantly along the wire circumference for a particular x, a valid assumption provided $a \ll r$. It immediately follows from the continuity equation for charge that the linear charge density profile should be of the form $\rho_l(x)=\rho_o\sin(\pi x/l)$, and thus $q_o=\int_0^{l/2}dx\rho_o\left|\sin(\pi x/l)\right|=\rho_o l/\pi$. Using these sinusoidal profiles we find the so-called "self-inductance" L_s and "self-capacitance" C_s of the coil by computing numerically the integrals Eq.(19) and (20); the associated frequency and effective impedance are ω_s and Z_s respectively. The "self-resistances" R_s are given analytically by Eq.(21) and (22) using $I_{rms}^2=\frac{1}{l}\int_{-l/2}^{l/2}dx\left|I_o\cos(\pi x/l)\right|^2=\frac{1}{2}I_o^2$, $|\mathbf{p}|=q_o\sqrt{\left(\frac{2}{\pi}h\right)^2+\left(\frac{4N\cos(\pi N)}{(4N^2-1)\pi}r\right)^2}$ and

$$|\mathbf{m}|=I_o\sqrt{\left(\frac{2}{\pi}N\pi r^2\right)^2+\left(\frac{\cos(\pi N)(12N^2-1)-\sin(\pi N)\pi N(4N^2-1)}{(16N^4-8N^2+1)\pi}hr\right)^2}$$

, and therefore the associated Q_s factors can be calculated.

The results for two examples of resonant coils with subwavelength modes of $\lambda_s / r \geq 70$ (i.e. those highly suitable for near-field coupling and well within the quasi-static limit) are presented in Table 1. Numerical results are shown for the wavelength and absorption, radiation and total loss rates, for the two different cases of subwavelength-coil resonant modes. Note that, for conducting material, copper (σ=5.998•10^-7 S/m) was used. It can be seen that expected quality factors at microwave frequencies are $Q_{s,abs} \geq 1000$ and $Q_{s,rad} \geq 5000$.

Table 1

single coil	λ_s / r	f (MHz)	$Q_{s,rad}$	$Q_{s,abs}$	Q_s
r=30cm, h=20cm, a=1cm, N=4	74.7	13.39	4164	8170	2758
r=10cm, h=3cm, a=2mm, N=6	140	21.38	43919	3968	3639

Referring to Fig. 4, in some examples, energy is transferred between two self-resonant conducting-wire coils. The electric and magnetic fields are used to couple the different resonant conducting-wire coils at a distance D between their centers. Usually, the electric coupling highly dominates over the magnetic coupling in the system under consideration for coils with $h \gg 2r$ and, oppositely, the magnetic coupling highly dominates over the electric coupling for coils with $h \ll 2r$. Defining the charge and current distributions of two coils 1,2 respectively as $\rho_{1,2}(\mathbf{x})$ and $\mathbf{j}_{1,2}(\mathbf{x})$, total charges and peak currents respectively as $q_{1,2}$ and $I_{1,2}$, and capacitances and inductances respectively as $C_{1,2}$ and $L_{1,2}$, which are the analogs of $\rho(\mathbf{x})$, $\mathbf{j}(\mathbf{x})$, q_o, I_o, C and L for the single-coil case and are therefore well defined, we can *define* their mutual capacitance and inductance through the total energy:

$$W \equiv W_1 + W_2 + \frac{1}{2}\left(q_1^* q_2 + q_2^* q_1\right) / M_C + \frac{1}{2}\left(I_1^* I_2 + I_2^* I_1\right) M_L$$

$$\Rightarrow 1/M_C = \frac{1}{4\pi\varepsilon_o q_1 q_2}\iint d\mathbf{x}d\mathbf{x}'\frac{\rho_1(\mathbf{x})\rho_2(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}u, \quad M_L = \frac{\mu_o}{4\pi I_1 I_2}\iint d\mathbf{x}d\mathbf{x}'\frac{\mathbf{j}_1(\mathbf{x})\cdot\mathbf{j}_2(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}u, \quad (23)$$

where $W_1 = \frac{1}{2}q_1^2/C_1 = \frac{1}{2}I_1^2 L_1$, $W_2 = \frac{1}{2}q_2^2/C_2 = \frac{1}{2}I_2^2 L_2$ and the retardation factor of $u = \exp\left(i\omega|\mathbf{x}-\mathbf{x}'|/c\right)$ inside the integral can been ignored in the quasi-static regime $D \ll \lambda$ of interest, where each coil is within the near field of the other. With this definition, the coupling factor is given by $k = \sqrt{C_1 C_2}/M_C + M_L/\sqrt{L_1 L_2}$.

Therefore, to calculate the coupling rate between two self-resonant coils, again the current profiles are needed and, by using again the assumed sinusoidal current profiles, we compute numerically from Eq.(23) the mutual capacitance $M_{C,s}$ and inductance $M_{L,s}$ between two self-resonant coils at a distance D between their centers, and thus $k = 1/Q_\kappa$ is also determined.

Table 2

pair of coils	D/r	Q	$Q_\kappa = 1/k$	U
r=30cm, h=20cm, a=1cm, N=4, $\lambda/r \approx 75$, $Q_s^{abs} \approx 8170$, $Q_s^{rad} \approx 4164$	3	2758	38.9	70.9
	5	2758	139.4	19.8
	7	2758	333.0	8.3
	10	2758	818.9	3.4
r=10cm, h=3cm, a=2mm, N=6, $\lambda/r \approx 140$, $Q_s^{abs} \approx 3968$, $Q_s^{rad} \approx 43919$	3	3639	61.4	59.3
	5	3639	232.5	15.7
	7	3639	587.5	6.2
	10	3639	1580	2.3

Referring to Table 2, relevant parameters are shown for exemplary examples featuring pairs or identical self resonant coils. Numerical results are presented for the average wavelength and loss rates of the two normal modes (individual values not shown), and also the coupling rate and figure-of-merit as a function of the coupling distance D, for the two cases of modes presented in Table1. It can be seen that for medium distances $D/r = 10-3$ the expected coupling-to-loss ratios are in the range $U \sim 2-70$.

2.1.1 Experimental Results

An experimental realization of an example of the above described system for wireless energy transfer consists of two self-resonant coils, one of which (the source coil) is coupled inductively to an oscillating circuit, and the second (the device coil) is coupled inductively to a resistive load, as shown schematically in Fig. 5. Referring to Fig. 5, A is a single copper loop of radius 25cm that is part of the driving circuit, which outputs a sine wave with frequency 9.9MHz. s and d are respectively the source and device coils referred to in the text. B is a loop of wire attached to the load ("light-bulb"). The various κ's represent direct couplings between the objects. The angle between coil d and the loop A is adjusted so that their direct coupling is zero, while coils s and d are aligned coaxially. The direct coupling between B and A and between B and s is negligible.

The parameters for the two identical helical coils built for the experimental validation of the power transfer scheme were $h = 20$ cm, $a = 3$ mm, $r = 30$ cm and $N = 5.25$. Both coils are made of copper. Due to imperfections in the construction, the spacing between loops of the helix is not uniform, and we have encapsulated the uncertainty about their uniformity by attributing a 10% (2 cm) uncertainty to h. The expected resonant frequency given these dimensions is $f_0 = 10.56 \pm 0.3$ MHz, which is approximately 5% off from the measured resonance at around 9.90 MHz.

The theoretical Q for the loops is estimated to be ~ 2500 (assuming perfect copper of resistivity $\rho = 1/\sigma = 1.7\times10^{-8}\,\Omega$m) but the measured value is 950 ± 50. We believe the discrepancy is mostly due to the effect of the layer of poorly conducting copper oxide on the surface of the copper wire, to which the current is confined by the short skin depth ($\sim 20\mu$m) at this frequency. We have therefore used the experimentally observed Q (and $\Gamma_1 = \Gamma_2 = \Gamma = \omega/(2Q)$ derived from it) in all subsequent computations.

The coupling coefficient κ can be found experimentally by placing the two self-resonant coils (fine-tuned, by slightly adjusting h, to the same resonant frequency when isolated) a distance D apart and measuring the splitting in the frequencies of the two resonant modes in the transmission spectrum. According to Eq.(13) derived by coupled-mode theory, the splitting in the transmission spectrum should be $\delta_P = 2\sqrt{\kappa^2 - \Gamma^2}$, when $\kappa_{A,B}$ are kept very small by keeping A and B at a relatively large distance. The comparison between experimental and theoretical results as a function of distance when the two the coils are aligned coaxially is shown in Fig. 6.

Fig. 7 shows a comparison of experimental and theoretical values for the strong-coupling factor $U = \kappa / \Gamma$ as a function of the separation between the two coils. The theory values are obtained by using the theoretically obtained κ and the experimentally measured Γ. The shaded area represents the spread in the theoretical U due to the $\sim 5\%$ uncertainty in Q. As noted above, the maximum theoretical efficiency depends only on the parameter U, which is plotted as a function of distance in Fig. 7. U is greater than 1 even for $D = 2.4\,\text{m}$ (eight times the radius of the coils), thus the sytem is in the strongly-coupled regime throughout the entire range of distances probed.

The power-generator circuit was a standard Colpitts oscillator coupled inductively to the source coil by means of a single loop of copper wire 25cm in radius (see Fig. 5). The load consisted of a previously calibrated light-bulb, and was attached to its own loop of insulated wire, which was in turn placed in proximity of the device coil and inductively coupled to it. Thus, by varying the distance between the light-bulb and the device coil, the parameter $U_B = \kappa_B / \Gamma$ was adjusted so that it matched its optimal value, given theoretically by Eq.(14) as $U_{B*} = \sqrt{1 + U^2}$. Because of its inductive nature, the loop connected to the light-bulb added a small reactive component to κ_B which was compensated for by slightly retuning the coil. The work extracted was determined by adjusting the power going into the Colpitts oscillator until the light-bulb at the load was at its full nominal brightness.

In order to isolate the efficiency of the transfer taking place specifically between the source coil and the load, we measured the current at the mid-point of each of the self-resonant coils with a current-probe (which was not found to lower the Q of the coils noticeably.) This gave a measurement of the current parameters I_1 and I_2 defined above.

The power dissipated in each coil was then computed from $P_{1,2} = \Gamma L |I_{1,2}|^2$, and the efficiency was directly obtained from $\eta = P_B / (P_1 + P_2 + P_B)$. To ensure that the experimental setup was well described by a two-object coupled-mode theory model, we positioned the device coil such that its direct coupling to the copper loop attached to the Colpitts oscillator was zero. The experimental results are shown in Fig. 8, along with the theoretical prediction for maximum efficiency, given by Eq.(15).

Using this example, we were able to transmit significant amounts of power using this setup from the source coil to the device coil, fully lighting up a 60W light-bulb from distances more than 2m away, for example. As an additional test, we also measured the total power going into the driving circuit. The efficiency of the wireless power-transmission itself was hard to estimate in this way, however, as the efficiency of the Colpitts oscillator itself is not precisely known, although it is expected to be far from 100%. Nevertheless, this gave an overly conservative lower bound on the efficiency. When transmitting 60W to the load over a distance of 2m, for example, the power flowing into the driving circuit was 400W. This yields an overall wall-to-load efficiency of $\sim 15\%$, which is reasonable given the expected $\sim 40\%$ efficiency for the wireless power transmission at that distance and the low efficiency of the driving circuit.

From the theoretical treatment above, we see that in typical examples it is important that the coils be on resonance for the power transmission to be practical. We found experimentally that the power transmitted to the load dropped sharply as one of the coils was detuned from resonance. For a fractional detuning $\Delta f / f_0$ of a few times the inverse loaded Q, the induced current in the device coil was indistinguishable from noise.

The power transmission was not found to be visibly affected as humans and various everyday objects, such as metallic and wooden furniture, as well as electronic devices large and small, were placed between the two coils, even when they drastically obstructed the line of sight between source and device. External objects were found to have an effect only when they were closer than 10cm from either one of the coils. While some materials (such as aluminum foil, styrofoam and humans) mostly just shifted the resonant frequency, which could in principle be easily corrected with a feedback circuit of the type described earlier, others (cardboard, wood, and PVC) lowered Q when placed closer than a few centimeters from the coil, thereby lowering the efficiency of the transfer.

This method of power transmission is believed safe for humans. When transmitting 60W (more than enough to power a laptop computer) across 2m, we estimated that the magnitude of the magnetic field generated is much weaker than the Earth's magnetic field for all distances except for less than about 1cm away from the wires in the coil, an indication of the safety of the scheme even after long-term use. The power radiated for these parameters was ~ 5 W, which is roughly an order of magnitude higher than cell phones but could be drastically reduced, as discussed below.

Although the two coils are currently of identical dimensions, it is possible to make the device coil small enough to fit into portable devices without decreasing the efficiency. One could, for instance, maintain the product of the characteristic sizes of the source and device coils constant.

These experiments demonstrated experimentally a system for power transmission over medium range distances, and found that the experimental results match theory well in multiple independent and mutually consistent tests.

The efficiency of the scheme and the distances covered can be improved by silver-plating the coils, which may increase their Q, or by working with more elaborate geometries for the resonant objects. Nevertheless, the performance characteristics of the system presented here are already at levels where they could be useful in practical applications.

2.2 Capacitively-loaded conducting loops or coils

In some examples, one or more of the resonant objects are capacitively-loaded conducting loops or coils. Referring to Fig. 9 a helical coil with N turns of conducting wire, as described above, is connected to a pair of conducting parallel plates of area A spaced by distance d via a dielectric material of relative permittivity ε, and everything is surrounded by air (as shown, $N=1$ and $h=0$). The plates have a capacitance

$C_p = \varepsilon_o \varepsilon A / d$, which is added to the distributed capacitance of the coil and thus modifies its resonance. Note however, that the presence of the loading capacitor may modify the current distribution inside the wire and therefore the total effective inductance L and total effective capacitance C of the coil may be different respectively from L_s and C_s, which are calculated for a self-resonant coil of the same geometry using a sinusoidal current profile. Since some charge may accumulate at the plates of the external loading capacitor, the charge distribution ρ inside the wire may be reduced, so $C < C_s$, and thus, from the charge conservation equation, the current distribution $\mathbf{j}$ may flatten out, so $L > L_s$. The resonant frequency for this system may be $\omega = 1/\sqrt{L(C+C_p)} < \omega_s = 1/\sqrt{L_s C_s}$, and $I(x) \to I_o \cos(\pi x / l) \Rightarrow C \to C_s \Rightarrow \omega \to \omega_s$, as $C_p \to 0$.

In general, the desired CMT parameters can be found for this system, but again a very complicated solution of Maxwell's Equations is required. Instead, we will analyze only a special case, where a reasonable guess for the current distribution can be made. When $C_p \gg C_s > C$, then $\omega \approx 1/\sqrt{LC_p} \ll \omega_s$ and $Z \approx \sqrt{L/C_p} \ll Z_s$, while all the charge is on the plates of the loading capacitor and thus the current distribution is constant along the wire. This allows us now to compute numerically L from Eq.(19). In the case $h = 0$ and N integer, the integral in Eq.(19) can actually be computed analytically, giving the formula $L = \mu_o r\left[\ln(8r/a) - 2\right]N^2$. Explicit analytical formulas are again available for R from Eq.(21) and (22), since $I_{rms} = I_o$, $|\mathbf{p}| \approx 0$ and $|\mathbf{m}| = I_o N \pi r^2$ (namely only the magnetic-dipole term is contributing to radiation), so we can determine also $Q_{abs} = \omega L / R_{abs}$ and $Q_{rad} = \omega L / R_{rad}$. At the end of the calculations, the validity of the assumption of constant current profile is confirmed by checking that indeed the condition $C_p \gg C_s \Leftrightarrow \omega \ll \omega_s$ is satisfied. To satisfy this condition, one could use a large external capacitance, however, this would usually shift the operational frequency lower than the optimal frequency, which we will determine shortly; instead, in typical examples, one often prefers coils with very small self-capacitance C_s to begin with, which usually holds, for the types of coils under consideration, when $N=1$, so that the self-capacitance comes from the charge distribution across the single turn, which is almost always very small, or when $N>1$ and $h \gg 2Na$, so that the dominant self-capacitance comes from the charge distribution across adjacent turns, which is small if the separation between adjacent turns is large.

The external loading capacitance C_p provides the freedom to tune the resonant frequency (for example by tuning A or d). Then, for the particular simple case $h=0$, for which we have analytical formulas, the total $Q=\omega L/(R_{abs}+R_{rad})$ becomes highest at the optimal frequency

$$\omega_Q = \left[\frac{c^4}{\pi}\sqrt{\frac{\varepsilon_o}{2\sigma}}\cdot\frac{1}{aNr^3}\right]^{2/7}, \qquad (24)$$

reaching the value

$$Q_{\max} = \frac{6}{7\pi}\left(2\pi^2\eta_o\frac{\sigma a^2N^2}{r}\right)^{3/7}\cdot\left[\ln\left(\frac{8r}{a}\right)-2\right]. \qquad (25)$$

At lower frequencies Q is dominated by ohmic loss and at higher frequencies by radiation. Note, however, that the formulas above are accurate as long as $\omega_Q \ll \omega_s$ and, as explained above, this holds almost always when $N=1$, and is usually less accurate when $N>1$, since $h=0$ usually implies a large self-capacitance. A coil with large h can be used, if the self-capacitance needs to be reduced compared to the external capacitance, but then the formulas for L and ω_Q, $Q_{\max}$ are again less accurate. Similar qualitative behavior is expected, but a more complicated theoretical model is needed for making quantitative predictions in that case.

The results of the above analysis for two examples of subwavelength modes of $\lambda/r \geq 70$ (namely highly suitable for near-field coupling and well within the quasi-static limit) of coils with $N=1$ and $h=0$ at the optimal frequency Eq.(24) are presented in Table 3. To confirm the validity of constant-current assumption and the resulting analytical formulas, mode-solving calculations were also performed using another completely independent method: computational 3D finite-element frequency-domain (FEFD) simulations (which solve Maxwell's Equations in frequency domain exactly apart for spatial discretization) were conducted, in which the boundaries of the conductor were modeled using a complex impedance $\zeta_c = \sqrt{\mu_o \omega / 2\sigma}$ boundary condition, valid as long as $\zeta_c / \zeta_o \ll 1$ ($<10^{-5}$ for copper in the microwave). Table 3 shows Numerical FEFD (and in parentheses analytical) results for the wavelength and absorption, radiation and total loss rates, for two different cases of subwavelength-loop resonant modes. Note that copper was used for the conducting material ($\sigma = 5.998 \cdot 10^7 S/m$). Specific parameters of the plot in Fig. 4 are highlighted in bold in the table. The two methods (analytical and computational) are in good agreement and show that, in some examples, the optimal frequency is in the low-MHz microwave range and the expected quality factors are $Q_{abs} \geq 1000$ and $Q_{rad} \geq 10000$.

Table 3

single coil	λ / r	f	Q_{rad}	Q_{abs}	Q
r=30cm, a=2cm ε=10, A=138cm^2, d=4mm	**111.4 (112.4)**	**8.976 (8.897)**	**29546 (30512)**	**4886 (5117)**	**4193 (4381)**
r=10cm, a=2mm ε=10, A=3.14cm^2, d=1mm	69.7 (70.4)	43.04 (42.61)	10702 (10727)	1545 (1604)	1350 (1395)

Referring to Fig. 10, in some examples, energy is transferred between two capacitively-loaded coils. For the rate of energy transfer between two capacitively-loaded coils 1 and 2 at distance D between their centers, the mutual inductance M_L can be evaluated numerically from Eq.(23) by using constant current distributions in the case $\omega \ll \omega_s$. In the case $h = 0$, the coupling may be only magnetic and again we have an analytical formula, which, in the quasi-static limit $r \ll D \ll \lambda$ and for the relative orientation shown in Fig. 10, is $M_L \approx \pi\mu_o / 2 \cdot (r_1 r_2)^2 N_1 N_2 / D^3$, which means that $k \propto \left(\sqrt{r_1 r_2} / D\right)^3$ may be independent of the frequency ω and the number of turns N_1, N_2. Consequently, the resultant coupling figure-of-merit of interest is

$$U = k\sqrt{Q_1 Q_2} \approx \left(\frac{\sqrt{r_1 r_2}}{D}\right)^3 \cdot \frac{\pi^2 \eta_o \frac{\sqrt{r_1 r_2}}{\lambda} \cdot N_1 N_2}{\prod_{j=1,2}\left(\sqrt{\frac{\pi\eta_o}{\lambda\sigma}} \cdot \frac{r_j}{a_j} N_j + \frac{8}{3}\pi^5 \eta_o \left(\frac{r_j}{\lambda}\right)^4 N_j^2\right)^{1/2}}, \tag{26}$$

which again is more accurate for $N_1 = N_2 = 1$.

From Eq.(26) it can be seen that the optimal frequency ω_U, where the figure-of-merit is maximized to the value $U_{\max}$, is close to the frequency $\omega_{Q_1 Q_2}$ at which $Q_1 Q_2$ is maximized, since k does not depend much on frequency (at least for the distances $D \ll \lambda$ of interest for which the quasi-static approximation is still valid). Therefore, the optimal frequency $\omega_U \approx \omega_{Q_1 Q_2}$ may be mostly independent of the distance D between the two coils and may lie between the two frequencies ω_{Q_1} and ω_{Q_2} at which the single-coil Q_1 and Q_2 respectively peak. For same coils, this optimal frequency is given by Eq.(24) and then the strong-coupling factor from Eq.(26) becomes

$$U_{\max} = kQ_{\max} \approx \left(\frac{r}{D}\right)^3 \cdot \frac{3}{7}\left(2\pi^2 \eta_o \frac{\sigma a^2 N^2}{r}\right)^{3/7}. \tag{27}$$

In some examples, one can tune the capacitively-loaded conducting loops or coils, so that their angular resonant frequencies are close to ω_U within Γ_U, which is half the angular frequency width for which $U > U_{\max} / 2$.

Referring to Table 4, numerical FEFD and, in parentheses, analytical results based on the above are shown for two systems each composed of a matched pair of the loaded coils described in Table 3. The average wavelength and loss rates are shown along with the coupling rate and coupling to loss ratio figure-of-merit $U = \kappa / \Gamma$ as a function of the coupling distance D, for the two cases. Note that the average numerical Γ_{rad} shown are slightly different from the single-loop value of Figure 3. Analytical results for Γ_{rad} are not shown but the single-loop value is used. (The specific parameters corresponding to the plot in Fig. 10 are highlighted with bold in the table.) Again we chose $N = 1$ to make the constant-current assumption a good one and computed M_L numerically from Eq.(23). Indeed the accuracy can be confirmed by their agreement with the computational FEFD mode-solver simulations, which give κ through the frequency splitting of the two normal modes of the combined system ($\delta_E = 2\kappa$ from Eq.(4)). The results show that for medium distances $D/r = 10 - 3$ the expected coupling-to-loss ratios are in the range $U \sim 0.5 - 50$.

Table 4

pair of coils	D/r	Q^{rad}	$Q = \omega/2\Gamma$	$Q_\kappa = \omega/2\kappa$	κ/Γ
r=30cm, a=2cm ε=10, A=138cm², d=4mm $\lambda/r \approx 112$ $Q^{abs} \approx 4886$	3	30729	4216	62.6 (63.7)	67.4 (68.7)
	5	29577	4194	235 (248)	17.8 (17.6)
	7	**29128**	**4185**	**589 (646)**	**7.1 (6.8)**
	10	28833	4177	1539 (1828)	2.7 (2.4)
r=10cm, a=2mm ε=10, A=3.14cm², d=1mm $\lambda/r \approx 70$ $Q^{abs} \approx 1546$	3	10955	1355	85.4 (91.3)	15.9 (15.3)
	5	10740	1351	313 (356)	4.32 (3.92)
	7	10759	1351	754 (925)	1.79 (1.51)
	10	10756	1351	1895 (2617)	0.71 (0.53)

2.2.1 Derivation of optimal power-transmission efficiency

Referring to Fig. 11, to rederive and express Eq.(15) in terms of the parameters which are more directly accessible from particular resonant objects, such as the capacitively-loaded conducting loops, one can consider the following circuit-model of the system, where the inductances L_s, L_d represent the source and device loops respectively, R_s, R_d their respective losses, and $C\ , C_d$ are the required corresponding capacitances to achieve for both resonance at frequency ω. A voltage generator V_g is considered to be connected to the source and a load resistance R_l to the device. The mutual inductance is denoted by M.

Then from the source circuit at resonance ($\omega L\ = 1/\omega C\ $):

$$V_g = I_s R_s - j\omega M I_d \Rightarrow \frac{1}{2} V_g^* I_s = \frac{1}{2} \left| I_s \right|^2 R_s + \frac{1}{2} j\omega M I_d^* I_s, \tag{28}$$

and from the device circuit at resonance ($\omega L_d = 1 / \omega C_d$):

$$0 = I_d \left(R_d + R_l \right) - j\omega M I_s \Rightarrow j\omega M I_s = I_d \left(R_d + R_l \right) \tag{29}$$

So by substituting Eq.(29) to Eq.(28) and taking the real part (for time-averaged power) we get:

$$P_g = \mathrm{Re}\left\{ \frac{1}{2} V_g^* I_s \right\} = \frac{1}{2} \left| I_s \right|^2 R_s + \frac{1}{2} \left| I_d \right|^2 \left(R_d + R_l \right) = P_s + P_d + P_l, \tag{30}$$

where we identified the power delivered by the generator $P_g = \mathrm{Re}\left\{ V_g^* I_s / 2 \right.$,the power lost inside the source $P_s = \left| I_s \right|^2 R_s / 2$, the power lost inside the device $P_d = \left| I_d \right|^2 R_d / 2$ and the power delivered to the load $P_l = \left| I_d \right|^2 R_l / 2$. Then, the power transmission efficiency is:

$$\eta_{\mathrm{P}} \equiv \frac{P_l}{P_g} = \frac{R_l}{\left| \frac{I_s}{I_d} \right|^2 R_s + \left(R_d + R_l \right)} \overset{(29)}{=} \frac{R_l}{\frac{\left(R_d + R_l \right)^2}{\left(\omega M \right)^2} R_s + \left(R_d + R_l \right)}. \tag{31}$$

If we now choose the load impedance R_l to optimize the efficiency by $\eta_{\mathrm{P}}'(R_l) = 0$, we get the optimal load impedance

$$\frac{R_{l*}}{R_d} = \sqrt{1 + \frac{(\omega M)^2}{R_s R_d}} \tag{32}$$

and the maximum possible efficiency

$$\eta_{\mathrm{P}*} = \frac{R_{l*} / R_d - 1}{R_{l*} / R_d + 1} = \left[\frac{\omega M / \sqrt{R_s R_d}}{1 + \sqrt{1 + \left(\omega M / \sqrt{R_s R_d} \right)^2}} \right]^2. \tag{33}$$

To check now the correspondence with the CMT model, note that $\kappa_l = R_l / 2L_d$, $\Gamma_d = R_d / 2L_d$, $\Gamma_s = R_s / 2L_s$, and $\kappa \quad \omega M / 2\sqrt{L_s L_d}$, so then $U_l = \kappa_l / \Gamma_d = R_l / R_d$ and $U = \kappa / \sqrt{\Gamma_s \Gamma_d} = \omega M / \sqrt{R_s R_d}$. Therefore, the condition Eq.(32) is identical to the condition Eq.(14) and the optimal efficiency Eq.(33) is identical to the general Eq.(15). Indeed, as the CMT analysis predicted, to get a large efficiency, we need to design a system that has a large strong-coupling factor U.

2.2.2 Optimization of U

The results above can be used to increase or optimize the performance of a wireless energy transfer system, which employs capacitively-loaded coils. For example, from the scaling of Eq.(27) with the different system parameters, one sees that to maximize the system figure-of-merit U, in some examples, one can:

-- Decrease the resistivity of the conducting material. This can be achieved, for example, by using good conductors (such as copper or silver) and/or lowering the temperature. At very low temperatures one could use also superconducting materials to achieve extremely good performance.

-- Increase the wire radius a. In typical examples, this action can be limited by physical size considerations. The purpose of this action is mainly to reduce the resistive losses in the wire by increasing the cross-sectional area through which the electric current is flowing, so one could alternatively use also a Litz wire, or ribbon, or any low AC-resistance structure, instead of a circular wire.

-- For fixed desired distance D of energy transfer, increase the radius of the loop r. In typical examples, this action can be limited by physical size considerations.

-- For fixed desired distance vs. loop-size ratio D/r, decrease the radius of the loop r. In typical examples, this action can be limited by physical size considerations.

-- Increase the number of turns N. (Even though Eq.(27) is expected to be less accurate for $N > 1$, qualitatively it still provides a good indication that we expect an improvement in the coupling-to-loss ratio with increased N.) In typical examples, this action can be limited by physical size and possible voltage considerations, as will be discussed in following paragraphs.

-- Adjust the alignment and orientation between the two coils. The figure-of-merit is optimized when both cylindrical coils have exactly the same axis of cylindrical symmetry (namely they are "facing" each other). In some examples, particular mutual coil angles and orientations that lead to zero mutual inductance (such as the orientation where the axes of the two coils are perpendicular and the centers of the two coils are on one of the two axes) should be avoided.

-- Finally, note that the height of the coil h is another available design parameter, which can have an impact on the performance similar to that of its radius r, and thus the design rules can be similar.

The above analysis technique can be used to design systems with desired parameters. For example, as listed below, the above described techniques can be used to determine the cross sectional radius a of the wire used to design a system including two same single-turn loops with a given radius in order to achieve a specific performance in terms of $U = \kappa / \Gamma$ at a given D / r between them, when the loop material is copper ($\sigma=5.998 \cdot 10^7 S/m$):

$$D / r = 5,\ U \geq 10,\ r = 30cm \Rightarrow a \geq 9mm$$
$$D / r = 5,\ U \geq 10,\ r = 5cm \Rightarrow a \geq 3.7mm$$
$$D / r = 5,\ U \geq 20,\ r = 30cm \Rightarrow a \geq 20mm$$
$$D / r = 5,\ U \geq 20,\ r = 5cm \Rightarrow a \geq 8.3mm$$
$$D / r = 10,\ U \geq 1,\ r = 30cm \Rightarrow a \geq 7mm$$
$$D / r = 10,\ U \geq 1,\ r = 5cm \Rightarrow a \geq 2.8mm$$
$$D / r = 10,\ U \geq 3,\ r = 30cm \Rightarrow a \geq 25mm$$
$$D / r = 10,\ U \geq 3,\ r = 5cm \Rightarrow a \geq 10mm$$

Similar analysis can be done for the case of two dissimilar loops. For example, in some examples, the device under consideration may be identified specifically (e.g. a laptop or a cell phone), so the dimensions of the device object (r_d, h_d, a_d, N_d) may be restricted. However, in some such examples, the restrictions on the source object (r_s, h_s, a_s, N_s) may be much less, since the source can, for example, be placed under the floor or on the ceiling. In such cases, the desired distance between the source and device may be fixed; in other cases it may be variable. Listed below are examples (simplified to the case $N_s = N_d = 1$ and $h_s = h_d = 0$) of how one can vary the dimensions of the source object to achieve a desired system performance in terms of $U_{sd} = \kappa / \sqrt{\Gamma_s \Gamma_d}$, when the material is again copper (σ=$5.998 \cdot 10^7 S/m$):

$$D = 1.5m,\ U_{sd} \geq 15,\ r_d = 30cm,\ a_d = 6mm \Rightarrow r_s = 1.158m,\ a_s \geq 5mm$$
$$D = 1.5m,\ U_{sd} \geq 30,\ r_d = 30cm,\ a_d = 6mm \Rightarrow r_s = 1.15m,\ a_s \geq 33mm$$
$$D = 1.5m, U_{sd} \geq 1,\ r_d = 5cm,\ a_d = 4mm \Rightarrow r_s = 1.119m,\ a_s \geq 7mm$$
$$D = 1.5m,\ U_{sd} \geq 2,\ r_d = 5cm,\ a_d = 4mm \Rightarrow r_s = 1.119m,\ a_s \geq 52mm$$
$$D = 2m,\ U_{sd} \geq 10,\ r_d = 30cm,\ a_d = 6mm \Rightarrow r_s = 1.518m,\ a_s \geq 7mm$$
$$D = 2m,\ U_{sd} \geq 20,\ r_d = 30cm,\ a_d = 6mm \Rightarrow r_s = 1.514m,\ a_s \geq 50mm$$
$$D = 2m,\ U_{sd} \geq 0.5,\ r_d = 5cm,\ a_d = 4mm \Rightarrow r_s = 1.491m,\ a_s \geq 5mm$$
$$D = 2m,\ U_{sd} \geq 1,\ r_d = 5cm,\ a_d = 4mm \Rightarrow r_s = 1.491m,\ a_s \geq 36mm$$

2.2.3 Optimization of k

As described below, in some examples, the quality factor Q of the resonant objects may be limited from external perturbations and thus varying the coil parameters may not lead to significant improvements in Q. In such cases, one can opt to increase the strong-coupling factor U by increasing the coupling factor k. The coupling does not depend on the frequency and may weakly depend on the number of turns. Therefore, in some examples, one can:

-- Increase the wire radii a_1 and a_2. In typical examples, this action can be limited by physical size considerations.

-- For fixed desired distance D of energy transfer, increase the radii of the coils r_1 and r_2. In typical examples, this action can be limited by physical size considerations.

-- For fixed desired distance vs. coil-sizes ratio $D/\sqrt{r_1 r_2}$, only the weak (logarithmic) dependence of the inductance remains, which suggests that one should decrease the radii of the coils r_1 and r_2. In typical examples, this action can be limited by physical size considerations.

-- Adjust the alignment and orientation between the two coils. In typical examples, the coupling is optimized when both cylindrical coils have exactly the same axis of cylindrical symmetry (namely they are "facing" each other). Particular mutual coil angles and orientations that lead to zero mutual inductance (such as the orientation where the axes of the two coils are perpendicular and the centers of the two coils are on one of the two axes) should obviously be avoided.

-- Finally, note that the heights of the coils h_1 and h_2 are other available design parameters, which can have an impact to the coupling similar to that of their radii r_1 and r_2, and thus the design rules can be similar.

Further practical considerations apart from efficiency, e.g. physical size limitations, will be discussed in detail below.

2.2.4 Optimization of overall system performance

In embodiments, the dimensions of the resonant objects may be determined by the particular application. For example, when the application is powering a laptop or a cell-phone, the device resonant object cannot have dimensions that exceed those of the laptop or cell-phone respectively. For a system of two loops of specified dimensions, in terms of loop radii $r_{s,d}$ and wire radii $a_{s,d}$, the independent parameters left to adjust for the system optimization are: the number of turns $N_{s,d}$, the frequency *f*, the power-load consumption rate $\kappa_l = R_l / 2L_d$ and the power-generator feeding rate $\kappa_g = R_g / 2L_s$, where R_g is the internal (characteristic) impedance of the generator.

In general, in various examples, the dependent variable that one may want to increase or optimize may be the overall efficiency η. However, other important variables may need to be taken into consideration upon system design. For example, in examples featuring capacitively-loaded coils, the designs can be constrained by, the currents flowing inside the wires $I_{s,d}$ and other components and the voltages across the capacitors $V_{s,d}$. These limitations can be important because for $\sim Watt$ power applications the values for these parameters can be too large for the wires or the capacitors respectively to handle. Furthermore, the total loaded (by the load) quality factor of the device $Q_{d[l]} = \omega / 2(\Gamma_d + \Gamma_l) = \omega L_d / (R_d + R_l)$ and the total loaded (by the generator) quality factor of the source $Q_{s[g]} = \omega / 2(\Gamma_s + \Gamma_g) = \omega L_s / (R_s + R_g)$ are quantities that should be preferably small, because to match the source and device resonant frequencies to within their Q's, when those are very large, can be challenging experimentally and more sensitive to slight variations. Lastly, the radiated powers $P_{s,rad}$ and $P_{d,rad}$ may need to be minimized for concerns about far-field interference and safety, even though, in general, for a magnetic, non-radiative scheme they are already typically small. In the following, we examine then the effects of each one of the independent variables on the dependent ones.

We define a new variable wp to express the power-load consumption rate for some particular value of U through $U_l = \kappa_l / \Gamma_d = \sqrt{1 + wp \cdot U^2}$. Then, in some examples, values which may impact the choice of this rate are: $U_l = 1 \Leftrightarrow wp = 0$ to minimize the required energy stored in the source (and therefore I_s and V_s), $U_l = \sqrt{1+U^2} > 1 \Leftrightarrow wp = 1$ to maximize the efficiency, as seen earlier, or $U_l \gg 1 \Leftrightarrow wp \gg 1$ to decrease the required energy stored in the device (and therefore I_d and V_d) and to decrease or minimize $Q_{d[l]}$. Similar is the impact of the choice of the power-generator feeding rate $U_g = \kappa_g / \Gamma_s$, with the roles of the source/device and generator/load reversed.

In some examples, increasing N_s and N_d may increase Q_s and Q_d, and thus U and the efficiency significantly. It also may decrease the currents I_s and I_d, because the inductance of the loops may increase, and thus the energy $W_{s,d} = L_{s,d} |I_{s,d}|^2 / 2$ required for given output power P_l can be achieved with smaller currents. However, in some examples, increasing N_d and thus Q_d can increase $Q_{d[l]}$, $P_{d,rad}$ and the voltage across the device capacitance V_d. Similar can be the impact of increasing N_s on $Q_{s[g]}$, $P_{s,rad}$ and V_s. As a conclusion, in some examples, the number of turns N_s and N_d may be chosen large enough (for high efficiency) but such that they allow for reasonable voltages, loaded Q's and/or powers radiated.

With respect to the resonant frequency, again, there may be an optimal one for efficiency. Close to that optimal frequency $Q_{d[l]}$ and/or $Q_{s[g]}$ can be approximately maximum. In some examples, for lower frequencies the currents may typically get larger but the voltages and radiated powers may get smaller. In some examples, one may choose the resonant frequency to maximize any of a number of system parameters or performance specifications, such as efficiency.

One way to decide on an operating regime for the system may be based on a graphical method. Consider two loops of $r_s = 25cm,\ r_d = 15cm,\ h_s = h_d = 0,\ a_s = a_d = 3mm$ and distance $D = 2m$ between them. In Fig. 12, we plot some of the above dependent variables (currents, voltages and radiated powers normalized to *1Watt* of output power) in terms of frequency f and N_d, given some choice for wp and N_s. Fig. 12 depicts the trend of system performance explained above. In Fig. 13, we make a contour plot of the dependent variables as functions of both frequency and *wp* but for both N_s and N_d fixed. For example, in embodiments, a reasonable choice of parameters for the system of two loops with the dimensions given above may be: $N_s = 2,\ N_d = 6$, *f=10MHz* and *wp=10*, which gives the following performance characteristics: $\eta = 20.6\%$, $Q_{d[l]} = 1264$, $I_s = 7.2A, I_d = 1.4A,$ $V_s = 2.55kV, V_d = 2.30kV,\ P_{s,rad} = 0.15W, P_{d,rad} = 0.006W$. Note that the results in Figs. 12, 13 and the calculated performance characteristics are made using the analytical formulas provided above, so they are expected to be less accurate for large values of $N_s,\ N_d$, but still may give a good estimate of the scalings and the orders of magnitude.

Finally, in embodiments, one could additionally optimize for the source dimensions, if, for example, only the device dimensions are limited. Namely, one can add r_s and a_s in the set of independent variables and optimize with respect to these all the dependent variables of the system. In embodiments, such an optimization may lead to improved results.

2.3 Inductively-loaded conducting rods

A straight conducting rod of length $2h$ and cross-sectional radius a has distributed capacitance and distributed inductance, and therefore can support a resonant mode of angular frequency ω. Using the same procedure as in the case of self-resonant coils, one can define an effective total inductance L and an effective total capacitance C of the rod through formulas Eqs.(19) and (20). With these definitions, the resonant angular frequency and the effective impedance may be given again by the common formulas $\omega = 1/\sqrt{LC}$ and $Z = \sqrt{L/C}$ respectively. To calculate the total inductance and capacitance, one can assume again a sinusoidal current profile along the length of the conducting wire. When interested in the lowest mode, if we denote by x the coordinate along the conductor, such that it runs from $-h$ to $+h$, then the current amplitude profile may have the form $I(x) = I_o \cos(\pi x / 2h)$, since it has to be zero at the open ends of the rod. This is the well-known half-wavelength electric dipole resonant mode.

In some examples, one or more of the resonant objects may be inductively-loaded conducting rods. Referring to Fig. 14, a straight conducting rod of length $2h$ and cross-sectional radius a, as in the previous paragraph, is cut into two equal pieces of length h, which may be connected via a coil wrapped around a magnetic material of relative permeability μ, and everything is surrounded by air. The coil has an inductance L_C, which is added to the distributed inductance of the rod and thus modifies its resonance. Note however, that the presence of the center-loading inductor may modify the current distribution inside the wire and therefore the total effective inductance L and total effective capacitance C of the rod may be different respectively from L_s and C_s, which are calculated for a self-resonant rod of the same total length using a sinusoidal current profile, as in the previous paragraph. Since some current may be running inside the coil of the external loading inductor, the current distribution $\mathbf{j}$ inside the rod may be reduced, so $L < L_s$, and thus, from the charge conservation equation, the linear charge distribution ρ_l may flatten out towards the center (being positive in one side of the rod and negative in the other side of the rod, changing abruptly through the inductor), so $C > C_s$. The resonant frequency for this system may be $\omega = 1/\sqrt{(L + L_c\ C} < \omega_s = 1/\sqrt{L_s C_s}$, and $I(x) \to I_o \cos(\pi x/2h) \Rightarrow\ L \to L_s \Rightarrow\ \omega \to \omega_s$, as $L_c \to 0$.

In general, the desired CMT parameters can be found for this system, but again a very complicated solution of Maxwell's Equations is generally required. In a special case, a reasonable estimate for the current distribution can be made. When $L_c \gg L_s > L$, then $\omega \approx 1/\sqrt{L_c C} \ll \omega_s$ and $Z \approx \sqrt{L_c / C} \gg Z_s$, while the current distribution is triangular along the rod (with maximum at the center-loading inductor and zero at the ends) and thus the charge distribution may be positive constant on one half of the rod and equally negative constant on the other side of the rod. This allows us to compute numerically C from Eq.(20). In this case, the integral in Eq.(20) can actually be computed analytically, giving the formula $1/C = 1/(\pi\varepsilon_o h)\left[\ln(h/a) - 1\right]$. Explicit analytical formulas are again available for R from Eq.(21) and (22), since $I_{rms} = I_o$, $|\mathbf{p}| = q_o h$ and $|\mathbf{m}| = 0$ (namely only the electric-dipole term is contributing to radiation), so we can determine also $Q_{abs} = 1/\omega C R_{abs}$ and $Q_{rad} = 1/\omega C R_{rad}$. At the end of the calculations, the validity of the assumption of triangular current profile may be confirmed by checking that indeed the condition $L_c \gg L_s \Leftrightarrow \omega \ll \omega_s$ is satisfied. This condition may be relatively easily satisfied, since typically a conducting rod has very small self-inductance L_s to begin with.

Another important loss factor in this case is the resistive loss inside the coil of the external loading inductor L_c and it may depend on the particular design of the inductor. In some examples, the inductor may be made of a Brooks coil, which is the coil geometry which, for fixed wire length, may demonstrate the highest inductance and thus quality factor. The Brooks coil geometry has N_{Bc} turns of conducting wire of cross-sectional radius a_{Bc} wrapped around a cylindrically symmetric coil former, which forms a coil with a square cross-section of side r_{Bc}, where the inner side of the square is also at radius r_{Bc} (and thus the outer side of the square is at radius $2r_{Bc}$), therefore $N_{Bc} \approx (r_{Bc} / 2a_{Bc})^2$. The inductance of the coil is then $L_c = 2.0285\mu_o r_{Bc} N_{Bc}^2 \approx 2.0285\mu_o r_{Bc}^5 / 8a_{Bc}^4$ and its resistance $R_c \approx \frac{1}{\sigma}\frac{l_{Bc}}{\pi a_{Bc}^2}\sqrt{1+\frac{\mu_o\omega\sigma}{2}\left(\frac{a_{Bc}}{2}\right)^2}$, where the total wire length is $l_{Bc} \approx 2\pi(3r_{Bc}/2)N_{Bc} \approx 3\pi r_{Bc}^3 / 4a_{Bc}^2$ and we have used an approximate square-root law for the transition of the resistance from the dc to the ac limit as the skin depth varies with frequency.

The external loading inductance L_c provides the freedom to tune the resonant frequency. For example, for a Brooks coil with a fixed size r_{Bc}, the resonant frequency can be reduced by increasing the number of turns N_{Bc} by decreasing the wire cross-sectional radius a_{Bc}. Then the desired resonant angular frequency $\omega = 1/\sqrt{L_c C}$ may be achieved for $a_{Bc} \approx \left(2.0285\mu_o r_{Bc}^5 \omega^2 C\right)^{1/4}$ and the resulting coil quality factor may be $Q_c \approx 0.169\mu_o\sigma r_{Bc}^2\omega / \sqrt{1+\omega^2\mu_o\sigma\sqrt{2.0285\mu_o (r_{Bc}/4)^5 C}}$. Then, for the particular simple case $L_c \gg L_s$, for which we have analytical formulas, the total $Q = 1/\omega C(R_c + R_{abs} + R_{rad})$ becomes highest at some optimal frequency ω_Q, reaching the value $Q_{\max}$, that may be determined by the loading-inductor specific design. For example, for the Brooks-coil procedure described above, at the optimal frequency $Q_{\max} \approx Q_c \approx 0.8\left(\mu_o\sigma^2 r_{Bc}^3 / C\right)^{1/4}$. At lower frequencies it is dominated by ohmic loss inside the inductor coil and at higher frequencies by radiation. Note, again, that the above formulas are accurate as long as $\omega_Q \ll \omega_s$ and, as explained above, this may be easy to design for by using a large inductance.

The results of the above analysis for two examples, using Brooks coils, of subwavelength modes of $\lambda / h \geq 200$ (namely highly suitable for near-field coupling and well within the quasi-static limit) at the optimal frequency ω_Q are presented in Table 5.

Table 5 shows in parentheses (for similarity to previous tables) analytical results for the wavelength and absorption, radiation and total loss rates, for two different cases of subwavelength-rod resonant modes. Note that copper was used for the conducting material ($\sigma=5.998\cdot10^7 S/m$). The results show that, in some examples, the optimal frequency may be in the low-MHz microwave range and the expected quality factors may be $Q_{abs} \geq 1000$ and $Q_{rad} \geq 100000$.

Table 5

single rod	λ / h	f (MHz)	Q_{rad}	Q_{abs}	Q
h=30cm, a=2cm μ=1, r_{Bc}=2cm, a_{Bc}=0.88mm, N_{Bc}=129	(403.8)	(2.477)	($2.72*10^6$)	(7400)	(7380)
h=10cm, a=2mm μ=1, r_{Bc}=5mm, a_{Bc}=0.25mm, N_{Bc}=103	(214.2)	(14.010)	($6.92*10^5$)	(3908)	(3886)

In some examples, energy may be transferred between two inductively-loaded rods. For the rate of energy transfer between two inductively-loaded rods 1 and 2 at distance D between their centers, the mutual capacitance M_C can be evaluated numerically from Eq.(23) by using triangular current distributions in the case $\omega \ll \omega_s$. In this case, the coupling may be only electric and again we have an analytical formula, which, in the quasi-static limit $h \ll D \ll \lambda$ and for the relative orientation such that the two rods are aligned on the same axis, is $1/M_C \approx 1/2\pi\varepsilon_o \cdot (h_1 h_2)^2 / D^3$, which means that $k \propto \left(\sqrt{h_1 h_2} / D\right)^3$ is independent of the frequency ω. One can then get the resultant strong-coupling factor U.

It can be seen that the frequency ω_U, where the figure-of-merit is maximized to the value $U_{\max}$, is close to the frequency $\omega_{Q_1Q_2}$, where Q_1Q_2 is maximized, since k does not depend much on frequency (at least for the distances $D \ll \lambda$ of interest for which the quasi-static approximation is still valid). Therefore, the optimal frequency $\omega_U \approx \omega_{Q_1Q_2}$ may be mostly independent of the distance D between the two rods and may lie between the two frequencies ω_{Q_1} and ω_{Q_2} at which the single-rod Q_1 and Q_2 respectively peak. In some typical examples, one can tune the inductively-loaded conducting rods, so that their angular eigenfrequencies are close to ω_U within Γ_U, which is half the angular frequency width for which $U > U_{\max}/2$.

Referring to Table 6, in parentheses (for similarity to previous tables) analytical results based on the above are shown for two systems each composed of a matched pair of the loaded rods described in Table 5. The average wavelength and loss rates are shown along with the coupling rate and coupling to loss ratio figure-of-merit $U = \kappa / \Gamma$ as a function of the coupling distance D, for the two cases. Note that for Γ_{rad} the single-rod value is used. Again we chose $L_c \gg L_s$ to make the triangular-current assumption a good one and computed M_C numerically from Eq.(23). The results show that for medium distances $D/h = 10-3$ the expected coupling-to-loss ratios are in the range $U \sim 0.5-100$.

Table 6

pair of rods	D/h	$Q_\kappa = 1/k$	U
h=30cm, a=2cm μ=1, r_{Bc}=2cm, a_{Bc}=0.88mm, N_{Bc}=129 $\lambda/h \approx 404$ $Q \approx 7380$	3	(70.3)	(105.0)
	5	(389)	(19.0)
	7	(1115)	(6.62)
	10	(3321)	(2.22)
h=10cm, a=2mm μ=1, r_{Bc}=5mm, a_{Bc}=0.25mm, N_{Bc}=103 $\lambda/h \approx 214$ $Q \approx 3886$	3	(120)	(32.4)
	5	(664)	(5.85)
	7	(1900)	(2.05)
	10	(5656)	(0.69)

2.4 Dielectric disks

In some examples, one or more of the resonant objects are dielectric objects, such as disks. Consider a two dimensional dielectric disk object, as shown in Fig. 15(a), of radius r and relative permittivity ε surrounded by air that supports high-Q "whispering-gallery" resonant modes. The loss mechanisms for the energy stored inside such a resonant system are radiation into free space and absorption inside the disk material. High-Q_{rad} and long-tailed subwavelength resonances can be achieved when the dielectric permittivity ε is large and the azimuthal field variations are slow (namely of small principal number m). Material absorption is related to the material loss tangent: $Q_{abs} \sim \mathrm{Re}\{\varepsilon\}/\mathrm{Im}\{\varepsilon\}$. Mode-solving calculations for this type of disk resonances were performed using two independent methods: numerically, 2D finite-difference frequency-domain (FDFD) simulations (which solve Maxwell's Equations in frequency domain exactly apart for spatial discretization) were conducted with a resolution of *30pts/r*; analytically, standard separation of variables (SV) in polar coordinates was used.

Table 7

single disk	λ/r	Q^{abs}	Q^{rad}	Q
Re{ε}=147.7, m=2	**20.01 (20.00)**	**10103 (10075)**	**1988 (1992)**	**1661 (1663)**
Re{ε}=65.6, m=3	9.952 (9.950)	10098 (10087)	9078 (9168)	4780 (4802)

The results for two TE-polarized dielectric-disk subwavelength modes of $\lambda/r \geq 10$ are presented in Table 7. Table 7 shows numerical FDFD (and in parentheses analytical SV) results for the wavelength and absorption, radiation and total loss rates, for two different cases of subwavelength-disk resonant modes. Note that disk-material loss-tangent $\mathrm{Im}\{\varepsilon\}/\mathrm{Re}\{\varepsilon\}=10^{-4}$ was used. (The specific parameters corresponding to the plot in Fig. 15(a) are highlighted with bold in the table.) The two methods have excellent agreement and imply that for a properly designed resonant low-loss-dielectric object values of $Q_{rad} \geq 2000$ and $Q_{abs} \sim 10000$ are achievable. Note that for the 3D case the computational complexity would be immensely increased, while the physics would not be significantly different. For example, a spherical object of $\varepsilon=147.7$ has a whispering gallery mode with $m=2$, $Q_{rad}=13962$, and $\lambda/r=17$.

The required values of ε, shown in Table 7, might at first seem unrealistically large. However, not only are there in the microwave regime (appropriate for approximately meter-range coupling applications) many materials that have both reasonably high enough dielectric constants and low losses (e.g. Titania, Barium tetratitanate, Lithium tantalite etc.), but also ε could signify instead the effective index of other known subwavelength surface-wave systems, such as surface modes on surfaces of metallic materials or plasmonic (metal-like, negative-ε) materials or metallo-dielectric photonic crystals or plasmono-dielectric photonic crystals.

To calculate now the achievable rate of energy transfer between two disks 1 and 2, as shown in Fig. 15(b) we place them at distance D between their centers. Numerically, the FDFD mode-solver simulations give κ through the frequency splitting of the normal modes of the combined system ($\delta_E = 2\kappa$ from Eq.(4)), which are even and odd superpositions of the initial single-disk modes; analytically, using the expressions for the separation-of-variables eigenfields $\mathbf{E}_{1,2}(\mathbf{r})$ CMT gives κ through

$$\kappa = \omega_1 / 2 \cdot \int d^3 r \varepsilon_2(r) E_2^*(r) E_1(r) / \int d^3 r \varepsilon(r) \left| E_1(r) \right|^2 ,$$

where $\varepsilon_j(\mathbf{r})$ and $\varepsilon(\mathbf{r})$ are the dielectric functions that describe only the disk j (minus the constant ε_o background) and the whole space respectively. Then, for medium distances $D/r = 10-3$ and for non-radiative coupling such that $D<2r_C$, where $r_C = m\lambda / 2\pi$ is the radius of the radiation caustic, the two methods agree very well, and we finally find , as shown in Table 8, strong-coupling factors in the range $U \sim 1-50$. Thus, for the analyzed examples, the achieved figure-of-merit values are large enough to be useful for typical applications, as discussed below.

Table 8

two disks	D/r	Q^{rad}	$Q=\omega/2\Gamma$	$\omega/2\kappa$	κ/Γ
Re{ε}=147.7, m=2	3	2478	1989	46.9 (47.5)	42.4 (35.0)
$\lambda/r \approx 20$	5	2411	1946	298.0 (298.0)	6.5 (5.6)
$Q^{abs} \approx 10093$	7	2196	1804	769.7 (770.2)	2.3 (2.2)
	10	**2017**	**1681**	**1714 (1601)**	**0.98 (1.04)**
Re{ε}=65.6, m=3	3	7972	4455	144 (140)	30.9 (34.3)
$\lambda/r \approx 10$	5	9240	4824	2242 (2083)	2.2 (2.3)
$Q^{abs} \approx 10096$	7	9187	4810	7485 (7417)	0.64 (0.65)

Note that even though particular examples are presented and analyzed above as examples of systems that use resonant electromagnetic coupling for wireless energy transfer, those of self-resonant conducting coils, capacitively-loaded resonant conducting coils, inductively-loaded resonant conducting rods and resonant dielectric disks, any system that supports an electromagnetic mode with its electromagnetic energy extending much further than its size can be used for transferring energy. For example, there can be many abstract geometries with distributed capacitances and inductances that support the desired kind of resonances. In some examples, the resonant structure can be a dielectric sphere. In any one of these geometries, one can choose certain parameters to increase and/or optimize U or, if the Q's are limited by external factors, to increase and/or optimize for k or, if other system performance parameters are of importance, to optimize those.

Illustrative example

In one example, consider a case of wireless energy transfer between two identical resonant conducting loops, labeled by L_1 and L_2. The loops are capacitively-loaded and couple inductively via their mutual inductance. Let r_A denote the loops' radii, N_A their numbers of turns, and b_A the radii of the wires making the loops. We also denote by D_{12} the center-to-center separation between the loops.

Resonant objects of this type have two main loss mechanisms: ohmic absorption and far-field radiation. Using the same theoretical method as in previous sections, we find that for r_A=7cm, b_A=6mm, and N_A=15 turns, the quality factors for absorption, radiation and total loss are respectively, $Q_{A,abs} = \pi f / \Gamma_{A,abs} = 3.19\times10^4$, $Q_{A,rad} = \pi f / \Gamma_{A,rad} = 2.6\times10^8$ and $Q_A = \pi f / \Gamma_A = 2.84\times10^4$ at a resonant frequency $f = 1.8\times10^7$ Hz (remember that L_1 and L_2 are identical and have the same properties). $\Gamma_{A,abs}$, $\Gamma_{A,rad}$ are respectively the rates of absorptive and radiative loss of L_1 and L_2, and the rate of coupling between L_1 and L_2 is denoted by κ_{12}.

When the loops are in fixed distinct parallel planes separated by D_{12} =1.4m and have their centers on an axis (C) perpendicular to their planes, as shown in Fig. 17a(Left), the coupling factor for inductive coupling (ignoring retardation effects) is $k_{12} \equiv \kappa_{12} / \pi f = 7.68\times10^{-5}$, independent of time, and thus the strong-coupling factor is $U_{12} \equiv k_{12} Q_A = 2.18$. This configuration of parallel loops corresponds to the largest possible coupling rate κ_{12} at the particular separation D_{12}.

We find that the energy transferred to L_2 is maximum at time $\boldsymbol{T_* = \kappa t_* = \tan^{-1}(2.18) = 1.14 \Rightarrow t_* = 4775(1/f)}$ from Eq.(5), and constitutes $\boldsymbol{\eta_{E*} = 29\%}$ of the initial total energy from Eq.(6a), as shown in Fig. 17a(Right). The energies radiated and absorbed are respectively $\boldsymbol{\eta_{rad,E}(t_*) = 7.2\%}$ and $\boldsymbol{\eta_{abs,E}(t_*) = 58.1\%}$ of the initial total energy, with $\boldsymbol{5.8\%}$ of the energy remaining in L_1.

We would like to be able to further increase the efficiency of energy transfer between these two resonant objects at their distance D_{12}. In some examples, one can use an intermediate resonator between the source and device resonators, so that energy is transferred more efficiently from the source to the device resonator indirectly through the intermediate resonator.

3. Efficient energy-transfer by a chain of three 'strongly coupled' resonances

Fig. 16 shows a schematic that generally describes one example of the invention, in which energy is transferred wirelessly among three resonant objects. Referring to Fig. 16, energy is transferred, over a distance D_{1B}, from a resonant source object R_1 of characteristic size r_1 to a resonant intermediate object R_B of characteristic size r_B, and then, over an additional distance D_{B2}, from the resonant intermediate object R_B to a resonant device object R_2 of characteristic size r_2, where $D_{1B} + D_{B2} = D$. As described above, the source object R_1 can be supplied power from a power generator that is coupled to the source object R_1. In some examples, the power generator can be wirelessly, e.g., inductively, coupled to the source object R_1. In some examples, the power generator can be connected to the source object R_1 by means of a wire or cable. Also, the device object R_2 can be connected to a power load that consumes energy transferred to the device object R_2. For example, the device object can be connected to e.g. a resistor, a battery, or other device. All objects are resonant objects. The wireless near-field energy transfer is performed using the field (e.g. the electromagnetic field or acoustic field) of the system of three resonant objects.

Different temporal schemes can be employed, depending on the application, to transfer energy among three resonant objects. Here we will consider a particularly simple but important scheme: a one-time finite-amount energy-transfer scheme

3.1 Finite-amount energy-transfer efficiency

Let again the source, intermediate and device objects be 1, B, 2 respectively and their resonance modes, which we will use for the energy exchange, have angular frequencies $\omega_{1,B,2}$, frequency-widths due to intrinsic (absorption, radiation etc.) losses $\Gamma_{1,B,2}$ and (generally) vector fields $\mathbf{F}_{1,B,2}(\mathbf{r})$, normalized to unity energy. Once the three resonant objects are brought in proximity, they can interact and an appropriate analytical framework for modeling this resonant interaction is again that of the well-known coupled-mode theory (CMT), which can give a good description of the system for resonances having quality factors of at least, for example, 10. Then, using $e^{-i\omega t}$ time dependence, for the chain arrangement shown in Fig.16, the field amplitudes can be shown to satisfy, to lowest order:

$$\begin{aligned}
\frac{d}{dt}a_1(t) &= -i(\omega_1 - i\Gamma_1)a_1(t) + i\kappa_{11}a_1(t) + i\kappa_{1B}a_B(t) \\
\frac{d}{dt}a_B(t) &= -i(\omega_B - i\Gamma_B)a_B(t) + i\kappa_{BB}a_B(t) + i\kappa_{B1}a_1(t) + i\kappa_{B2}a_2(t) \\
\frac{d}{dt}a_2(t) &= -i(\omega_2 - i\Gamma_2)a_2(t) + i\kappa_{22}a_2(t) + i\kappa_{2B}a_B(t)
\end{aligned} \quad (34)$$

where $\kappa_{11,BB,22}$ are the shifts in each object's frequency due to the presence of the other, which are a second-order correction and can be absorbed into the eigenfrequencies by setting $\omega_{1,B,2} \to \omega_{1,B,2} + \kappa_{11,BB,22}$, and κ_{ij} are the coupling coefficients, which from the reciprocity requirement of the system must satisfy $\kappa_{ij} = \kappa_{ji}$. Note that, in some examples, the direct coupling coefficient κ_{12} between the resonant objects 1 and 2 may be much smaller than the coupling coefficients κ_{1B} and κ_{B2} between these two resonant objects with the intermediate object B, implying that the direct energy transfer between 1 and 2 is substantially dominated by the indirect energy transfer through the intermediate object. In some examples, if the coupling rates κ_{1B} and κ_{B2} are at least 5 times larger than the direct coupling rate κ_{12}, using an intermediate resonator may lead to an improvement in terms of energy transfer efficiency, as the indirect transfer may dominate the direct transfer. Therefore, in the CMT Eqs.(34) above, the direct coupling coefficient κ_{12} has been ignored, to analyze those particular examples.

The three resonant modes of the combined system are found by substituting $[a_1(t)\ a_B(t), a_2(t)] = [A_1, A_B, A_2]e^{-i\bar{\omega}t}$. When the resonators 1 and 2 are at exact resonance $\omega_1 = \omega_2 = \omega_A$ and for $\Gamma_1 = \Gamma_2 = \Gamma_A$, the resonant modes have complex resonant frequencies

$$\bar{\omega}_{\pm} = \omega_{AB} \pm \sqrt{(\Delta\omega_{AB})^2 + \kappa_{1B}^2 + \kappa_{B2}^2} \text{ and } \bar{\omega}_{ds} = \omega_A - i\Gamma_A \quad (35a)$$

where $\omega_{AB}=\left[(\omega_A+\omega_B)-i(\Gamma_A+\Gamma_B)\right]/2$, $\Delta\omega_{AB}=\left[(\omega_A-\omega_B)-i(\Gamma_A-\Gamma_B)\right]/2$ and whose splitting we denote as $\tilde{\delta}_E \equiv \bar{\omega}_+ - \bar{\omega}_-$, and corresponding resonant field amplitudes

$$\vec{V}_\pm=\begin{bmatrix}A_1\\A_B\\A_2\end{bmatrix}_\pm=\begin{bmatrix}\kappa_{1B}\\ \Delta\omega_{AB}\mp\sqrt{(\Delta\omega_{AB})^2+\kappa_{1B}^2+\kappa_{B2}^2}\\ \kappa_{B2}\end{bmatrix} \text{ and } \vec{V}_{ds}=\begin{bmatrix}A_1\\A_B\\A_2\end{bmatrix}_{ds}=\begin{bmatrix}-\kappa_{B2}\\0\\ \kappa_{1B}\end{bmatrix} \tag{35b}$$

Note that, when all resonators are at exact resonance $\omega_1=\omega_2(=\omega_A)=\omega_B$ and for $\Gamma_1=\Gamma_2(=\Gamma_A)=\Gamma_B$, we get $\Delta\omega_{AB}=0$, $\tilde{\delta}_E=2\sqrt{\kappa_{1B}^2+\kappa_{B2}^2}$, and then

$$\bar{\omega}_\pm=\omega_A\pm\sqrt{\kappa_{1B}^2+\kappa_{B2}^2}-i\Gamma_A \text{ and } \bar{\omega}_{ds}=\omega_A-i\Gamma_A \tag{36a}$$

$$\vec{V}_\pm=\begin{bmatrix}A_1\\A_B\\A_2\end{bmatrix}_\pm=\begin{bmatrix}\kappa_{1B}\\ \mp\sqrt{\kappa_{1B}^2+\kappa_{B2}^2}\\ \kappa_{B2}\end{bmatrix} \text{ and } \vec{V}_{ds}=\begin{bmatrix}A_1\\A_B\\A_2\end{bmatrix}_{ds}=\begin{bmatrix}-\kappa_{B2}\\0\\ \kappa_{1B}\end{bmatrix}, \tag{36b}$$

namely we get that the resonant modes split to a lower frequency, a higher frequency and a same frequency mode.

Assume now that at time $t=0$ the source object 1 has finite energy $|a_1(0)|^2$, while the intermediate and device objects have $|a_B(0)|^2=|a_2(0)|^2=0$. Since the objects are coupled, energy will be transferred from 1 to B and from B to 2. With these initial conditions, Eqs.(34) can be solved, predicting the evolution of the field-amplitudes. The energy-transfer efficiency will be $\tilde{\eta}_E \equiv |a_2(t)|^2/|a_1(0)|^2$. The ratio of energy converted to loss due to a specific loss mechanism in resonators 1, B and 2, with respective loss rates $\Gamma_{1,\text{loss}}$, $\Gamma_{\text{B,loss}}$ and $\Gamma_{2,\text{loss}}$ will be $\tilde{\eta}_{loss,E}=\int_0^t d\tau\left[2\Gamma_{1,\text{loss}}|a_1(\tau)|^2+2\Gamma_{\text{B,loss}}|a_B(\tau)|^2+2\Gamma_{2,\text{loss}}|a_2(\tau)|^2\right]/|a_1(0)|^2$. At exact resonance $\omega_1 = \omega_2 (= \omega_A) = \omega_B$ (an optimal condition) and in the special symmetric case $\Gamma_1 = \Gamma_2 = \Gamma_A$ and $\kappa_{1B} = \kappa_{B2} = \kappa$, the field amplitudes are

$$a_1(\tilde{T}) = \frac{1}{2} e^{-i\omega_A t} e^{-\tilde{T}/\tilde{U}} \left[\tilde{\Delta} \frac{\sin(\sqrt{1-\tilde{\Delta}^2}\tilde{T})}{\sqrt{1-\tilde{\Delta}^2}} + \cos(\sqrt{1-\tilde{\Delta}^2}\tilde{T}) + e^{-\tilde{\Delta}\tilde{T}} \right] \quad (37a)$$

$$a_B(\tilde{T}) = \frac{1}{2} e^{-i\omega_A t} e^{-\tilde{T}/\tilde{U}} \frac{\sin(\sqrt{1-\tilde{\Delta}^2}\tilde{T})}{\sqrt{1-\tilde{\Delta}^2}} \quad (37b)$$

$$a_2(\tilde{T}) = \frac{1}{2} e^{-i\omega_A t} e^{-\tilde{T}/\tilde{U}} \left[\tilde{\Delta} \frac{\sin(\sqrt{1-\tilde{\Delta}^2}\tilde{T})}{\sqrt{1-\tilde{\Delta}^2}} + \cos(\sqrt{1-\tilde{\Delta}^2}\tilde{T}) - e^{-\tilde{\Delta}\tilde{T}} \right] \quad (37c)$$

where $\tilde{T} \equiv \sqrt{2}\kappa t$, $\tilde{\Delta}^{-1} = 2\sqrt{2}\kappa/(\Gamma_B - \Gamma_A)$ and $\tilde{U} = 2\sqrt{2}\kappa/(\Gamma_A + \Gamma_B)$.

In some examples, the system designer can adjust the duration of the coupling t at will. In some examples, the duration t can be adjusted to maximize the device energy (and thus efficiency $\tilde{\eta}_E$). Then, in the special case above, it can be inferred from Eq.(37c) that $\tilde{\eta}_E$ is maximized for the $\tilde{T} = \tilde{T}_*$ that satisfies

$$\left[\tilde{\Delta} - \tilde{U}\left(1-\tilde{\Delta}^2\right)\right] \frac{\sin(\sqrt{1-\tilde{\Delta}^2}\tilde{T})}{\sqrt{1-\tilde{\Delta}^2}} + \left(1-\tilde{\Delta}\tilde{U}\right)\left[\cos(\sqrt{1-\tilde{\Delta}^2}\tilde{T}) - e^{\tilde{\Delta}\tilde{T}}\right] = 0 \,. \quad (38)$$

In general, this equation may not have an obvious analytical solution, but it does admit a simple solution in the following two cases:

When $\Gamma_A = \Gamma_B \Leftrightarrow \tilde{\Delta} = 0, \tilde{U} = \sqrt{2}\kappa/\Gamma_B$, the energy transfer from resonator 1 to resonator 2 is maximized at

$$\tilde{T}_*\left(\tilde{\Delta} = 0\right) = 2\tan^{-1}\tilde{U} \quad (39)$$

resulting in an energy-transfer efficiency

$$\tilde{\eta}_E\left(\tilde{T}_*, \tilde{\Delta} = 0\right) = \left[\frac{\tilde{U}^2}{1+\tilde{U}^2} \exp\left(-\frac{2\tan^{-1}\tilde{U}}{\tilde{U}}\right)\right]^2, \quad (40)$$

which has the form of the two-object energy-transfer efficiency of Eq.(6b) but squared.

When $\Gamma_A = 0 \Leftrightarrow \tilde{\Delta}^{-1} = \tilde{U} = 2\sqrt{2}\kappa/\Gamma_B$, the energy transfer from resonator 1 to resonator 2 is maximized at

$$\tilde{T}_*\left(\tilde{\Delta}^{-1}=\tilde{U}\right)=\begin{cases}\pi\tilde{U}\Big/\sqrt{\tilde{U}^2-1}, \tilde{U}>1 \\ \infty, \tilde{U}\leq 1\end{cases} \tag{41}$$

resulting in an energy-transfer efficiency

$$\eta_E\left(\tilde{T}_*,\tilde{\Delta}^{-1}=\tilde{U}\right)=\frac{1}{4}\cdot\begin{cases}\left[1+\exp\left(-\pi\Big/\sqrt{\tilde{U}^2-1}\right)\right]^2, \tilde{U}>1 \\ 1, \tilde{U}\leq 1\end{cases}. \tag{42}$$

In both cases, and in general for any $\tilde{\Delta}$, the efficiency is an increasing function of $\tilde{U}$. Therefore, once more resonators that have high quality factors are preferred. In some examples, one may design resonators with *Q*>50. In some examples, one may design resonators with *Q*>100.

Illustrative example

Returning to our illustrative example, in order to improve the ~29% efficiency of the energy transfer from L_1 to L_2, while keeping the distance D_{12} separating them fixed, we propose to introduce an intermediate resonant object that couples strongly to both L_1 and L_2, while having the same resonant frequency as both of them. In one example, we take that mediator to also be a capacitively-loaded conducting-wire loop, which we label by L_B. We place L_B at equal distance ($D_{1B}=D_{B2}=D_{12}/2=0.7$m) from L_1 and L_2 such that its axis also lies on the same axis (C), and we orient it such that its plane is parallel to the planes of L_1 and L_2, which is the optimal orientation in terms of coupling. A schematic diagram of the three-loops configuration is depicted in Fig. 17b(Left).

In order for L_B to couple strongly to L_1 and L_2, its size needs to be substantially larger than the size of L_1 and L_2. However, this increase in the size of L_B has considerable drawback in the sense that it may also be accompanied by significant decrease in its radiation quality factor. This feature may often occur for the resonant systems of this type: stronger coupling can often be enabled by increasing the objects' size, but it may imply stronger radiation from the object in question. Large radiation may often be undesirable, because it could lead to far-field interference with other RF systems, and in some systems also because of safety concerns. For r_B=70cm, b_B=1.5cm, and N_B=1 turn, we get $Q_{B,abs} = \pi f / \Gamma_{B,abs} = 7706$, $Q_{B,rad} = \pi f / \Gamma_{B,rad} = 400$, so $Q_B = \pi f / \Gamma_B = 380$, and $k_{1B} \equiv \kappa_{1B} / \pi f = k_{B2} = 0.0056$, so $\tilde{U} = 2\sqrt{2}\kappa / (\Gamma_A + \Gamma_B) = 5.94$ and $\tilde{\Delta}^{-1} = 2\sqrt{2}\kappa / (\Gamma_B - \Gamma_A) = 6.1$, at $f = 1.8 \times 10^7$ Hz. Note that since the coupling rates κ_{1B} and κ_{B2} are ≈ 70 times larger than κ_{12}, indeed we can ignore the direct coupling between L_1 and L_2, and focus only on the indirect energy transfer through the intermediate loop L_B, therefore the analysis of the previous section can be used.

The optimum in energy transferred to L_2 occurs at time $\tilde{T}_* = \sqrt{2}\kappa t_* = 3.21 \Rightarrow t_* = 129(1/f)$, calculated from Eq.(38), and is equal to $\tilde{\eta}_{E*} = 61.5\%$ of the initial energy from Eq.(37c). [Note that, since $Q_A \gg Q_B$, we could have used the analytical conclusions of the case $\tilde{\Delta}^{-1} = \tilde{U}$ and then we would have gotten a very close approximation of $\tilde{T}_* = 3.19$ from Eq.(41).] The energy radiated is $\tilde{\eta}_{rad,E}(t_*) = 31.1\%$, while the energy absorbed is $\tilde{\eta}_{abs,E}(t_*) = 3.3\%$, and 4.1% of the initial energy is left in L_1. Thus, the energy transferred, now indirectly, from L_1 to L_2 has increased by factor of 2 relative to the two-loops direct transfer case. Furthermore, the transfer time in the three-loops case is now ≈ 35 times shorter than in the two-loops direct transfer, because of the stronger coupling rate. The dynamics of the energy transfer in the three-loops case is shown in Fig. 17b(Right).

Note that the energy radiated in the three-loop system has undesirably increased by factor of 4 compared to the two-loop system. We would like to be able to achieve a similar improvement in energy-transfer efficiency, while not allowing the radiated energy to increase. In this specification, we disclose that, in some examples, this can be achieved by appropriately varying the values of the coupling strengths between the three resonators.

4. Efficient energy-transfer by a chain of three resonances with adiabatically varying coupling strengths

Consider again the system of a source resonator R_1, a device resonator R_2 and an intermediate resonator R_B. For the purposes of the present analysis, R_1 and R_2 will be assumed to have negligible mutual interactions with each other, while each of them can be strongly coupled to R_B, with coupling rates κ_{1B} and κ_{B2} respectively. Note that, in some examples of wireless energy transfer systems, for the resonant object R_B to be able to have strong coupling with other resonant objects, it may be accompanied with inferior loss properties compared to R_1 and R_2, usually in terms of substantially larger radiation losses.

It was seen in a previous section that, when the resonators 1 and 2 are at exact resonance $\omega_1 = \omega_2 = \omega_A$ and for $\Gamma_1 = \Gamma_2 = \Gamma_A$, the system supports a resonant state (eigenstate) with resonant frequency (eigenfrequency) $\bar{\omega}_{ds} = \omega_A - i\Gamma_A$ and resonant field amplitudes $\vec{V}_{ds} = \left[-\kappa_{B2} \quad 0 \quad \kappa_{1B}\right]^T \Big/ \sqrt{\kappa_{1B}^2 + \kappa_{B2}^2}$, where here we normalized it. This eigenstate $\vec{V}_{ds}$ we call the "dark state" in analogy with atomic systems and the related phenomenon of Electromagnetically Induced Transparency (EIT), wherein complete population transfer between two quantum states through a third lossy state, coupled to each of the other two states, is enabled. The dark state is the most essential building block of our proposed efficient weakly-radiative energy-transfer scheme, because it has no energy at all in the intermediate (lossy) resonator R_B, i.e. $a_B(t)=0$ $\forall$ t whenever the three-object system is in state $\vec{V}_{ds}$. In fact, if $\Gamma_A \rightarrow 0$, then this state is completely lossless, or if $\Gamma_{A,rad} \rightarrow 0$, then this state is completely non-radiative. Therefore, we disclose using predominantly this state to implement the wireless energy transfer. By doing that, the proposed energy transfer scheme can be made completely lossless, in the limit $\Gamma_A \rightarrow 0$, no matter how large is the loss rate Γ_B, as shown in Fig. 20, or completely non-radiative, in the limit $\Gamma_{A,rad} \rightarrow 0$, no matter how large is the radiative loss rate $\Gamma_{B,rad}$. Since the energy transfer efficiency increases as the quality factors of the first (source) and second (device) resonances increase, one may design these resonators to have a high quality factor. In some examples, one may design resonators with Q_A>50. In some examples, one may design resonators with Q_A>100.

Let us demonstrate how it is possible to use the dark state for energy transfer with minimal loss. From the expression of $\vec{V}_{ds}$ one can see that, if the three-object system is in the state $\vec{V}_{ds}$, then, in general, there is energy in the source resonator with field amplitude proportional to the coupling rate κ_{B2} between the device resonator and the intermediate resonator, and there is also energy in the device resonator with field amplitude proportional to the coupling rate κ_{1B} between the source resonator and the intermediate resonator. Then, $\kappa_{1B}=0$ corresponds to all the system's energy being in R_1, while $\kappa_{B2}=0$ corresponds to all the system's energy being in R_2.

So, the important considerations necessary to achieve efficient weakly-radiative energy transfer, consist of preparing the system initially in state $\vec{V}_{ds}$ and varying the coupling rates in time appropriately to evolve this state $\vec{V}_{ds}$ in a way that will cause energy transfer. Thus, if at t=0 all the energy is in R_1, then one should have $\kappa_{1B}(t=0) \ll \kappa_{B2}(t=0)$, for example $\kappa_{1B}(t=0)=0$ and $\kappa_{B2}(t=0)\neq 0$. In order for the total energy of the system to end up in R_2, at a time t_{EIT} when the full variation of the coupling rates has been completed, we should have $\kappa_{1B}(t=t_{EIT}) \gg \kappa_{B2}(t=t_{EIT})$, for example $\kappa_{1B}(t=t_{EIT})\neq 0$ and $\kappa_{B2}(t=t_{EIT})=0$. This ensures that the initial and final states of the three-object system are parallel to $\vec{V}_{ds}$. However, a second important consideration is to keep the three-object system at all times in $\vec{V}_{ds}(t)$, even as $\kappa_{1B}(t)$ and $\kappa_{B2}(t)$ are varied in time. This is crucial in order to prevent the system's energy from getting into any of the two other eigenstates $\vec{V}_{\pm}$ and thus getting into the intermediate object R_B, which may be highly radiative or lossy in general, as in the example of Fig. 17. This consideration requires changing $\kappa_{1B}(t)$ and $\kappa_{B2}(t)$ slowly enough so as to make the entire three-object system adiabatically follow the time evolution of $\vec{V}_{ds}(t)$. The criterion for adiabatic following can be expressed, in analogy to the population transfer case as

$$\left|\left\langle \vec{V}_{\pm} \left| \frac{d\vec{V}_{ds}}{dt} \right\rangle\right| \ll \left|\bar{\omega}_{\pm} - \bar{\omega}_{ds}\right| \quad (43)$$

where $\vec{V}_{\pm}$ are the remaining two eigenstates of the system, with corresponding eigenvalues $\bar{\omega}_{\pm}$, as shown earlier. Note that any functional dependence of the coupling rates with time (with duration parameter t_{EIT}) will work, provided it satisfies the adiabaticity criterion Eq.(43) above. The time functional can be linear, sinusoidal (as in the illustrative example to follow) or the temporal analog of a Butterworth (maximally flat) taper, a Chebyshev taper, an exponential taper and the like.

Referring to Fig. 18, an example coupling rate adjustment system 300 for adjusting coupling rates for the one or more of the resonator structures R_1, R_2, or R_B is shown. As described, the coupling rates between the first and intermediate resonator structures and the intermediate and second resonator structures are characterized by κ_{1B} and κ_{B2} respectively. These coupling rates, κ_{1B} and κ_{B2}, are several times (e.g., 70 times) greater than the coupling rate κ_{12} between the first and second resonator structure. In some examples, the coupling rate adjustment system can be a mechanical, electrical, or electro-mechanical system for dynamically adjusting, e.g., rotating, or effecting a translational movement, of the one or more resonator structures with respect to each other.

In some examples, the coupling rate κ_{1B} is much smaller than the coupling rate the coupling rate κ_{B2} at the beginning of the energy transfer. By the end, i.e., when a substantial amount of energy has been transferred from the first resonator structure R_1 to the second resonator structure, R_2, the coupling rate κ_{1B} is much greater than the coupling rate κ_{B2}. In some examples, the coupling rate κ_{1B} can be set to a fixed value while the coupling rate κ_{B2} is being varied from its maximum to its minimum value. In some examples, the coupling rate κ_{B2} can be set to a fixed value while the coupling rate κ_{1B} is being varied from its minimum to its maximum value. In some examples, the coupling rate κ_{1B} can be varied from a minimum to a maximum value while the coupling rate κ_{B2} is being varied from its maximum to minimum value.

Referring now to Fig. 19, a graph for implementing an example coupling rate adjustment system 300 is shown. As shown, in some examples, the coupling rate κ_{1B} is set at its minimum value at time, t=0, and increased as a function of time (see, for example, equation 44), while the coupling rate κ_{B2} is at its maximum value at t=0 and decreased as a function of time (see, for example, equation 45). Accordingly, at the beginning (t=0), the value of κ_{1B} is much smaller than the value of κ_{B2}. In some examples, the value of κ_{1B} can be selected to be any value much smaller than the value of κ_{B2}. During the wireless energy transfer, the value of κ_{1B} is increased, while the value of κ_{B2} is decreased. After a predetermined amount of time t_{EIT} has elapsed (e.g., after a substantial amount of energy has been transferred to the second resonator), the value of κ_{1B} becomes much greater than the value of κ_{B2}.

In some implementations, the coupling rate adjustment system 300 can effect an adjustment of coupling rates between the resonator structures by changing a relative orientation of one or more of the resonator structures with respect to each other. For example, referring again to Fig. 18, the first and second resonator structures, R_1 and R_2, can be rotated about their respective axes (e.g., varying angles θ_1 and θ_2), with respect to the intermediate resonator structure R_B to simultaneously change κ_{1B} and κ_{B2}. Alternatively, the orientation of the intermediate resonator structure, R_B, can be adjusted, e.g., rotated about an axis, with respect to the first and second resonator structures to simultaneously change κ_{1B} and κ_{B2}. Alternatively, the orientation of only the first resonator structure R_1 can be rotated about its respective axis to change κ_{1B}, while the orientations of R_2 and R_B are fixed and thus κ_{B2} is fixed to a value intermediate between the minimum and maximum values of κ_{1B}. Alternatively, the orientation of only the second resonator structure R_2 can be rotated about its respective axis to change κ_{B2}, while the orientations of R_1 and R_B are fixed and thus κ_{1B} is fixed to a value intermediate between the minimum and maximum values of κ_{B2}.

In some implementations, the coupling rate adjustment system 300 can effect an adjustment of coupling rates between the resonator structures by translationally moving one or more of the resonator structures with respect to each other. For example, the positions of the first and second resonator structures, R_1 and R_2, can be adjusted, e.g., moved along an axis, with respect to the intermediate resonator structure R_B to simultaneously change κ_{1B} and κ_{B2}. Alternatively, a position of the intermediate resonator structure, R_B, can be adjusted, e.g., moved along an axis, with respect to the first and second resonator structures to simultaneously change κ_{1B} and κ_{B2}. Alternatively, a position of only the first resonator structure, R_1, can be adjusted, e.g., moved along an axis, with respect to the intermediate R_B resonator structure to change κ_{1B}, while the positions of R_2 and R_B are fixed and thus κ_{B2} is fixed to a value intermediate between the minimum and maximum values of κ_{1B}. Alternatively, a position of only the second resonator structure, R_2, can be adjusted, e.g., moved along an axis, with respect to the intermediate R_B resonator structure to change κ_{B2}, while the positions of R_1 and R_B are fixed and thus κ_{1B} is fixed to a value intermediate between the minimum and maximum values of κ_{B2}.

In some examples, the coupling rate adjustment system 300 can dynamically adjust an effective size of the resonator objects to effect adjustments in the coupling rates κ_{1B} and κ_{B2} similar to that described above. The effective size can be adjusted by changing a physical size of the resonator objects. For example, the physical size can be adjusted by effecting mechanical changes in area, length, or other physical aspect of one or more of the resonator structures. The effective size can also be adjusted through non-mechanical changes, such as, but not limited to, applying a magnetic field to change the permeability of the one or more of the resonator structures.

In principle, one would think of making the transfer time t_{EIT} as long as possible to ensure adiabaticity. However there is limitation on how slow the transfer process can optimally be, imposed by the losses in R_1 and R_2. Such a limitation may not be a strong concern in typical atomic EIT case, because the initial and final states there can be chosen to be non-lossy ground states. However, in our case, losses in R_1 and R_2 are not avoidable, and can be detrimental to the energy transfer process whenever the transfer time t_{EIT} is not less than $1/\Gamma_A$. This is because, even if the three-object system is carefully kept in $\vec{V}_{ds}$ at all times, the total energy of the system will decrease from its initial value as a consequence of losses in R_1 and R_2. Thus the duration of the transfer may be a compromise between these two limits: the desire to keep t_{EIT} long enough to ensure near-adiabaticity, but short enough not to suffer from losses in R_1 and R_2.

Given a particular functional variation of the coupling rates with time with variation duration parameter t_{EIT}, one may calculate the optimal energy transfer efficiency in the following way: First, for each t_{EIT}, determine the optimal time t_*, at which the energy at R_2 is maximized and the transfer process may be be terminated. Then find the optimal variation time t_{EIT*} based on the counteracting mechanisms discussed above. The optimal efficiency of energy transfer $\tilde{\eta}_{EIT,E*}$ can then be calculated. In most cases, this procedure may need to be done numerically using the CMT Eqs.(34) as analytical solutions may not be possible. With respect to optimizing the functional dependence of the coupling rates with time, one may choose one that minimizes the coupling of energy to the eigenstates $\vec{V}_{\pm}$ for a given t_{EIT}, which may lead to the temporal analog of a Chebyshev taper.

In some examples, the optimal t_{EIT} may not be long enough for the adiabadicity criterion of Eq.(43) to be always satisfied. In those cases, some energy may get into at least one of the lossy states $\vec{V}_{\pm}$. Still significant improvement in efficiency and radiation loss may be achieved by the mode of operation where the coupling rates are variable, compared to the mode of operation where the coupling rates are constant, provided the maximum energy that enters the states $\vec{V}_{\pm}$ is much less in the variable rate scenario than in the constant rate scenario. In examples, using the proposed scheme of time-varying coupling rates may be advantageous as long as the maximum energy stored in the intermediate resonator is substantially small. In some examples, substantially small may be at most 5% of the peak total energy of the system. In some examples, substantially small may be at most 10% of the peak total energy of the system.

We can now also see why the mode of operation of the system where the coupling rates are kept constant in time may cause a considerable amount of lost (and especially radiated) energy, compared to the proposed mode of operation where the coupling rates are varied adiabatically in time. The reason is that, when $\kappa_{1B}=\kappa_{B2}$=const, the energies in R_1 and R_2 will always be equal to each other if the three-object system is to stay in $\vec{V}_{ds}$. So one cannot transfer energy from R_1 to R_2 by keeping the system purely in state $\vec{V}_{ds}$; note that even the initial state of the system, in which all the energy is in R_1 and there is no energy in R_3, cannot be solely in $\vec{V}_{ds}$ for fixed nonzero κ_{1B} and κ_{B2}, and has nonzero components along the eigenstates $\vec{V}_{\pm}$ which implies a finite energy will build up in R_B, and consequently result in an increased radiation, especially if $\Gamma_{B,rad} \gg \Gamma_{A,rad}$, which may be the case if the resonator R_B is chosen large enough to couple strongly to R_1 and R_2, as explained earlier.

Illustrative example

The previous analysis explains why a considerable amount of energy was radiated when the inductive coupling rates of the loops were kept constant in time, like in Fig. 17b. Let us now consider the modifications necessary for an adiabatically-varied-κ three-loops indirect transfer scheme, as suggested in the previous section, aiming to reduce the total radiated energy back to its reasonable value in the two-loops direct transfer case (Fig.17a), while maintaining the total energy transfer at level comparable to the constant-κ three-loops indirect transfer case (Fig. 17b). In one example, shown in Fig. 17c(Left and Right), we will keep the orientation of L_B fixed, and start initially (t=0) with L_1 perpendicular to L_B for $\kappa_{1B}=0$ and L_2 parallel to L_B for κ_{B2}=max, then uniformly rotate L_1 and L_2, at the same rates, until finally, at ($t=t_{EIT}$), L_1 becomes parallel to L_B for κ_{1B}=max and L_2 perpendicular to L_B for $\kappa_{B2}=0$, where we stop the rotation process. In this example, we choose a sinusoidal temporal variation of the coupling rates:

$$\kappa_{1B}(t) = \kappa \sin(\pi t / 2t_{EIT}) \tag{44}$$

$$\kappa_{B2}(t) = \kappa \cos(\pi t / 2t_{EIT}) \tag{45}$$

for $0<t<t_{EIT}$, and $k_{1B} \equiv \kappa_{1B} / \pi f = k_{B2} = 0.0056$ as before. By using the same CMT analysis as in Eq. (34), we find, in Fig. 17c(Center), that for an optimal $t_{EIT*} = 1989(1/f)$, an optimum transfer of $\tilde{\eta}_{EIT,E*} = 61.2\%$ can be achieved at $t_* = 1796(1/f)$, with only 8.2% of the initial energy being radiated, 28.6% absorbed, and 2% left in L_1. This is quite remarkable: by simply rotating the loops during the transfer, the energy radiated has dropped by factor of 4, while keeping the same 61% level of the energy transferred.

This considerable decrease in radiation may seem surprising, because the intermediate resonator L_B, which mediates all the energy transfer, is highly radiative ($\approx$ 650 times more radiative than L_1 and L_2), and there is much more time to radiate, since the whole process lasts 14 times longer than in Fig. 17b. Again, the clue to the physical mechanism behind this surprising result can be obtained by observing the differences between the curves describing the energy in R_B in Fig. 17b and Fig. 17c. Unlike the case of constant coupling rates, depicted in Fig. 17b, where the amount of energy ultimately transferred to L_2 goes first through the intermediate loop L_B, with peak energy storage in L_B as much as 30% of the peak total energy of the system, in the case of time-varying coupling rates, shown in Fig. 17c, there is almost little or no energy in L_B at all times during the transfer. In other words, the energy is transferred quite efficiently from L_1 to L_2, mediated by L_B without considerable amount of energy ever being in the highly radiative intermediate loop L_B. (Note that direct transfer from L_1 to L_2 is identically zero here since L_1 is always perpendicular to L_2, so all the energy transfer is indeed mediated through L_B). In some examples, improvement in efficiency and/or radiated energy can still have been accomplished if the energy transfer had been designed with a time t_{EIT} smaller than its optimal value (perhaps to speed up the process), if the maximum energy accumulated inside the intermediate resonator was less than 30%. For example, improvement can have been achieved for maximum energy accumulation inside the intermediate resonator of 5% or even 10%.

An example implementation of the coupling rate adjustment system 300 is described below, where the resonators are capacitively-loaded loops, which couple to each other inductively. At the beginning (t=0), the coupling rate adjustment system 300 sets the relative orientation of the first resonator structure L_1 to be perpendicular to the intermediate resonator structure L_B. At this orientation, the value of the coupling rate κ_{1B} between the first and intermediate resonator structure is at its minimum value. Also, the coupling rate adjustment system 300 can set the relative orientation of the second resonator structure L_2 to be parallel to the intermediate resonator structure L_B. At this orientation, the value of the coupling rate κ_{B2} is at a maximum value. During wireless energy transfer, the coupling rate adjustment system 300 can effect the rotation of the first resonator structure L_1 about its axis so that the value of κ_{1B} is increased. In some examples, the coupling rate adjustment system 300 can also effect the rotation of the second resonator structure, L_2, about its axis so that the value of κ_{B2} is decreased. In some examples, a similar effect can be achieved by fixing L_1 and L_2 to be perpendicular to each other and rotating only L_B to be parallel to L_2 and perpendicular to L_1 at t=0 and parallel to L_1 and perpendicular to L_2 at $t=t_{EIT}$. In some examples, a similar effect can be achieved by fixing L_B and one of L_1 and L_2 (e.g., L_1) at a predetermined orientation (e.g. at 45 degrees with respect to the intermediate resonator L_B) and rotating only the other of L_1 and L_2 (e.g., L_2 from parallel to L_B at t=0 to perpendicular to L_B at $t=t_{EIT}$).

Similarly, in some implementations, at the beginning (t=0), the coupling rate adjustment system 300 can set the position of the first resonator structure L_1 at a first large predetermined distance from the intermediate resonator structure L_B so that the value of the coupling rate κ_{1B} is at its minimum value. Correspondingly, the coupling rate adjustment system 300 can set the position of the second resonator structure L_2 at a second small predetermined distance from the intermediate resonator structure L_B so that the value of the coupling rate κ_{B2} between the first and intermediate resonator structure is at its maximum value. During wireless energy transfer, the coupling rate adjustment system 300 can affect the position of the first resonator structure L_1 to bring it closer to

L_B so that the value of κ_{1B} is increased. In some examples, the coupling rate adjustment system 300 can also effect the position of the second resonator structure, L_2, to take it away from L_B so that the value of κ_{B2} is decreased. In some examples, a similar effect can be achieved by fixing L_1 and L_2 to be at a fixed distance to each other and effecting the position of only L_B to be close to L_2 and away from L_1 at t=0 and close to L_1 and away from L_2 at $t=t_{EIT}$. In some examples, a similar effect can be achieved by fixing L_B and one of L_1 and L_2 (e.g., L_1) at a predetermined (not too large but not too small) distance and effecting the position only the other of L_1 and L_2 (e.g., L_2 from close to L_B at t=0 to away from L_B at $t=t_{EIT}$).

5. Comparison of static and adiabatically dynamic systems

In the abstract case of energy transfer from R_1 to R_2, where no constraints are imposed on the relative magnitude of κ, Γ^A_{rad}, Γ^B_{rad}, Γ^A_{abs}, and Γ^B_{abs}, it is not certain that the adiabatic-κ (EIT-like) system will always perform better than the constant-κ one, in terms of the transferred and radiated energies. In fact, there could exist some range of the parameters (κ, Γ^A_{rad}, Γ^B_{rad}, Γ^A_{abs}, Γ^B_{abs}), for which the energy radiated in the constant-κ transfer case is less than that radiated in the EIT-like case. For this reason, we investigate both the adiabatic-κ and constant-κ transfer schemes, as we vary some of the crucial parameters of the system. The percentage of energies transferred and lost (radiated+absorbed) depends only on the relative values of κ, $\Gamma_A = \Gamma^A_{rad} + \Gamma^A_{abs}$ and $\Gamma_B = \Gamma^B_{rad} + \Gamma^B_{abs}$. Hence we first calculate and visualize the dependence of these energies on the relevant parameters κ/Γ_B and Γ_B/Γ_A, in the contour plots shown in Fig. 21.

The way the contour plots are calculated is as follows. For each value of (κ/Γ_B, Γ_B/Γ_A) in the adiabatic case, where $\kappa_{1B}(t)$ and $\kappa_{B2}(t)$ are given by Eq. (44)-(45), one tries range of values of t_{EIT}. For each t_{EIT}, the maximum energy transferred E_2(%) over $0< t <t_{EIT}$, denoted by max(E_2, t_{EIT}), is calculated together with the total energy lost at that maximum transfer. Next the maximum of max(E_2, t_{EIT}) over all values of t_{EIT} is selected

and plotted as single point on the contour plot in Fig. 21a. We refer to this point as the optimum energy transfer (%) in the adiabatic-κ case for the particular (κ/Γ_B, Γ_B/Γ_A) under consideration. We also plot in Fig. 21d the corresponding value of the total energy lost (%) at the optimum of E_2. We repeat these calculations for all pairs (κ/Γ_B, Γ_B/Γ_A) shown in the contour plots. In the constant-κ transfer case, for each (κ/Γ_B, Γ_B/Γ_A), the time evolution of E_2(%) and E_{lost} are calculated for $0<t<2/\kappa$, and optimum transfer, shown in Fig. 21b, refers to the maximum of $E_3(t)$ over $0<t<2/\kappa$. The corresponding total energy lost at optimum constant-transfer is shown in Fig. 21e. Now that we calculated the energies of interest as functions of (κ/Γ_B, Γ_B/Γ_A), we look for ranges of the relevant parameters in which the adiabatic-κ transfer has advantages over the constant-κ one. So, we plot the ratio of $(E_2)_{adiabatic\text{-}\kappa}/(E_2)_{constant\text{-}\kappa}$ in Fig. 21c, and $(E_{lost})_{constant\text{-}\kappa}$ / $(E_{lost})_{adiabatic\text{-}\kappa}$ in Fig. 21f. We find that, for $\Gamma_B/\Gamma_A>50$, the optimum energy transferred in the adiabatic-κ case exceeds that in the constant-κ case, and the improvement factor can be larger than 2. From Fig. 21f, one sees that the adiabatic-κ scheme can reduce the total energy lost by factor of 3 compared to the constant-κ scheme, also in the range Γ_B/Γ_A >50. As in the constant-κ case, also in the adiabatic-κ case the efficiency increases as the ratio of the maximum value, κ, of the coupling rates to the loss rate of the intermediate object (and thus also the first and second objects for $\Gamma_B/\Gamma_A>1$) increases. In some examples, one may design a system so that κ is larger than each of Γ_B and Γ_A. In some examples, one may design a system so that κ is at least 2 times larger than each of Γ_B and Γ_A. In some examples, one may design a system so that κ is at least 4 times larger than each of Γ_B and Γ_A.

Although one may be interested in reducing the total energy lost (radiated + absorbed) as much as possible in order to make the transfer more efficient, the undersirable nature of the radiated energy may make it important to consider reducing the energy radiated. For this purpose, we calculate the energy radiated at optimum transfer in both the adiabatic-κ and constant-κ schemes, and compare them. The relevant parameters in this case are κ/Γ_B, Γ_B/Γ_A, Γ_{rad}^A/Γ_A, and Γ_{rad}^B/Γ_B. The problem is more complex because the parameter space is now 4-dimensional. So we focus on those particular cross sections that can best reveal the most important differences between the two schemes. From Fig. 21c and 21f, one can guess that the best improvement in both E_2 and E_{lost} occurs for $\Gamma_B / \Gamma_A \geq 500$. Moreover, knowing that it is the intermediate object R_B that makes the main difference between the adiabatic-κ and constant-κ schemes, being "energy-empty" in the adiabatic-κ case and "energy-full" in the constant-κ one, we first look at the special situation where $\Gamma_{rad}^{A}=0$. In Fig. 22a and Fig. 22b, we show contour plots of the energy radiated at optimum transfer, in the constant-κ and adiabatic-κ schemes respectively, for the particular cross section having $\Gamma_B / \Gamma_A=500$ and $\Gamma_{rad}^{A}=0$. Comparing these two figures, one can see that, by using the adiabatic-κ scheme, one can reduce the energy radiated by factor of 6.3 or more.

To get quantitative estimate of the radiation reduction factor in the general case where $\Gamma_{A,rad} \neq 0$, we calculate the ratio of energies radiated at optimum transfers in both schemes, namely,

$$\frac{(E_{rad})_{\text{constant}-\kappa}}{(E_{rad})_{\text{adiabatic}-\kappa}}=\frac{2\int_0^{t_*^{\text{constant}-\kappa}}\left\{\frac{\Gamma_{rad}^{B}}{\Gamma_{rad}^{A}}\left|a_B^{\text{constant}-\kappa}(t)\right|^2+\left|a_1^{\text{constant}-\kappa}(t)\right|^2+\left|a_2^{\text{constant}-\kappa}(t)\right|^2\right\}}{2\int_0^{t_*^{\text{adiabatic}-\kappa}}\left\{\frac{\Gamma_{rad}^{B}}{\Gamma_{rad}^{A}}\left|a_B^{\text{adiabatic}-\kappa}(t)\right|^2+\left|a_1^{\text{adiabatic}-\kappa}(t)\right|^2+\left|a_2^{\text{adiabatic}-\kappa}(t)\right|^2\right\}} \quad (46)$$

which depends only on $\Gamma_{rad}^{B} / \Gamma_{rad}^{A}$, the time-dependent mode amplitudes, and the optimum transfer times in both schemes. The latter two quantities are completely determined by κ/Γ_B and Γ_B / Γ_A. Hence the only parameters relevant to the calculations of the ratio of radiated energies are $\Gamma_{rad}^{B} / \Gamma_{rad}^{A}$, κ/Γ_B and Γ_B / Γ_A, thus reducing the dimensionality of the investigated parameter space from down to 3. For convenience, we multiply the first relevant parameter $\Gamma_{rad}^{B} / \Gamma_{rad}^{A}$ by Γ_B/Γ_A which becomes $(\Gamma_{rad}^{B}/\Gamma_B)/(\Gamma_{rad}^{A}/\Gamma_A)$, i.e. the ratio of quantities that specify what percentage of each object's loss is radiated. Next, we calculate the ratio of energies radiated as function of ($\Gamma_{rad}^{B}/\Gamma_B$)/($\Gamma_{rad}^{A}/\Gamma_A$) and κ/Γ_B in the two special cases Γ_B/Γ_A=50, and Γ_B/Γ_A=500, and plot them in Fig. 22c and Fig. 22d, respectively. We also show, in Fig. 22e, the dependence of $(E_{rad})_{constant\text{-}\kappa}/(E_{rad})_{EIT\text{-}like}$ on κ/Γ_B and Γ_B/Γ_A, for the special case $\Gamma_{rad}^{A}=0$. As can be seen from Fig. 22c-22d, the adiabatic-κ scheme is less radiative than the constant-κ scheme whenever $\Gamma_{rad}^{B}/\Gamma_B$ is larger than $\Gamma_{rad}^{A}/\Gamma_A$, and the radiation reduction ratio increases as Γ_B/Γ_A and κ/Γ_B are increased (see fig. 22e). In some examples, the adiabatic-κ scheme is less radiative than the constant-κ scheme whenever $\Gamma_{rad}^{B}/\Gamma_{rad}^{A}$ is larger than about 20. In some examples, the adiabatic-κ scheme is less radiative than the constant-κ scheme whenever $\Gamma_{rad}^{B}/\Gamma_{rad}^{A}$ is larger than about 50.

It is to be understood that while three resonant objects are shown in the previous examples, other examples can feature four or more resonant objects. For example, in some examples, a single source object can transfer energy to multiple device objects through one intermediate object. In some examples, energy can be transferred from a source resonant object to a device resonant object, through two or more intermediate resonant objects, and so forth.

6. System Sensitivity to Extraneous Objects

In general, the overall performance of an example of the resonance-based wireless energy-transfer scheme depends strongly on the robustness of the resonant objects' resonances. Therefore, it is desirable to analyze the resonant objects' sensitivity to the near presence of random non-resonant extraneous objects. One appropriate analytical model is that of "perturbation theory" (PT), which suggests that in the presence of an extraneous perturbing object p the field amplitude $a_1(t)$ inside the resonant object 1 satisfies, to first order:

$$\frac{da_1}{dt} = -i(\omega_1 - i\Gamma_1)a_1 + i\left(\delta\kappa_{11(p)} + i\delta\Gamma_{1(p)}\right)a_1 \qquad (47)$$

where again ω_1 is the frequency and Γ_1 the intrinsic (absorption, radiation etc.) loss rate, while $\delta\kappa_{11(p)}$ is the frequency shift induced onto 1 due to the presence of p and $\delta\Gamma_{1(p)}$ is the extrinsic due to p (absorption inside p, scattering from p etc.) loss rate. $\delta\Gamma_{1(p)}$ is defined as $\delta\Gamma_{1(p)} \equiv \Gamma_{1(p)} - \Gamma_1$, where $\Gamma_{1(p)}$ is the total perturbed loss rate in the presence of p. The first-order PT model is valid only for small perturbations. Nevertheless, the parameters $\delta\kappa_{11(p)}$, $\delta\Gamma_{1(p)}$ are well defined, even outside that regime, if a_1 is taken to be the amplitude of the exact perturbed mode. Note also that interference effects between the radiation field of the initial resonant-object mode and the field scattered off the extraneous object can for strong scattering (e.g. off metallic objects) result in total $\Gamma_{1,\text{rad}(p)}$ that are smaller than the initial $\Gamma_{1,\text{rad}}$ (namely $\delta\Gamma_{1,\text{rad}(p)}$ is negative).

It has been shown that a specific relation is desired between the resonant frequencies of the source and device-objects and the driving frequency. In some examples, all resonant objects must have the same eigenfrequency and this must be equal to the driving frequency. In some implementations, this frequency-shift can be "fixed" by applying to one or more resonant objects and the driving generator a feedback mechanism that corrects their frequencies. In some examples, the driving frequency from the generator can be fixed and only the resonant frequencies of the objects can be tuned with respect to this driving frequency.

The resonant frequency of an object can be tuned by, for example, adjusting the geometric properties of the object (e.g. the height of a self-resonant coil, the capacitor plate spacing of a capacitively-loaded loop or coil, the dimensions of the inductor of an inductively-loaded rod, the shape of a dielectric disc, etc.) or changing the position of a non-resonant object in the vicinity of the resonant object.

In some examples, referring to Fig. 23a, each resonant object is provided with an oscillator at fixed frequency and a monitor which determines the eigenfrequency of the object. At least one of the oscillator and the monitor is coupled to a frequency adjuster which can adjust the frequency of the resonant object. The frequency adjuster determines the difference between the fixed driving frequency and the object frequency and acts, as described above, to bring the object frequency into the required relation with respect to the fixed frequency. This technique assures that all resonant objects operate at the same fixed frequency, even in the presence of extraneous objects.

In some examples, referring to Fig. 23(b), during energy transfer from a source object to a device object, the device object provides energy or power to a load, and an efficiency monitor measures the efficiency of the energy-transfer or power-transmission. A frequency adjuster coupled to the load and the efficiency monitor acts, as described above, to adjust the frequency of the object to maximize the efficiency.

In other examples, the frequency adjusting scheme can rely on information exchange between the resonant objects. For example, the frequency of a source object can be monitored and transmitted to a device object, which is in turn synched to this frequency using frequency adjusters, as described above. In other embodiments the frequency of a single clock can be transmitted to multiple devices, and each device then synched to that frequency using frequency adjusters, as described above.

Unlike the frequency shift, the extrinsic perturbing loss due to the presence of extraneous perturbing objects can be detrimental to the functionality of the energy-transfer scheme, because it is difficult to remedy. Therefore, the total perturbed quality factors $Q_{(p)}$ (and the corresponding perturbed strong-coupling factor $U_{(p)}$ should be quantified.

In some examples, a system for wireless energy-transfer uses primarily magnetic resonances, wherein the energy stored in the near field in the air region surrounding the resonator is predominantly magnetic, while the electric energy is stored primarily inside the resonator. Such resonances can exist in the quasi-static regime of operation ($r \ll \lambda$) that we are considering: for example, for coils with $h \ll 2r$, most of the electric field is localized within the self-capacitance of the coil or the externally loading capacitor and, for dielectric disks, with $\epsilon \gg 1$ the electric field is preferentially localized inside the disk. In some examples, the influence of extraneous objects on magnetic resonances is nearly absent. The reason is that extraneous non-conducting objects p that could interact with the magnetic field in the air region surrounding the resonator and act as a perturbation to the resonance are those having significant magnetic properties (magnetic permeability $Re\{\mu\}>1$ or magnetic loss $Im\{\mu\}>0$). Since almost all every-day non-conducting materials are non-magnetic but just dielectric, they respond to magnetic fields in the same way as free space, and thus will not disturb the resonance of the resonator. Extraneous conducting materials can however lead to some extrinsic losses due to the eddy currents induced inside them or on their surface (depending on their conductivity). However, even for such conducting materials, their presence will not be detrimental to the resonances, as long as they are not in very close proximity to the resonant objects.

The interaction between extraneous objects and resonant objects is reciprocal, namely, if an extraneous object does not influence a resonant object, then also the resonant object does not influence the extraneous object. This fact can be viewed in light of safety considerations for human beings. Humans are also non-magnetic and can sustain strong magnetic fields without undergoing any risk. A typical example, where magnetic fields $B\sim 1T$ are safely used on humans, is the Magnetic Resonance Imaging (MRI) technique for medical testing. In contrast, the magnetic near-field required in typical embodiments in order to provide a few Watts of power to devices is only $B\sim 10^{-4}T$, which is actually comparable to the magnitude of the Earth's magnetic field. Since, as explained above, a strong electric near-field is also not present and the radiation produced from this non-radiative scheme is minimal, the energy-transfer apparatus, methods and systems described herein is believed safe for living organisms.

An advantage of the presently proposed technique using adiabatic variations of the coupling rates between the first and intermediate resonators and between the intermediate and second resonators compared to a mode of operation where these coupling rates are not varied but are constant is that the interactions of the intermediate resonator with extraneous objects can be greatly reduced with the presently proposed scheme. The reason is once more the fact that there is always a substantially small amount of energy in the intermediate resonator in the adiabatic-κ scheme, therefore there is little energy that can be induced from the intermediate object to an extraneous object in its vicinity. Furthermore, since the losses of the intermediate resonator are substantially avoided in the adiabatic-κ case, the system is less immune to potential reductions of the quality factor of the intermediate resonator due to extraneous objects in its vicinity.

6.1 Capacitively-loaded conducting loops or coils

In some examples, one can estimate the degree to which the resonant system of a capacitively-loaded conducting-wire coil has mostly magnetic energy stored in the space surrounding it. If one ignores the fringing electric field from the capacitor, the electric and magnetic energy densities in the space surrounding the coil come just from the electric and magnetic field produced by the current in the wire; note that in the far field, these two energy densities must be equal, as is always the case for radiative fields. By using the results for the fields produced by a subwavelength ($r \ll \lambda$) current loop (magnetic dipole) with $h = 0$, we can calculate the ratio of electric to magnetic energy densities, as a function of distance D_p from the center of the loop (in the limit $r \ll D_p$) and the angle θ with respect to the loop axis:

$$\frac{w_e(x)}{w_m(x)} = \frac{\varepsilon_o |E(x)|^2}{\mu_o |H(x)|^2} = \frac{\left(1+\frac{1}{x^2}\right)\sin^2\theta}{\left(\frac{1}{x^2}+\frac{1}{x^4}\right)4\cos^2\theta + \left(1-\frac{1}{x^2}+\frac{1}{x^4}\right)\sin^2\theta};\ x = 2\pi\frac{D_p}{\lambda}$$
$$\Rightarrow \frac{\oiint_{S_p} w_e(x)\,dS}{\oiint_{S_p} w_m(x)\,dS} = \frac{1+\frac{1}{x^2}}{1+\frac{1}{x^2}+\frac{3}{x^4}};\ x = 2\pi\frac{D_p}{\lambda}, \quad (48)$$

where the second line is the ratio of averages over all angles by integrating the electric and magnetic energy densities over the surface of a sphere of radius D_p. From Eq.(48) it is obvious that indeed for all angles in the near field ($x \ll 1$) the magnetic energy density is dominant, while in the far field ($x \gg 1$) they are equal as they should be. Also, the preferred positioning of the loop is such that objects which can interfere with its resonance lie close to its axis ($\theta = 0$), where there is no electric field. For example, using the systems described in Table 4, we can estimate from Eq.(48) that for the loop of $r = 30cm$ at a distance $D_p = 10r = 3m$ the ratio of average electric to average magnetic energy density would be $\sim 12\%$ and at $D_p = 3r = 90cm$ it would be $\sim 1\%$, and for the loop of $r = 10cm$ at a distance $D_p = 10r = 1m$ the ratio would be $\sim 33\%$ and at $D_p = 3r = 30cm$ it would be $\sim 2.5\%$. At closer distances this ratio is even smaller and thus the energy is predominantly magnetic in the near field, while in the radiative far field, where they are necessarily of the same order (ratio$\rightarrow 1$), both are very small, because the fields have significantly decayed, as capacitively-loaded coil systems are designed to radiate very little. Therefore, this is the criterion that qualifies this class of resonant system as a magnetic resonant system.

To provide an estimate of the effect of extraneous objects on the resonance of a capacitively-loaded loop including the capacitor fringing electric field, we use the perturbation theory formula, stated earlier,

$\delta\Gamma_{1,abs(p)} = \omega_1 / 4 \cdot \int d^3\mathbf{r}\, \mathrm{Im}\{\varepsilon_p(\mathbf{r})\}|\mathbf{E}_1(\mathbf{r})|^2 / W$ with the computational FEFD results for the field of an example like the one shown in the plot of Fig. 5 and with a rectangular object of dimensions *30cm x 30cm x 1.5m* and permittivity *ε=49+16i* (consistent with human muscles) residing between the loops and almost standing on top of one capacitor (*~3cm* away from it) and find $\delta Q_{abs(human)} \sim 10^5$ and for *~10cm* away $\delta Q_{abs(human)} \sim 5 \cdot 10^5$. Thus, for ordinary distances (*~1m*) and placements (not immediately on top of the capacitor) or for most ordinary extraneous objects p of much smaller loss-tangent, we conclude that it is indeed fair to say that $\delta Q_{abs(p)} \rightarrow \infty$. The only perturbation that is expected to affect these resonances is a close proximity of large metallic structures.

Self-resonant coils can be more sensitive than capacitively-loaded coils, since for the former the electric field extends over a much larger region in space (the entire coil) rather than for the latter (just inside the capacitor). On the other hand, self-resonant coils can be simple to make and can withstand much larger voltages than most lumped capacitors. Inductively-loaded conducting rods can also be more sensitive than capacitively-loaded coils, since they rely on the electric field to achieve the coupling.

6.2 Dielectric disks

For dielectric disks, small, low-index, low-material-loss or far-away stray objects will induce small scattering and absorption. In such cases of small perturbations these extrinsic loss mechanisms can be quantified using respectively the analytical first-order perturbation theory formulas

$$\left[\delta Q_{1,rad(p)}\right]^{-1} \equiv 2\delta\Gamma_{1,rad(p)} / \omega_1 \propto \int d^3\mathbf{r}\left[\mathrm{Re}\left\{\varepsilon_p(\mathbf{r})\right\}\left|\mathbf{E}_1(\mathbf{r})\right|\right]^2 \Big/ W$$

$$\left[\delta Q_{1,abs(p)}\right]^{-1} \equiv 2\delta\Gamma_{1,abs(p)} / \omega_1 = \int d^3\mathbf{r}\,\mathrm{Im}\left\{\varepsilon_p(\mathbf{r})\right\}\left|\mathbf{E}_1(\mathbf{r})\right|^2 \Big/ 2W$$

where $W = \int d^3\mathbf{r}\varepsilon(\mathbf{r})\left|\mathbf{E}_1(\mathbf{r})\right|^2 / 2$ is the total resonant electromagnetic energy of the unperturbed mode. As one can see, both of these losses depend on the square of the resonant electric field tails **E**1 at the site of the extraneous object. In contrast, the coupling factor from object 1 to another resonant object 2 is, as stated earlier,

$$k_{12} = 2\kappa_{12} / \sqrt{\omega_1\omega_2} \approx \int d^3\mathrm{r}\varepsilon_2(\mathrm{r})\mathrm{E}_2^*(\mathrm{r})\mathrm{E}_1(\mathrm{r}) / \int d^3\mathrm{r}\varepsilon(\mathrm{r})\left|\mathrm{E}_1(\mathrm{r})\right|^2$$

and depends *linearly* on the field tails $\mathbf{E}_1$ of 1 inside 2. This difference in scaling gives us confidence that, for, for example, exponentially small field tails, coupling to other resonant objects should be much faster than all extrinsic loss rates ($\kappa_{12} \gg \delta\Gamma_{1,2(p)}$), at least for small perturbations, and thus the energy-transfer scheme is expected to be sturdy for this class of resonant dielectric disks.

However, we also want to examine certain possible situations where extraneous objects cause perturbations too strong to analyze using the above first-order perturbation theory approach. For example, we place a dielectric disk close to another off-resonance object of large Re{ε}, Im{ε} and of same size but different shape (such as a human being *h*), as shown in Fig. 24a, and a roughened surface of large extent but of small Re{ε}, Im{ε} (such as a wall *w*), as shown in Fig. 24b. For distances $D_{h,w} / r = 10-3$ between the disk-center and the "human"-center or "wall", the numerical FDFD simulation results presented in Figs. 24a and 24b suggest that, the disk resonance seems to be fairly robust, since it is not detrimentally disturbed by the presence of extraneous objects, with the exception of the *very* close proximity of high-loss objects. To examine the influence of large perturbations on an entire energy-transfer system we consider two resonant disks in the close presence of both a "human" and a "wall". Comparing Table 8 to the table in Figure 24c, the numerical FDFD simulations show that the system performance deteriorates from $U{\sim}1-50$ to $U_{(hw)}{\sim}0.5-10$, i.e. only by acceptably small amounts.

In general, different examples of resonant systems have different degree of sensitivity to external perturbations, and the resonant system of choice depends on the particular application at hand, and how important matters of sensitivity or safety are for that application. For example, for a medical implantable device (such as a wirelessly powered artificial heart) the electric field extent must be minimized to the highest degree possible to protect the tissue surrounding the device. In such cases where sensitivity to external objects or safety is important, one should design the resonant systems so that the ratio of electric to magnetic energy density w_e / w_m is reduced or minimized at most of the desired (according to the application) points in the surrounding space.

7 Applications

The non-radiative wireless energy transfer techniques described above can enable efficient wireless energy-exchange between resonant objects, while suffering only modest transfer and dissipation of energy into other extraneous off-resonant objects. The technique is general, and can be applied to a variety of resonant systems in nature. In this Section, we identify a variety of applications that can benefit from or be designed to utilize wireless power transmission.

Remote devices can be powered directly, using the wirelessly supplied power or energy to operate or run the devices, or the devices can be powered by or through or in addition to a battery or energy storage unit, where the battery is occasionally being charged or re-charged wirelessly. The devices can be powered by hybrid battery/energy storage devices such as batteries with integrated storage capacitors and the like. Furthermore, novel battery and energy storage devices can be designed to take advantage of the operational improvements enabled by wireless power transmission systems.

Devices can be turned off and the wirelessly supplied power or energy used to charge or recharge a battery or energy storage unit. The battery or energy storage unit charging or recharging rate can be high or low. The battery or energy storage units can be trickle charged or float charged. It would be understood by one of ordinary skill in the art that there are a variety of ways to power and/or charge devices, and the variety of ways could be applied to the list of applications that follows.

Some wireless energy transfer examples that can have a variety of possible applications include for example, placing a source (e.g. one connected to the wired electricity network) on the ceiling of a room, while devices such as robots, vehicles, computers, PDAs or similar are placed or move freely within the room. Other applications can include powering or recharging electric-engine buses and/or hybrid cars and medical implantable devices. Additional example applications include the ability to power or recharge autonomous electronics (e.g. laptops, cell-phones, portable music players, house-hold robots, GPS navigation systems, displays, etc), sensors, industrial and manufacturing equipment, medical devices and monitors, home appliances (e.g. lights, fans, heaters, displays, televisions, counter-top appliances, etc.), military devices, heated or illuminated clothing, communications and navigation equipment, including equipment built into vehicles, clothing and protective-wear such as helmets, body armor and vests, and the like, and the ability to transmit power to physically isolated devices such as to implanted medical devices, to hidden, buried, implanted or embedded sensors or tags, to and/or from roof-top solar panels to indoor distribution panels, and the like.

A number of examples of the invention have been described. Nevertheless, it will be understood that various modifications can be made without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A method for transferring energy wirelessly, the method comprising:
transferring energy wirelessly from a first resonator structure to an intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B};
transferring energy wirelessly from the intermediate resonator structure to a second resonator structure, wherein the coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2}; and
during the wireless energy transfers, adjusting at least one of the coupling rates κ_{1B} and κ_{B2} to reduce energy accumulation in the intermediate resonator structure and improve wireless energy transfer from the first resonator structure to the second resonator structure through the intermediate resonator structure.

2. The method of claim 1, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} minimizes energy accumulation in the intermediate resonator structure and causes wireless energy transfer from the first resonator structure to the second resonator structure.

3. The method of claims 1 or 2, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} maintains energy distribution in the field of the three-resonator system in an eigenstate having substantially no energy in the intermediate resonator structure.

4. The method of claim 3, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} further causes the eigenstate to evolve substantially adiabatically from an initial state with substantially all energy in the resonator structures in the first resonator structure to a final state with substantially all of the energy in the resonator structures in the second resonator structure.

5. The method of any of claims 1 to 4, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} comprises adjustments of both coupling rates κ_{1B} and κ_{B2} during wireless energy transfer.

6. The method of claim 1, wherein the resonator structures each have a quality factor larger than 10.

7. The method of any of the preceding claims, wherein resonant energy in each of the resonator structures comprises electromagnetic fields.

8. The method of claim 7, wherein the maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} for inductive coupling between the intermediate resonator structure and each of the first and second resonator structures are each larger than twice the loss rate Γ for each of the first and second resonators.

9. The method of claim 8, wherein the maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} for inductive coupling between the intermediate resonator structure and each of the first and second resonator structures are each larger than four (4) times the loss rate Γ for each of the first and second resonators.

10. The method of claim 7, wherein each resonator structure has a resonant frequency between 50 KHz and 500 MHz.

11. The method of any of the preceding claims, wherein the maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} are each at least five (5) times greater than the coupling rate between the first resonator structure and the second resonator structure.

12. The method of any of the preceding claims, wherein the intermediate resonator structure has a rate of radiative energy loss that is at least twenty (20) times greater than that for either the first resonator structure or the second resonator structure.

13. The method of claim 1, wherein the first and second resonator structures are substantially identical.

14. The method of any of the preceding claims, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} causes peak energy accumulation in the intermediate resonator structure to be less than five percent (5%) of the peak total energy in the three resonator structures.

15. The method of any of the preceding claims, wherein adjusting at least one of the coupling rates κ_{1B} and κ_{B2} comprises adjusting a relative position and/or orientation between one or more pairs of the resonator structures.

16. The method of any of the preceding claims, wherein adjusting at least one of the coupling rates κ_{1B} and κ_{B2} comprises adjusting a resonator property of one or more of the resonator structures.

17. The method of claim 16, wherein the resonator property comprises mutual inductance.

18. The method of any of the preceding claims, wherein at least one of the resonator structures comprises a capacitively loaded loop or coil of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

19. The method of any of the preceding claims, wherein at least one of the resonator structures comprises an inductively loaded rod of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

20. An apparatus comprising:
first, intermediate, and second resonator structures, wherein a coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B} and a coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2}; and
means for adjusting at least one of the coupling rates κ_{1B} and κ_{B2} during wireless energy transfers among the resonator structures to reduce energy accumulation in the intermediate resonator structure and improve wireless energy transfer from the first resonator structure to the second resonator structure through the intermediate resonator structure.

21. The apparatus of claim 20, wherein the means for adjusting comprises a rotation stage for adjusting the relative orientation of the intermediate resonator structure with respect to the first and second resonator structures.

22. The apparatus of claim 20, wherein the means for adjusting comprises a translation stage for moving the first and/or second resonator structures relative to the intermediate resonator structure.

23. The apparatus of claim 20, wherein the means for adjusting comprises a mechanical, electro-mechanical, or electrical staging system for dynamically adjusting the effective size of one or more of the resonator structures.

24. The method of claim 4, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} causes peak energy accumulation in the intermediate resonator

structure during the wireless energy transfers to be less than ten percent (10%) of the peak total energy in the three resonator structures.

25. The method of any of claims 1-19 and 24, wherein the wireless energy transfers are non-radiative energy transfers mediated by a coupling of a resonant field evanescent tail of the first resonator structure and a resonant field evanescent tail of the intermediate resonator structure and a coupling of the resonant field evanescent tail of the intermediate resonator structure and a resonant field evanescent tail of the second resonator structure.

26. The method of claim 25, wherein the first and second resonator structures each have a quality factor greater than 50.

27. The method of claim 25, wherein the first and second resonator structures each have a quality factor greater than 100.

28. A method for transferring energy wirelessly, the method comprising:
transferring energy wirelessly from a first resonator structure to a intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B};
transferring energy wirelessly from the intermediate resonator structure to a second resonator, wherein the coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2}; and
during the wireless energy transfers, adjusting at least one of the coupling rates κ_{1B} and κ_{B2} to cause an energy distribution in the field of the three-resonator system to have substantially no energy in the intermediate resonator structure while wirelessly transferring energy from the first resonator structure to the second resonator structure through the intermediate resonator structure.

29. The method of claim 28, wherein having substantially no energy in the intermediate resonator structure means that peak energy accumulation in the intermediate resonator structure is less than ten percent (10%) of the peak total energy in the three resonator structures throughout the wireless energy transfer.

30. The method of claim 28, wherein having substantially no energy in the intermediate resonator structure means that peak energy accumulation in the intermediate resonator structure is less than five percent (5%) of the peak total energy in the three resonator structures throughout the wireless energy transfer.

31. The method of any of claims 28 to 30, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} maintains the energy distribution in the field of the three-resonator system in an eigenstate having the substantially no energy in the intermediate resonator structure.

32. The method of claim 31, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} further causes the eigenstate to evolve substantially adiabatically from an initial state with substantially all energy in the resonator structures in the first resonator structure to a final state with substantially all of the energy in the resonator structures in the second resonator structure.

33. The method of any of claims 28 to 32, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} comprises adjustments of both coupling rates κ_{1B} and κ_{B2} during wireless energy transfers.

34. The method of any of claims 28 to 33, wherein resonant energy in each of the resonator structures comprises electromagnetic fields.

35. The method of claim 34, wherein the maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} for inductive coupling between the intermediate resonator structure and each of the first and second resonator structures are each larger than twice the loss rate Γ for each of the first and second resonators.

36. The method of claim 34, wherein the maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} for inductive coupling between the intermediate resonator structure and each of the first and second resonator structures are each larger than four (4) times the loss rate Γ for each of the first and second resonators.

37. The method of any of claims 34 to 36, wherein each resonator structure has a resonant frequency between 50 KHz and 500 MHz.

38. The method of any of claims 28 to 37, wherein the maximum value of the coupling rate κ_{1B} and the maximum value of the coupling rate κ_{B2} are each at least five (5) times greater than the coupling rate between the first resonator structure and the second resonator structure.

39. The method of any of claims 28 to 38, wherein the intermediate resonator structure has a rate of radiative energy loss that is at least twenty (20) times greater than that for either the first resonator structure or the second resonator structure.

40. The method of any of claims 28 to 39, wherein the first and second resonator structures are substantially identical.

41. The method of any of claims 28 to 40, wherein adjusting at least one of the coupling rates κ_{1B} and κ_{B2} comprises adjusting a relative position and/or orientation between one or more pairs of the resonator structures.

42. The method of any of claims 28-41, wherein adjusting at least one of the coupling rates κ_{1B} and κ_{B2} comprises adjusting a resonator property of one or more of the resonator structures.

43. The method of claim 42, wherein the resonator property comprises mutual inductance.

44. The method of any of claims 28 to 43, wherein at least one of the resonator structures comprises a capacitively loaded loop or coil of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

45. The method of any of claims 28 to 44, wherein at least one of the resonator structures comprises an inductively loaded rod of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

46. The method of any of claims 28 to 45, wherein the wireless energy transfers are non-radiative energy transfers mediated by a coupling of a resonant field evanescent tail of the first resonator structure and a resonant field evanescent tail of the intermediate resonator structure and a coupling of the resonant field evanescent tail of the intermediate resonator structure and a resonant field evanescent tail of the second resonator structure.

47. The method of claim 46, wherein the first and second resonator structures each have a quality factor greater than 50.

48. The method of claim 47, wherein the first and second resonator structures each have a quality factor greater than 100.

49. The method of any of claims 28 to 48, wherein the adjustment of at least one of the coupling rates κ_{1B} and κ_{B2} to cause the energy distribution in the field of the three-

resonator system to have substantially no energy in the intermediate resonator structure improves wireless energy transfer between the first and second resonator structures.

50. An apparatus comprising:

first, intermediate, and second resonator structures, wherein a coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B} and a coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2}; and

means for adjusting at least one of the coupling rates κ_{1B} and κ_{B2} during wireless energy transfers among the resonator structures to cause an energy distribution in the field of the three-resonator system to have substantially no energy in the intermediate resonator structure while wirelessly transferring energy from the first resonator structure to the second resonator structure through the intermediate resonator structure.

51. The apparatus of claim 50, wherein having substantially no energy in the intermediate resonator structure means that peak energy accumulation in the intermediate resonator structure is less than ten percent (10%) of the peak total energy in the three resonator structures throughout the wireless energy transfers.

52. The apparatus of claim 50, wherein having substantially no energy in the intermediate resonator structure means that peak energy accumulation in the intermediate resonator structure is less than five percent (5%) of the peak total energy in the three resonator structures throughout the wireless energy transfers.

53. The apparatus of any of claims 50 to 52, wherein the means for adjusting is configured to maintain the energy distribution in the field of the three-resonator system in an eigenstate having the substantially no energy in the intermediate resonator structure.

54. The apparatus of any of claims claim 50 to 53, wherein the means for adjusting comprises a rotation stage for adjusting the relative orientation of the intermediate resonator structure with respect to the first and second resonator structures.

55. The apparatus of any of claims 50 to 54, wherein the means for adjusting comprises a translation stage for moving the first and/or second resonator structures relative to the intermediate resonator structure.

56. The apparatus of any of claims 50 to 55, wherein the means for adjusting comprises a mechanical, electro-mechanical, or electrical staging system for dynamically adjusting the effective size of one or more of the resonator structures.

57. The apparatus of any of claims 50 to 56, wherein at least one of the resonator structures comprises a capacitively loaded loop or coil of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

58. The apparatus of any of claims 50 to 57, wherein at least one of the resonator structures comprises an inductively loaded rod of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon.

59. The apparatus of any of claims 50 to 58, further comprising a source coupled to the first resonator structure and a load coupled to the second resonator structure.

60. The method of any of claims 1-19 and 24-27, wherein the adjustment of the at least one of the coupling rates defines a first mode of operation,
wherein the reduction in the energy accumulation in the intermediate resonator structure is relative to energy accumulation in the intermediate resonator structure for a second mode of operation of wireless energy transfer among the three resonator structures having a coupling rate κ'_{1B} for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate κ'_{B2} for wireless energy transfer

from the intermediate resonator structure to the second resonator structure with κ'_{1B} and κ'_{B2} each being substantially constant during the second mode of wireless energy transfer, and
wherein the adjustment of the coupling rates κ_{1B} and κ_{2B} in the first mode of operation satisfies $\kappa_{1B}, \kappa_{B2} < \sqrt{\left(\kappa'^{2}_{1B} + \kappa'^{2}_{B2}\right)/2}$.

61. The method of claim 60, wherein the first mode of operation has a greater efficiency of energy transferred from the first resonator to the second resonator compared to that for the second mode of operation.

62. The method of claim 61, wherein the first and second resonator structures are substantially identical and each one has a loss rate Γ_A, the intermediate resonator structure has a loss rate Γ_B, and wherein Γ_B / Γ_A is greater than 50.

63. The method of claim 60, wherein a ratio of energy lost to radiation and total energy wirelessly transferred between the first and second resonator structures in the first mode of operation is less than that for the second mode of operation.

64. The method of claim 63, wherein the first and second resonator structures are substantially identical and each one has a loss rate Γ_A and a loss rate only due to radiation $\Gamma_{A,rad}$, the intermediate resonator structure has a loss rate Γ_B and a loss rate only due to radiation $\Gamma_{B,rad}$ and wherein $\Gamma_{B,rad} / \Gamma_B > \Gamma_{A,rad} / \Gamma_A$.

65. The method of claim 60, wherein in the first mode of operation the intermediate resonator structure interacts less with extraneous objects than it does in the second mode of operation.

66. The method of any of claims 1-19, 24-27, and 60-65, wherein during the wireless energy transfer from the first resonator structure to the second resonator structure at least one of the coupling rates is adjusted so that $\kappa_{1B} << \kappa_{B2}$ at a start of the energy transfer and $\kappa_{1B} >> \kappa_{B2}$ by a time a substantial portion of the energy has been transferred from the first resonator structure to the second resonator structure.

67. The method of claim 66, wherein the coupling rate κ_{B2} is maintained at a fixed value and the coupling rate κ_{1B} is increased during the wireless energy transfer from the first resonator structure to second resonator structure.

68. The method of claim 66, wherein the coupling rate κ_{1B} is maintained at a fixed value and the coupling rate κ_{B2} is decreased during the wireless energy transfer from the first resonator structure to second resonator structure.

69. The method of claim 66, wherein, during the wireless energy transfer from the first resonator structure to second resonator structure, the coupling rate κ_{1B} is increased and the coupling rate κ_{B2} is decreased.

70. The method of any of claims 28-49, wherein the adjustment of the at least one of the coupling rates defines a first mode of operation,
wherein energy accumulation in the intermediate resonator structure during the wireless energy transfer from the first resonator structure to second resonator structure is smaller than that for a second mode of operation of wireless energy transfer among the three resonator structures having a coupling rate κ'_{1B} for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate κ'_{B2} for wireless energy transfer from the intermediate resonator structure to the second resonator structure with κ'_{1B} and κ'_{B2} each being substantially constant during the second mode of wireless energy transfer, and

wherein the adjustment of the coupling rates κ_{1B} and κ_{B2} in the first mode of operation satisfies $\kappa_{1B}, \kappa_{B2} < \sqrt{\left(\kappa'^{2}_{1B} + \kappa'^{2}_{B2}\right)/2}$.

71. The method of claim 70, wherein the first mode of operation has a greater efficiency of energy transferred from the first resonator to the second resonator compared to that for the second mode of operation.

72. The method of claim 71, wherein the first and second resonator structures are substantially identical and each one has a loss rate Γ_A, the intermediate resonator structure has a loss rate Γ_B, and wherein Γ_B/Γ_A is greater than 50.

73. The method of claim 70, wherein a ratio of energy lost to radiation and total energy wirelessly transferred between the first and second resonator structures in the first mode of operation is less than that for the second mode of operation.

74. The method of claim 73, wherein the first and second resonator structures are substantially identical and each one has a loss rate Γ_A and a loss rate only due to radiation $\Gamma_{A,rad}$, the intermediate resonator structure has a loss rate Γ_B and a loss rate only due to radiation $\Gamma_{B,rad}$ and wherein $\Gamma_{B,rad}/\Gamma_B > \Gamma_{A,rad}/\Gamma_A$.

75. The method of claim 70, wherein in the first mode of operation the intermediate resonator structure interacts less with extraneous objects than it does in the second mode of operation.

76. The method of any of claims 28-49 and 70-75, wherein during the wireless energy transfer from the first resonator structure to the second resonator structure at least one of the coupling rates is adjusted so that $\kappa_{1B} << \kappa_{B2}$ at a start of the energy transfer and

$\kappa_{1B} >> \kappa_{B2}$ by a time a substantial portion of the energy has been transferred from the first resonator structure to the second resonator structure.

77. The method of claim 76, wherein the coupling rate κ_{B2} is maintained at a fixed value and the coupling rate κ_{1B} is increased during the wireless energy transfer from the first resonator structure to second resonator structure.

78. The method of claim 76, wherein the coupling rate κ_{1B} is maintained at a fixed value and the coupling rate κ_{B2} is decreased during the wireless energy transfer from the first resonator structure to second resonator structure.

79. The method of claim 76, wherein, during the wireless energy transfer from the first resonator structure to second resonator structure, the coupling rate κ_{1B} is increased and the coupling rate κ_{B2} is decreased.

80. A method for transferring energy wirelessly, the method comprising:
transferring energy wirelessly from a first resonator structure to a intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B};
transferring energy wirelessly from the intermediate resonator structure to a second resonator, wherein the coupling rate between the intermediate resonator structure and the second resonator structure with a coupling rate is κ_{B2}; and
during the wireless energy transfers, adjusting at least one of the coupling rates κ_{1B} and κ_{B2} to define a first mode of operation in which energy accumulation in the intermediate resonator structure is reduced relative to that for a second mode of operation of wireless energy transfer among the three resonator structures having a coupling rate κ'_{1B} for wireless energy transfer from the first resonator structure to the intermediate resonator

structure and a coupling rate κ'_{B2} for wireless energy transfer from the intermediate resonator structure to the second resonator structure with κ'_{1B} and κ'_{B2} each being substantially constant during the second mode of wireless energy transfer, and
wherein the adjustment of the coupling rates κ_{1B} and κ_{B2} in the first mode of operation satisfies $\kappa_{1B}, \kappa_{B2} < \sqrt{\left(\kappa'^{2}_{1B} + \kappa'^{2}_{B2}\right)/2}$.

81. An apparatus comprising:
first, intermediate, and second resonator structures, wherein a coupling rate between the first resonator structure and the intermediate resonator structure is κ_{1B} and a coupling rate between the intermediate resonator structure and the second resonator structure is κ_{B2}; and
means for adjusting at least one of the coupling rates κ_{1B} and κ_{B2} during wireless energy transfers among the resonator structures to define a first mode of operation in which energy accumulation in the intermediate resonator structure is reduced relative to that for a second mode of operation for wireless energy transfer among the three resonator structures having a coupling rate κ'_{1B} for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate κ'_{B2} for wireless energy transfer from the intermediate resonator structure to the second resonator structure with κ'_{1B} and κ'_{B2} each being substantially constant during the second mode of wireless energy transfer, and
wherein the adjustment of the coupling rates κ_{12} and κ_{B2} in the first mode of operation satisfies $\kappa_{1B}, \kappa_{B2} < \sqrt{\left(\kappa'^{2}_{1B} + \kappa'^{2}_{B2}\right)/2}$.

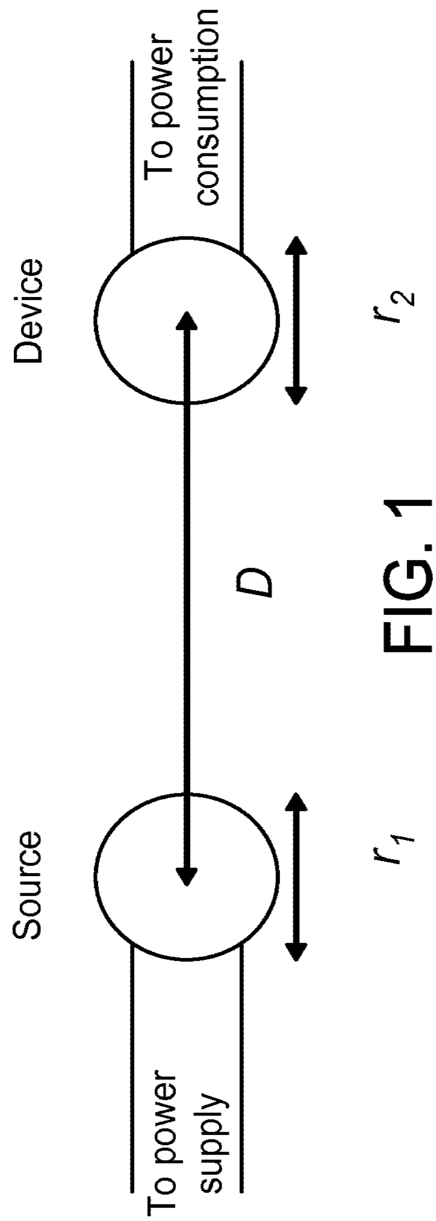


FIG. 1

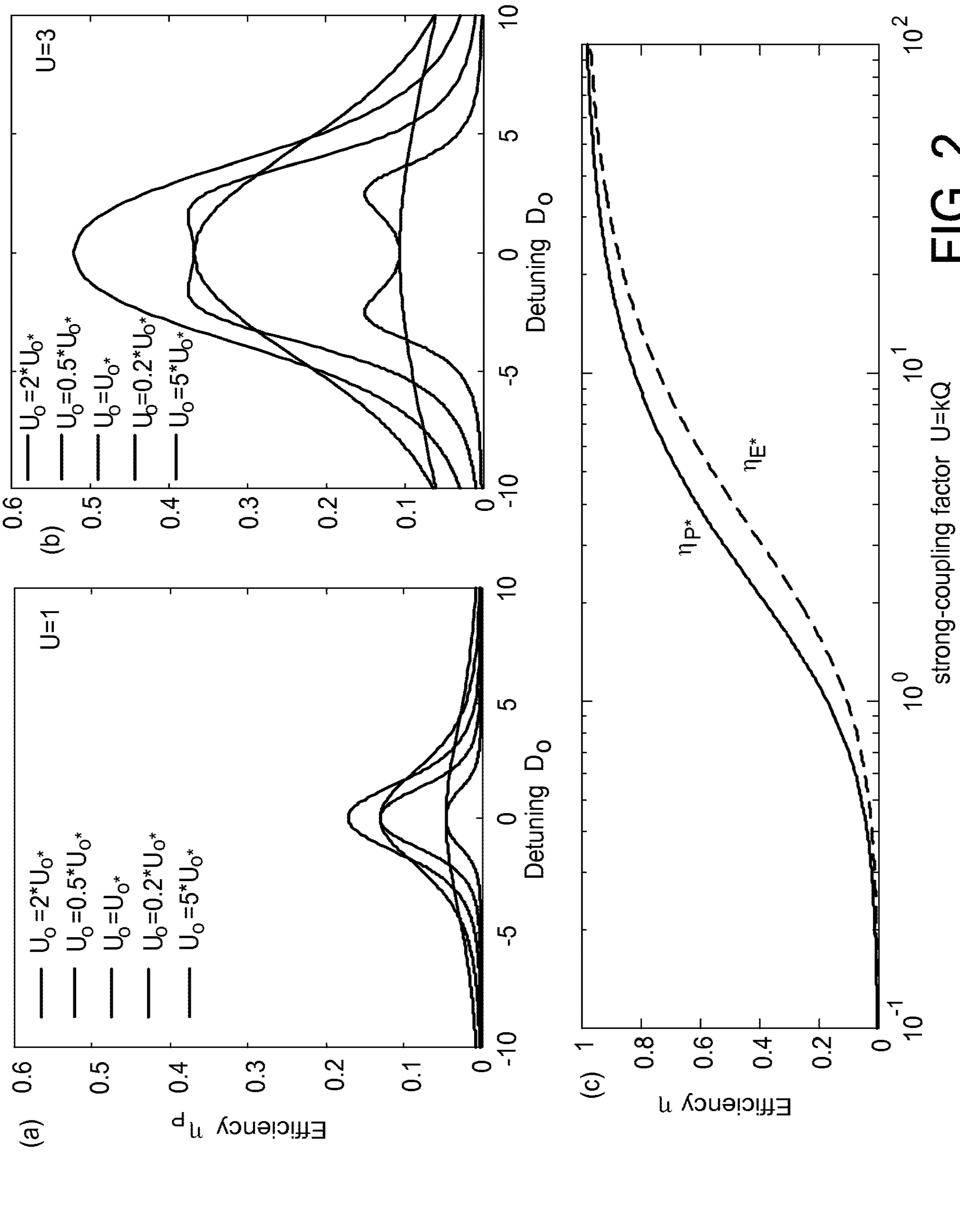

(a)
U=1
Efficiency η_P
Detuning D_o
$U_o=2*U_o*$
$U_o=0.5*U_o*$
$U_o=U_o*$
$U_o=0.2*U_o*$
$U_o=5*U_o*$
(b)
U=3
Detuning D_o
(c)
Efficiency η
strong-coupling factor U=kQ
η_{P*}
η_{E*}

FIG. 2

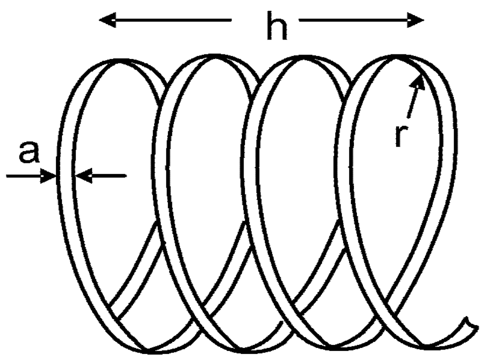


FIG. 3

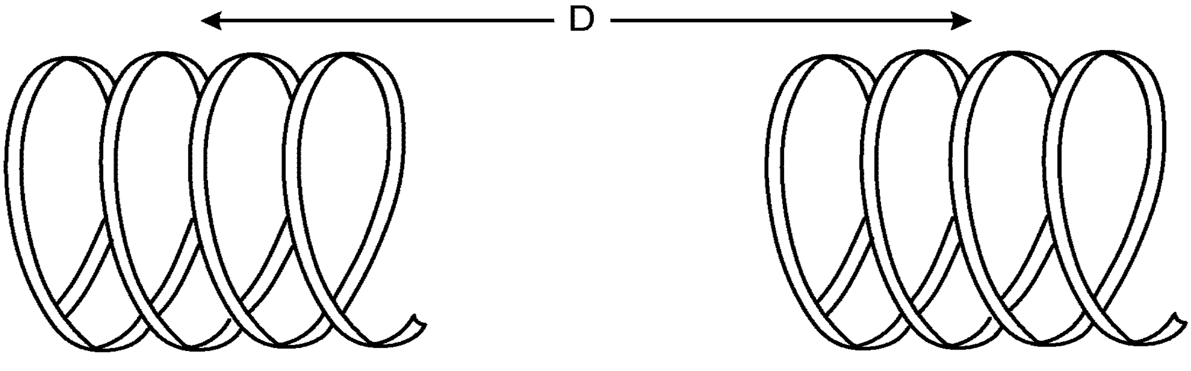


FIG. 4

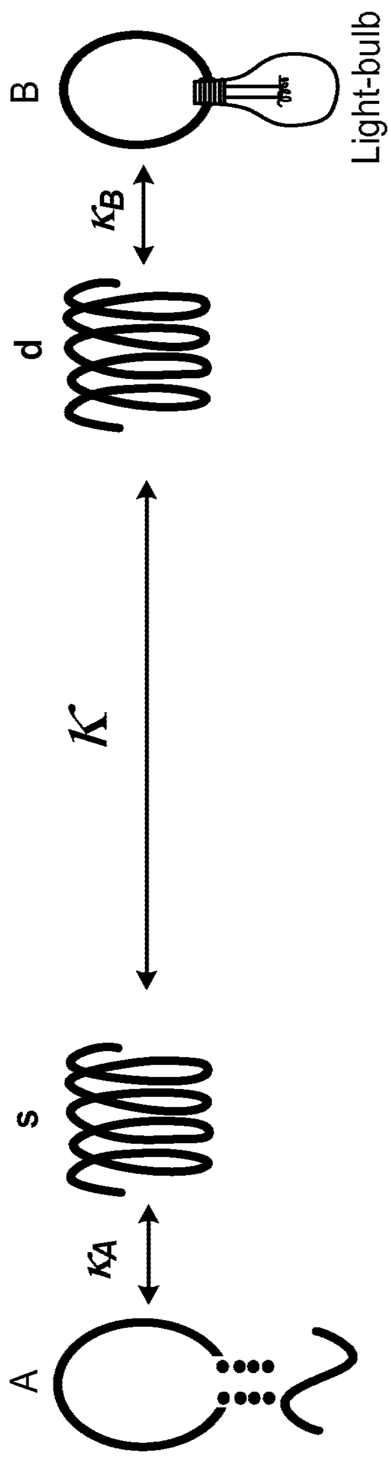
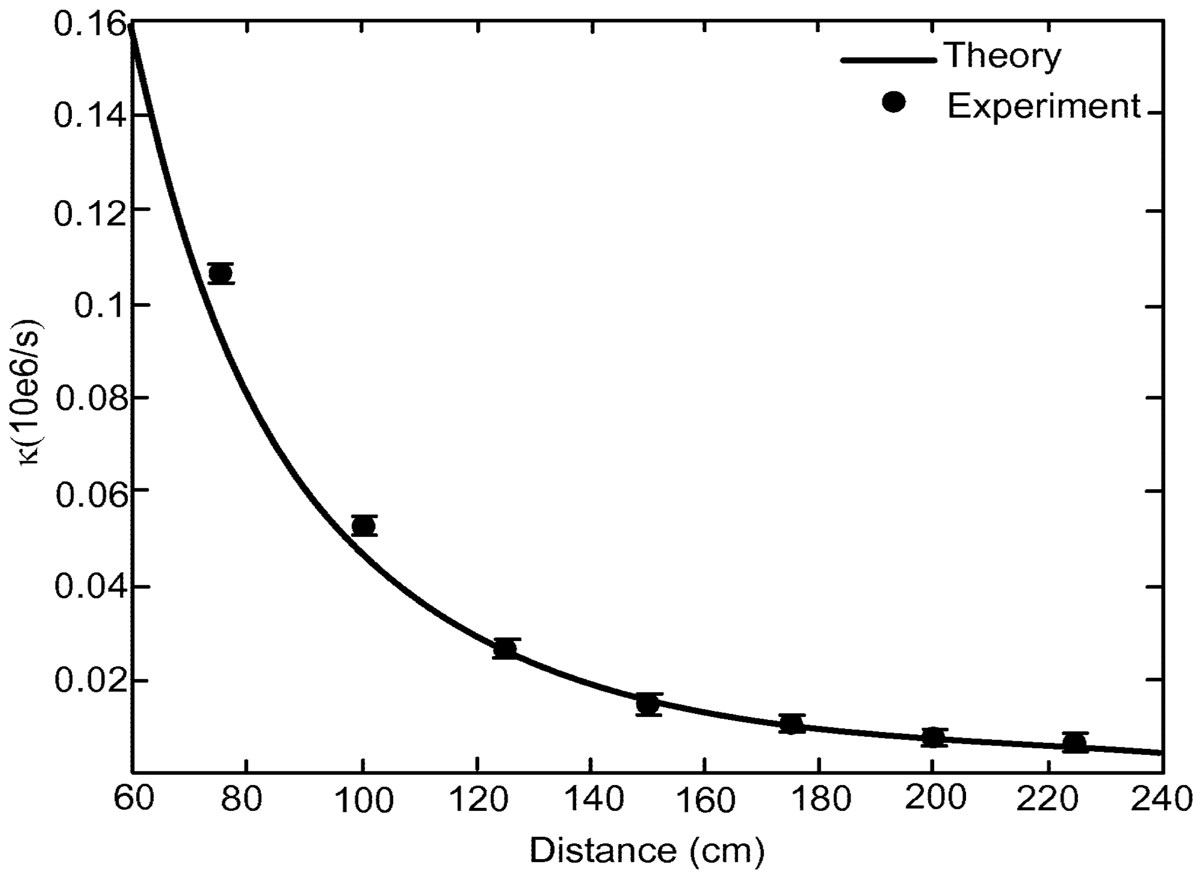
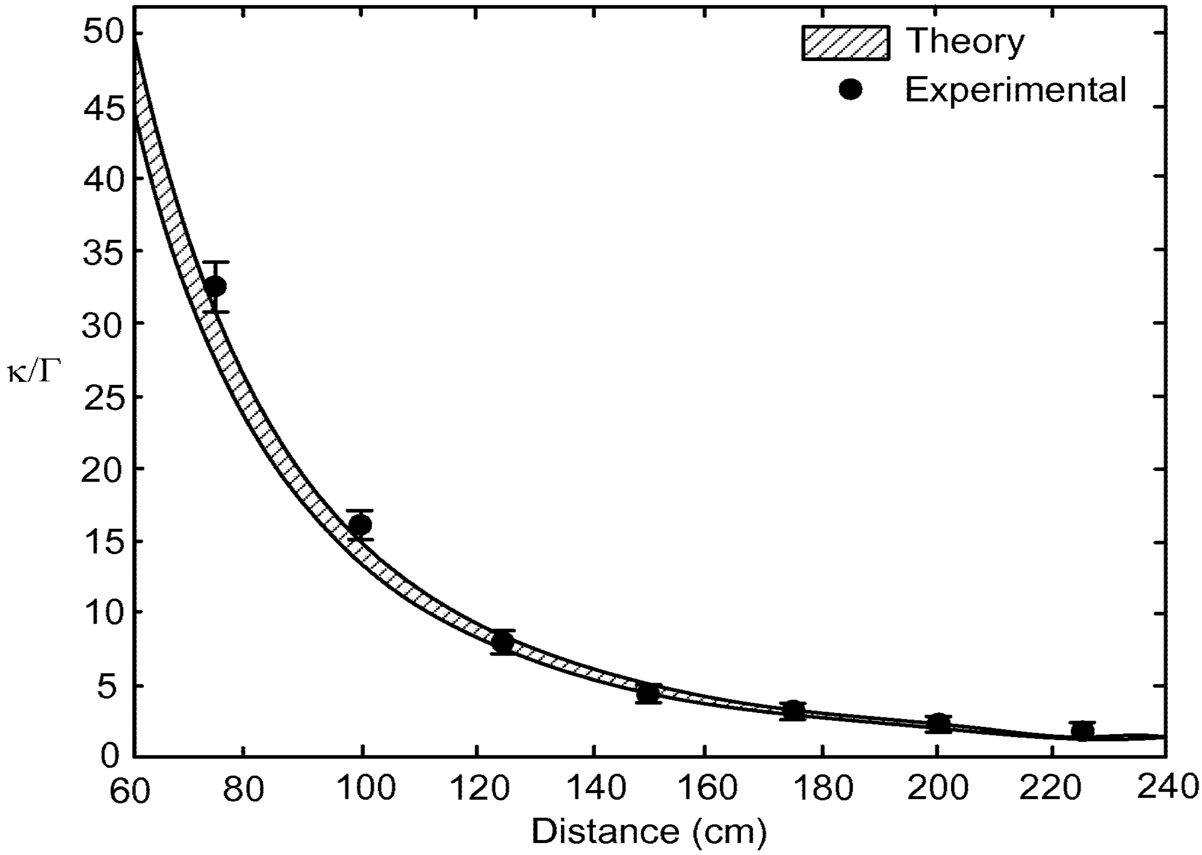


FIG. 5



Comparison of experimental and theoretical values for κ as a function of the separation between the source and device coils.

FIG. 6



Comparison of experimental and theoretical values for the parameter κ/Γ as a function of the separation between the two coils. The theory values are obtained by using the theoretically obtained κ and the experimentally measured Γ. The shaded area represents the spread in the theoretical κ/Γ due to the ~5% uncertainty in *Q*.

FIG.7

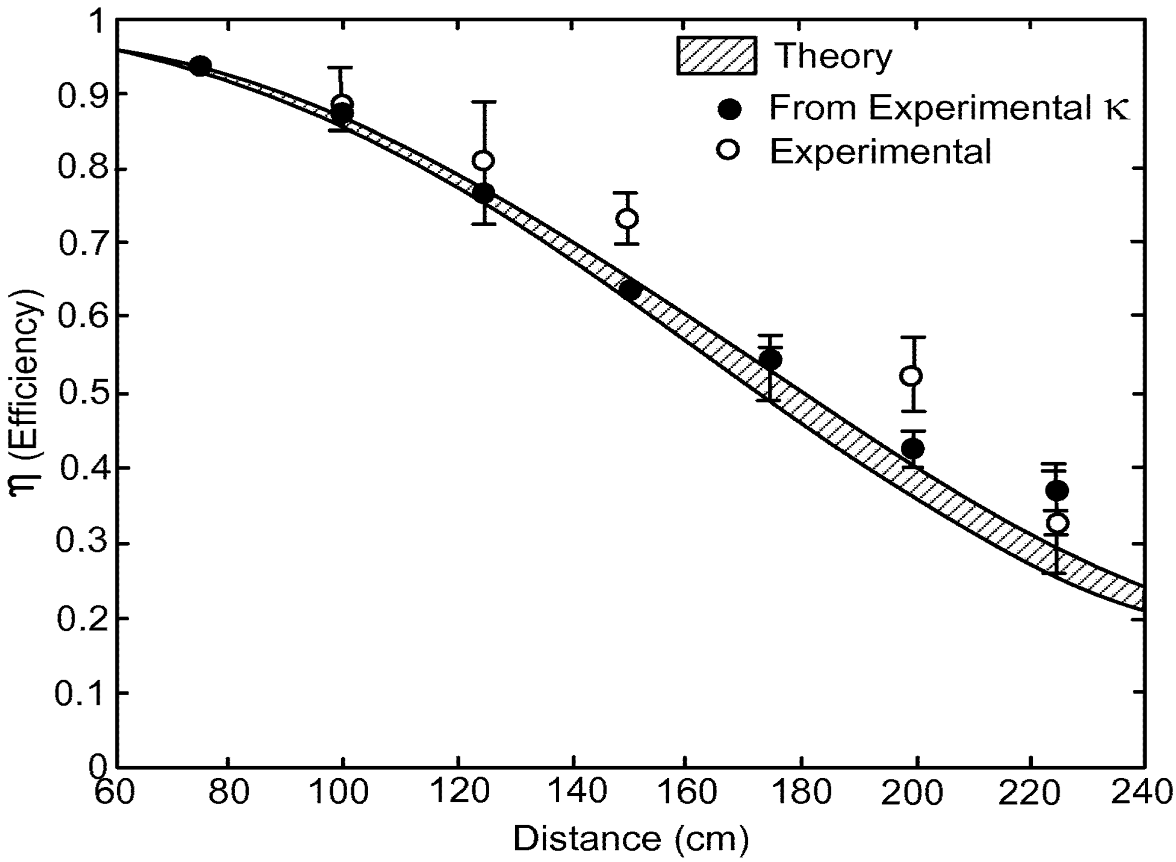

Theory
From Experimental κ
Experimental
η (Efficiency)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
60
80
100
120
140
160
180
200
220
240
Distance (cm)

FIG. 8

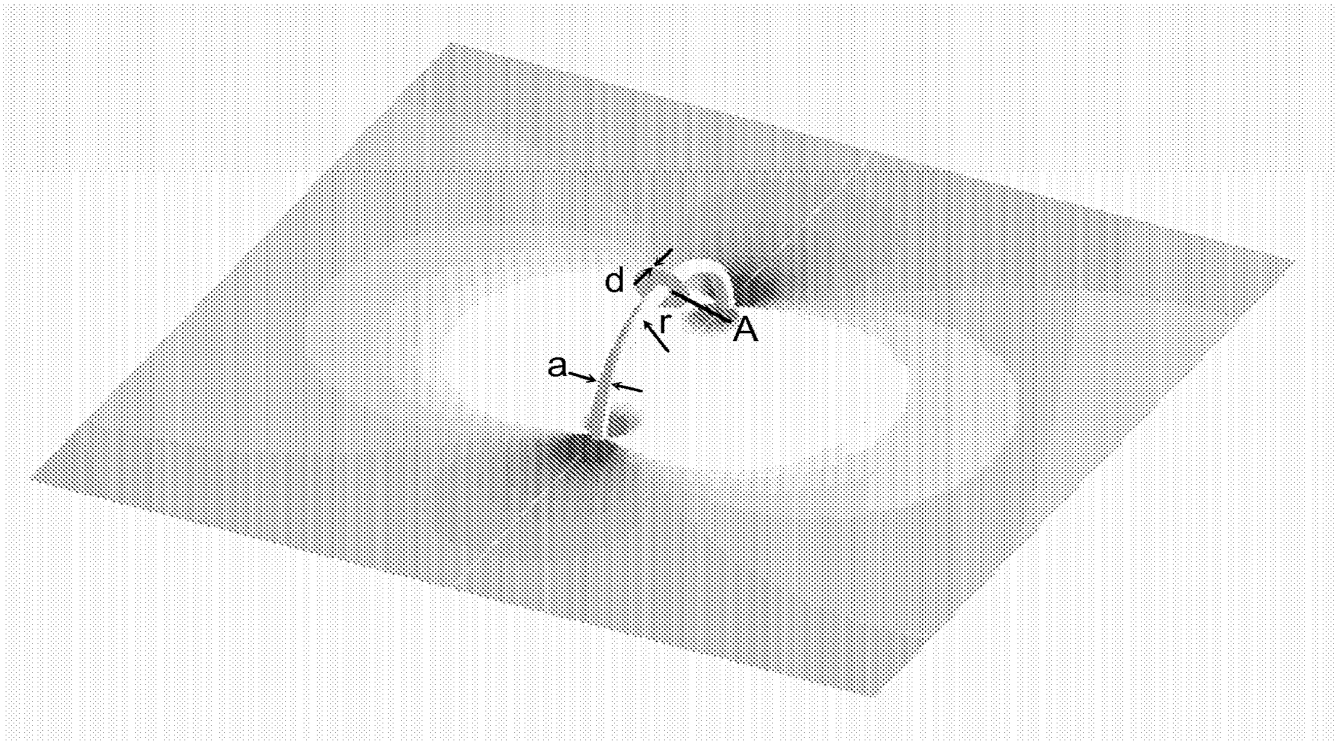


FIG. 9

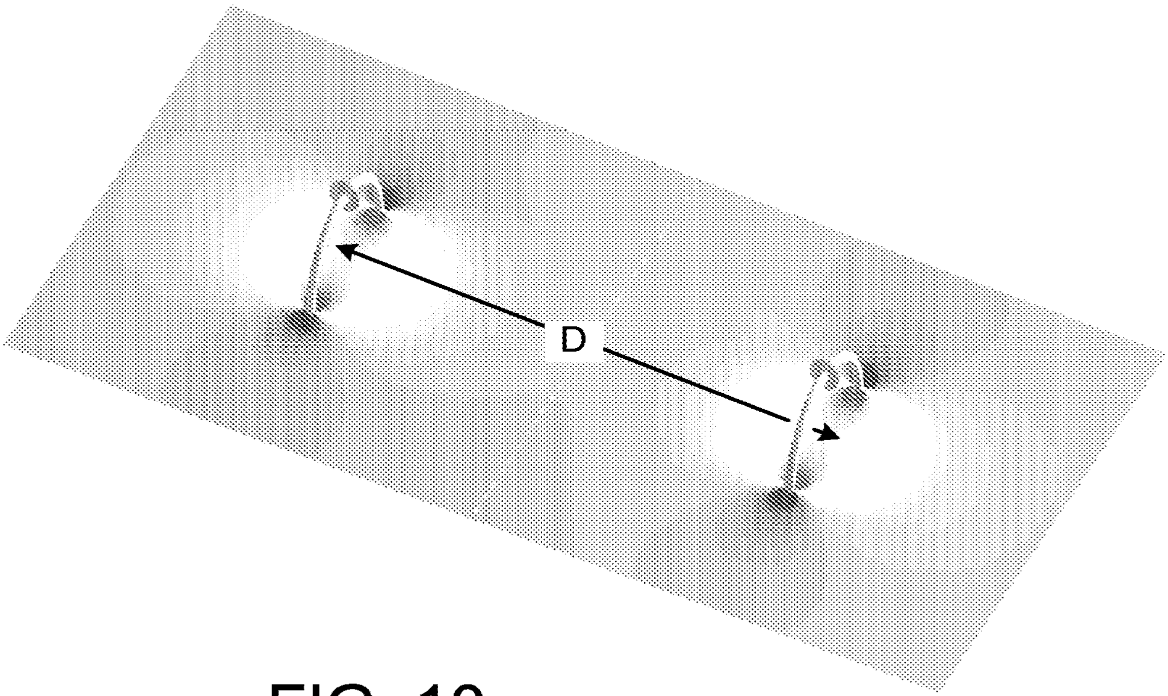


FIG. 10

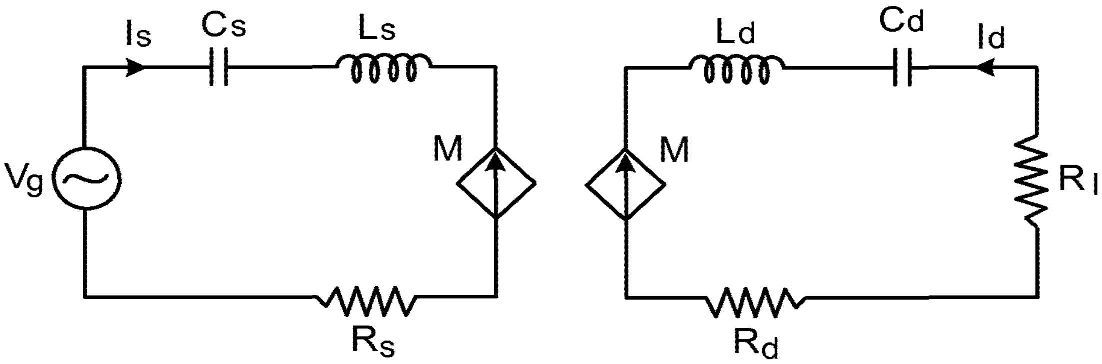


FIG. 11

r_s=25cm, r_d=15cm, a_s=a_d=3mm, D=2m   wp=1, N_s=2

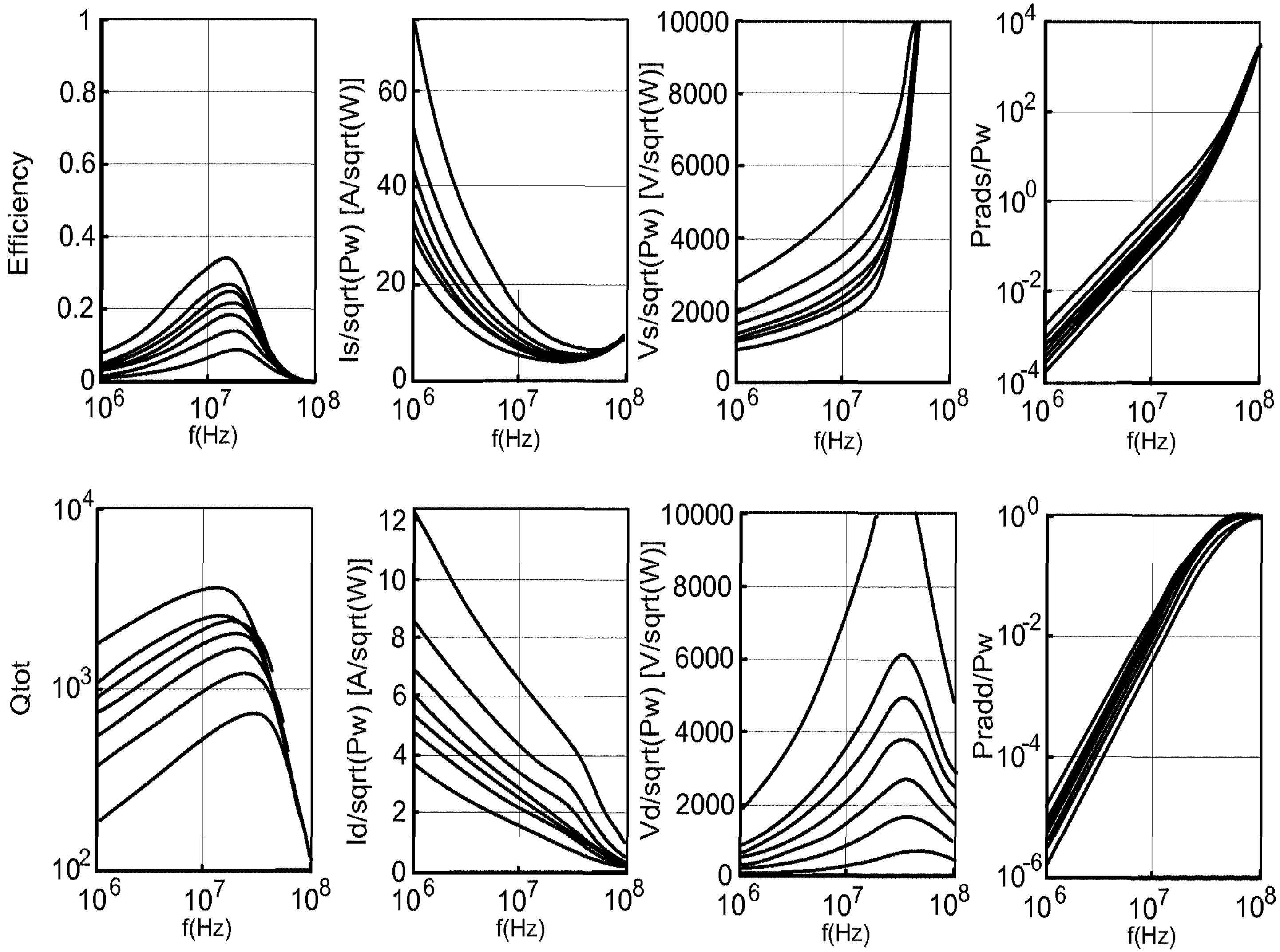
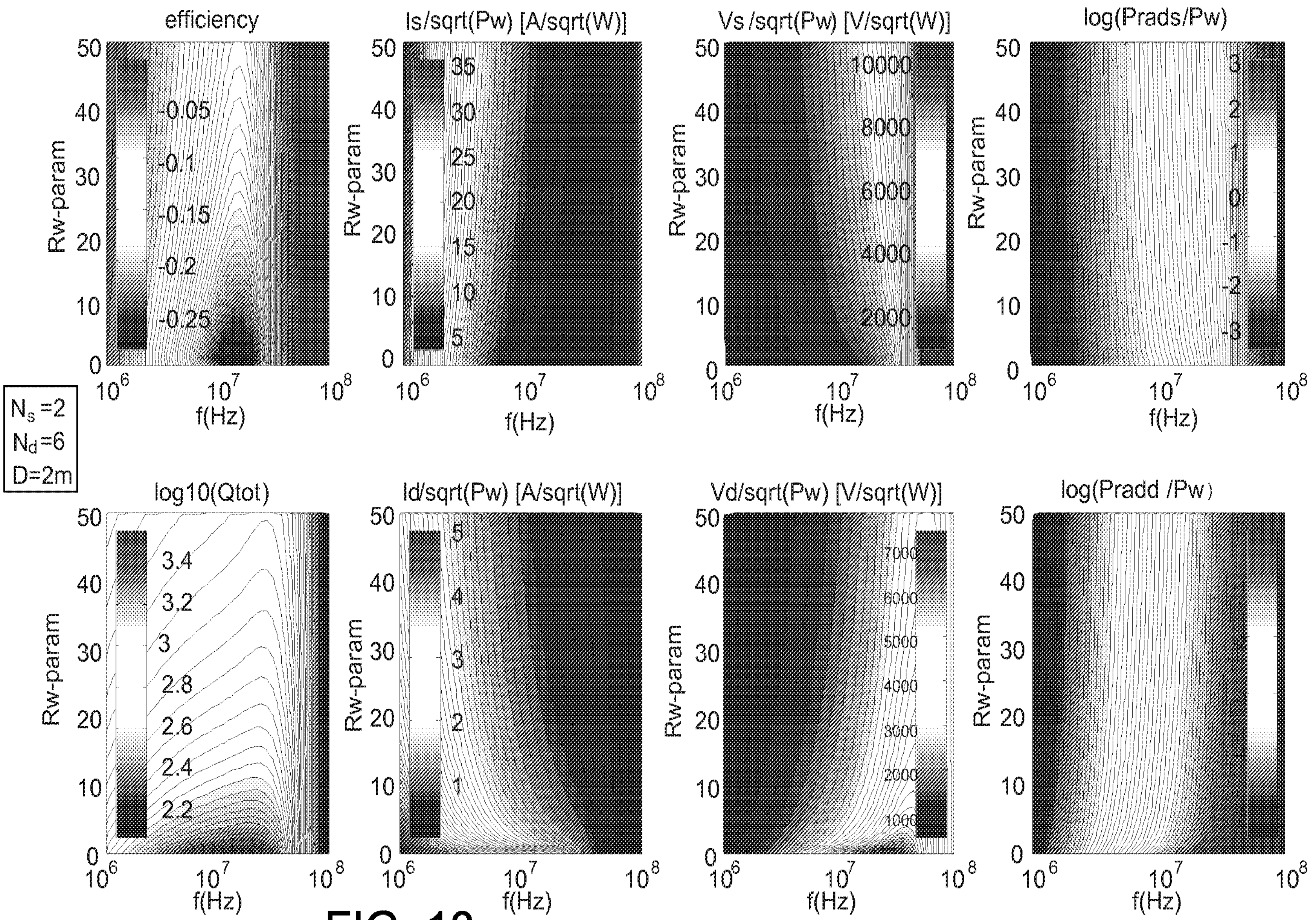


FIG. 12



efficiency
Is/sqrt(Pw) [A/sqrt(W)]
Vs /sqrt(Pw) [V/sqrt(W)]
log(Prads/Pw)
log10(Qtot)
Id/sqrt(Pw) [A/sqrt(W)]
Vd/sqrt(Pw) [V/sqrt(W)]
log(Pradd /Pw)
Rw-param
f(Hz)
N_s =2
N_d =6
D=2m

FIG. 13

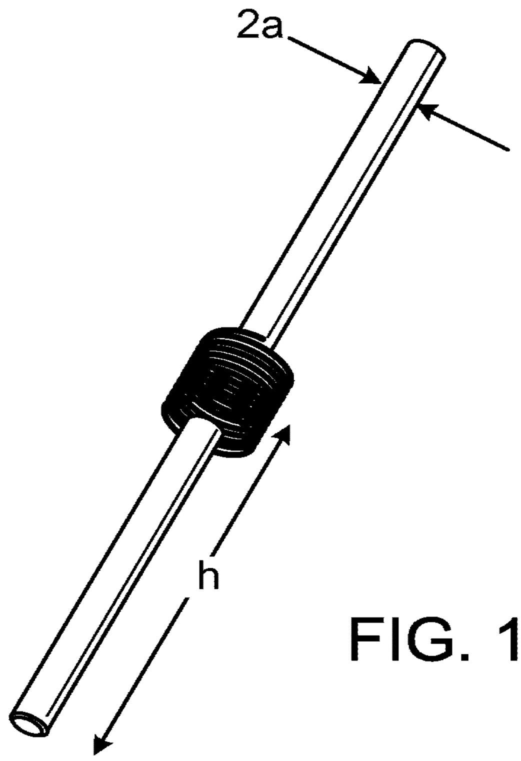
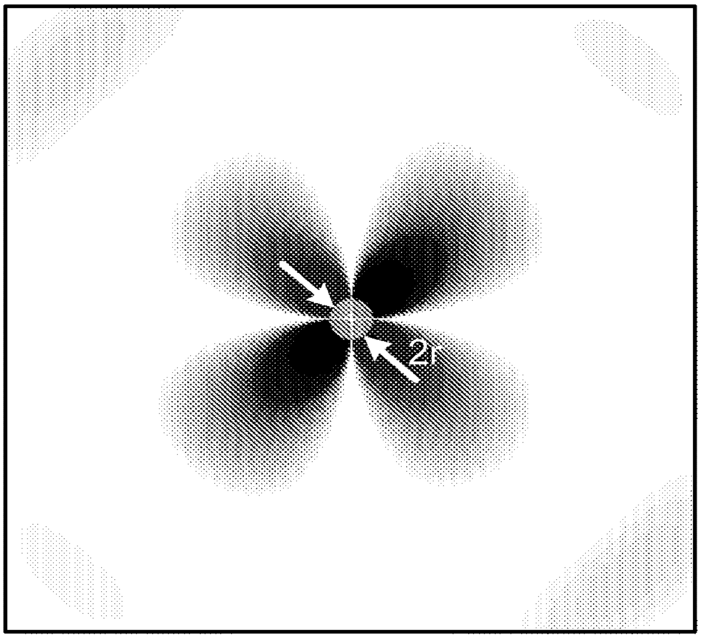


FIG. 14

(a)



(b)

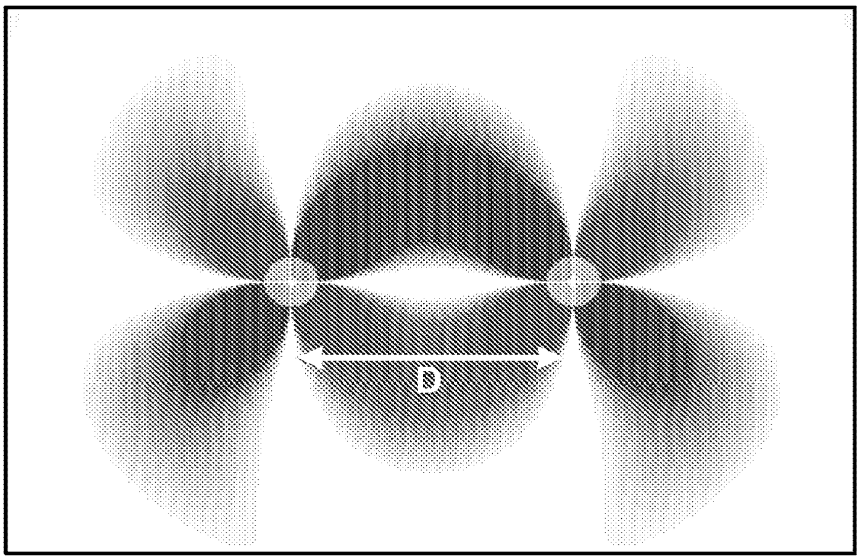


FIG. 15

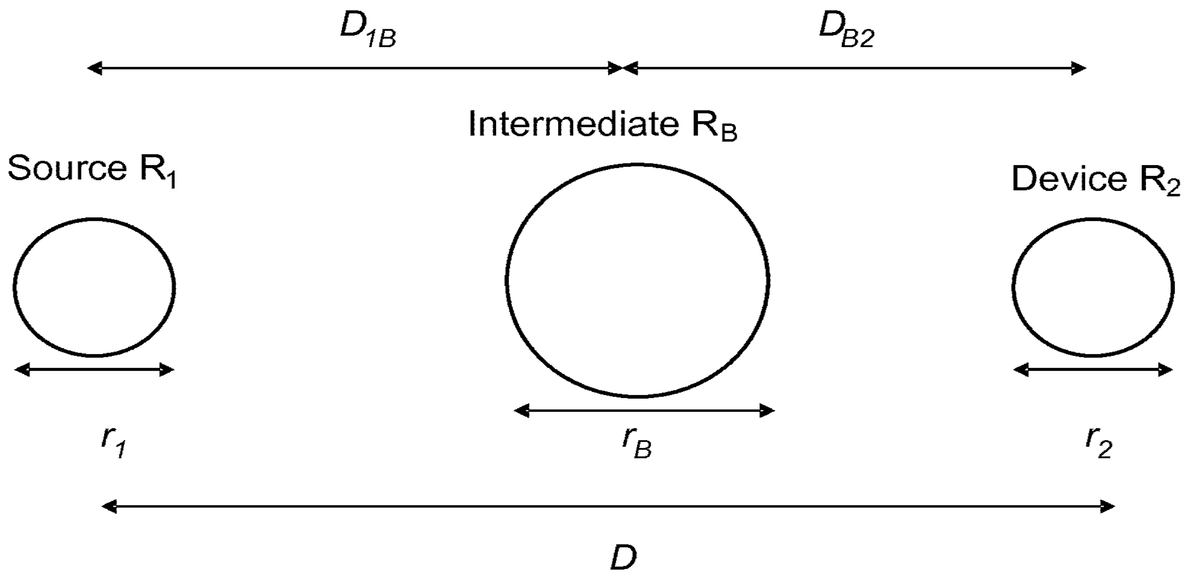
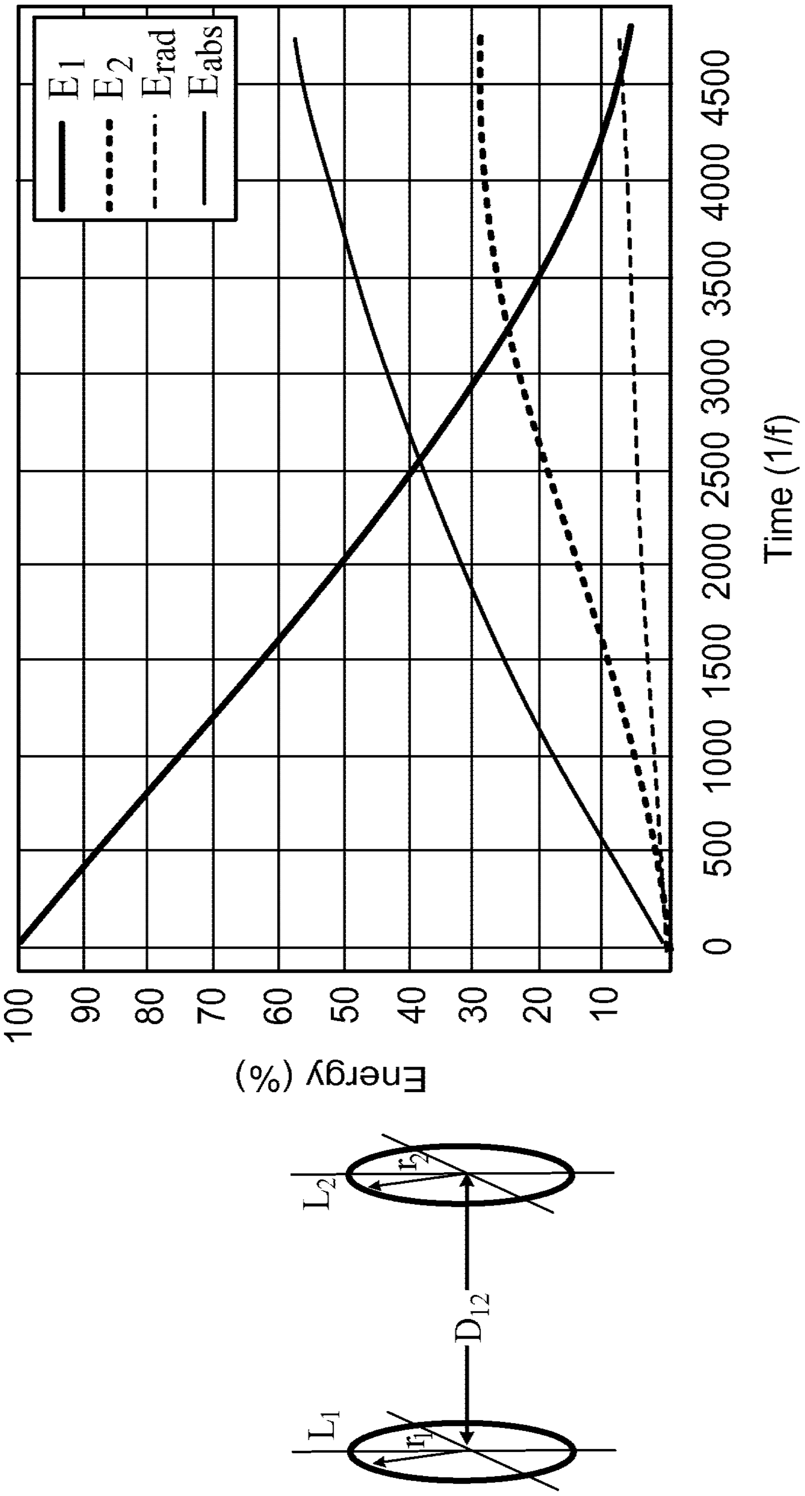


FIG. 16



E_1
E_2
E_{rad}
E_{abs}
Energy (%)
100
90
80
70
60
50
40
30
20
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Time (1/f)
L_1
r_1
D_{12}
L_2
r_2

FIG. 17A

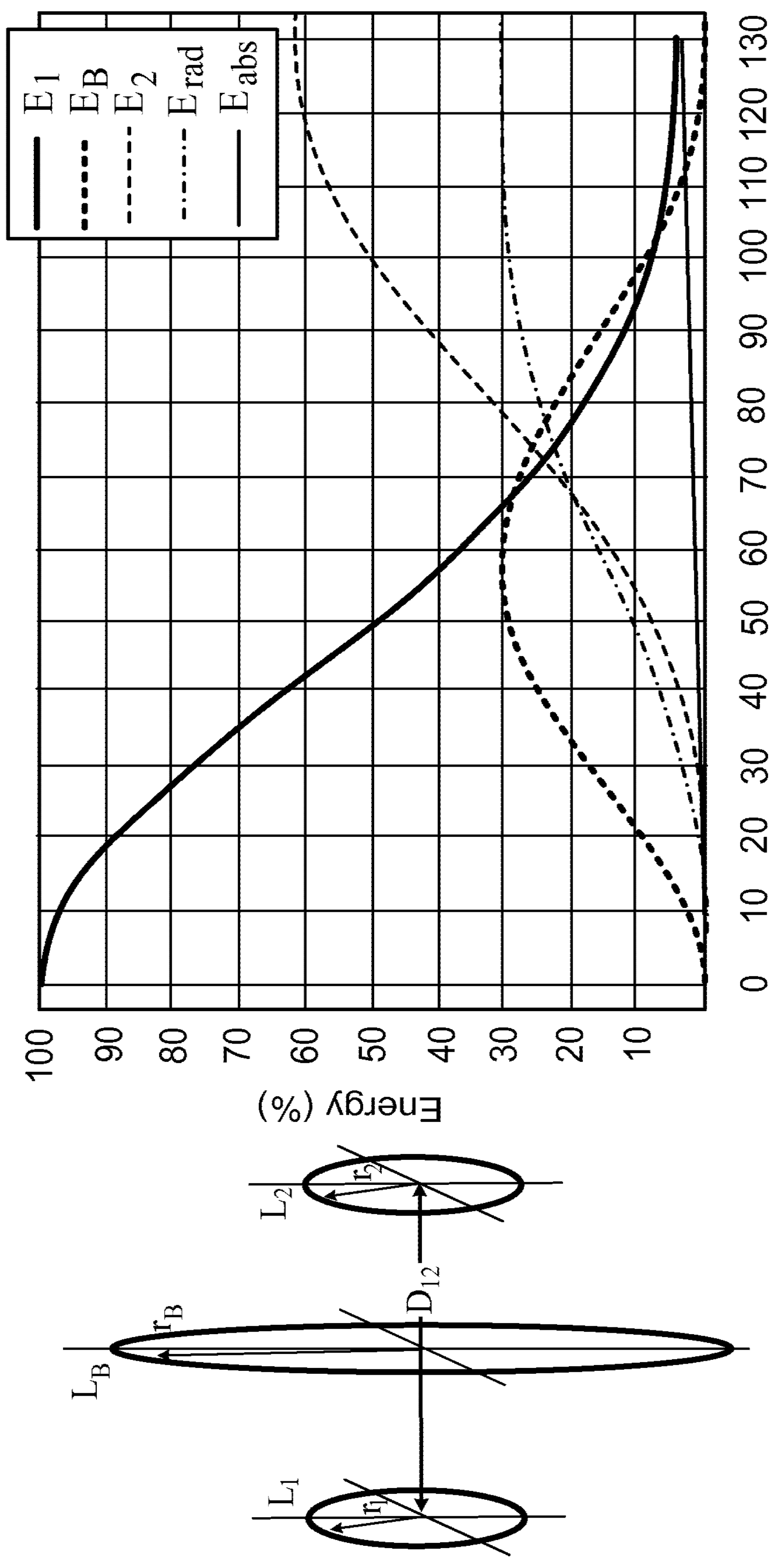

E1
EB
E2
Erad
Eabs
Energy (%)
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Time (1/f)
L1
r1
LB
rB
D12
L2
r2

FIG. 17B

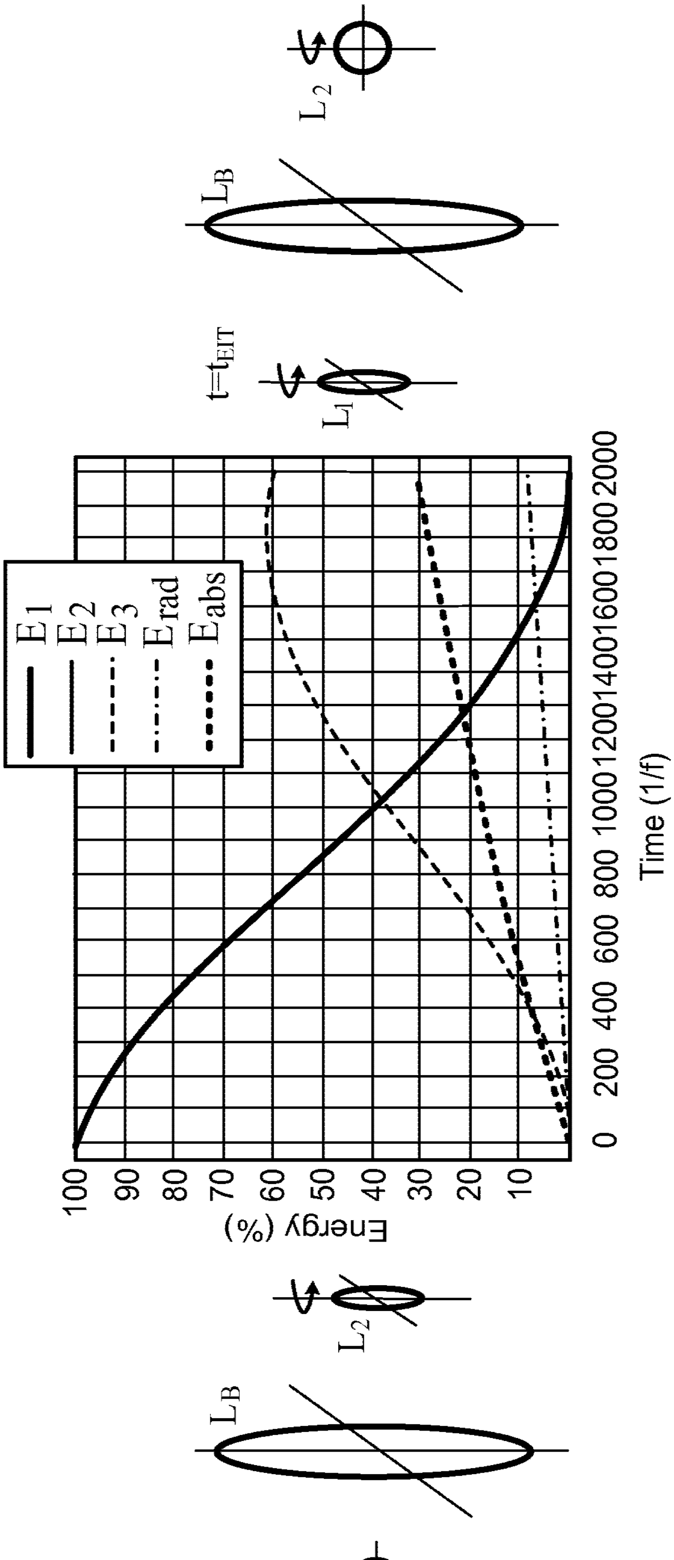

t=0
L1
LB
L2
Energy (%)
100
90
80
70
60
50
40
30
20
10
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (1/f)
E1
E2
E3
Erad
Eabs
t=tEIT
L1
LB
L2

FIG. 17C

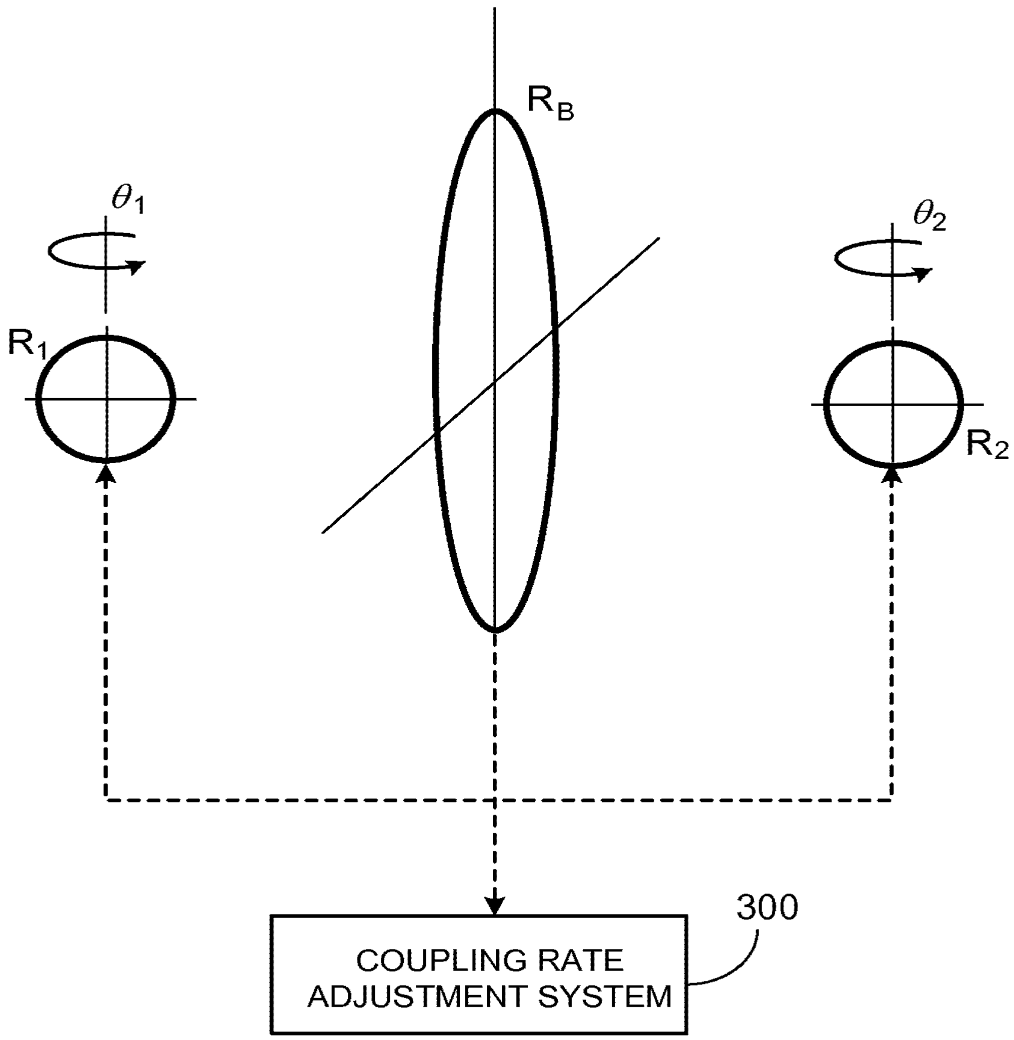


FIG. 18

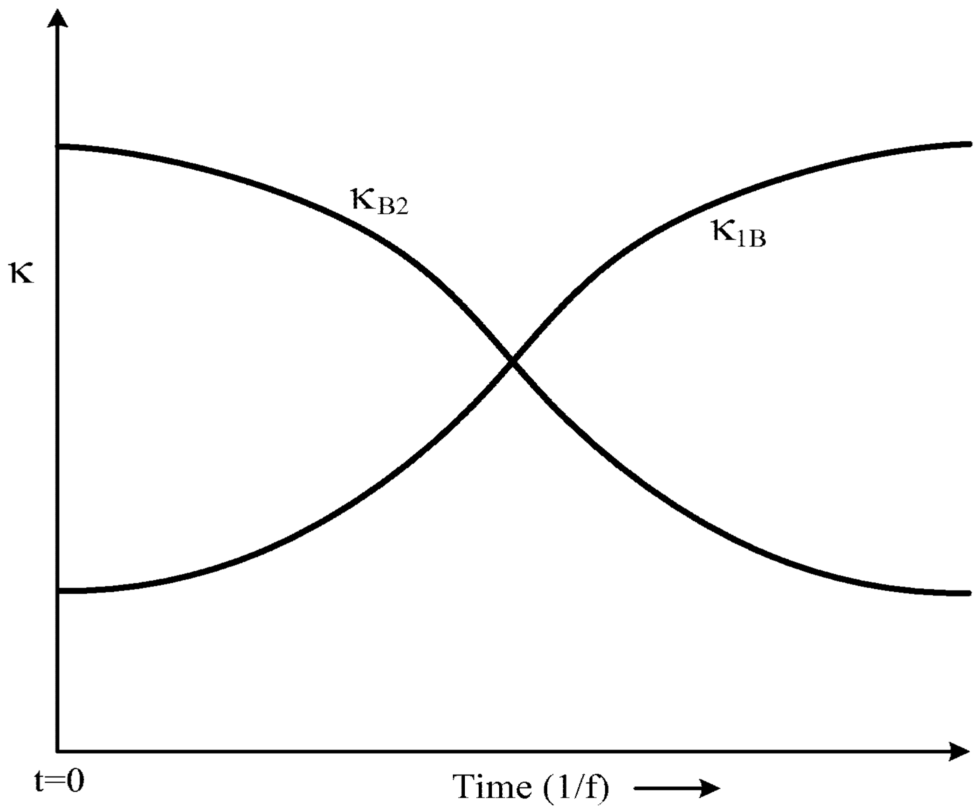
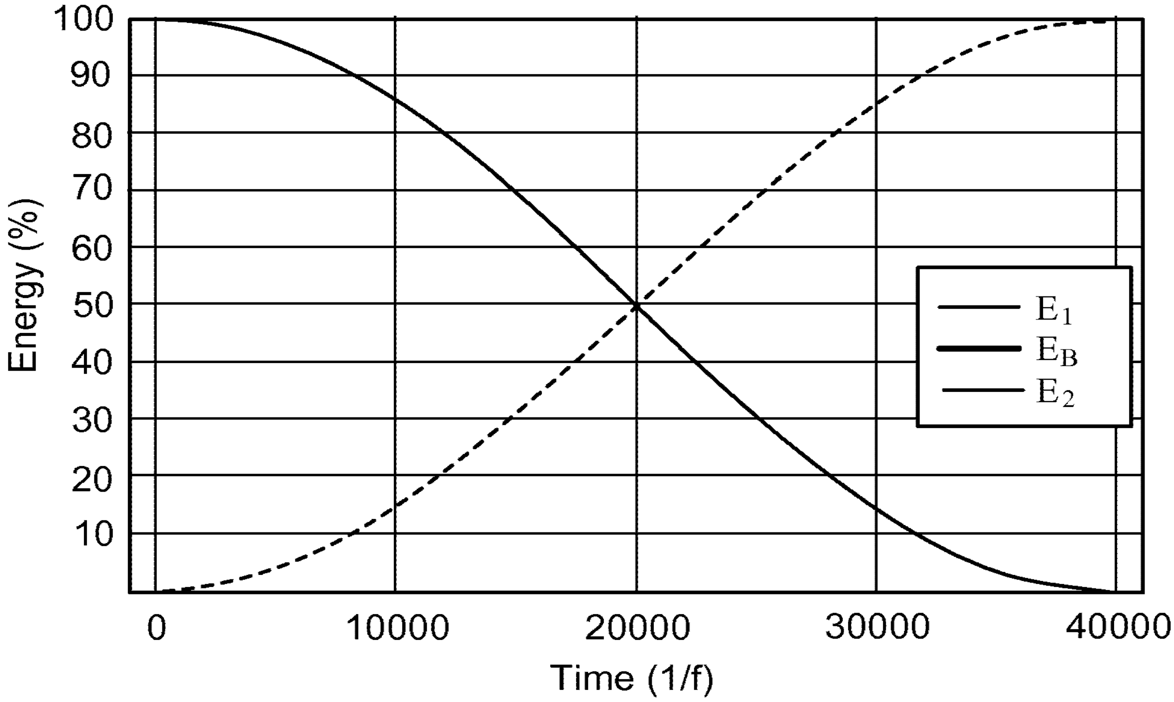


FIG. 19



100
90
80
70
60
50
40
30
20
10
Energy (%)
0
10000
20000
30000
40000
Time (1/f)
E1
EB
E2

FIG. 20

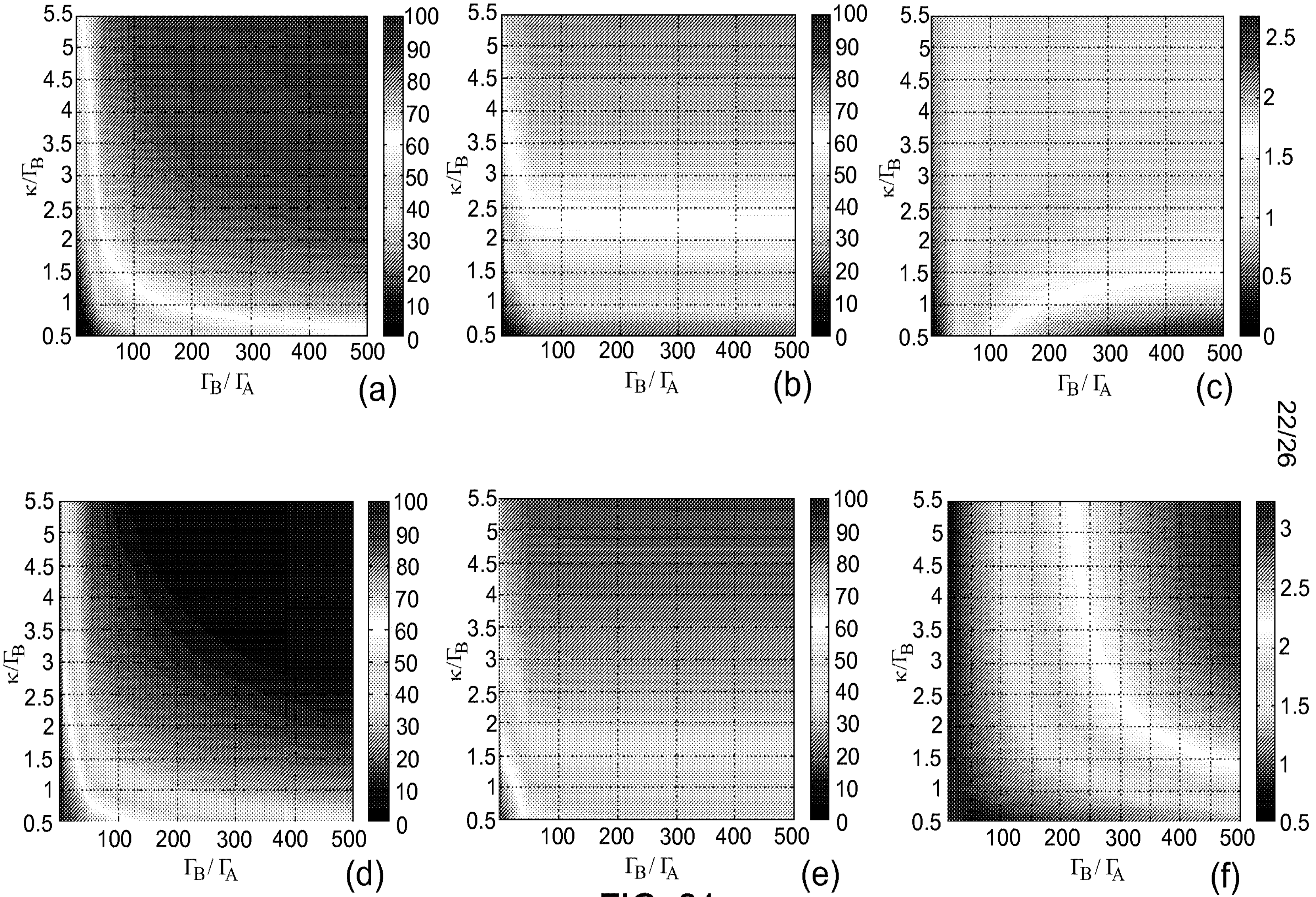


FIG. 21

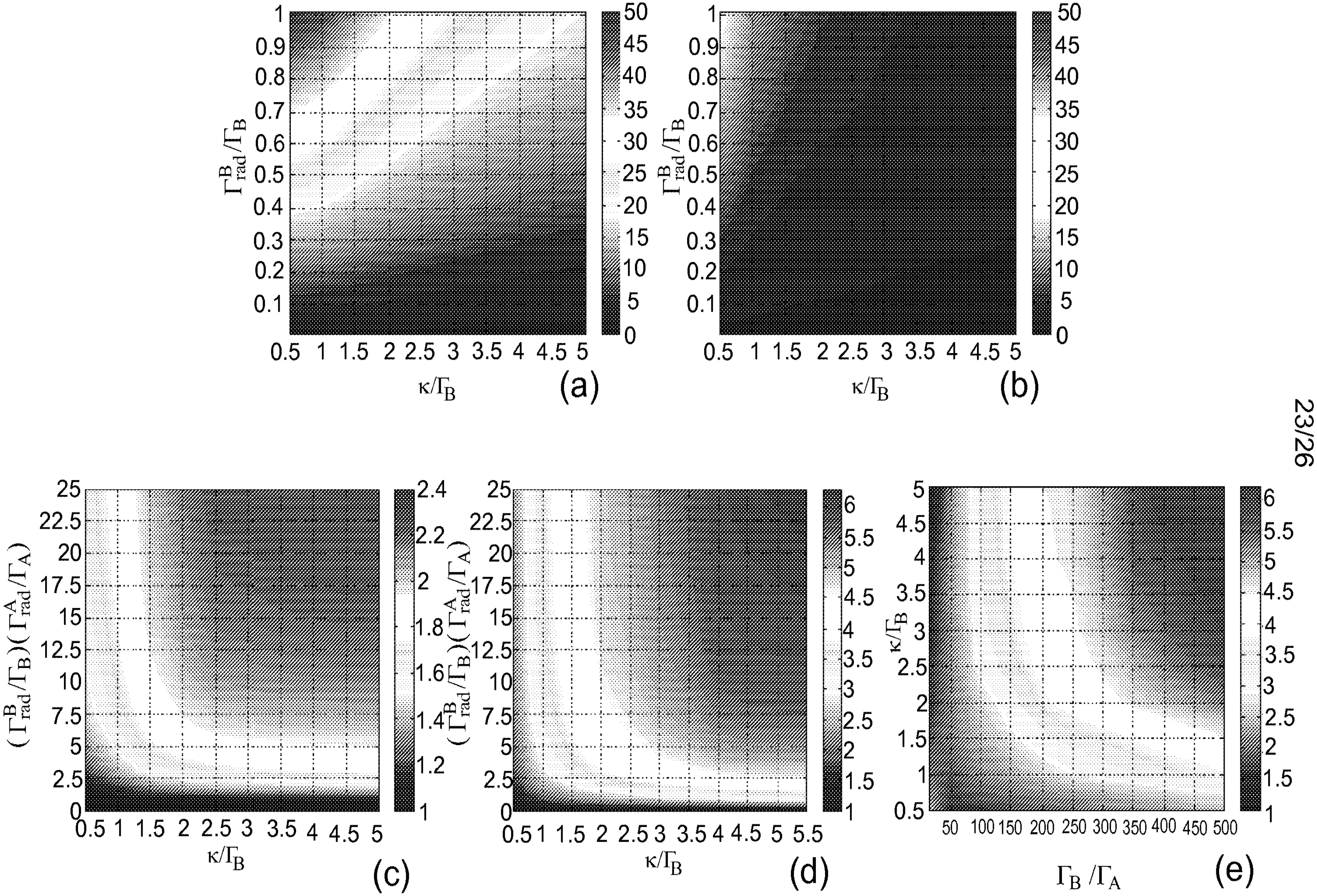

(a)
(b)
(c)
(d)
(e)
$\Gamma_{rad}^{B}/\Gamma_{B}$
κ/Γ_{B}
$(\Gamma_{rad}^{B}/\Gamma_{B})(\Gamma_{rad}^{A}/\Gamma_{A})$
Γ_{B}/Γ_{A}
0 5 10 15 20 25 30 35 40 45 50
1 1.2 1.4 1.6 1.8 2 2.2 2.4
1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6

FIG. 22

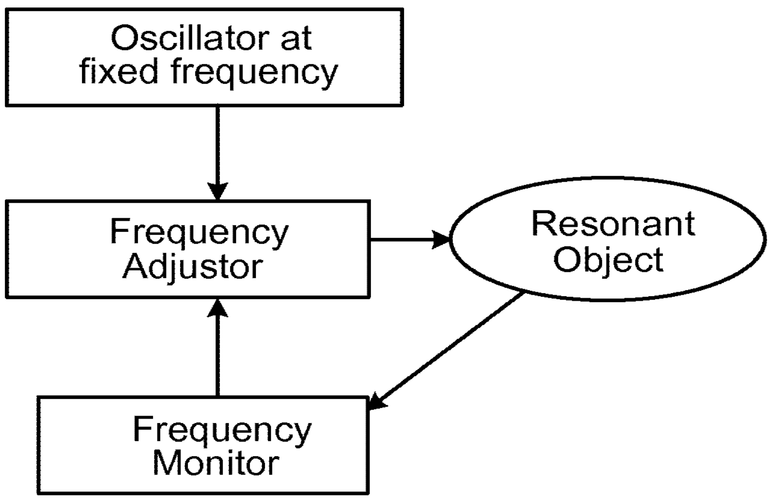


FIG. 23a

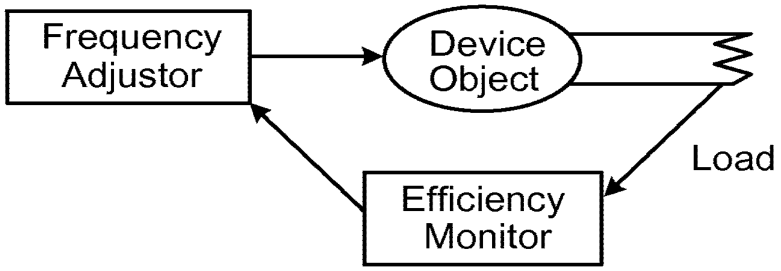
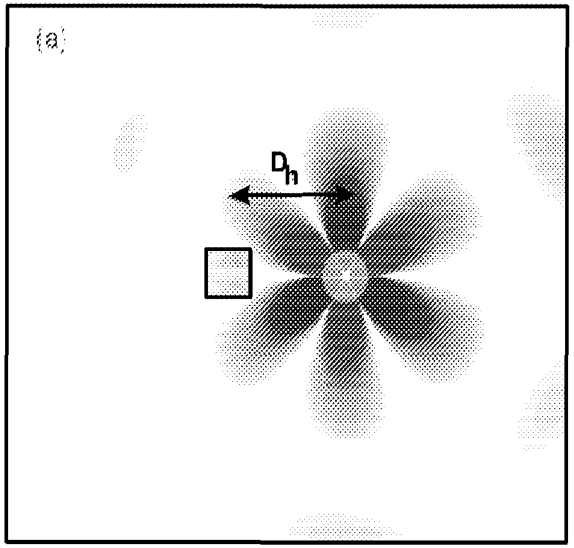
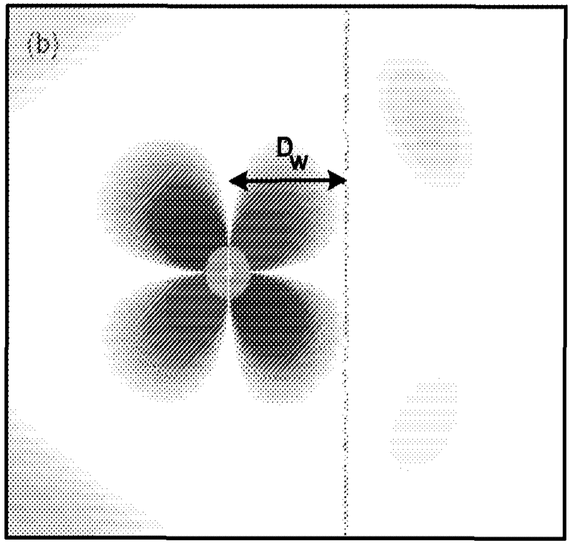


FIG. 23b



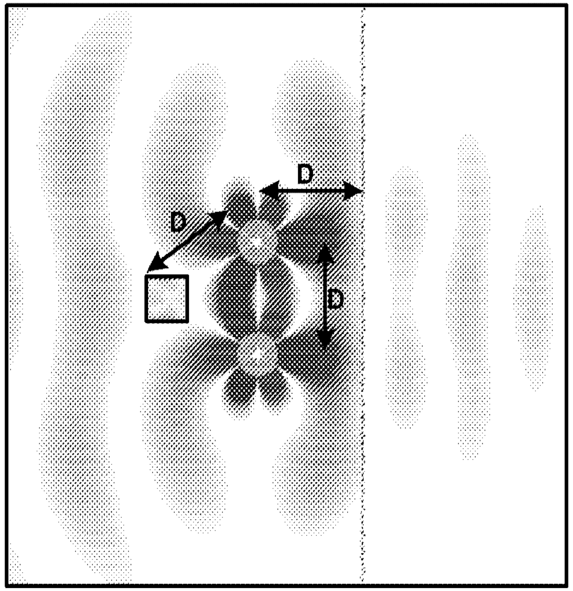


Disk with "human"	D_h/r	$Q_{c\text{-}h}^{abs}$	$Q_{c[h]}^{rad}$	$Q_{c[h]}$
Re{ε}=147.7, m=2	3	230	981	183
$\lambda/r \approx 20$	5	2917	1984	1057
$Q_c^{abs} \approx 10096$	7	11573	2230	1578
	10	41496	2201	1732
Re{ε}=65.6, m=3	3	1827	6197	1238
$\lambda/r \approx 10$	**5**	**58431**	**11808**	**4978**
$Q_c^{abs} \approx 10096$	7	249748	9931	4908
	10	867552	9078	4754

FIG. 24a

Disk with "wall"	D_w/r	$Q_{c\text{-}w}^{abs}$	$Q_{c[w]}^{rad}$	$Q_{c[w]}$
Re{ε}=147.7, m=2	3	16725	1235	1033
$\lambda/r \approx 20$	**5**	**31659**	**1922**	**1536**
$Q_c^{abs} \approx 10098$	7	49440	2389	1859
	10	82839	2140	1729
Re{ε}=65.6, m=3	3	53154	6228	3592
$\lambda/r \approx 10$	5	127402	10988	5053
$Q_c^{abs} \approx 10097$	7	159192	10168	4910
	10	191506	9510	4775

FIG. 24b



Two disks with "human" and "wall"	D/r	$Q_{c\text{-}h}^{abs}$	$Q_{c\text{-}w}^{abs}$	$Q_{c[hw]}^{rad}$	$Q_{c[hw]} = \omega/2\Gamma_{c[hw]}$	$\omega/2\kappa_{[hw]}$	$\kappa_{[hw]}/\Gamma_{c[hw]}$
Re{ε}=147.7, m=2	3	3300	12774	536	426	48	8.8
$\lambda/r \approx 20$	5	5719	26333	1600	1068	322	3.3
$Q_c^{abs} \approx 10100$	7	13248	50161	3542	2097	973	2.2
	10	18447	68460	3624	2254	1768	1.3
Re{ε}=65.6, m=3	3	2088	36661	6764	1328	141	9.4
$\lambda/r \approx 10$	**5**	**72137**	**90289**	**11945**	**4815**	**2114**	**2.3**
$Q_c^{abs} \approx 10100$	7	237822	129094	12261	5194	8307	0.6

FIG. 24c

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 09/59244

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01P 7/00 (2009.01)
USPC - 333/219
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC - 333/219

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 333/219; 307/126; 455/522 (keyword limited - see terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
pubwest (DB=PGPB,USPT,EPAB,JPAB), Google Scholar
Terms - wireless energy, coupling rate, resonate, energy accumulation, near-field, transfer, intermediate

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/0222542 A1 (Joannopoulos et al.) 27 September 2007 (27.09.2007), abstract, para [0013], [0015], [0016], [0026], [0027], [0035]	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
Y	US 3,517,350 A (Beaver) 23 June 1970 (23.06.1970), col 2, ln 69-72; col 7, ln 22-39	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
X, P	US 2009/0153273 A1 (Chen) 18 June 2009 (18.06.2009), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
X, P	WO 2008/118178 A1 (Karalis et al.) 02 October 2008 (02.10.2008), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
A	US 6,960,968 B2 (Odendaal et al.) 01 November 2005 (01.11.2005), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
A	US 7,069,064 B2 (Gevorgian et al.) 27 June 2006 (27.06.2006), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
A	US 1,119,732 A (Tesla) 01 December 1914 (01.12.1914), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 November 2009 (16.11.2009)	07 DEC 2009

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (April 2007)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 09/59244

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 5, 7-12, 14-19, 25-27, 33-49 and 54-79
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (April 2007)

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Published:
— *with international search report (Art. 21(3))*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

WO 2010/090538 A1

(54) Title: INDUCTIVE POWER TRANSFER APPARATUS

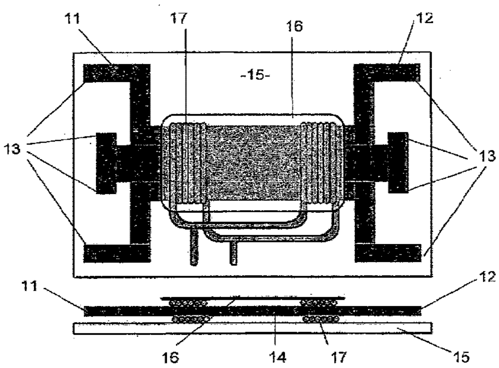

FIGURE 8

(57) Abstract: A magnetic flux pad for generating or receiving magnetic flux has two pole areas (11, 12), a permeable core (14) and a coil (16) wound about the core. The pad allows useable flux to be generated at a significant height above a surface of the pad.

INDUCTIVE POWER TRANSFER APPARATUS

Field of the Invention

This invention relates to apparatus for generating or receiving magnetic flux. The invention has particular, but not sole, application to a low profile, substantially flat device, such as a pad, for power transfer using an Inductive Power Transfer (IPT) system.

Background

IPT systems, and use of a pad including one or more windings that may comprise the primary or secondary windings for inductive power transfer, are introduced in our published international patent application WO 2008/140333, the contents of which are incorporated herein by reference. One particular application of IPT power transfer pads is electric vehicle charging. IPT power transfer pads are used both in the vehicle as a power "pick-up" device (i.e. the secondary side winding of the IPT system), and at a stationary location such as a garage floor as the "charging pad" (i.e. the primary side winding) from which power is sourced.

In the development of pick-ups for inductively charging electric vehicles a problem of some concern is the clearance available under the vehicle. With conventional pick-up circuits power in sufficient quantities can be provided at distances up to perhaps 100 mm at which time the coupling factor becomes so small that it becomes impractical.

It is generally conceded that the power required to charge a typical electric vehicle overnight is about 2.0 kW, so that in an overnight charging mode some 24 kWH can be transferred. With modern electric vehicles this is enough energy to travel more than 100 km and is ideal for small vehicles used for tasks such as dropping children at schools, running errands, short commutes and the like.

Inductively coupled chargers commonly use two power pads that are circular in shape and may have dimensions of 400 mm diameter by 25 mm thick as shown in Figure 1. However, to use an inductive charger such as this the vehicle must be positioned relatively accurately over the charging pad - typically within 50 mm of perfect alignment - and the separation between the power pad on the vehicle and the power pad on the ground must be closely controlled. In principle inductive power transfer may be accomplished for vertical spacings between 0 mm and 100 mm but if the system is set up for 100 mm it will have quite a large reduction in power at

120 mm and will be inoperable below 50 mm. This state of affairs occurs because both the self inductance and the mutual inductance of the power pads vary widely as the distance between the pads changes. The self inductance and the mutual inductance as a function of the separation for two identical circular pads that have the construction of Figure 1, are shown in Figure 2. Thus at 100 mm the power pad receiver or pick-up may have a pick-up voltage of 100 V and a short circuit current of 5.0 A for a power rating of 500 W. If the IPT system electronics operates with a Q factor of 4, then 2 kW can be transferred to the battery though there are still difficulties to overcome in producing the power needed at the appropriate battery voltage.

The induced voltage in the pick-up pad (i.e. the vehicle mounted power pad) is very separation sensitive – corresponding to the variation in mutual inductance shown in Figure 2 - so that at 120 mm it is reduced by approximately 40% while at 50 mm it is increased by a factor of 2. A reduction in power means that the vehicle does not get fully charged in the usual time, but the more challenging situation is that at smaller separations the power transferred may be so high that the components of the circuit are overloaded. Also, as the separation is reduced the self inductance of the pick-up coil also changes so that the circuit operates off-frequency putting extra stress on the power supply. As the separation gets smaller still this stress on the power supply caused by the non-tuned pick-up on the primary side cannot be sustained and the system must be shut down. In practice it is feasible to operate with a separation between 40 and 100 mm but a larger range is too difficult.

A range of separation from 40 to 100 mm is quite small. If the vehicle has a relatively high ground clearance then either the power pad on the vehicle has to be lowered or the power pad on the ground has to be raised. Automatic systems for doing this compromise the reliability of the charging system. Alternatively the pad on the ground can be on a fixed but a raised platform but such a pad is a tripping hazard when a car is not being charged and this situation is generally to be avoided in a garage or other location involving vehicles and pedestrians.

The known power pad construction of Figure 1 comprises an aluminium case 1 containing typically eight ferrite bars 2 and a coil 3. Current in the coil causes magnetic flux in the ferrite bars and this flux has flux lines that start on the ferrite bars and propagate to the other end of the bar in a path containing the coil that may be thought of as a semi-elliptical shape. The flux lines 4 for a single bar are shown in Figure 3. The flux lines leave the ferrite in an upward direction and propagate to the other end of the bar, entering it at right angles. No flux goes out the back of the pad as the solid aluminium backing plate 1 prevents it. In the actual pad the eight bars give a flux pattern shown approximately in cross section in Figure 4. A simulation of the actual flux pattern is shown in Figure 4A.

From Figure 4A it can be seen that at the highest point the flux lines are essentially horizontal. Therefore, to get the maximum separation possible between the primary pad and the secondary pad it would be advantageous to detect this horizontal flux. However, the horizontal flux is still relatively close to the pad (extending from the pad approximately one quarter of the diameter of the pad) and there is no horizontal flux at all at the very centre of the power pad. Thus at the very point where maximum flux density would be ideal – the centre – the actual usable horizontal flux component is zero.

Summary

It is an object of the invention to provide an improved apparatus or method for generating or receiving magnetic flux, or an improved IPT power transfer pad, or to at least provide a useful alternative.

Accordingly in one aspect the invention provides a magnetic flux pad having a front face and a back face for generating or receiving magnetic flux, the pad comprising:

two pole areas for sending or receiving flux;

a magnetically permeable core magnetically connecting the pole areas;

a coil wound about the core; and

whereby the flux enters the pad at one of the pole areas and exits the pad at the other pole area.

In some embodiments a flux shaping means is provided such that flux is directed into a space beyond the front face of the pad. The flux shaping means may be located adjacent to the back face of the pad and may advantageously comprise a member, such as a plate, constructed from a flux repelling material.

In some embodiments a flux shaping means is provided such that flux is substantially prevented from escaping from the core. The flux shaping means may comprise a flux repelling member located adjacent to the front face of the pad. It may further comprise a flux repelling member located adjacent to the rear face of the pad.

The coil may comprise a plurality of coils. The coils may be connected electrically in parallel and/or magnetically in series.

In another aspect the invention provides a magnetic flux pad having a front face and a back face for generating a magnetic flux in a space beyond the front face of the pad, the pad comprising:

two pole areas for sending or receiving flux;

a magnetically permeable core magnetically connecting the pole areas;

a coil wound about the core;

a flux repelling means provided adjacent to a rear face; and

whereby the flux enters the pad at one of the pole areas and exits the pad at the other pole area.

In a further aspect the invention provides an IPT power transfer pad including: a magnetic flux carrying member having a high magnetic permeability and two ends, each end being substantially adjacent a peripheral edge of the pad; and one or more windings provided about at least a part of the flux carrying member; and wherein said pad is configured such that magnetic flux exits or enters the flux carrying member substantially only at or adjacent to the ends.

In a still further aspect the invention provides an IPT system including a first magnetic flux pad or IPT power transfer pad for connection to a power supply and a second magnetic flux pad or IPT power transfer pad for connection to a load, the first and second magnetic flux pads or IPT power pads constructed according to any one of the above-described aspects and having one or more windings with the same number of turns, and wherein the number of turns is selected dependent on a required operating frequency

In another aspect the invention provides an IPT system including a magnetic flux pad according to any one of the preceding statements.

In some embodiments the system supplies power to an electric vehicle, such as an electric vehicle charging system.

Further aspects of the invention will become apparent from the following description.

Drawing Description

One or more embodiments are described below by way of example with reference to the accompanying drawings, in which:

Figure 1 is a perspective view of part of a known form of IPT power transfer pad;

Figure 2 is a graph of inductance measurements and flux linkage efficiency with respect to height displacement for a pad such as that of Figure 1;

Figure 3 is a diagrammatic elevation in cross section of a part of the pad of Figure 1 showing flux lines;

Figure 4 is a plan view and elevation of a cross section of the pad of Figure 1 showing flux lines;

Figure 4A is an elevation in cross section of a computer generated simulation of the magnetic field (indicated by flux lines) of the pad of Figure 1;

Figure 5 is a plan view and elevation in cross section of an embodiment of a new IPT power transfer pad;

Figure 6 is a diagrammatic view of the pad of Figure 5 showing one example of a winding arrangement;

Figure 7 is a diagrammatic elevation in cross section of the pad of Figure 5, and showing flux lines;

Figure 7A is an elevation in cross section of a computer generated simulation of the magnetic field (indicated by flux lines) of the pad of Figure 6;

Figure 8 is a plan view of another embodiment of a new pad based on the design of the pad of Figure 5;

Figure 9 is a graph of inductance measurements and flux linkage efficiency with respect to height displacement for a pad such as that of Figure 7;

Figure 10 is a graph of inductance measurements and flux linkage efficiency with respect to height displacement for both the pad of Figure 1 (referred to as the Circular pad) and the pad of Figure 7 (referred to as the Polarised pad);

Figure 11 is an isometric view of two separated ferrite cores showing an arrangement used for the purpose of simulating their performance in a power transfer system;

Figure 12 is a computer generated flux plot in a pad as shown in Figure 11 with 25 A current in windings provided about the ferrite core;

Figure 13 is a computer generated plot showing flux density in the ferrite core of the pad referred to in Figure 12 taken through an XY plane half way through the thickness (Z axis) of the ferrite core;

Figure 14 is a plan view of the arrangement of Figure 11 illustrating the position of a cut plane through the XZ axis at a point half way through the width (Y axis) of the ferrite cores of the assembly;

Figure 15 is a computer generated flux plot on the cut plane of Figure 14 for a 100mm separation between the pads;

Figure 16 is a computer generated flux plot on the cut plane of Figure 14 for a 200mm separation between the pads, and;

Figure 17 is a computer generated plot showing flux density in the cut plane of Figure 14 for a 200mm separation between the pads.

Description of One or More Embodiments

A new concept in IPT power transfer arrangements is now disclosed. The embodiments described in this document relate to flux transmission and reception apparatus. These are commonly (although not necessarily) provided in the form of a discrete unit which may conveniently be referred to as power transfer pads i.e. arrangements that may be portable and which typically have a greater extent in two dimensions relative to a third dimension so that they may be used in applications such as electric vehicle charging where one pad is provided on a ground surface (such as a garage floor) and another in the vehicle. However, the disclosed subject matter may also be provided in other arrangements including permanent structures such as a roadway for example, and does not need to take the form of a pad.

Referring to the arrangement of Figure 5, a pad is shown which combines three leakage flux control techniques to produce a much enhanced performance. In this regard it uses a novel "flux pipe", generally referenced 10, to connect two separated pole area that provide flux transmitter/receiver portions that comprise pole areas 11 and 12. The flux pipe provides a generally elongate region of high permeance allowing a high flux concentration from which ideally no flux escapes. The flux pipe 10 has a core 14 of a material such as ferrite to attract flux to stay in the core. A back-plate 15 of aluminium is provided adjacent to a rear face of the pad and acts to 'frighten' or repel flux from leaking from the core 14. Above the core 14 there may be a separate aluminium plate 16 adjacent to a front face of the pad to complete the same 'frightening' or shaping task. Magnetic flux is attracted to the ferrite, and it is repulsed by the aluminium. With electric circuits there is a large difference between the conductivity of conductors, typically 5.6×10^7 for copper; and air – in the order of 10^{-14} – but this situation does not pertain with magnetic fields where the difference in permeability between ferrite and air is only the order of 10,000 : 1. Thus in magnetic circuits leakage flux in air is always present and this has to be controlled to get the best outcome.

The ends of the core 14 comprise the transmitter/receiver portions 11 and 12. The top plate 16 does not cover the end portions 11 and 12, so the flux is directed upwardly from the ends to provide flux in the space beyond the front face of the pad as will be seen further below.

Plate 16 cannot be electrically connected to the backing plate 15 or the combination would constitute a short circuited turn. There is a winding on the flux core to electrically connect to the pick-up and the third flux control technique concerns this winding. It is well known that long toroidal windings have zero or very small leakage flux outside them. In the situation here a toroidal winding covering the full length of the flux pipe would have too much inductance but the winding can be partitioned into several windings 17 that are magnetically in series but electrically in parallel, as shown in Figure 6. In practice two windings in magnetic series-electrical parallel placed with one at or toward each end of the flux pipe is a good approximation to a continuous winding and in some circumstances may outperform a single winding.

The provision of a winding arrangement that covers substantially the full length of the core 14 means that little flux escapes from the core. For example, in the embodiment having two windings connected electrically in parallel (magnetically in series), the flux linkages in each winding must be the same so essentially no flux can escape from the core. Thus, plate 16, in this embodiment, is not essential.

The flux paths from a pick-up as in Figure 5 are shown diagrammatically in Figure 7 by flux lines 20. In Figure 7A a computer generated simulation of the magnetic field (indicated by flux lines 20) of the pad of Figure 6 is shown. As before they are approximately semi-elliptical but they are from a much larger base than the power pad ferrites of Figure 1 and therefore can operate over much larger separations. At the centre of the pick-up the flux paths are horizontal as required. A practical pick-up is shown in Figure 8, and measured self inductance and mutual inductance for this pick-up are illustrated in Figure 9. A performance comparison of the circular pad of figure 1 and the new pick up of figure 8 is shown in figure 10. The pad design of Figures 5 and 8 is polarised so that the ends 11 and 12 must be aligned, but that is relatively easy to implement.

As shown in Figure 8, some embodiments may include pole areas 11 and 12 that include finger portions 13. These allow the flux to be distributed more widely while using a minimal quantity of permeable material, thus lowering weight and cost.

A useful feature of the new pad design disclosed herein is that the winding number of the primary and secondary coils may in some embodiments be kept the same. This is quite different from the conventional IPT system setup, which normally has an elongated loop of one turn on the primary side and has a winding with multiple turns on the secondary side. This setup has two significant features, 1) the magnetic structure of both the primary and the secondary of the charger pads are the same, and 2) the induced voltage and uncompensated power at the secondary output (i.e. the pick-up pad) are independent of the operating frequency by varying the number of turns in relation to the frequency change.

The uncompensated power (S_u) and induced voltage (V_{oc}) of an IPT pick-up are commonly known and are expressed in equation 1 and 2, where I_1 is the primary track current, L_1 is the primary track inductance and N_1 and N_2 are the number of turns in the primary and secondary respectively. N_1 is equal to N_2 in this new pad design.

Under these conditions the rated uncompensated power for the pick-up S_u, the mutually coupled voltage V_{oc} and the terminal voltage on the primary V_1 are given by

$$S_u = \frac{\omega \cdot M^2 \cdot I_1^2}{L_2} \propto \frac{f \cdot (N_1 N_2)^2 \cdot I_1^2}{N_2^2} \propto f \cdot N^2 \cdot I_1^2 \quad (1)$$

$$V_{oc} = j\omega \cdot N_1 N_2 \cdot I_1 \propto f \cdot N^2 \cdot I_1 \quad (2)$$

And

$$V_1 = j\omega \cdot L_1 \cdot I_1 \propto f \cdot N^2 \cdot I_1 \quad (3)$$

Note that the short circuit current is proportional to M/L and is independent of the number of turns

$$I_{SC} = I\frac{M}{L_2} = I \cdot k \quad (4)$$

where k is the magnetic coupling factor between the primary and the secondary. As mentioned earlier, the pick-up induced voltage and the uncompensated power are to be the same for a different operating frequency. This also means that the terminal voltage and the short circuit current are also equal. Equations 1 and 2 can be rewritten as shown in equations 5 and 6 respectively for the same uncompensated power and induced voltage but different operating frequency.

$$f_a N_a^2 I_a^2 = f_b N_b^2 I_b^2 \quad (5)$$

$$f_a N_a^2 I_a = f_b N_b^2 I_b \quad (6)$$

From equation 5:

$$N_b I_b = N_a I_a \sqrt{\frac{f_a}{f_b}} \qquad (7)$$

Using equation 6 and 7:

$$\frac{N_b}{N_a} = \frac{f_a N_a I_a}{f_b N_b I_b} = \frac{f_a}{f_b}\sqrt{\frac{f_b}{f_a}} = \sqrt{\frac{f_a}{f_b}} \qquad (8)$$

Using equation 3 and 6:

$$\frac{I_b}{I_a} = \sqrt{\frac{f_a N_a^{\,2}}{f_b N_b^{\,2}}} = \sqrt{\frac{f_a}{f_b} \cdot \frac{f_b}{f_a}} = 1 \qquad (9)$$

Equation 5 to 9 indicate that the pick-up uncompensated power and V_{oc} will be the same for different frequency while the primary current is kept the same and the winding turns are varied according to equation 8. For example, a charger pad with 15 turns on both primary and secondary, designed to operate at 38.4 kHz, would need to have the number of turns increased to 21 at 20 kHz in order to keep the pick-up V_{oc} and uncompensated power the same. In other words, this feature enables charger pads with the same magnetic design to be used at a different frequency, and the pick-up output characteristic can be maintained the same simply by scaling the turns number accordingly. However, as shown in equation 10, the core flux is proportional to the number of turns and current, thus keeping the current constant and varying the number of turns will vary the core flux, and hence the flux density. By substituting equation 8 into equation 10, it can be shown that the flux in the core is varying proportional to $\sqrt{(f_a/f_b)}$, which is equivalent to equation 8. Thus, if the operating frequency is scaled down, the cross sectional area of the ferrite core may need to be increased to avoid ferrite saturation. An increase of cross sectional area is preferably done by increasing the thickness of the ferrite core so the magnetic reluctance path of the charger pad remains nearly identical.

$$\phi = \frac{L \cdot I}{N} = \frac{N^2 \cdot I}{N \cdot R_m} \qquad (10)$$
$$\propto N \cdot I$$

where R_m is the magnetic reluctance of the flux path.

The eddy current loss (P_e) and hysteresis loss (P_h) equations for the core are shown in equation 11 and 12 in units of W/m^3. If the ferrite core cross sectional area are kept the same, the ratio of the eddy current loss and hysteresis loss for two different operating frequencies are given by equations 13 and 14.

$$P_e \propto B^2 f^2 \propto \frac{\phi^2 f^2}{A^2} \propto \frac{N^2 I^2 f^2}{A^2} \qquad (11)$$

$$P_h \propto f \cdot B^n \propto f \cdot \left(\frac{\phi}{A}\right)^n \propto f \cdot \left(\frac{N \cdot I}{A}\right)^n \qquad (12)$$

where n is the Steinmetz coefficient for the material and is normally in the range of 1.6 – 2.

$$\frac{P_{e.b}}{P_{e.a}} = \frac{N_b^{\,2} I^2 f_b^{\,2}}{N_a^{\,2} I^2 f_a^{\,2}} = \left(\frac{N_b f_b}{N_a f_a}\right)^2 = \left(\sqrt{\frac{f_a}{f_b}} \cdot \frac{f_b}{f_a}\right)^2 = \frac{f_b}{f_a} \qquad (13)$$

$$\frac{P_{h.b}}{P_{h.a}} = \frac{f_b (N_b I_b)^2}{f_a (N_a I_a)^2} = \frac{f_b N_b^{\,2}}{f_a N_a^{\,2}} = 1 \qquad (14)$$

The above expressions suggest that for the same cross sectional area and volume, the hysteresis loss of the core will remain constant regardless of the frequency but the eddy current loss in the core will decrease proportionally to the decrease of operating frequency. As the overall power loss in a ferrite core is dominated by its hysteresis loss, most of the attributes, apart from the core flux density, of the charger pad will remain approximately the same with the operating frequency scaling process.

However, as discussed earlier the trade off of operating at a lower frequency is the increase of flux density in the core by $\sqrt{(f_a/f_b)}$. Thus to accommodate the higher flux density the ferrite cross sectional area should be increased in order to keep the flux density the same. With this increased volume of ferrite and keeping flux density constant, the power loss density in the ferrite core is expected to be lower as shown below. Equation 11 and 12 express the eddy current loss and hysteresis loss in terms of watt per m^3, thus the total eddy current and hysteresis loss should take into account the ferrite volume (A*L) shown in equation 15 and 16 respectively.

$$\frac{P_{e.b}}{P_{e.a}} = \frac{\frac{\phi_b^{\,2}}{A_b^{\,2}} \cdot f_b^{\,2} \cdot A_b \cdot L}{\frac{\phi_a^{\,2}}{A_a^{\,2}} \cdot f_a^{\,2} \cdot A_a \cdot L} = \frac{N_b^{\,2} I^2 f_b^{\,2}}{N_a^{\,2} I^2 f_a^{\,2}} \cdot \frac{A_a}{A_b} = \frac{f_b}{f_a} \cdot \frac{A_a}{A_b} \qquad (15)$$

where L is the length of the charger pad ferrite core length and is kept constant.

$$\frac{P_{h.b}}{P_{h.a}} = \frac{f_b \cdot \left(\frac{\phi_b}{A_b}\right)^2}{f_a \cdot \left(\frac{\phi_a}{A_a}\right)^2} \cdot \frac{A_b \cdot L}{A_a \cdot L} = \frac{f_b \cdot \left(\frac{N_b I}{A_b}\right)^2}{f_a \cdot \left(\frac{N_a I}{A_a}\right)^2} \cdot \frac{A_b}{A_a} = \frac{f_b}{f_a} \cdot \left(\frac{N_b}{N_a}\right)^2 \cdot \frac{A_a}{A_b} = \frac{A_a}{A_b} \qquad (16)$$

Referring to the example discussed earlier where a charger pad operating frequency was scaled from 38.4 kHz to 20 kHz, the ferrite area will need to be increased by a factor of 1.385 √(38.4 kHz/20 kHz) in order to keep the flux density the same. Thus the eddy current and hysteresis loss of the charger pad, operating at 20 kHz, will be reduced by 37.59% and 72.17% respectively, compared with operating at 38.4 kHz at the same core flux density.

A simulated example

Referring now to Figures 11 to 17 a simulation of coupled power pads according to the invention will be described to provide an example of a possible embodiment and its use. In this example a coupled system of power pads is simulated with the pick-up winding open circuited. Figure 11 shows the arrangement of the ferrite core which is essentially 93 x 28 x 16 mm blocks of ferrite ground to give very close fitting, and then glued together. The ferrite is surrounded by an aluminium wall with an 8 mm gap between the ferrite and the aluminium, and is 5 mm above an aluminium backing plate. A flux plot for the driven pad (i.e. the pad connected to a power supply) is shown in Figure 12 for the situation where there are two coils driven magnetically in series, electrically in parallel with a current of 23 A. In these circumstances the flux density midway through the ferrite is shown in Figures 12 and 13. As shown the “flux pipe” is very effective in carrying the flux from one end of the pad to the other. Also, it can be seen from Figures 15 and 16 that there is essentially no leakage flux beyond the region between the pads.

For coupled pads a cut-plane is shown in Figure 14 and the other Figures use measurements along this cut-plane to illustrate the performance of the system. The flux lines at 100 mm spacing between pads are given in Figure 15 and for 200 mm spacing in Figure 16. The flux density in the ferrites is shown in Figure 18. The constant flux density in the ferrites of Figure 18 shows that the flux pipe efficiently carries flux from one end of the pad to the other and thereby provides good magnetic coupling between the two pads. The maximum flux density in the driven pad (in the ferrite) is approximately 0.2 T which is safely below saturation for this ferrite. The flux density in the pick-up pad is lower but will increase substantially to about the same as the transmitter pad when the pick-up is resonated.

Therefore, the invention provides a low profile device, referred to herein as a pad, which can be used as a magnetic flux generator that can be used to generate useful flux a significant distance from the device. The device can also be used as a receiver of flux to thereby produce electric energy from the received field. The ability of the pad to generate or receive flux over a significant distance is particularly useful for charging or energising an electric vehicle. Although certain examples and embodiments have been disclosed herein it will be understood that various modifications and additions that are within the scope and spirit of the invention will occur to those skilled in the art to which the invention relates. All such modifications and additions are intended to be included in the scope of the invention as if described specifically herein.

The word "comprise" and variations such as "comprising", unless the context clearly requires the contrary, is intended to be interpreted in an inclusive sense (i.e. as meaning "including, but not limited to").

CLAIMS:

1. A magnetic flux pad having a front face and a back face for generating or receiving magnetic flux, the pad comprising:
   two pole areas for sending or receiving flux;
   a magnetically permeable core magnetically connecting the pole areas;
   a coil wound about the core; and
   whereby the flux enters the pad at one of the pole areas and exits the pad at the other pole area.

2. A magnetic flux pad as claimed in claim 1 including a flux shaping means such that flux is directed into a space beyond the front face of the pad.

3. A magnetic flux pad as claimed in claim 2 wherein the flux shaping means is located adjacent to the back face of the pad.

4. A magnetic flux pad as claimed in claim 2 or claim 3 wherein the flux shaping means comprises a member constructed from a flux repelling material.

5. A magnetic flux pad as claimed in claim 1 including a flux shaping means such that flux is substantially prevented from escaping from the core.

6. A magnetic flux pad as claimed in claim 5 wherein the flux shaping means comprises a flux repelling member located adjacent to the front face of the pad.

7 A magnetic flux pad as claimed in claim 6 wherein the flux shaping means further comprises a flux repelling member located adjacent to the rear face of the pad.

8. A magnetic flux pad as claimed in any one of the preceding claims wherein the coil comprises a plurality of coils.

9. A magnetic flux pad as claimed in claim 8 wherein the coils are connected electrically in parallel.

10. A magnetic flux pad as claimed in claim 8 wherein the coils are connected magnetically in series.

11. A magnetic flux pad as claimed in any one of the preceding claims wherein each pole area includes a plurality of fingers.

12. A magnetic flux pad having a front face and a back face for generating a magnetic flux in a space beyond the front face of the pad, the pad comprising:

two pole areas for sending or receiving flux;

a magnetically permeable core magnetically connecting the pole areas;

a coil wound about the core;

a flux repelling means provided adjacent to a rear face; and

whereby the flux enters the pad at one of the pole areas and exits the pad at the other pole area.

13. An IPT power transfer pad including: a magnetic flux carrying member having a high magnetic permeability and two ends, each end being substantially adjacent a peripheral edge of the pad; and one or more windings provided about at least a part of the flux carrying member; and wherein said pad is configured such that magnetic flux exits or enters the flux carrying member substantially only at or adjacent to the ends.

14. An IPT system including a first magnetic flux pad or IPT power transfer pad for connection to a power supply and a second magnetic flux pad or IPT power transfer pad for connection to a load, the first and second magnetic flux pads or IPT power pads constructed according to any one of claims 1-13 and having one or more windings with the same number of turns, and wherein the number of turns is selected dependent on a required operating frequency.

15. An IPT system including a magnetic flux pad or IPT power transfer pad according to any one of claims 1-13.

16. An IPT system as claimed in claim 14 or claim 15 wherein the system supplies power to an electric vehicle.

17. A magnetic flux pad substantially as herein described with reference to the accompanying drawings.

18. An IPT system substantially as herein described with reference to the accompanying drawings.

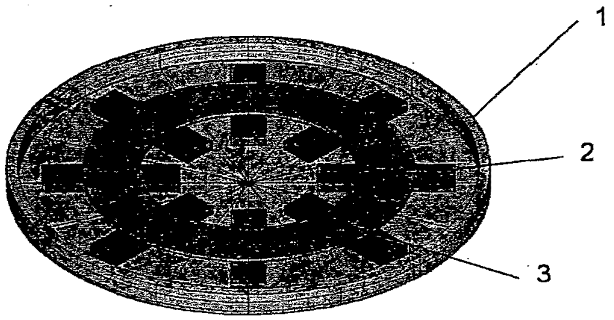

FIGURE 1

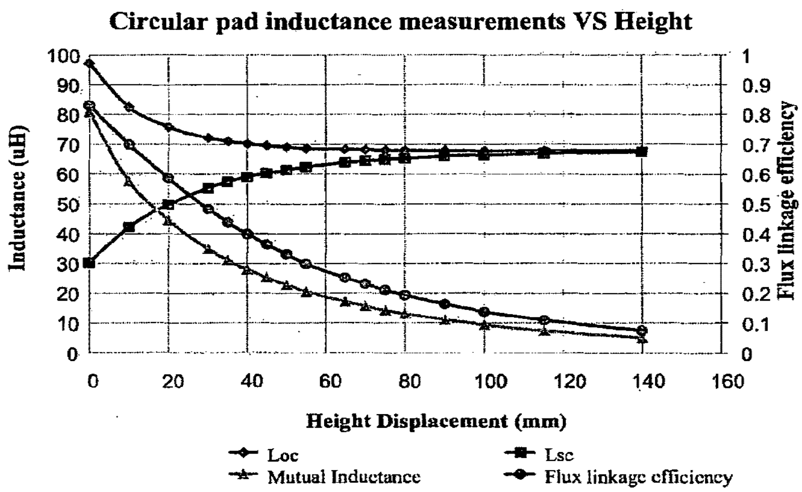

FIGURE 2

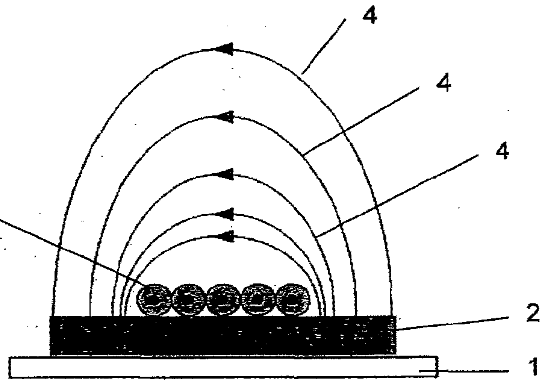

FIGURE 3

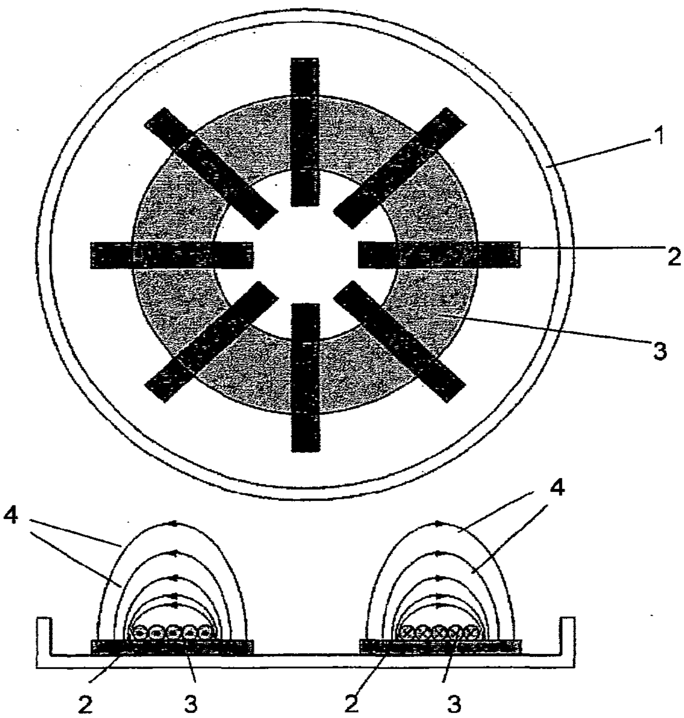

FIGURE 4

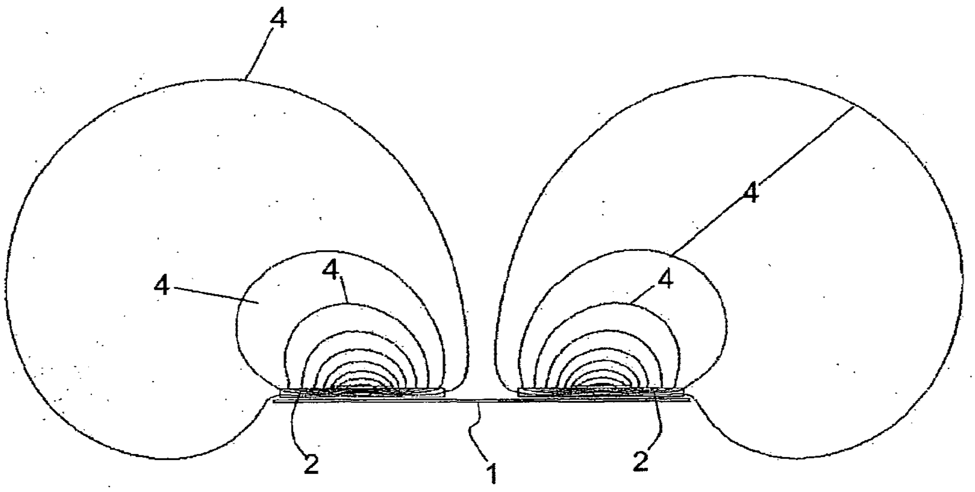

FIGURE 4A

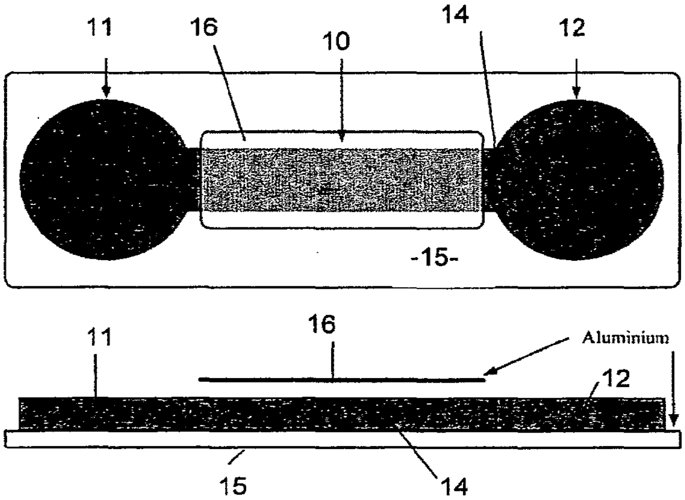

FIGURE 5

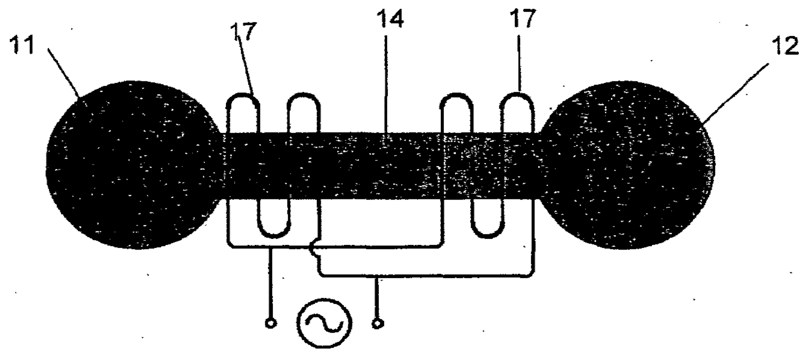

FIGURE 6

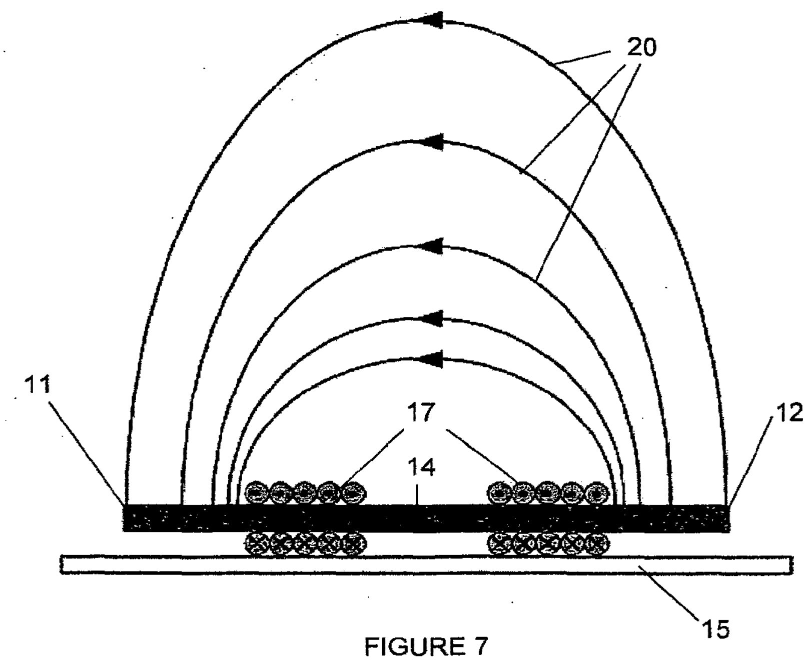

FIGURE 7

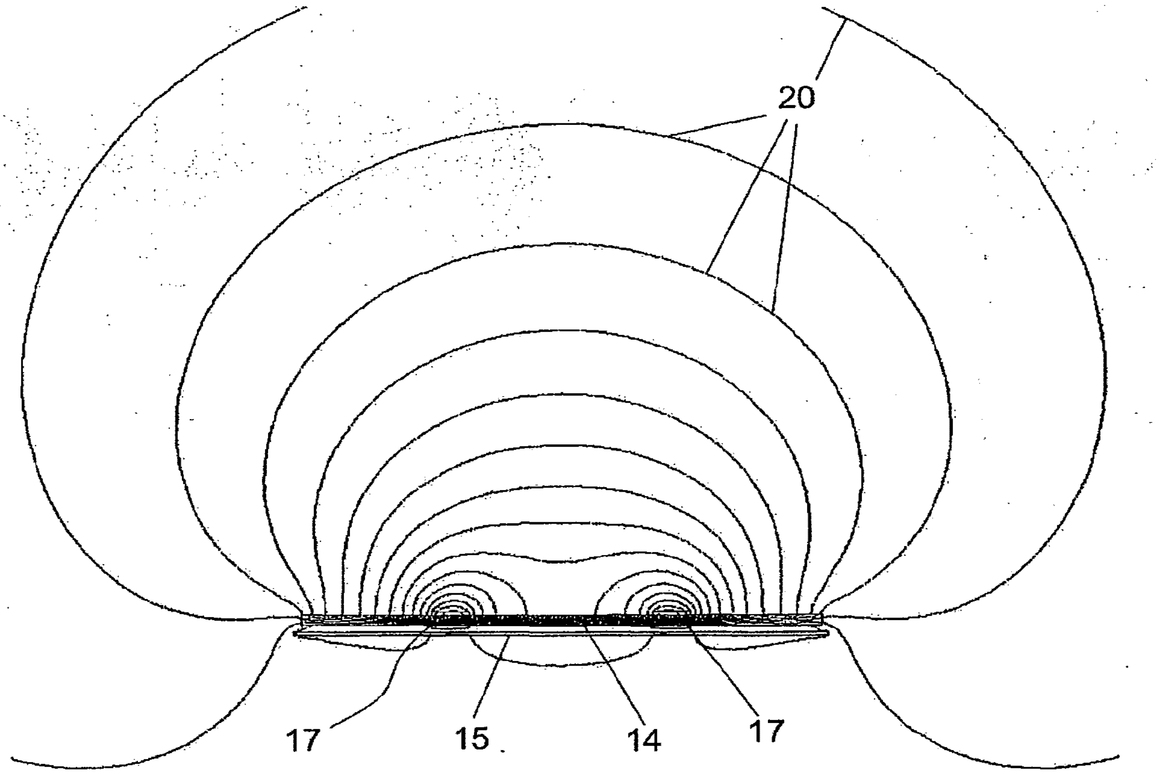

FIGURE 7A

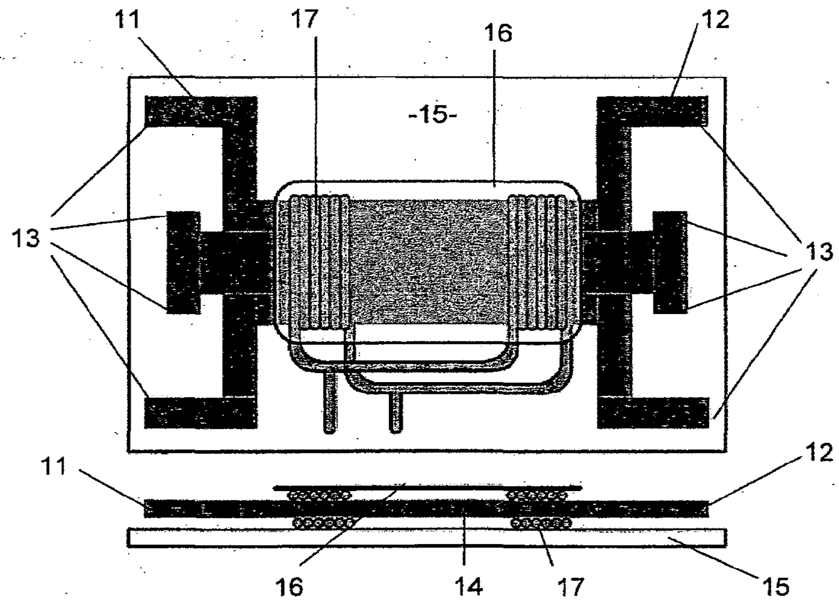

FIGURE 8

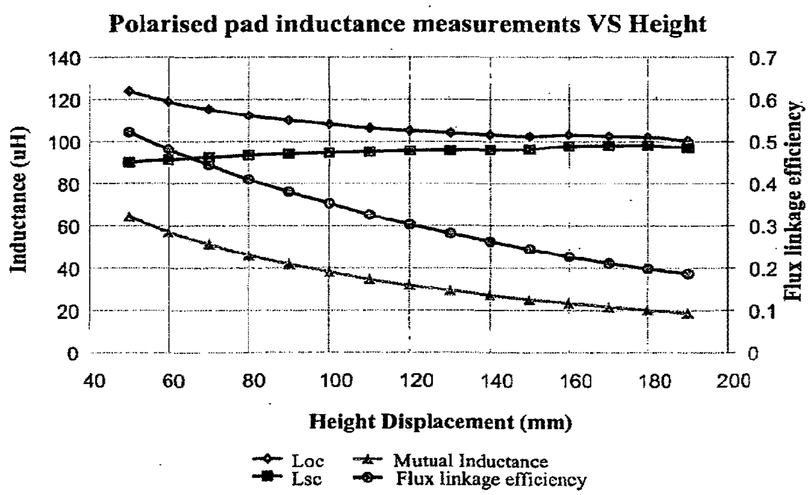

FIGURE 9

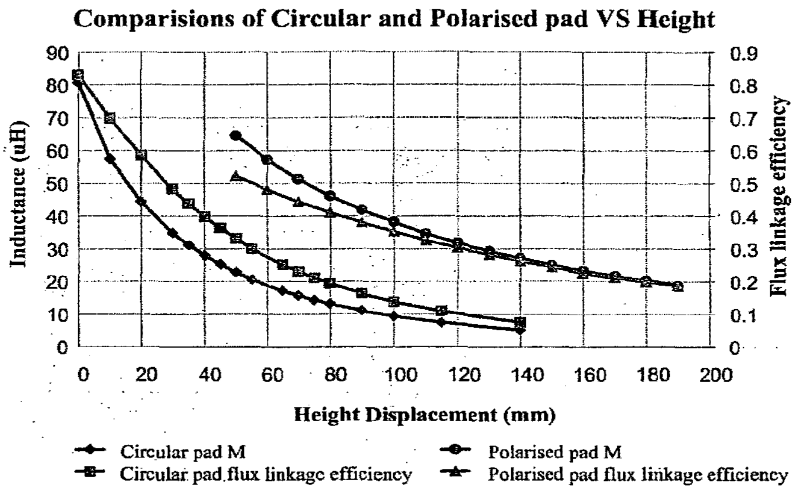
Comparisions of Circular and Polarised pad VS Height
Inductance (uH)
90
80
70
60
50
40
30
20
10
0
Flux linkage efficiency
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
160
180
200
Height Displacement (mm)
Circular pad M
Circular pad flux linkage efficiency
Polarised pad M
Polarised pad flux linkage efficiency

FIGURE 10

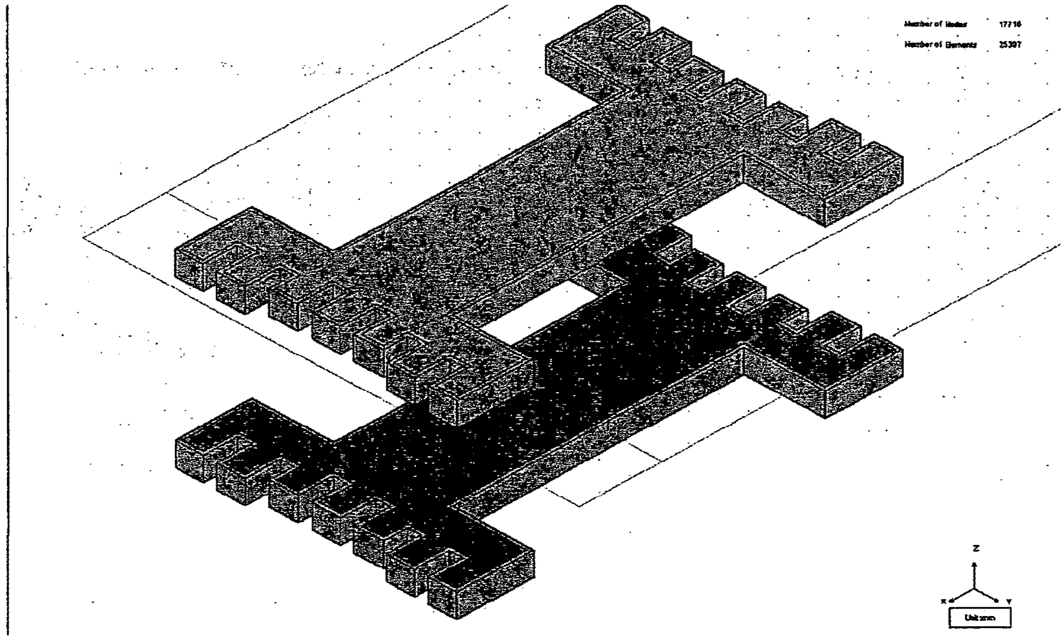

FIGURE 11

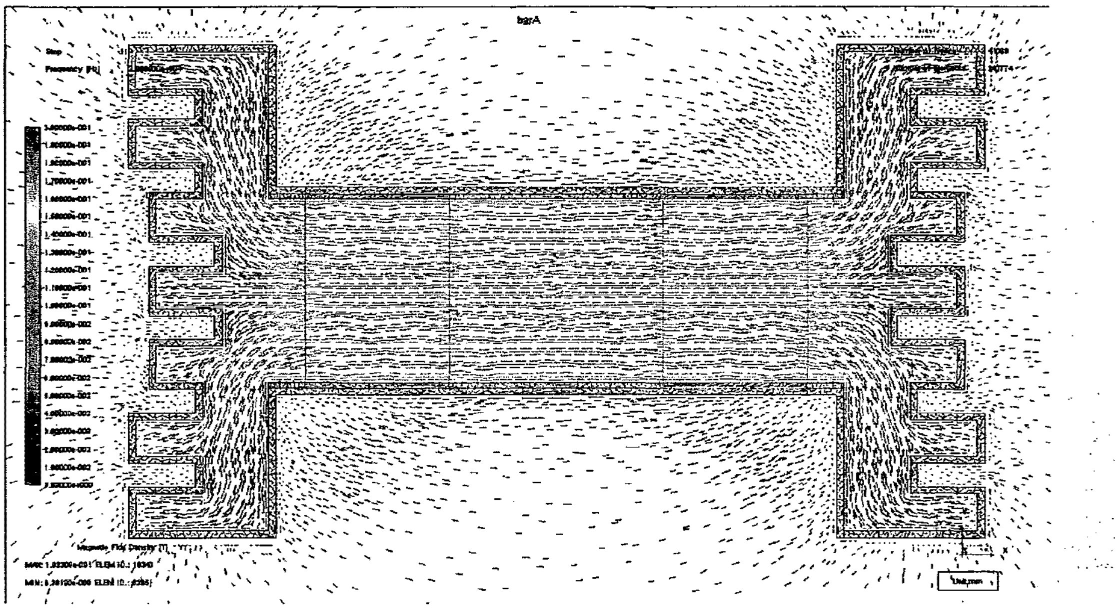

FIGURE 12

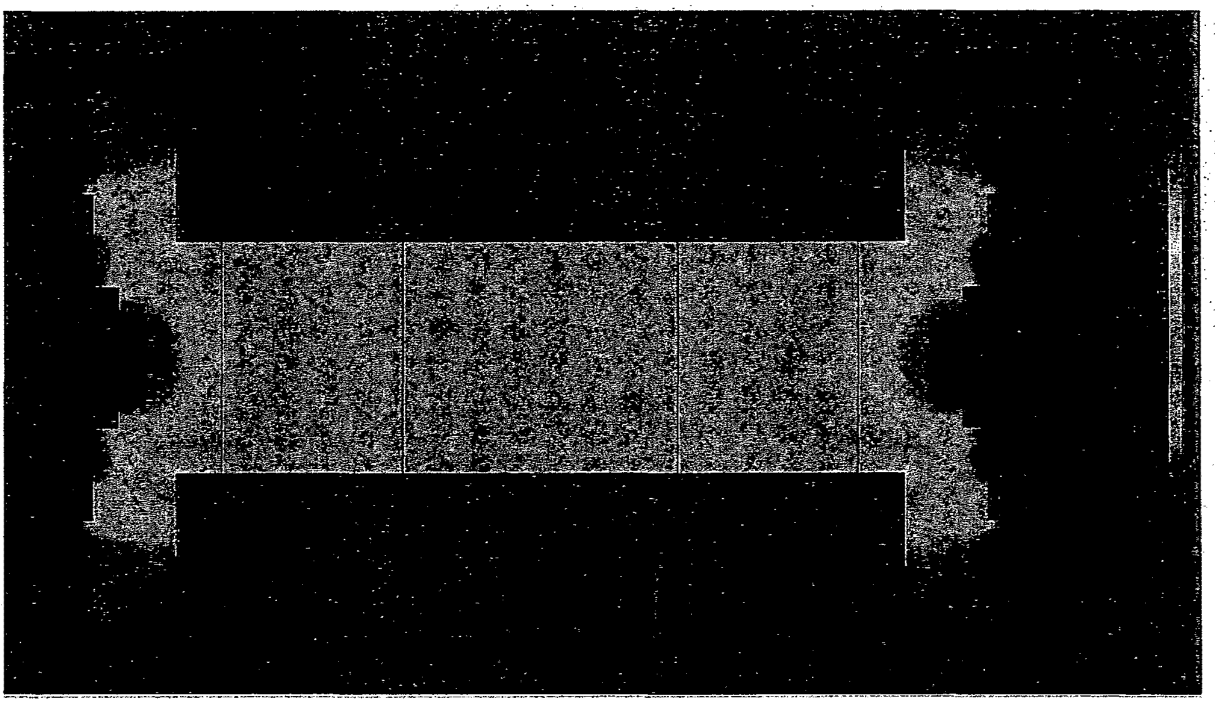

FIGURE 13

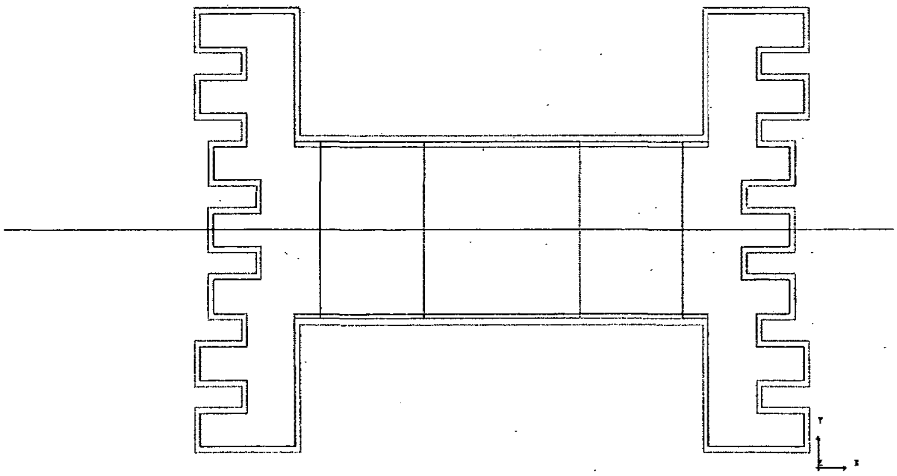

FIGURE 14

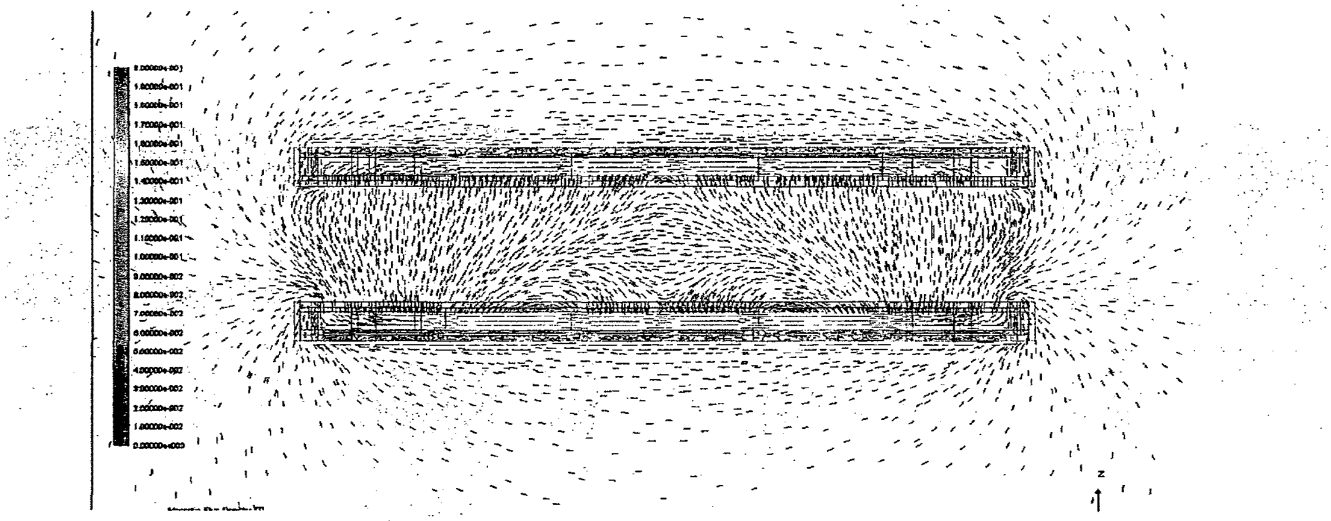

FIGURE 15

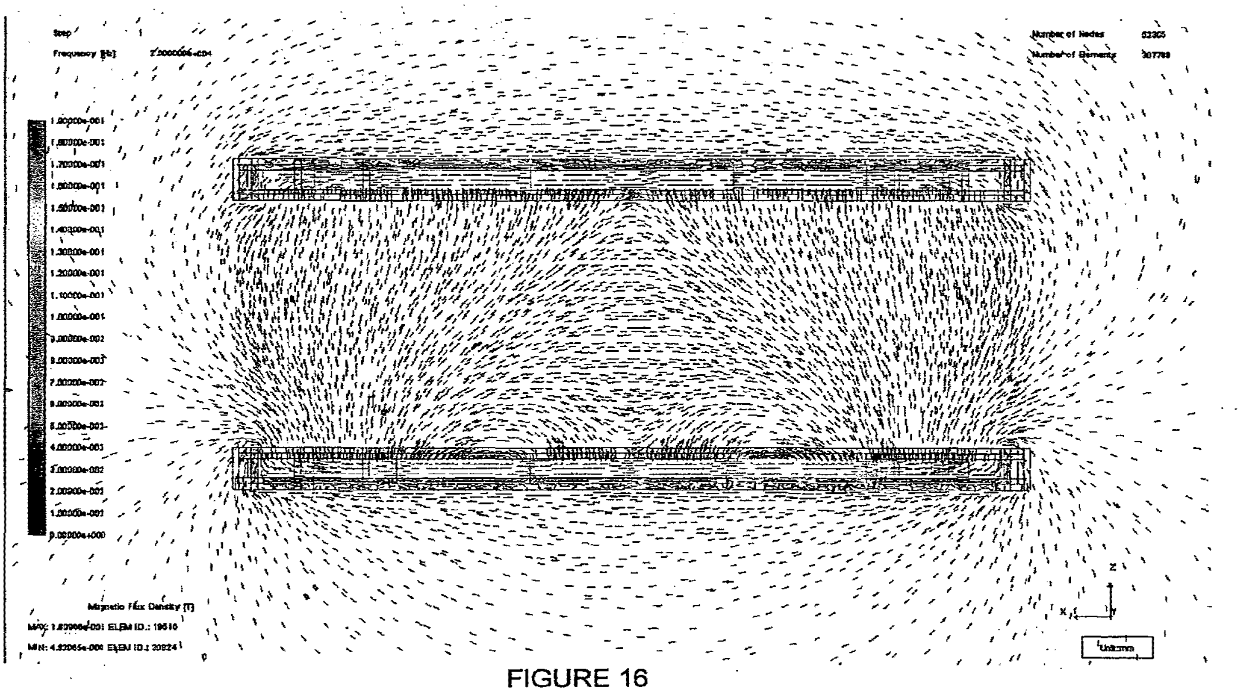

FIGURE 16

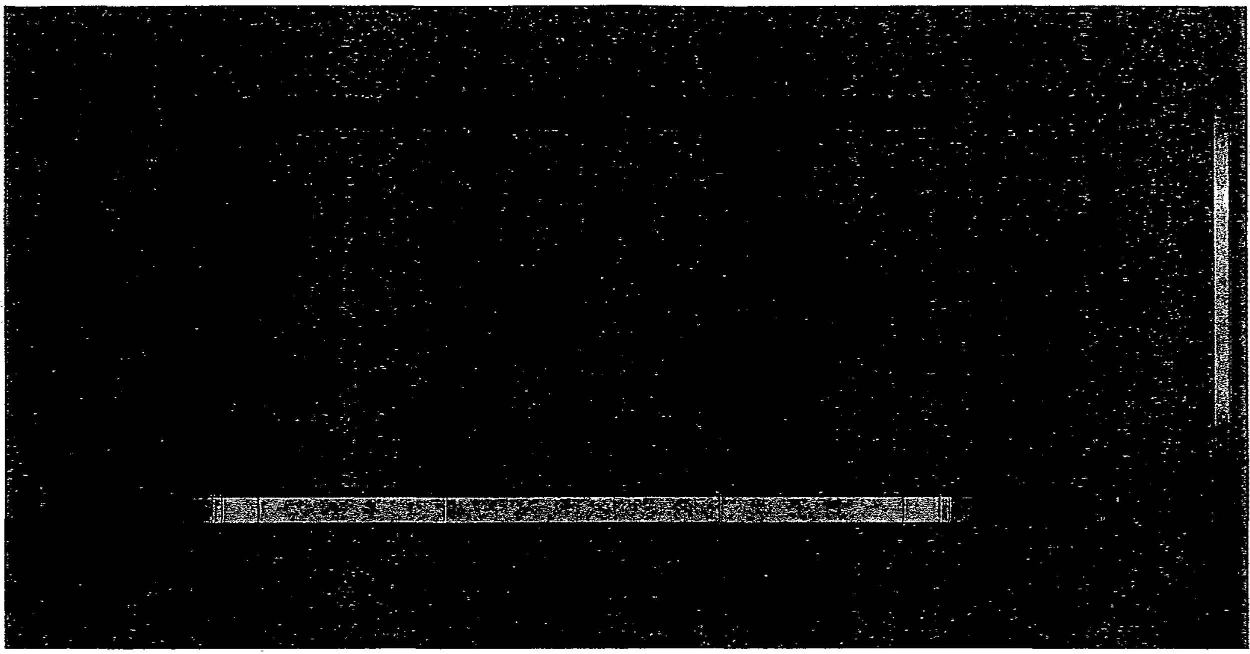

FIGURE 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/NZ2010/000017

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

H02J 3/00 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPI: magnetic, flux, pad, inductive, power, transfer and similar terms
Google Patents& Esp@ce: inductive, power, transfer and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 7,042,196 B2 (KA-LAI et al.) 9 May 2006 Figs. 1b, 4a, 4c; column 18, lines 21-22, column 18, lines 30-40, column 19, lines 13-17, column 19, lines 18-24,	1-3, 5, 8-10, 13, 14, 15 1-7, 12, 13, 15
Y	WO 2005/024865 A2 (SPLASHPOWER LIMITED) 17 March 2005 Fig. 7; page 4, lines 25-30, page 10, lines 6-16	1-7, 12, 13, 15
	WO 2008/140333 A2 (AUKLAND UNISERVICES LIMITED) 20 November 2008 whole document	
	WO 2007/126321 A1 (AUKLAND UNISERVICES LIMITED) 8 November 2007 whole document	

☐ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31 May 2010	24 JUN 2010
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. +61 2 6283 7999	Authorized officer **JAMES WILLIAMS** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6283 2599

Form PCT/ISA/210 (second sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/NZ2010/000017

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [X] Claims Nos.: **17;18**
   because they relate to subject matter not required to be searched by this Authority, namely:
   The claims do not comply with Rule 6.2(a) because they rely on references to the description and/or drawings.

2. [ ] Claims Nos.:
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. [ ] Claims Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. [ ] As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

[ ] The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

[ ] No protest accompanied the payment of additional search fees.

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	7042196	AU	2003233895	AU	2003240999	AU	2003282214
		AU	2008255158	CN	1653669	CN	101699708
		CN	101699709	CN	101699710	CN	101699711
		EP	1506554	EP	1506605	GB	2398176
		GB	2388715	GB	2388716	GB	2399225
		GB	2399226	GB	2399227	GB	2399228
		GB	2399229	GB	2399230	JP	2009010394
		US	2003210106	US	6906495	US	2005140482
		US	2005135122	US	7239110	US	2006076922
		US	7248017	US	2005116683	US	7525283
		US	2006061323	US	7622891	US	2009189565
		US	7714537	US	2009096414	WO	03096361
		WO	03096512	WO	2004038888	ZA	200408863
WO	2005/024865	EP	1665299	US	2007064406		
WO	2008/140333	AU	2008251143	CA	2687060	CN	101689761
		EP	2156532	KR	20100017582	NZ	555128
		US	2010109604				
WO	2007/126321	CN	101461114	EP	2013957	NZ	546955
		US	2009303749				

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX

Electronic Acknowledgement Receipt

EFS ID:	15082206
Application Number:	13752169
International Application Number:	
Confirmation Number:	6134
Title of Invention:	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS
First Named Inventor/Applicant Name:	Andre B. Kurs
Customer Number:	87084
Filer:	John A. Monocello/Keisha Forsman
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0075-P01
Receipt Date:	28-FEB-2013
Filing Date:	28-JAN-2013
Time Stamp:	17:21:01
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Transmittal Letter	WTCY-0075-P01_IDS_CL_02-28-13.pdf	101682 9dad204c0d50af8a2f43c469e30523a6b53fb85b	no	2

Warnings:

Information:

2	Information Disclosure Statement (IDS) Form (SB08)	WTCY-0075-P01_IDS_02-28-13.pdf	380142 5f3a060168b5c0d9bfbc4b7ed86340bd55735b9b	no	58
Warnings:					
Information:					
This is not an USPTO supplied IDS fillable form					
3	Foreign Reference	CA142352.pdf	693325 e5723dd4ffa9701eba6dd133967c8e7879af32bf	no	18
Warnings:					
Information:					
4	Foreign Reference	DE3824972_EngAbstractOnly.pdf	688181 82a9b5b4fd11f1e6939666bdcf8561b8677339a0	no	10
Warnings:					
Information:					
5	Foreign Reference	JP02097005A_EngAbstractOnly.pdf	604537 082a34c0ce1696734d3ac08c81a57726a92d6bb1	no	5
Warnings:					
Information:					
6	Foreign Reference	WO1992017929A1.pdf	3308390 501df9845eef069a9cf90d3e0c627b504850d5dc	no	71
Warnings:					
Information:					
7	Foreign Reference	WO1993023908A1.pdf	1138035 a5e4c81c824d12298743c613a31eafdf8c587727	no	28
Warnings:					
Information:					
8	Foreign Reference	WO1994028560A1.pdf	1616905 5e2bb98f11e8b25d57efaed633b57dac7ccd3189	no	49
Warnings:					
Information:					
9	Foreign Reference	WO1996002970A1.pdf	1329708 8e762e90e706e3351fb0ed0509bb6d1fbf56b045	no	33
Warnings:					
Information:					
10	Foreign Reference	JP09298847A_EngAbstractIncluded.pdf	895747 63f5eb587714a16ef7e51e9bb40a0ed989dc4d3b	no	6

Warnings:					
Information:					
11	Foreign Reference	JP10164837A_EngAbstractIncluded.pdf	4136965 e825ede890597eb982c96e6313d274356bbcc554	no	10
Warnings:					
Information:					
12	Foreign Reference	WO199850993A1.pdf	1348073 486534ff5d88cae6a140b4e01f2cf2e8d464db3c	no	30
Warnings:					
Information:					
13	Foreign Reference	JP11188113_EngAbstractOnly.pdf	563252 3ded78dee1cafacfd6e1c796491741dd6cd4e170	no	8
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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

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Confirmation No.:	6134	
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Title:	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS	

INFORMATION DISCLOSURE STATEMENT

Mail Stop Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

In compliance with the duty imposed by 37 C.F.R. § 1.56, and in accordance with 37 C.F.R. §§ 1.97 *et. seq*., the referenced materials are brought to the attention of the Examiner for consideration in connection with the above-identified patent application.

Further, Applicants respectfully direct the Examiner's attention to the below-listed related non-published applications. These items, which refer to non-published applications that, at this time and according to each application's current prosecution history, may be related to the prosecution of the present case. Related published applications are provided on the accompanying form SB08 where applicable. Applicants' reference to the co-pending applications is not an admission of the materiality of any application or the prosecution history thereof, nor is it an admission that any of the below or attached co-pending applications constitute prior art.

UN PUB. APPLICATION NO.	FILING DATE	ATTORNEY DOCKET NO.
1. 12/639,718	December 16, 2009	WTCY-0026-P06
2. 13/534,966	June 27, 2012	WTCY-0076-P01
3. 13/562,528	July 31, 2012	WTCY-0077-P01
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5. 13/589,992	August 20, 2012	WTCY-0034-P03
6. 13/603,002	September 4, 2012	WTCY-0057-P02
7. 13/608,956	September 10, 2012	WTCY-0064-P01
8. PCT/US12/54490	September 10, 2012	WTCY-0064-PWO
9. 13/612,494	September 12, 2012	WTCY-0065-P01
10. 13/621,503	September 17, 2012	WTCY-0005-P01
11. 13/654,980	October 18, 2012	WTCY-0070-P01
12. PCT/US12/60793	October 18, 2012	WTCY-0070-PWO

13. 13/668,756	November 5, 2012	WTCY-0071-P01
14. PCT/US12/63530	November 5, 2012	WTCY-0071-PWO
15. PCT/US13/23478	January 28, 2013	WTCY-0075-PWO

Pursuant to 37 C.F.R. §1.97(b), it is believed that no fee is required with the Information Disclosure Statement. However, if an Office Action on the merits has been mailed, Applicants hereby authorize the Commissioner to charge any additional fees to Deposit Account 50-3912 in order to have this Information Disclosure Statement considered. The Examiner is invited to contact the Applicants' Representative at the below-listed telephone number if there are any questions regarding this communication.

Respectfully submitted,

MORRIS P. KESLER ET AL.

By their Representatives,

Date February 27, 2013 By /John A. Monocello,III/

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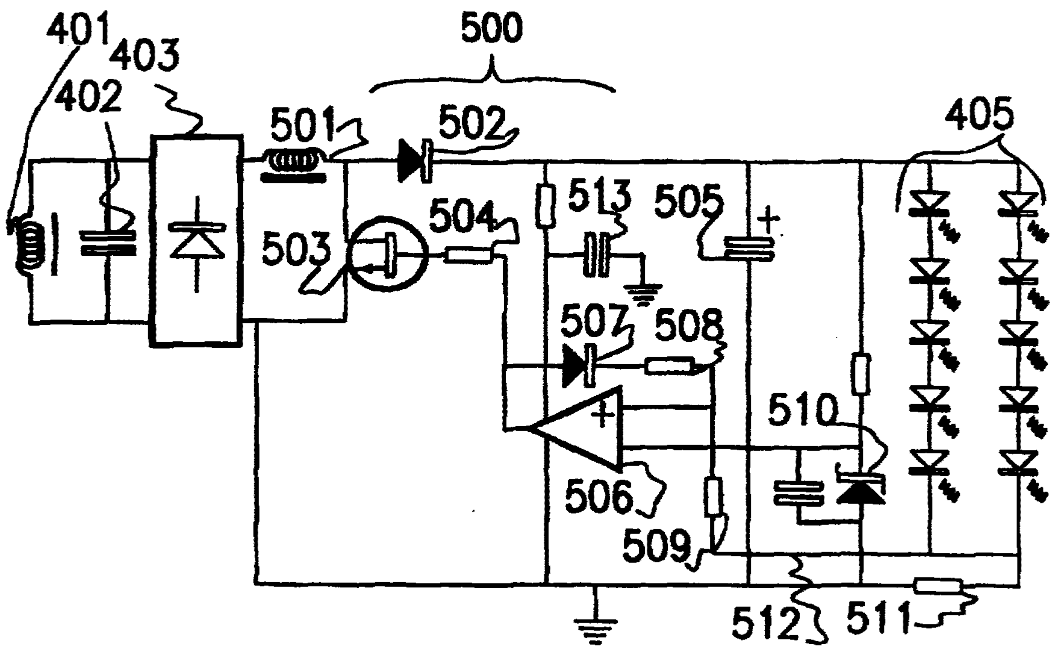
(54) Title: INDUCTIVELY POWERED LIGHTING



(57) Abstract

An inductively powered lamp unit (500) that uses an inductive power pick up comprising a resonant circuit including an inductance (401) and capacitance (402), the induced current circulating in the resonant circuit is limited to a maximum value by a shorting switch (503) that closes a connection across the inductance (401) shorting the resonant circuit. The shorting switch (503) is controlled by a comparator (506) that compares the sensed current with a reference value (510). Voltage control may be similarly implemented. Power is supplied to LED's (405), control data may also be conveyed through the inductive link. Applications include roadway markers, fire escape indicators, underwater or explosive environmental lighting.

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INDUCTIVELY POWERED LIGHTING.

TECHNICAL FIELD OF THE INVENTION

This invention relates to the field of electrically driven lighting, to means for driving one or more lamps using inductive power transfer, and more particularly but not exclusively to the provision of emergency lights, indicating lights, and roadway signal lighting powered from adjacent concealed cables.

BACKGROUND

Transmission of electrical power to articles which consume power over significant gaps by means of inductive power transfer has become increasingly feasible with developments in resonant primary and resonant secondary conductors, means to control and limit the resonant secondaries, and suitable energising power supplies.

There are a number of applications where even a fixed source of light is advantageously driven by an inductively powered source, rather than by simple direct connections using conductive materials.

In most of the situations below, some of which are particularly adverse for conventional lighting, a particularly reliable lighting source is an advantage and in most of these situations the nature of inductive powering of lights will inherently enhance the reliability of a system over that using alternative power supplies such as direct connections, internal batteries, or solar cells with rechartable batteries. Some situations include:

where electrical isolation is necessary, as in lights used in or near water such as in swimming pools or areas where people work in contact with water,
where corrosive or conductive fluids are likely to occur,

where sparks may cause explosions, as in coal mines and in operating theatres or in certain other industrial sites where flammable powders, gases, or the like are found, where the added robustness of buried cables assists in maintaining power transfer during exceptional circumstances,
where a surface on which lights are laid is prone to be replaced, such as on a roadway with a tar sealed surface.

In our US patent 5,293,328 we describe an inductive power transfer system having particular application to a multiplicity of vehicles.

OBJECT

It is an object of the present invention to provide an improved system for the inductive transfer of electrical energy to a source of light or one which will at least provide the public with a useful choice.

STATEMENT OF THE INVENTION

In one aspect the invention provides an inductively powered lamp unit; the lamp unit including one or more lamps capable of radiating light and comprising means to collect inductively transferred power from an external alternating primary magnetic field; said collection means comprising a resonant circuit having a resonant period and including at least one inductance and at least one capacitance; wherein the at least one inductance has a winding adapted to be intersected by a portion of the alternating magnetic field and thereby collect power as a secondary current, means capable of limiting the maximum amount of secondary current circulating in the resonant circuit, means to transfer power at an output from the resonant circuit to the lamp or lamps, and means to control the power provided to the lamp or lamps.

Preferably the means capable of limiting the amount of secondary current circulating in the resonant circuit comprises a shorting switch capable of closing a connection across the inductance; the shorting switch being controlled by a controller provided with means capable of sensing the magnitude of the output so that when the output exceeds a first, higher, predetermined threshold the shorting switch is closed for a period exceeding the resonant period of the circuit, or when the output falls below a second, lower, predetermined threshold the shorting switch is opened;

thereby limiting the secondary current flowing in the resonant circuit so that any magnetic flux generated by the secondary current does not have a significant counteracting effect on the primary field and so that the output of the resonant circuit is not able to exceed a predetermined maximum.

Preferably the means capable of sensing the magnitude of the output is configured so as to sense an output current.

Alternatively the means capable of sensing the magnitude of the output is configured so as to sense a relative or absolute output light intensity.

Preferably the resonant inductance comprises one or more coils, each coil being wrapped around an elongated member composed of a ferromagnetic material having a midpoint, which member is orientated when the lamp unit is placed in position so as to lie with its midpoint substantially adjacent to a primary conductor (capable when energised of radiating a primary field), and substantially at right angles to the direction of the primary conductor.

Preferably the lamp unit has a low profile and at least one window capable of transmitting light; the unit being capable of being attached to the surface of a roadway; and wherein the lamp or lamps comprise one or more light-emitting diodes.

It is also preferable that the lamp unit is packaged in a strong housing having a low profile and at least one window capable of transmitting light; the unit being capable of being attached onto the surface of a roadway, capable of withstanding loads applied by a road vehicle driving over it, and not capable of adversely affecting the integrity of the road vehicle nor deflecting the road vehicle from its course.

Preferably the lamp unit also includes at least one retroreflector unit for passively reflecting the light of vehicle beams.

In another aspect the invention provides a lighting installation comprising one or more inductively powered lamp units as described above, each affixed to a surface of a substrate, each lamp unit being capable of emitting light on being energised by inductive transfer of power across a space from a primary conductor located beneath the surface of the substrate; the primary conductor carrying, when in use, an alternating current.

Preferably the primary conductor radiates an external alternating magnetic field, at a frequency which is substantially the same as the resonant circuit in at least one of the lamp units; the frequency lying in the range of between 200 Hz and 2 MHz.

Preferably the primary conductor is laid down within a substrate in the topology of a loop, connected at a first open end to a power supply and having a second, closed end, the loop comprising a pair of closely spaced conductors, though spread apart in an axis substantially perpendicular to the surface of the substrate at each site where a lamp unit is to be placed.

Preferably the one or more inductively powered lamp units are placed upon the substrate so as to guide a moving person (whether on foot or steering a vehicle) to pass along a particular route.

Preferably one or more lamp units may be selectively addressed using the primary conductor as a medium, so that the light radiated therefrom may be changed from time to time.

Preferably selective addressing is accomplished by superimposing a message over the primary current, in the form of momentary variations of the amplitude of the primary current.

Preferably selective addressing is accomplished by superimposing a message over the primary current, in the form of momentary variations of the phase of the primary current.

Preferably selective addressing is accomplished by superimposing a message over the primary current, in the form of information carried within a carrier frequency, separate from the frequency of the power for inductive transfer.

Preferably selective addressing is accomplished by setting the frequency of the primary current so as to match the resonant frequency of the resonant circuit of the addressed one or more lamp units which, for this purpose, may each be provided with one of a variety of resonant frequencies.

In another aspect the invention provides an installation for laying out marking lights on a road, comprising a set of inductively powered roadway markers, a primary energising loop cable, and a power supply.

Preferably the power supply is capable of energising the primary energising loop in response to an external triggering event.

Preferably the power supply is capable of remotely controlling one or more lamp units by means of the primary energising loop.

Preferably the power supply is capable of remotely controlling one or more lamp units by means of the primary energising loop in response to an external triggering event.

In another aspect the invention provides an installation for laying out marking lights along a fire escape route or egress route in relation to a building, comprising a set of inductively powered lamp units, a primary energising loop cable capable of being buried within a substrate of the building, and a power supply having a battery backup; the installation being capable of being activated during an emergency.

Preferably the primary alternating current is a sine wave.

Preferably it has a frequency in the range of from 500 Hz to 1 MHz, although more preferably it has a frequency in the range of from about 10 KHz to about 50 KHz.

Preferably the alternating current is generated within a resonant power converter.

Preferably the concealed primary cable is electrically insulated and mechanically protected by being embedded within the substrate. Optionally it may be sealed into a slit cut into the substrate with a circular saw or the like.

Preferably the concealed cable comprises a pair of conductors orientated substantially perpendicular to the surface of the substrate, although optionally a pair of conductors may lie side by side within parallel slits. Preferably the cable is composed of a litz wire or other wire having a high surface-to-volume ratio such as a strip.

In another aspect the invention provides a lamp unit within a strong housing, comprising a resonant secondary or pickup coil and capacitor, one or more light-emitting lamps, and optionally power conditioning means.

Optionally the lamp unit has a low profile and may be applied to a road surface.

Optionally the lamp unit also contains one or more retro-reflector modules.

Preferably the power conditioning means comprises a current limit and optionally this may be built into light-emitting diodes or be an intrinsic property of metallic filament lamps.

In the case of light-emitting diodes, a pair of lamps or of banks of lamps may be connected in inverse parallel in order to utilise both half-cycles of an AC waveform.

In a further aspect the invention may provide a road-markings set of lamps comprising a series of lamp units, an embedded cable, and a power supply.

Optionally this invention may be used to highlight dangerous portions of a highway. Optionally it may be energised by the proximity of a vehicle.

In a related aspect the invention provides a pedestrian crossing, comprising means to detect the presence of a waiting pedestrian, sets of road markings, and a sequencer to energise the road markings lamps for a period of time before signaling to the pedestrian that a warning has been given.

In a yet further aspect the invention may provide a fire escape indication set of lamps.

Preferably the power supply for the invention is driven from a set of storage batteries so that it can operate in the at least temporary absence of a mains supply.

DRAWINGS

The following is a description of a preferred form of the invention, given by way of example only, with reference to the accompanying diagrams.

Fig 1: is an illustration of a section through a light housing above a pair of primary conductors embedded in a substrate.

Fig 2: is a perspective view of a row of lights energised inductively by alternating current in a concealed cable.

Fig 3: illustrates energisation using a cable carried within a single vertical slit.

Fig 4: shows a typical circuit for use in a light housing of the present invention.

Fig 5: shows a preferred circuit including control of the resonant pickup circuit.

Fig 6: shows a preferred circuit like Fig 5, also including means for detecting and responding to control impulses.

Fig 7: shows the interior of a roadway marker incorporating a pair of ferrite strips as pickup devices to collect inductive power.

Fig 8: shows the disposition of the primary inductive loop in an installation.

Fig 9: shows the flux about the primary conductors, entering the ferrite mainly at its ends.

Fig 10: shows options for controlling the output of individual lamp units by way of currents within the primary conductor.

PREFERRED EMBODIMENTS

One application of this invention is for 'self-illuminated "cats-eye style" roadway reflectors'. This specification describes an installation for laying out a series of marking or warning lights (which may also include retro-reflectors) along a generally linear course, and particular applications for these lights include roadway lighting. Here they may be substituted for the well-known "cats-eye" retro-reflectors which are placed upon the road and being of low profile, may be driven over. Many applications beyond the known range of uses for "cats-eye" reflectors become available for a system of self-powered units.

In relation to another application; fire egress lighting, the type of energisation used in this invention offers advantages over conventional lighting in that the invention is more resistant to fire damage than other types of emergency guidance and therefore will persist for a longer time.

We shall describe a basic type of light unit and cabling, (Example 1) and a more advanced type of light unit (Example 2) as reduced to practice, but it should be realised that these examples are in no way limiting and that further examples, exploiting the characteristic features of the invention, may become obvious to the skilled reader.

In principle, we feed alternating current at preferably about 36-40 KHz and at a sufficient current (typically 10-12A) into a cable buried within the substrate of the road or building or the like, and provide radiated magnetic flux from the cable at discrete sites for use in energising lamp units adapted for using inductive power transfer. Although it is convenient and effective to use resonating current and a resonant power supply to power the primary inductive loop (the cable) power of similar characteristics could be generated in other ways.

Principles of resonant pickup of inductive power do apply for effective operation of the lamp units and the Examples illustrate this.

EXAMPLE 1.

Our most basic system comprises:

(a) A power supply 200, generating a sine-wave output of a desired power level at usually around 40 KHz into a (mainly inductive) resonating cable 201, and in the applications described herein here at a power level of perhaps up to 100-200 watts although much higher levels can be generated.

(b) A cable 201 of up to 800-1000 m length having closed-loop topology which is placed alongside the intended position of a or each lamp unit 203, 204. We prefer to use litz wire in installations where efficiency and long-term reliability at high loading levels is important, although for cheapness ordinary insulated copper (or aluminium) cables can be used.

(c) One or more lamp units 203, 204, 100, laid out in a series like a chain, each of which units comprises a pickup coil preferably resonant at the power supply frequency, one or more lamps, and preferably power conditioning means. We generally prefer light-emitting diodes as they are reliable.

The cable can be laid out as a single U-shaped loop or can be run out along several branches, though preferably as a single length without joins. A particular application may require tuning, as only one length has the correct resonant frequency and for this purpose the installer can either vary the resonating capacitors within the power supply or add toroids (including air gaps) over the cable to artificially increase its inductance and thereby simulate a longer cable than is actually present. We prefer to run the cable at a low power and at a low voltage, for safety's sake.

As there are no exposed metallic conductors in an inductively powered lighting system, it may be used for long periods in a corrosive atmosphere or one where seawater is present. The relative absence of risk of sparks allows its use in inflammable or explosive situations.

Fig 1 illustrates the road warning lamp 100 of Example 3 in place on a road surface 102. In this drawing we have shown the energising cables 109 in a parallel pair of slits 108, although roading engineers prefer a single slit as 302 in Fig 3. The lamp 100 comprises a tough housing 101, having a clear or translucent window in front of an array of lights or preferably light-emitting diodes 103. These diodes derive their power from a secondary pickup coil 104 which is made resonant at about the preferred operating frequency by a capacitor 106, and the lamps are driven through a rectifier module 107. The slits 108 in the roadway 102 are preferably filled with a matrix. Fig 3 illustrates the vertical wiring alternative, in which the secondary coil 304 is placed above the slit 302 containing the pair of wires 305. Preferably the slit is cut deeper at about the intended position of each lamp unit 306, so that one of the cables 308 may be brought deeper and so increase the inductive field available at that point. Between lamp units, the cable 305 has a reduced inductance where its conducting members are closer together and so an increased length of cable can be driven with a limited voltage. A further way to enhance the magnetic flux at a lamp site is to use a ferrite rod or peg as at 205 in Fig 2. This may limit the freedom of placement of lamp units. Ferrite may be incorporated within lamp units, as suggested by the core of the inductor 401. At least one conductor may, instead of being litz wire, be a flat strip of metal, as this will raise the amount of surface available for carrying skin-effect currents.

Fig 4 shows one preferred circuit, in which 401 and 402 comprise a resonant circuit, 403 is a rectifier to make a DC voltage, and 405 is a set of LED lamps in series. 404 may be a shunt regulator acting as a current limiter, or a flasher module. Preferably, 404 is a repetitively acting shorting switch (see 503 with 501, 502 in Fig 5). If a current limiter is not used, the operating current in the lamps may be set to the usual preferred value of around 20 mA by choosing from a range of lamp units or placing a lamp unit so as to give a predetermined brightness.

EXAMPLE 2.

This portion of the specification describes a preferred inductively powered lamp unit. There are two versions, shown as Fig 5 (no ability for external control) and Fig 6 having internal means for detecting and responding to control impulses. Certain parts of these two circuits have been discussed in relation to Fig 4.

The non-controlled circuit is shown as 500 in Fig 5. The resonant pickup coil 401 may actually comprise two coils 704 (as in Fig 7) wound around each ferrite strip 703, and if several coils are used they are placed in series. The capacitor(s) of the resonant circuit are shown at 402; here 247 nF and including provision (pads) on the circuit board for adding a small "tuning" capacitor. The resonant frequency is at about 40 KHz. The bridge rectifier 403 is made up of four diodes (type BAT83), the output of which is passed through an inductor 501 (7.5 mH) and through a steering diode 502 (BAT83) to charge a capacitor 505 (33 μF, 25V). Power FET transistor 503 (type IFRD110) is used as a shorting switch to short out the resonant circuit from time to time, each time lasting for a number of cycles. Means to control the shorting switch comprise the operational amplifier/comparator 506 (type MC33171) which has at its inverting input a zener diode 510 (type TC9491) as a voltage reference. The comparator compares the zener voltage with a proportion of the current passed through the output lamps at resistor 610 (30 ohms) (via a 1K resistor 509) and uses a diode 507 (type BAT83) in series with a 68K resistor 508 as a non-inverting feedback loop, for hysteresis. This control circuit provides a controlled current centered on a design value and fluctuating to a small extent about that value when the resonant circuit is alternately shorted, then allowed to charge the capacitor 505. Typically, there are about 500 shorting events per second.

Providing current regulation of this type allows the lamp unit to emit substantially a controlled amount of light regardless of its position, within limits. Exact placement is not critical. It is not uncommon for a marker on a hot, tar-sealed road to be displaced laterally by tyres of heavy vehicles and this regulation provides some tolerance to displacement after positioning.

In our preferred circuit two chains (405) of high-intensity (orange) light-emitting diodes (type HLMT-CL00) are used to radiate light to one side of the lamp unit. Of course, other colours could be used.

Variations to Fig 5 include (for example) monitoring the ambient light with a light-dependent resistor, so that the brightness of the marker is proportional to daylight, or regulating current in terms of actual light output rather than lamp current.

Fig 6 illustrates one means 600 for rendering the circuit capable of being externally controlled. As suggested in Fig 10, it is possible to superimpose control signals over the resonant power circulating in the primary loop. This circuit is well-adapted for control by means of low-frequency tones or dual tones. Fig 6, which is a development of Fig 5 and includes the components of Fig 5, also includes means to short-circuit the pickup coil 401 from time to time (typically once per millisecond) and during that time read the current circulating in the primary loop. This circuit is tentative because it appears that an application-specific integrated circuit will be an appropriate implementation.

Box 602 represents a clock generator producing a pulse of 50 μsec every 1 msec. (There is no requirement to synchronise all clocks in all markers in an installation to pulse synchronously). Its output is passed to (a) an AND gate 606 shared by the comparator and supplying the gate of the power FET, 503. Its output also goes to the control input of a sample and hold circuit 603, which reads the current across a current sense resistor 601 inserted in the source lead of 503. At times when the switch 503 is closed, the resistor will, after a cycle or two at 40 KHz, or about 50 μsec, have a voltage on it representing the current in the primary inductive loop at that time. This voltage is taken to the signal input of the sample and hold circuit, and the output is passed to a circuit 604 which comprises a tone detector.

In this simple example we have provided a resistor 605 between the tone detector output and an input of the comparator, so that activation of the tone detector has an effect on the setting of the comparator 506 and the mean brightness of the lamps is altered as a result of detecting a specific tone carried within the primary inductive loop. "Stealing time" from the action of the comparator as for Fig 5 is of little moment because the inherent regulation can compensate. Repetitive sampling at a rate of about 1 KHz will satisfy the Nyquist criterion for control signals which are single or multiple tones of up to about 250 Hz.

Clearly there are many possible options; such as whether or not the tone detector outputs switch from one state to another state on each tone detection, or change state only during a tone, and there may be more than one tone and hence more than one action, or the detector output may be treated as a code signal passed to a microprocessor which will execute one of a series of actions on the light output from the lamps 405. There may be a red series and a yellow (or orange, green or blue or even infra-red) series of lamps which can be driven separately, or separately controllable lamps may face in various directions.

HIGHWAY MARKERS

In Fig 7, we show a highway marker 700 from above. The casing 701 encloses a pair of ferrite cores 703 (only one core and coil is labelled) which are on each side of a printed-circuit board 702 bearing the circuit of Fig 6 and along one edge a row of light-emitting diodes 705. We have not also illustrated retro-reflectors in this diagram, but they may be interspersed with the diodes 705.

Fig 8 shows part of a roadway installation in side view. A power supply 801 puts power into a loop of cable forming a primary inductive loop. In the portions where the two conductors are close together (802) the flux tends to cancel out and the cable radiated little flux. Hence it may be elongated. At positions (803) where a lamp unit (804) may be placed, the cable is spread apart, preferably using a spreader (805) to maintain spacing during and after installation. The end of the loop remote from the cable is shown at 806.

If the power supply is a resonant power supply, and this type of energisation is economical and, by energising the cable with a sine wave, minimises problems of radiation of radio or electromagnetic energy, it is preferable to use litz wire for the cables. We prefer 4 mm^2 litz wire. Our typical resonant power supplies are run at 24 volts, which allows for battery backup and safe running and at 24 volts it can power about a 25 metre long primary inductive pathway, and about 10-14 amperes at a 40 kHz frequency circulates in the cable when in operation. Using a higher voltage allows longer primary inductive loops to be used. If an unusually short cable is used, its inductance may be boosted with a lumped inductance, trimmed to make the installation resonate at 40 kHz.

EXAMPLE 3.

Our basic system may be embellished by providing for control of the output of the lamp units, either as a group or individually. Preferably this control is more than simply turning the entire set on or off. One approach is to provide each lamp unit in an installation with control electronics that can detect signals of some sort radiated from the primary conductor cable, because this cable is already functionally connected with all operational lamps.

It is possible to superimpose a message over the primary current, in the form of momentary variations of the amplitude of the primary current, which can be sensed within the or each lamp unit as changes in the operational settings of the regulating mechanism. Coding of the amplitude could follow any convenient code, such as the letters of the ASCII coding system, or Morse code, or some other system such as those used in serial bus digital control, such as the I^2C bus. This requires a small amount of complexity in each lamp unit that is capable of being addressed. Each "bit:" of the code would have to be sufficiently long in time to "catch" any lamp unit that at the time has shorted its inductive pickup coil, unless a separate data sensing arrangement was used. Information may be carried within a carrier frequency, separate from the frequency of the power for inductive transfer.

Variations of the phase of the primary current are another way to transmit data.

A cheap way of addressing lamp units is to make a variety of units each having a different resonant frequency. Then only those lamp unit that resonate at the frequency of the transmitted power can operate. If a resonant power supply is used, it might be provided with subsidiary switchable resonating capacitors. By this means it is possible to create a traveling wave of flashing lights, for decorative or directional purposes.

FIRE EGRESS INDICATION LAMPS

This is - as a preferred example - a fire-exit indicating network, which when energised provides a chain of illuminated beacons 203, 204 along the floor of a building. The beacons are intended to direct people to the nearest fire exit. In addition to the basic system above, we would usually include means to supply the power from batteries as in an emergency the mains power is likely to fail, and means to cause the power supply to start up when an emergency condition, such as a blackout at night, and/or a fire alarm is in effect. The energising cable 201 is preferably embedded into a concrete or similar floor, and may be embedded at a depth of several inches as our inductive power transfer system is a loosely coupled one that tolerates spacings of that order. The energising cable is placed along the floors of passageways that lead to fire exits, preferably along the centre lines of the passageways. The drive voltage may be as low as 12 volts, depending on the power required.

The lamp units are preferably light-emitting diodes or the like, embedded in wear-resistant transparent or translucent housings so that they remain capable of emitting visible light even after years in position. Preferably the lit lamps display a clearly understood and preferably standardised direction so that people in panic are not confused. Optionally the lamps or the power supply may be operated in an attention-getting flashing mode and optionally the lamp units may also generate audible signals. In fact, they may also generate vibrations so that blind people can locate and use the indicators. Our preferred lamp units may have bases about 10 cm square - containing the resonant pickup coil - with a height of perhaps 5 mm, and have a top made of a wear-resistant material such as polycarbonate or even glass. They may include other electronic devices such as a voltage sensor and a switch to short-circuit the coil when the voltage rises above a threshold. (This means of regulation limits the tendency of a resonant secondary to develop a large circulating current which tends to block the primary current from reaching past this secondary coil to reach others. On the other hand, as this application of inductive power transfer has substantially constant operating parameters, and it may be preferable to select a lamp unit for a particular position from a range of units having various brightnesses - actually flux collection and conversion capabilities.

These illuminated display devices may be glued onto a carpet, or let into holes cut in a carpet, or glued onto a hard surface, and need no electrical connections. Thus replacement of damaged or displaced units is not a skilled job. Typical buildings where the devices may be used include hotels, schools, hospitals, auditoriums, and other public buildings.

Advantages of this device include that the system is located on or in floors where it is unlikely to be damaged until after surrounding structures have been destroyed, and the floor location is compatible with people who are keeping low or even forced to crawl in order to avoid smoke and fumes. (Conventional practices of placing often illuminated EXIT signs high up above doorways can lead to obscuration by smoke).

The device has inherently a high reliability because the destruction of any lamp unit by flames or the like does not compromise the remainder - rendering its pickup coil an open circuit or a short circuit does not substantially affect the primary current and so the remainder of the lamp units may remain lit.

Furthermore the lamp units themselves are electrically isolated, and the energising power supply is preferably provided with fault detection means so that it provides no electrical hazards in itself.

A variant of this device can be used in theatres, hotels, houses and the like, and would be energised steadily or on pressure on a sensing pressure pad, to better indicate the positions of stairs in the dark.

ROADWAY - DETAILS

A similar arrangement can be used on roadways to better indicate lanes routes hazards and other events to motorists. A particular application is in providing warnings at pedestrian crossings. In the pedestrian crossing application, the power supply is connected to a reliable source of AC power and is arranged to be energised when (for example) a person steps onto a contact pad at the kerbside, or when a conventional button is pushed. The energising cables are placed along selected patterns and may be embedded within slits cut with a diamond saw. As our inductive power transfer system uses only loose coupling, the cables may be several centimetres deep and even the later addition of further road surfaces will not affect coupling of power from the cables. The cables are preferably sealed in place, using a suitable adhesive or the like so that the installation is substantially permanent.

The preferred slit dimensions for slits cut into roadways is 5 mm wide by 10 mm deep, rather than the more idealised parallel pair of slits shown in Fig 2. (Roads tend to crack and chip between parallel, close slits). Therefore we have also made a modified arrangement in which one of the pair of wires forming the cable is above the other, as shown in Fig 3, and optionally in order to enhance the flux at the position of a lamp we make the slit deeper at that site and push one conductor further away from the road surface at that point.

Preferably the cables are energised from a power supply operating at 12 or 24 volts, compatible with storage batteries fed from a wind generator or solar cells, although a higher voltage may be needed to inject resonant power into a longer run of cable, particularly if the more efficient litz wire is not available.

The lamp units may be built into the existing "cats-eye" housings widely used on roadways to demarcate lanes by means of retro-reflective inserts. Glues or other means to mount these devices are well known and the dimensions of existing housings are adequate for housing the power pickup coils, control electronics, and lamps. In order to catch drivers' attention we expect that high-intensity beams from light-emitting diode lamps will be used, aimed towards oncoming traffic. These lamps may be pulsed in a synchronised, attention-gathering manner by for example pulsing the power supply on and off. As the preferred resonant frequency is high, the decay time for power is small. Forty cycles of 40 KHz power = 1 millisecond. Alternatively the internal regulator within each housing may be arranged to operate in a cyclic manner, although this may not give as clear a signal of danger to an approaching driver.

In the pedestrian crossing application, a vandal-proof warning device would preferably comprise (a) a sensing pad for detecting a waiting pedestrian, a sequencer to first energise the array of warning lamps for a suitable time, and then means to energise a "Cross now" or "Walk" signal of some type which may be (a) conventional illuminated signs, (b) audible, and/or (c) made of further lamps on the roadway, this time over the crossing itself and orientated so that they are visible to the pedestrian.

In cases where the currents in the buried cables are likely to affect inductive sensors used for controlling automatic traffic lights, the operating frequency can be selected to be separated from that used by the traffic light, and the relatively low harmonic content of the resonant power means that a simple trap tuned to the fundamental frequency should reject any interference to the traffic light sensor.

In case further buried cables are used to provide power to moving vehicles according to our inductive power transfer principles, a separation in frequency should minimise any cross-interference between cables or affecting the pickup coils. It may well be preferable to adopt a different frequency of perhaps 40 KHz for these low-power lighting devices and run the vehicle power cables at 10 KHz, whereupon the tuned resonant circuits of the lighting devices should not develop any significant power when exposed to magnetic flux at a 10 KHz cycle rate.

VARIATIONS

In order to arrange for switching of lanes on a roadway, for example at a bridge where diurnal reversals in the flow of traffic promote the use of more lanes in one direction than another at one time, lane switching may be accomplished by linear arrays of illuminated housings which are laid on the road along predetermined lines or courses, and illuminated as required in order to steer cars into lanes.

These types of lights can also be used to demarcate sharp corners and the like and enhance areas of poor visibility. Here they have the advantage over conventional reflectors that by generating their own light they are effective outside (and particularly to either side of) the region illuminated by the headlights of a car. Preferably warning lights intended for motorists are intermittently energised by the approach of a motor vehicle, using a pressure pad or a proximity sensing device so that they can be maintained from a rechargeable storage battery with a solar cell as a source of power. When in operation, the bands of light emitted from the arrays of lamp units may extend far beyond the range of the driver's headlights.

UNDERWATER VARIATIONS

As inductive power transfer is inherently unaffected by non-magnetic materials that may appear or disappear in the gap, it may be used under water. Accordingly a series of housings containing lamps may be placed on the bottom (and sides, and edges) of a swimming pool to indicate lanes, and energised as required by buried cables concealed in the substance of the pool floor. These lamp units may be fixed in place, and various combinations energised by selecting particular runs of cable for various combinations of lamp unit spacing. Alternatively they may be clipped into retaining clips as and when required. Magnets, particularly magnets formed from ferrites, may be used to temporarily locate lamp units. Adjacent, magnetically soft ferrites may be included to act as flux concentrators.

OPTIONS

A light housing could be provided with more than one pickup coil and ancillary light sources, so that by changing the frequency of the power in the primary cable, different colours of light (for example) could be produced. Power modulation may also be arranged to select different lamps. Light emitting diodes are at present available in red, orange, yellow, green and blue, although the latter two are not particularly bright. Laser diodes of various visible colours may soon become cheap enough for use in this application, where their enhanced beam-forming ability will aid in the detection of these lights at a distance. Light-emitting diodes have an advantage in that their ON-voltage can be used to provide a degree of intrinsic regulation as shown in Figures 3 and 4 where even the rectifier can be deleted if a second string of LEDs with the opposite polarity is placed across the first string.

As the light housings will generally be fixed it is possible to extend the cable length by bringing the wires close together unless, at the site of a lamp, they are spread apart so that the magnetic field increases. To further enhance the field, a loop can be constructed in the primary cable, or a magnetically permeable coupler such as a ferrite can be used.

In situations where lateral variations in lighting may extend beyond the "tram-track" layout of primary coils, one wire may be placed above the other, providing a more diffuse field. If this field is weaker, a ferrite flux concentrator may be provided to increase the power available within the secondary device.

Movable lights may be mounted on a light track or on a surface such as a wall, ceiling, or table in such a way that they can be held in position without requiring direct electrical contact with the power source. In one example wall mountable lights can be mounted in one or more plastic channel members attached to the wall and may be allowed to slide along a channel member to a desired position whilst picking up inductive power from a primary circuit embedded in the wall or in the base of the channel member. As the attachment of the light to the surface does not require any direct electrical contacts whether sliding or stationary it is possible to adopt any number of different attachment means for the location or placement of the lights. The lights may take any desired shape or design.

In the case of a photographic studio the lights may have a base containing the resonant pick-up and an arm or stem extending therefrom which a suitable reflector or light housing is mounted and containing the light source. In such a case it is preferable to position the primary resonant circuit (or circuits) in a sinuous pattern in the wall or ceiling so that the lamp bases can be placed anywhere on the surface and still receive enough resonant power to activate its light source. An advantage of placing the primary cables in a "slit configuration" as previously described is that the primary cables generate an external alternating magnetic field which is predominately parallel to the surface of the substrate, allowing the lamp base to be moved from side to side of the "slit" containing the pair of cables and still receive enough power for its light source.

ADVANTAGES

Inductively powered lamp units in accordance with this invention have a variety of uses where direct contact between the power cables and the lamp units is undesirable. Examples of such uses include lights used in or near water such as in swimming pools or areas where people work in contact with water, lights used in corrosive environments or where conductive fluids are likely to occur, lights used in mines and in operating theatres or in certain other industrial sites where flammable powders, gases, or the like are found, and lights used in roadways, or where the lights need to be moved relative to the power supply (eg in display areas or in photographic studios).

Finally, it will be appreciated that various alterations and modifications may be made to the foregoing without departing from the scope of this invention as set forth.

CLAIMS

1. An inductively powered lamp unit; the lamp unit including one or more lamps capable of radiating light and comprising means to collect inductively transferred power from an external alternating primary magnetic field operating at at least one selected frequency;
said collection means comprising a resonant circuit having a resonant period corresponding to a selected frequency and including at least one inductance and at least one capacitance;
wherein the at least one inductance has a winding adapted to be intersected by a portion of the alternating magnetic field and thereby collect power as a secondary current,
means capable of limiting the maximum amount of secondary current circulating in the resonant circuit,
means to transfer power at an output from the resonant circuit to the lamp or lamps,
and means to control the power provided to the lamp or lamps.

2. An inductively powered lamp unit as claimed in claim 1 wherein the means capable of limiting the amount of secondary current circulating in the resonant circuit comprises a shorting switch capable of closing a connection across the inductance;
the shorting switch being controlled by a controller provided with means capable of sensing the magnitude of the output so that when the output exceeds a first, higher, predetermined threshold the shorting switch is closed for a period exceeding the resonant period of the circuit, or when the output falls below a second, lower, predetermined threshold the shorting switch is opened;
thereby limiting the secondary current flowing in the resonant circuit so that any magnetic flux generated by the secondary current does not have a significant counteracting effect on the primary field and so that the output of the resonant circuit is not able to exceed a predetermined maximum and so that the amount of light radiated from the inductively powered lamp unit is, above a lower limit of efficiency, substantially independent of the coupling efficiency between the external magnetic field and the resonant circuit.

3. An inductively powered lamp unit as claimed in claim 2 wherein the means capable of sensing the magnitude of the output is configured so as to sense an output current.

4. An inductively powered lamp unit as claimed in claim 2 wherein the means capable of sensing the magnitude of the output is configured so as to sense an amount of emitted light.

5. An inductively powered lamp unit as claimed in claim 2 wherein the resonant inductance comprises one or more coils, each coil being wrapped around an elongated member composed of a ferromagnetic material having a midpoint, which member is orientated when the lamp unit is placed in position so as to lie with its midpoint substantially adjacent to a primary conductor capable when energised of radiating a primary field, and substantially at right angles to the direction of the primary conductor.

6. An inductively powered lamp unit as claimed in claim 4 wherein the lamp unit has a low profile and at least one window capable of transmitting light; the unit being capable of being attached to the surface of a roadway; and wherein the lamp or lamps comprise one or more light-emitting diodes.

7. An inductively powered lamp unit as claimed in claim 1 wherein the means capable of limiting the amount of secondary current circulating in the resonant circuit comprises a shorting switch capable of closing a connection across the inductance; the shorting switch being controlled by a controller provided with means capable of sensing the magnitude of the output in comparison to a reference voltage and capable of sensing the phase of the secondary current, and capable of closing the shorting switch for a part of each cycle of the secondary current, as a in proportion to the difference between the output and the reference voltage, so that in use the magnitude of the output is held at a substantially constant level, and also so that the secondary current flowing in the resonant circuit is controlled and does not have a significant counteracting effect on the primary field, so that the output of the resonant circuit is not able to exceed a predetermined maximum, and so that the amount of light radiated from the inductively powered lamp unit is, above a lower limit of coupling efficiency,

substantially independent of the coupling efficiency between the external magnetic field and the resonant circuit.

8. A lighting installation comprising one or more inductively powered lamp units as claimed in claim 2, each affixed to a surface of a substrate, each lamp unit being capable of emitting light on being energised by inductive transfer of power across a space from a primary conductor located on or beneath the surface of the substrate; the primary conductor being capable of carrying an alternating current.

9. A lighting installation as claimed in claim 8 wherein in use the primary conductor radiates an external alternating magnetic field which is predominately parallel to the surface of the substrate, at a frequency which is substantially the same as the selected resonant period of the resonant circuit in at least one of the lamp units; the frequency lying in the range of between 200 Hz and 2 MHz.

10. A lighting installation as claimed in claim 9 wherein the primary conductor radiates an external alternating magnetic field at a frequency selected from a frequency range between 10 kHz and 80 kHz.

11. A lighting installation as claimed in claim 10, wherein the light produced by the or each lamp unit is capable of being controlled by control signals superimposed from time to time on the alternating magnetic field radiated by the primary conductor.

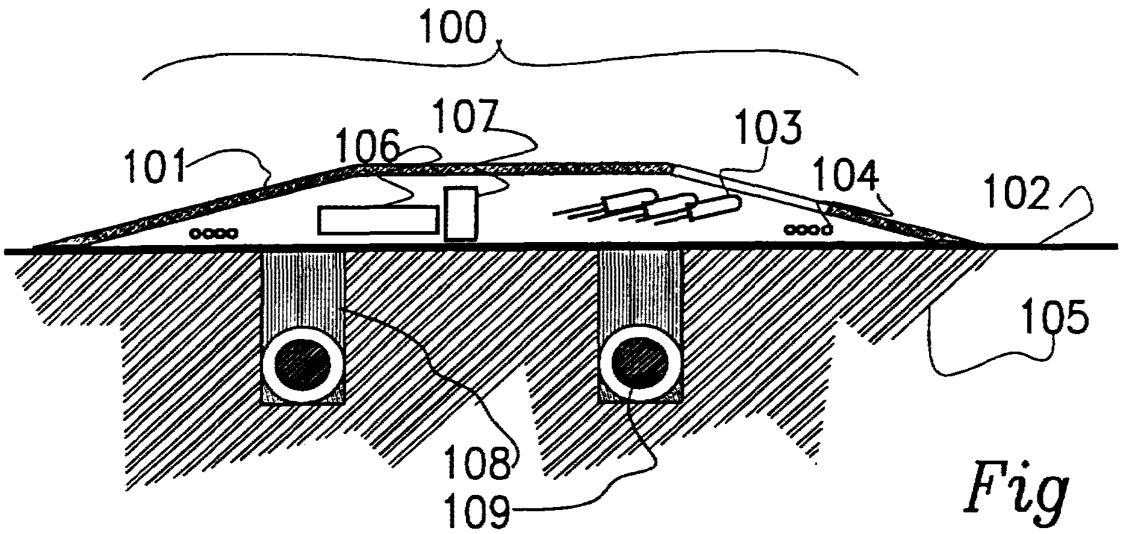

Fig 1

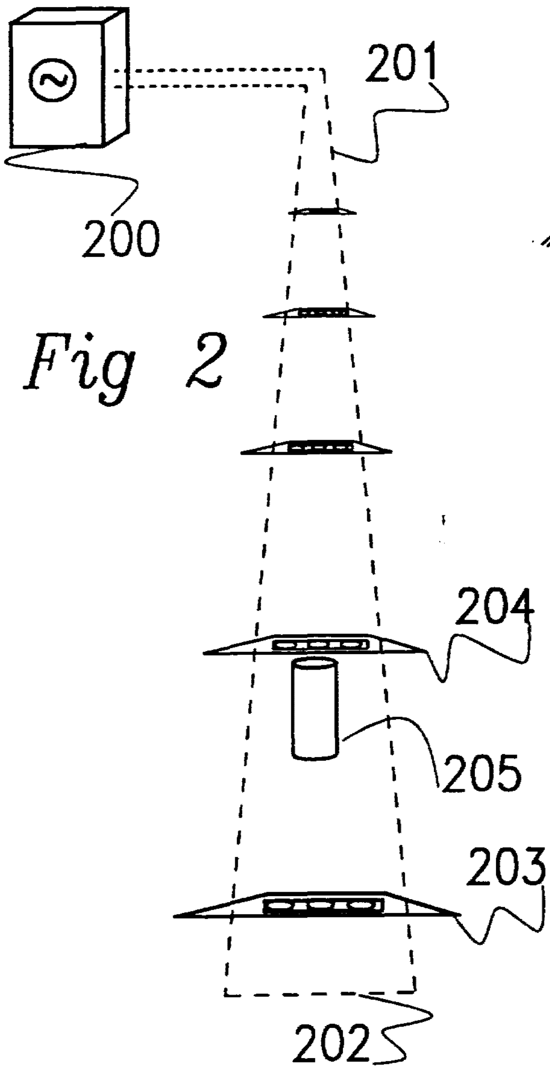

Fig 2

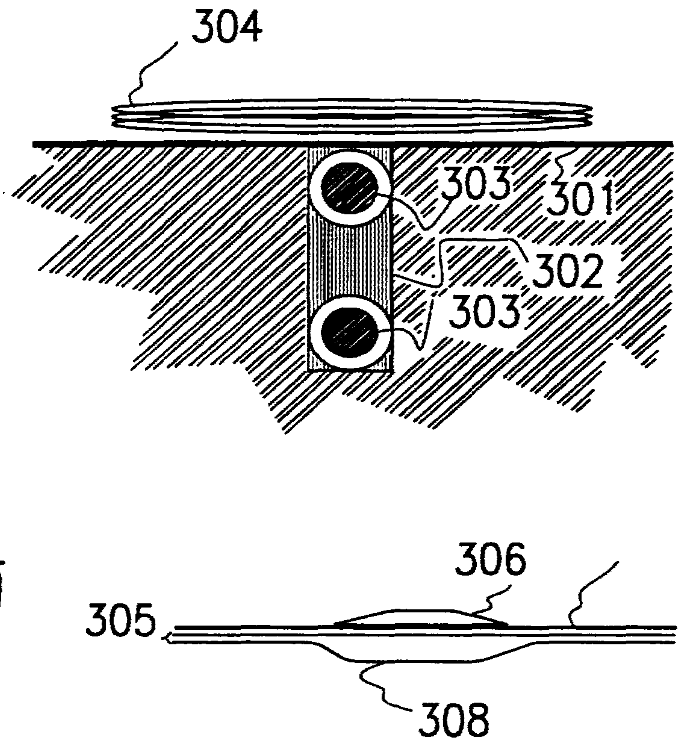

Fig 3

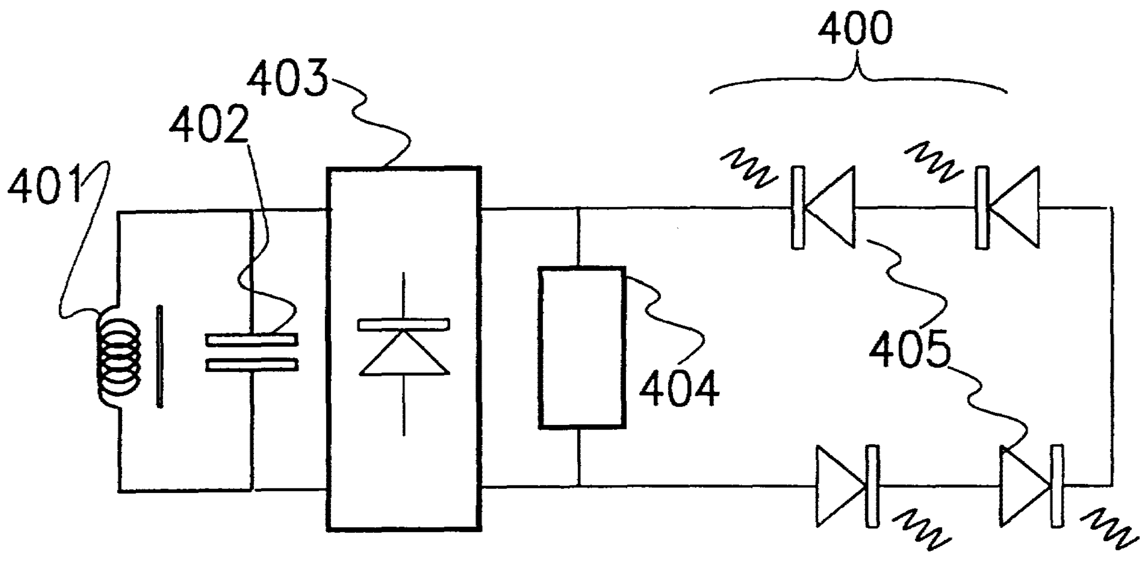
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Fig 4

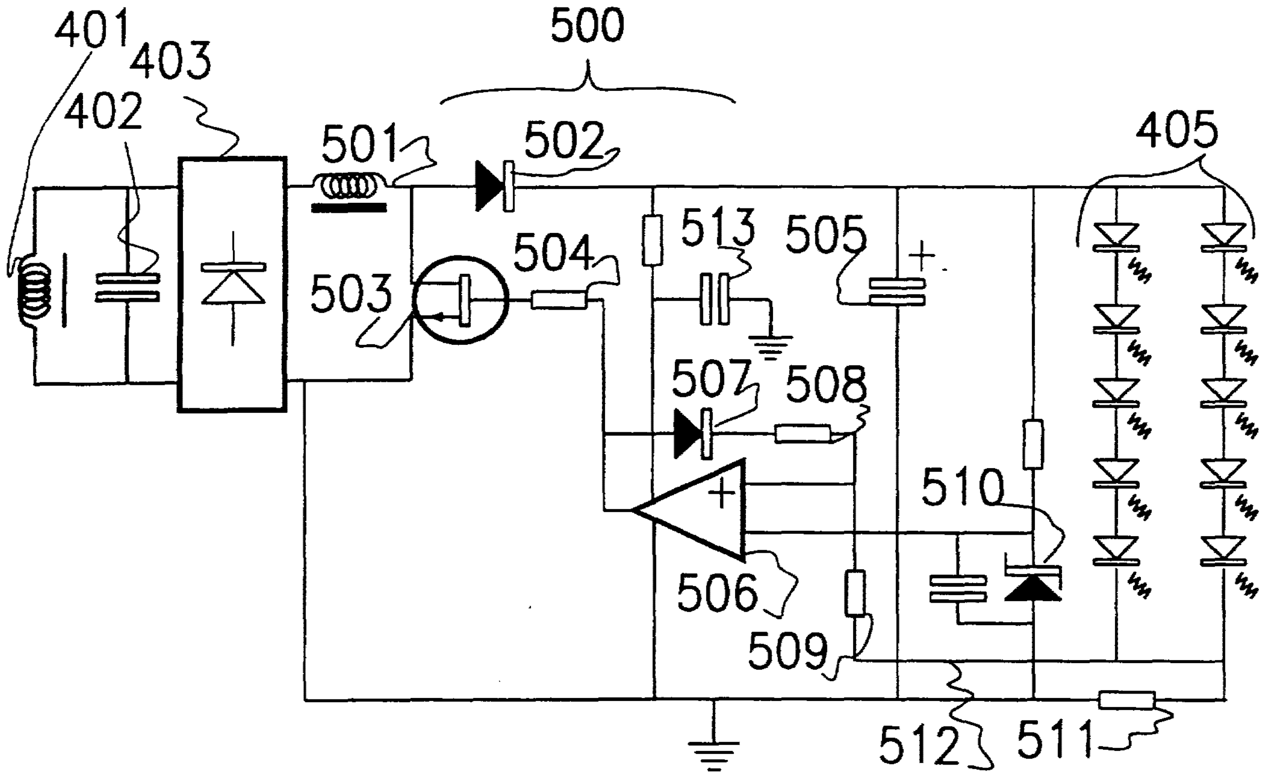
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Fig 5

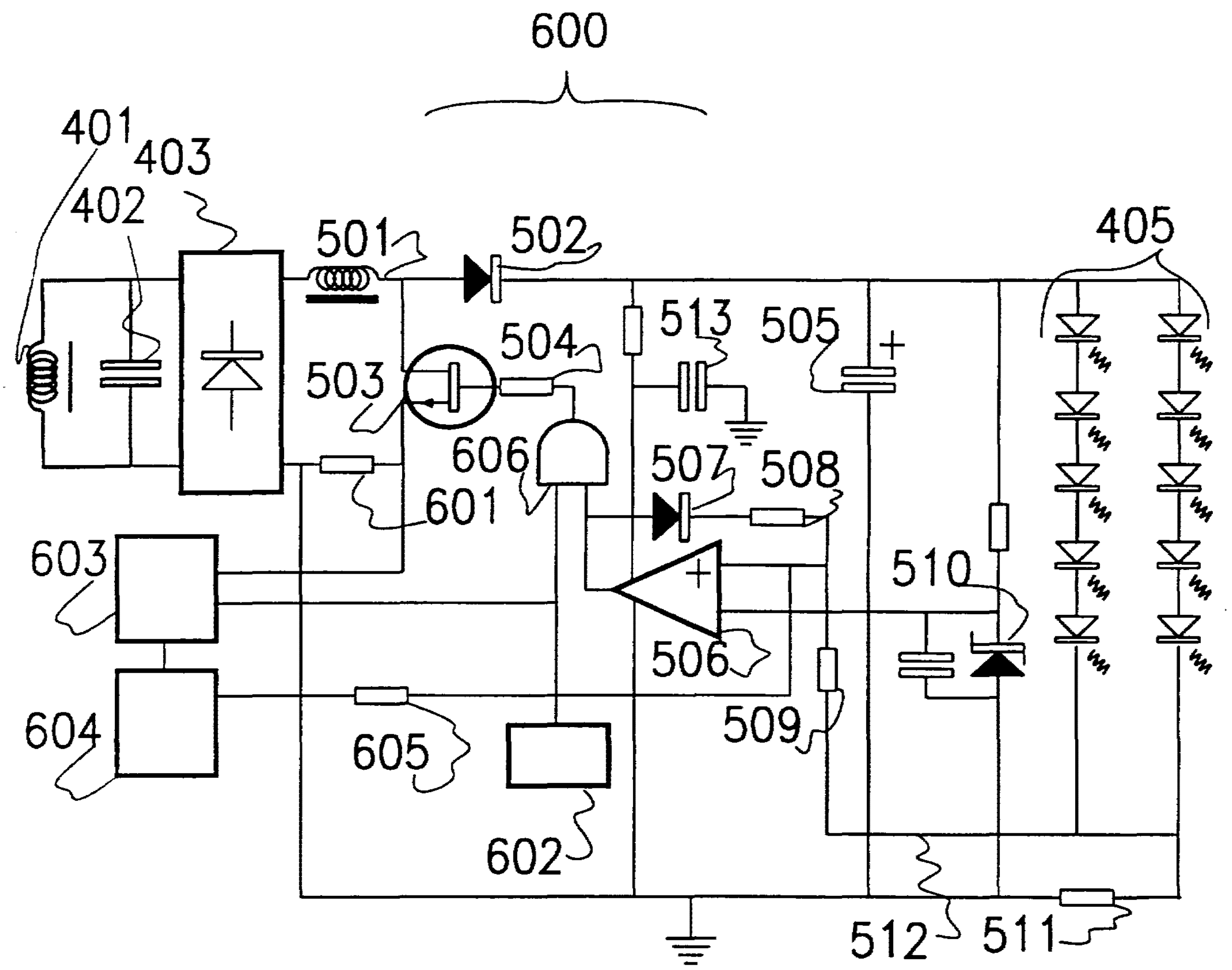
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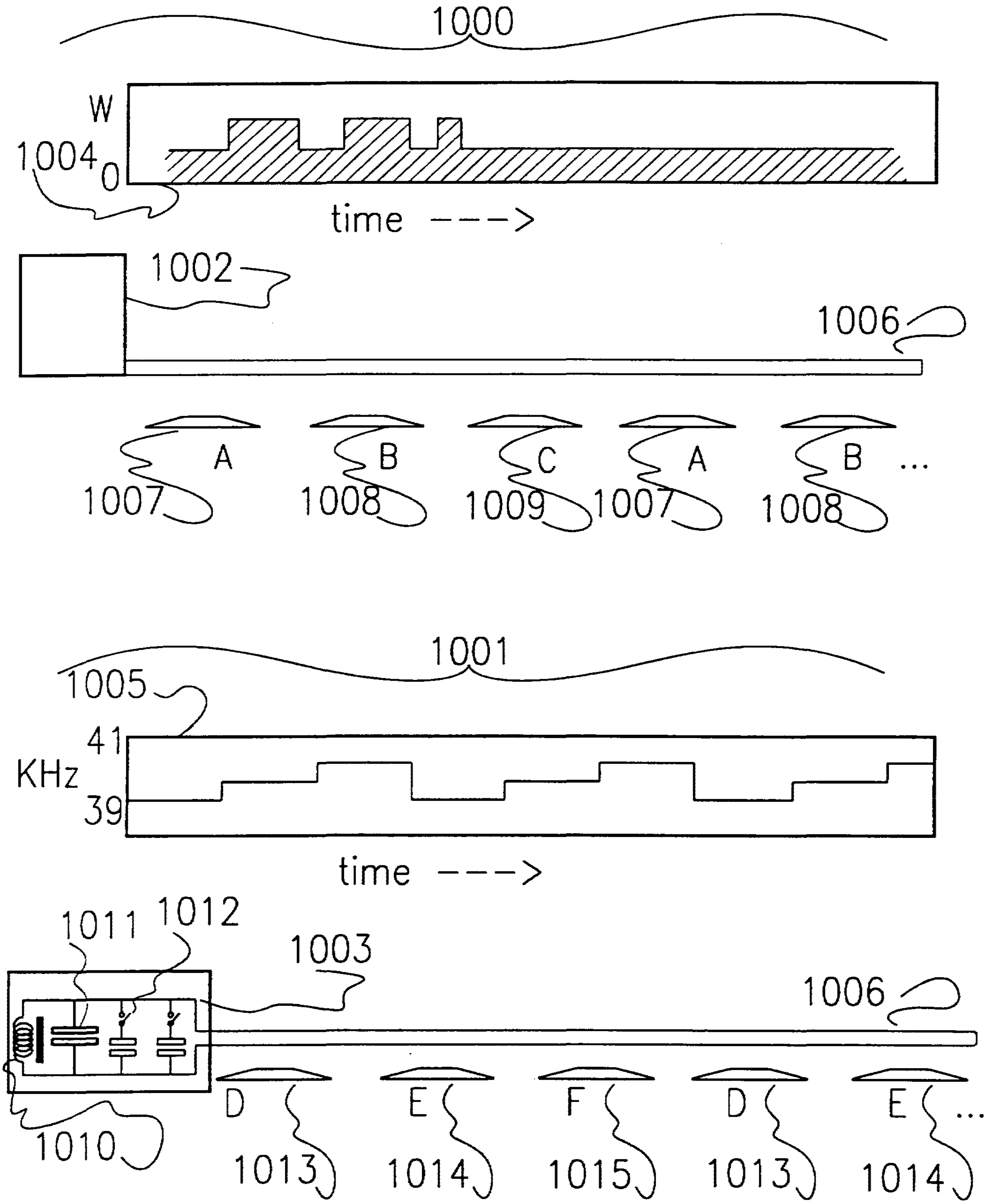
Fig 6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1006
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1015
1013
1014

Fig 10

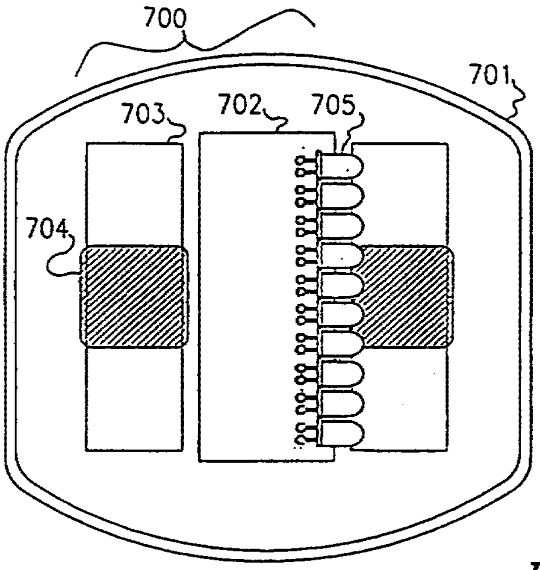


Fig 7

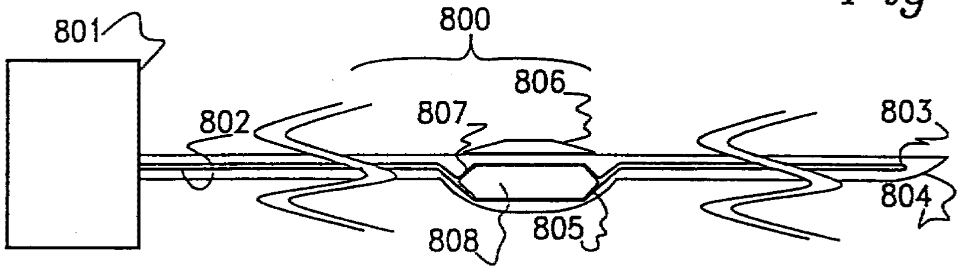


Fig 8

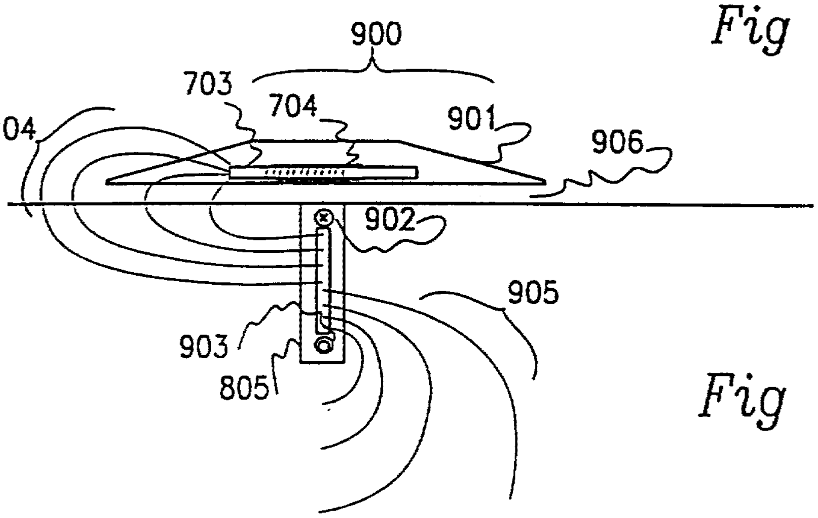


Fig 9

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/NZ 95/00061

A. CLASSIFICATION OF SUBJECT MATTER

Int Cl[6]: HO2J 17/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC : HO2J 17/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU : IPC AS ABOVE & F21V 23/00 GO8B 5/36 EO1F 9/06 F21S 7/00 HO4B 5/00

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPAT. JAPIO. JOPAL.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P.A.	WO 95/11545 A1 (AUCKLAND UNISERVICES LIMITED) 27 April 1995 FIGURE 14 PAGE 13 LINES 15/25	1-11
P.A.	WO 95/11544 A1 (AUCKLAND UNISERVICES LIMITED) 27 April 1995 FIGURE 14 PAGE 11 LINES 22/32	1-11
A	WO 93/04527 A1 (PIPER JW) 4 March 1993 FIGURE 9A PAGE 23 LINES 9/24 PAGE 24 LINES 5/8	1-11

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
3 November 1995	10 November 1995
Name and mailing address of the ISA/AU AUSTRALIAN INDUSTRIAL PROPERTY ORGANISATION PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No.: (06) 285 3929	Authorized officer **R. STOPFORD** Telephone No.: (06) 283 2177

Form PCT/ISA/210 (continuation of first sheet(2)) (July 1992) copsdd

PCT/INTERNATIONAL SEARCH REPORT	International Application No. PCT/NZ 95/00061

C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5293308 A (BOYS et al). 8 March 1994 FIGURE 14. 23. COLUMN 11 LINE 53 TO COLUMN 12 LINE 3 COLUMN 17 ;LINES 48/55 COLUMN 18 LINES 5/8	1-11
A	US 4914539 A (TURNER et al) 3 April 1990 FIGURE 2 COLUMN 5 LINE 17 TO COLUMN 7 LINE 20	1-11

Form PCT/ISA/210 (second sheet) (July 1992) copsdd

INTERNATIONAL SE. CH REPORT
Information on patent family members

International Application No.
PCT/NZ 95/00061

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	9511545	AU	80064/94	AU	80065/94	JP	7170681
		WO	9511544				
WO	9511544	AU	80064/94	AU	80065/94	JP	7170681
		WO	9511544	WO	9511545		
WO	9304527	AU	23966/92	NZ	239366	US	5450305
US	5293308	AU	12373/92	CA	2106784	EP	577611
		MX	9201100	NZ	237572	WO	9217929
US	4914539	NONE					

END OF ANNEX

Form PCT/ISA/210 (patent family annex) (July 1992) copsdd

No documents available for this priority number.

Espacenet

Bibliographic data: JP9298847 (A) — 1997-11-18

NON-CONTACT CHARGER

Inventor(s): CHIBA YOJI + (CHIBA YOJI)

Applicant(s): SONY CORP + (SONY CORP)

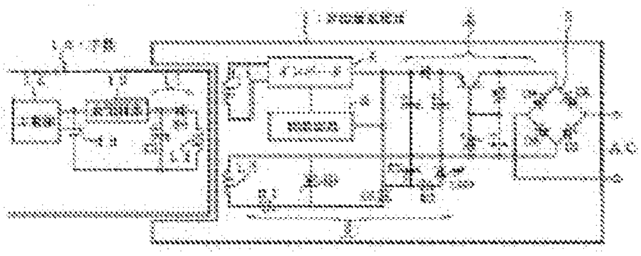
Classification: - **international:** ***H01M10/44; H01M10/46; H02J17/00; H02J7/00; H02J7/02; H02J7/10; H04M1/00;*** (IPC1-7): H01M10/44; H01M10/46; H02J17/00; H02J7/00; H02J7/02; H02J7/10; H04M1/00
- **cooperative:** Y02E60/12

Application number: JP19960132646 19960430

Priority number(s): JP19960132646 19960430

Abstract of JP9298847 (A)

PROBLEM TO BE SOLVED: To provide a non-contact charger whereby its conversion efficiency from an AC power into a DC power can be improved and both the maximum allowable current of its element and its loss can be reduced. SOLUTION: In a non-contact charger 1, an inverter 4 converts a DC voltage fed from a constant-voltage circuit 3 into a high-frequency voltage according to the control of a control circuit 5 to generate a magnetic line of force by a magnetic-force generating coil L1. On the other hand, in a slave machine 10, a coupling coil L2 takes out a high-frequency power from the magnetic line of force of the foregoing magnetic-force generating coil L1 by an electromagnetic induction, and after rectifying the high-frequency power by a rectification circuit 11, a rectified DC voltage is fed to a charging circuit 12 to charge a battery 13 by the rectified DC voltage. Also, a pickup coil L3 takes out the leakage magnetic flux generated between the magnetic-force generating coil L1 and the coupling coil L2 to feed it to a feedback circuit 6. After the high-frequency power in response to the foregoing leakage magnetic flux is converted into a DC voltage, the feedback circuit 6 feeds back it to the constant-voltage circuit 3. A light emitting diode LED is lit by the DC voltage obtained from the leakage magnetic flux to indicating that the battery 13 is being charged.



(19)日本国特許庁（ＪＰ）　(12) **公開特許公報**（Ａ）　(11)特許出願公開番号

特開平9－298847

(43)公開日　平成９年(1997)11月18日

(51)Int.Cl.⁶		識別記号	庁内整理番号	ＦＩ			技術表示箇所
Ｈ０２Ｊ	7/10			Ｈ０２Ｊ	7/10		Ｒ
Ｈ０１Ｍ	10/44			Ｈ０１Ｍ	10/44		Ｑ
	10/46				10/46		
Ｈ０２Ｊ	7/00	３０１		Ｈ０２Ｊ	7/00	３０１	Ｄ
	7/02				7/02		Ｕ

審査請求　未請求　請求項の数３　ＦＤ（全 ４ 頁）　最終頁に続く

(21)出願番号　特願平8－132646

(22)出願日　平成８年(1996)４月30日

(71)出願人　000002185
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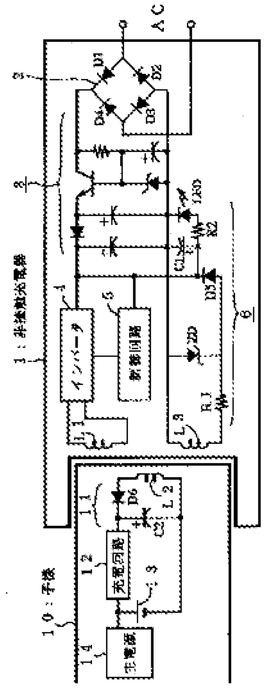
東京都品川区北品川６丁目７番35号　ソニー株式会社内

(54)【発明の名称】　非接触充電器

(57)【要約】

【課題】　交流→直流への変換効率を向上でき、また、素子の最大許容電流値や損失を低減できる非接触充電器を提供する。

【解決手段】　非接触充電器１では、インバータ４が定電圧回路３からの直流電圧を、制御回路５の制御に従って高周波に変換し、磁力発生コイルＬ１で磁力線を発生させる。一方、子機１０では、結合コイルＬ２が電磁誘導により上記磁力発生コイルＬ１の磁力線から高周波電力を取り出し、整流回路１１により整流した後、充電回路１２に供給する。充電回路１２は、整流された直流電圧によりバッテリ１３を充電する。また、ピックアップコイルＬ３は、磁力発生コイルＬ１と結合コイルＬ２間における漏洩磁束を取り出し、フィードバック回路６に供給する。フィードバック回路６は、上記漏洩磁束に応じた高周波電力を直流電圧に変換した後、定電圧回路３にフィードバックする。発光ダイオードＬＥＤは、漏洩磁束から得られた直流電圧によって点灯し、充電中であることを表示する。



【特許請求の範囲】
【請求項１】　電子機器のバッテリを充電する充電器であって、電子機器側に設けられた結合コイルに高周波電力を誘導する磁力発生コイルを有し、前記磁力発生コイルと前記結合コイル間の電磁誘導によって非接触で前記電子機器に充電電力を供給する非接触充電器において、
前記磁力発生コイル近傍に配置され、前記磁力発生コイルと前記結合コイル間における漏洩磁束による高周波電力を取り出すピックアップコイルと、
前記ピックアップコイルによって取り出した高周波電力を定電圧制御回路系の電源としてフィードバックするフィードバック手段とを具備することを特徴とする非接触充電器。
【請求項２】　前記ピックアップコイルによって取り出した高周波電力によって点灯する表示手段を具備することを特徴とする請求項１記載の非接触充電器。
【請求項３】　前記フィードバック手段は、前記高周波電力を直流に変換する整流手段を具備することを特徴とする請求項１記載の非接触充電器。
【発明の詳細な説明】
【０００１】
【発明の属する技術分野】本発明は、コードレス電話機の子機等に内蔵されたバッテリを充電する通信機用非接触充電器に関する。
【０００２】
【従来の技術】近年、ＰＨＳやセルラ、または家庭で用いられるコードレス電話機等では、その使用環境から防水性が必須となっている。そこで、機構面で考えた場合、問題となるのが、充電用に設けられた、筐体外部に露出する充電器とのコンタクト用端子部であり、これを回避し、全体の防水性能を向上させるために、非接触充電方式が普及してきた。
【０００３】上記非接触充電器では、充電器側のインバータ回路で発生した高周波電力を磁力発生コイル（Ｌ１）に供給し、充電される電話機側に内蔵された結合用コイル（Ｌ２）によって上記高周波電力を電磁誘導により取り出し、整流した直流電圧によりバッテリを充電するようになっている。
【０００４】
【発明が解決しようとする課題】しかしながら、従来の非接触充電器では、磁力発生コイル（Ｌ１）と結合用コイル（Ｌ２）の結合係数ｋがかなり小さいため、所定の電流で電話機側のバッテリを充電するためには、損失分も含めて、充電器で多大な電力が必要となり、商用交流電源から見た場合の交流→直流の変換効率を悪化させている。仮に、充電器にＡＣアダプタを接続するタイプであっても、直流電流をかなり必要とするため、アダプタそれ自体の定格容量をアップしなければならず、コストアップにつながるという問題があった。
【０００５】また、上述したように、充電器における電流が大となるため、電圧レギュレータを含めた制御素子の電流定格値を大きくしなければならず、コストアップにつながるという問題があた。また、ほとんどの充電器には、充電／非充電をユーザに認知させるために、例えば、スイッチング素子等によって制御されるＬＥＤ等の点灯装置が設けられているが、回路構成が複雑になるとともに、部品点数が増えるため、コストアップにつながるという問題があった。
【０００６】そこで本発明は、交流→直流への変換効率を向上させることができ、また、素子の最大許容電流値や損失を低減することができ、さらに、特別な回路を用いることなく、充電／非充電を表示できる非接触充電器を提供することを目的としている。
【０００７】
【課題を解決するための手段】上記目的を達成するため、この発明による非接触充電器は、電子機器のバッテリを充電する充電器であって、電子機器側に設けられた結合コイルに高周波電力を誘導する磁力発生コイルを有し、前記磁力発生コイルと前記結合コイル間の電磁誘導によって非接触で前記電子機器に充電電力を供給する非接触充電器において、前記磁力発生コイル近傍に配置され、前記磁力発生コイルと前記結合コイル間における漏洩磁束による高周波電力を取り出すピックアップコイルと、前記ピックアップコイルによって取り出した高周波電力を定電圧制御回路系の電源としてフィードバックするフィードバック手段とを具備することを特徴とする。
【０００８】
【発明の実施の形態】以下、本発明の実施の形態を図面を参照して説明する。
【０００９】Ａ．実施の形態
Ａ－１．実施の形態の構成
図１は本発明の実施の形態による非接触充電器と該非接触充電器で充電される電話機の子機の略構成を示す回路図であり、図２は、非接触充電器の断面図である。図において、非接触充電器１は、整流回路２、定電圧回路３、インバータ回路４、制御回路５、磁力発生コイルＬ１、ピックアップコイルＬ３、およびフィードバック回路６から構成されている。整流回路２は、ダイオードＤ１～Ｄ４からなるブリッジ回路より構成され、商用電源ＡＣを整流し、定電圧回路（レギュレータ）３に供給する。
【００１０】定電圧回路３は、整流された直流電圧を平滑化するとともに、所定電圧となるように制御し、インバータ回路４に供給する。インバータ回路４は、上記直流電圧を高周波に変換し、磁力発生コイルＬ１によって、磁力線を発生させる。制御回路５は、上記インバータ回路４を制御し、所定高周波を発生させる。ピックアップコイルＬ３は、磁力発生コイルＬ１と後述する子機側の結合コイルＬ１とによって電磁結合されなかった漏洩磁束を取り出し、フィードバック回路６に供給する。

【0011】フィードバック回路6は、抵抗器R1、ツェナーダイオードZD、ダイオードD5、コンデンサC1、抵抗器R2、発光ダイオードLEDから構成されており、上記漏洩磁束をダイオードD5により直流電圧に変換した後、コンデンサC1により平滑化し、定電圧回路3にフィードバックするとともに、抵抗器R2、発光ダイオードLEDを点灯させる。したがって、充電中の間は、ピックアップコイルL3によって漏洩磁束が取り出されるので、発光ダイオードLEDが点灯することになる。また、漏洩した分の電力は、直流電圧源に供給することで、交流（AC）一直流（DC）への変換効率を向上させることができる。

【0012】一方、子機（ハンドセット）10は、結合コイルL2、整流回路11、充電回路12、バッテリ13、主電源回路14を備えている。結合コイルL2は、上記非接触充電器1の磁力発生コイルL1に対して電磁誘導により結合し、高周波電力を取り出し、整流回路11に供給する。整流回路11は、ダイオードD6およびコンデンサC2から構成されており、ダイオードD6により上記高周波電力を整流し、コンデンサC2で平滑化した後、充電回路12に供給する。充電回路12は、上記直流電圧によりバッテリを13を充電する。主電源回路14は、バッテリ13の出力電圧から図示しない通信関連の回路を駆動するための駆動電圧を生成し、各部に供給する。

【0013】上述した磁力発生コイルL1およびピックアップコイルL3は、図2に示すように、子機10が充電時に非接触充電器1に載置される面の内側に同心円状に配置されている。また、結合コイルL2も同様に、図2に示すように、上記磁力発生コイルL1に対向するように、同心円状に配置されている。

【0014】B．実施の形態の動作

次に、上述した非接触充電器の動作について説明する。非接触充電器1では、商用電力ACが整流回路2により直流電圧に変換され、定電圧回路3により所定電圧に制御された後、インバータ4に供給される。該直流電圧は、インバータ4により、制御回路5の制御の従って高周波に変換され、磁力発生コイルL1に供給される。この結果、磁力発生コイルL1からは磁力線が発生する。一方、子機10では、結合コイルL2によって電磁誘導により上記磁力発生コイルL1の磁力線から高周波電力が取り出される。該高周波電力は、整流回路11により整流された後、充電回路12に供給される。充電回路12では、整流された直流電圧によりバッテリ13が充電される。

【0015】上記充電動作において、磁力発生コイルL1と結合コイルL2間で結合しきなかった漏洩磁束がピックアップコイルL3によって取り出され、フィードバック回路6に供給される。上記漏洩磁束に応じた高周波電力は、フィードバック回路6のダイオードD5によって整流され、コンデンサC1により平滑化されて、定電圧回路3にフィードバックされる。このとき、発光ダイオードLEDが点灯することで、充電中であることが表示される。

【0016】このように、上述した実施の形態では、非接触充電器1にピックアップコイルL3を設け、該ピックアップコイルL3で取りだした漏洩磁束に応じた高周波電力を、フィードバック回路6によって直流電圧に変換した後、直流電圧源にフィードバックすることにより、非接触充電器1における交流（AC）→直流（DC）への変換効率を向上させることができる。また、ピックアップコイルL3によって取り出され、漏洩磁束に応じた直流電圧によって点灯する発光ダイオードLEDを設けることにより、特別なスイッチング素子を用いることなく、充電中であることを表示することができる。また、漏洩磁束に応じた電力を直流電圧源にフィードバックすることにより、例えば、定電圧回路の素子の供給電流を削減することができるので、同一電源で同等の磁力線を発生させる場合、素子の最大許容電流値や損失を低めに設定でき、コストダウンを図ることができる。

【0017】

【発明の効果】以上説明したように、この発明によれば、電子機器のバッテリを充電する充電器であって、電子機器側に設けられた結合コイルに高周波電力を誘導する磁力発生コイルを有し、前記磁力発生コイルと前記結合コイル間の電磁誘導によって非接触で前記電子機器に充電電力を供給する非接触充電器において、前記磁力発生コイル近傍に配置され、前記磁力発生コイルと前記結合コイル間における漏洩磁束による高周波電力を取り出すピックアップコイルと、前記ピックアップコイルによって取り出した高周波電力を定電圧制御回路系の電源としてフィードバックするフィードバック手段とを具備するようにしたことにより、交流→直流への変換効率を向上させることができ、また、素子の最大許容電流値や損失を低減することができるという利点が得られる。

【図面の簡単な説明】

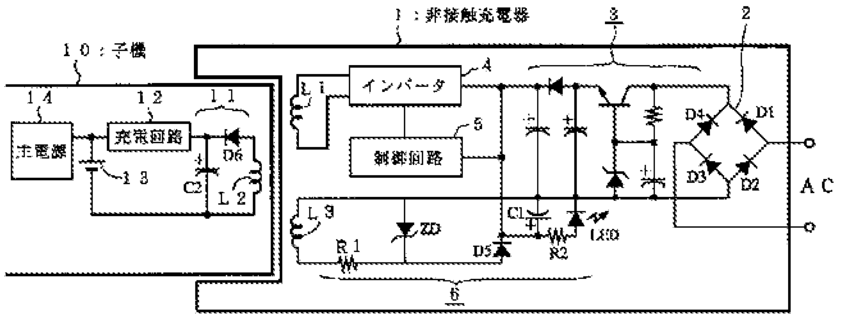
【図1】本発明の実施の形態による非接触充電器と該非接触充電器により充電される子機（ハンドセット）の略構成を示す回路図である。

【図2】非接触充電器と該非接触充電器により充電される子機（ハンドセット）の断面図である。

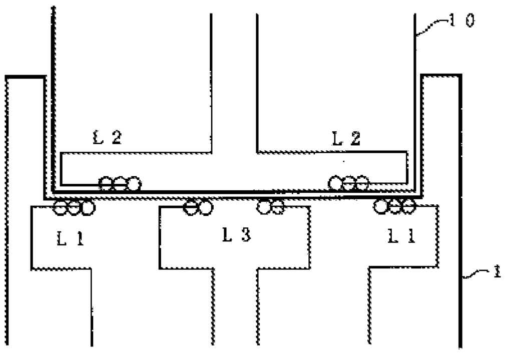
【符号の説明】

1……非接触充電器、2……整流回路、3……定電圧回路、4……インバータ回路、5……制御回路、6……フィードバック回路（フィードバック手段）、10……子機、11……整流回路、12……充電回路、13……バッテリ、14……主電源回路、L1……磁力発生コイル、L2……結合コイル、L3……ピックアップコイル、D5……ダイオード（整流手段）、LED……発光ダイオード（表示手段）。

【図1】



【図2】



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POWER SUPPLY

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Applicant(s): SONY CORP ± (SONY CORP)

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- **cooperative:** Y02B70/1475

Application number: JP19960315049 19961126

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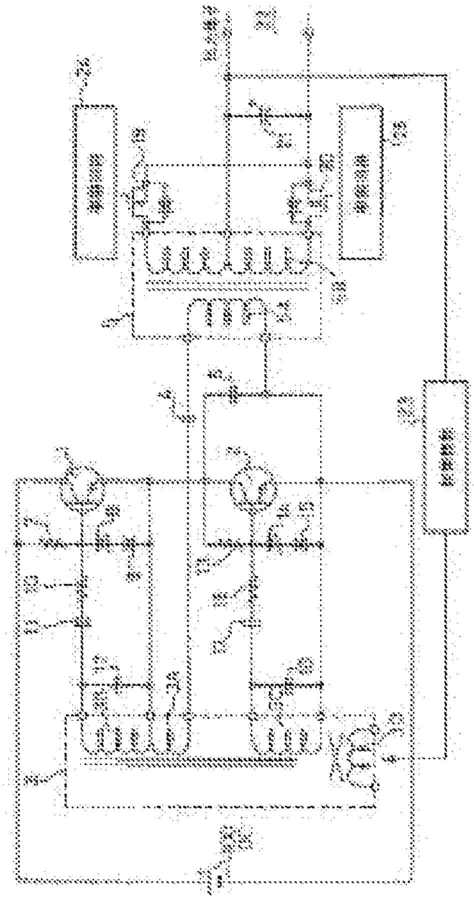
Abstract of JP10164837 (A)

PROBLEM TO BE SOLVED: To significantly reduce loss by using MOS-FETs for secondary-side rectification. SOLUTION: The positive end of a direct current 100 obtained by rectifying an AC input is connected with the negative end through the collectors and emitters of switching transistors 1, 2. The middle point is connected with one end of the primary-side coil 5A of voltage changing transformer 5 through the coil 3A of a saturable reactor transformer 3 and a resonance capacitor 4. One and the other ends of the secondary-side coil 5B of the voltage changing transformer 5 are connected with each other through the sources and drains of N-channel MOS-FETs 19, 20, respectively. A capacitor 21 for smoothing is connected between the connecting point and the middle tap of the secondary- side coil 5B. The MOS-FETs 19, 20 are on/off-controlled by drive circuits 24, 25, respectively, and synchronously controlled, so that they will be on only when current flows from the capacitor 21 side to the coil 5B, for example.



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	3/335			3/335	Ｆ

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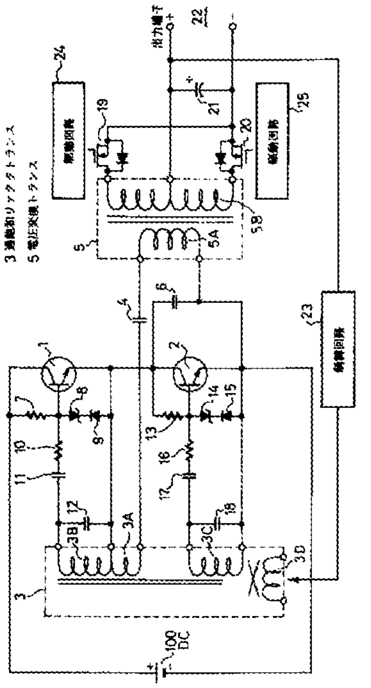
(54)【発明の名称】　**電源装置**

(57)【要約】
【課題】　２次側整流にＭＯＳ－ＦＥＴを用いて損失を大幅に減少させる。
【解決手段】　ＡＣ入力を整流したＤＣ１００の＋端がスイッチングトランジスタ１、２のコレクタ・エミッタ間を通じて一端に接続され、中点が過飽和リアクタトランス３のコイル３Ａ、共振コンデンサ４を通じて電圧変換トランス５の１次側コイル５Ａの一端に接続される。また電圧変換トランス５の２次側コイル５Ｂの一端及び他端が、それぞれＮチャンネルのＭＯＳ－ＦＥＴ１９、２０のソース・ドレイン間を通じて互いに接続され、この接続点と２次側コイル５Ｂの中間タップとの間に平滑用のコンデンサ２１が接続される。さらにＭＯＳ－ＦＥＴ１９、２０はそれぞれ駆動回路２４、２５によってオンオフが制御され、例えば図示の例ではコンデンサ２１側からコイル５Ｂに向かって電流が流れている期間にのみオンされるように同期制御される。



【特許請求の範囲】
【請求項1】　スイッチング素子を2石用いたハーフブリッジ構成を有し、
上記2石のスイッチング素子の中点に共振コンデンサと電圧変換用トランスが設けられると共に、
上記電圧変換用トランスの2次側整流としてMOS－FETを用いて同期整流を行うことを特徴とする電源装置。
【請求項2】　請求項1記載の電源装置において、
上記2次側整流用のMOS－FETの駆動信号として上記MOS－FETを流れる電流を検出した信号を用いることを特徴とする電源装置。
【請求項3】　請求項2記載の電源装置において、
上記MOS－FETに直列に電流検出トランスを接続して上記MOS－FETを流れる電流を検出することを特徴とする電源装置。
【請求項4】　請求項2記載の電源装置において、
上記MOS－FETに直列に電流検出抵抗を接続してその電圧降下により上記MOS－FETを流れる電流を検出することを特徴とする電源装置。
【請求項5】　請求項2記載の電源装置において、
上記MOS－FETのオン抵抗による電圧降下により上記MOS－FETを流れる電流を検出することを特徴とする電源装置。
【発明の詳細な説明】
【0001】
【発明の属する技術分野】本発明は、例えばAC入力を整流したDCで駆動されるパーソナルコンピュータの電源等に使用して好適な電源装置に関するものである。
【0002】
【従来の技術】例えばAC入力を整流したDCで駆動されるパーソナルコンピュータの電源においては、内部で必要な駆動電圧を得るために、いわゆるDC－DCコンバータ等の電源装置が用いられている。すなわち図9には、そのような電源装置の一例の構成を示す。
【0003】この図9において、DC70の＋端が、直列に接続された2石のスイッチングトランジスタ71、72のコレクタ・エミッタ間を通じてDC70の－端に接続される。これらのトランジスタ71、72の中点が過飽和リアクタトランス73のコイル3A、共振コンデンサ74を通じて電圧変換トランス75の1次側コイル5Aの一端に接続される。またこの1次側コイル5Aの他端がDC70の－端に接続される。さらにトランジスタ71、72の中点がコンデンサ76を通じてDC70の－端に接続される。
【0004】また、トランジスタ71のコレクタが抵抗器77を通じてトランジスタ71のベースに接続され、このトランジスタ71のベースが順方向のツェナーダイオード78と逆方向のダイオード79の直列回路を通じてトランジスタ71のエミッタに接続される。さらにトランジスタ71のベースが抵抗器80、コンデンサ81と、過飽和リアクタトランス73のコイル3B及びコンデンサ82の並列回路との直列回路を通じてトランジスタ71のエミッタに接続される。
【0005】さらにトランジスタ72のコレクタが抵抗器83を通じてトランジスタ72のベースに接続され、このトランジスタ72のベースが順方向のツェナーダイオード84と逆方向のダイオード85の直列回路を通じてトランジスタ72のエミッタに接続される。さらにトランジスタ72のベースが抵抗器86、コンデンサ87と、過飽和リアクタトランス73のコイル3C及びコンデンサ88の並列回路との直列回路を通じてトランジスタ72のエミッタに接続される。
【0006】また、上述の電圧変換トランス75の2次側コイル5Bの一端及び他端が、それぞれ整流用の順方向のダイオード89、90を通じて互いに接続される。さらにこの接続点と2次側コイル5Bの中間タップとの間に平滑用のコンデンサ91が接続される。そしてこのコンデンサ91の両端から出力端子92の＋端及び－端が導出される。さらにこの出力端子92の＋端がエラーアンプ93を通じて過飽和リアクタトランス73の制御コイル3Dに接続される。
【0007】そしてこの装置において、上述のスイッチングトランジスタ71、72が自励発振によって交互にオンオフされることによって、電圧変換トランス75の1次側コイル5Aには略正弦波の電流が流され、2次側コイル5Bには所望の電圧が取り出される。さらにこの取り出された電圧がダイオード89、90を通じて両波整流され、整流された電圧がコンデンサ91で平滑されて出力端子92に取り出される。
【0008】また、出力端子92の＋端に取り出された電圧の、所望の電圧からの変動分がエラーアンプ93で検出され、この変動分が過飽和リアクタトランス73の制御コイル3Dに供給される。これによってこの過飽和リアクタトランス73のコイル3A～3Cに取り出される信号の波形が変化され、トランジスタ71、72のスイッチング周波数が変化されて、出力端子92の＋端に取り出される電圧が所望の電圧に等しくなるように制御が行われる。
【0009】このようにして、上述の装置において、安定化された所望の電圧を出力端子92に取り出すことができる。そしてこの取り出された電圧は、例えばDCで駆動されるパーソナルコンピュータの電源として使用されるものである。
【0010】
【発明が解決しようとする課題】ところが上述の電源装置において、電圧変換トランス75の2次側整流用のダイオード89、90の順方向降下電圧Vf によって損失が発生する。すなわちこのようなダイオードの順方向降下電圧Vf は、一般的0．45V程度であるが、この順

方向降下電圧Vf によって上述の装置では、
１．１１×Io ×Vf〔W〕　　（但し、Io は出力電流〔A〕）
の損失が発生する。

【００１１】そしてこのような２次側整流用のダイオード８９、９０による損失が、例えば出力電流Io が１０〔A〕では５〔W〕、２０〔A〕では１０〔W〕にもなってしまい、特にパーソナルコンピュータのように低電圧、大電流が要求される電源では、出力に対する損失の割合が大きくなってしまうものである。

【００１２】この出願はこのような点に鑑みて成されたものであって、解決しようとする問題点は、従来の装置では、特にパーソナルコンピュータのように低電圧、大電流の電源が要求される場合に、２次側整流用ダイオードの順方向降下電圧によって、出力に対する損失の割合が大きくなってしまうというものである。

【００１３】

【課題を解決するための手段】このため本発明においては、電圧変換用トランスの２次側整流としてMOS－FETを用いて同期整流を行うようにしたものであって、これによれば、特に低オン抵抗のMOS－FETを用いることで、２次側整流での損失を大幅に減少させることができる。

【００１４】

【発明の実施の形態】すなわち本発明においては、スイッチング素子を２石用いたハーフブリッジ構成を有し、２石のスイッチング素子の中点に共振コンデンサと電圧変換用トランスが設けられると共に、電圧変換用トランスの２次側整流としてMOS－FETを用いて同期整流を行うものである。以下、図面を参照して本発明を説明するに、図１は本発明を適用した電源装置の一例の構成を示すブロック図である。

【００１５】この図１において、AC入力を整流したDC１００の＋端が、直列に接続された２石のスイッチングトランジスタ１、２のコレクタ・エミッタ間を通じてDC１００の－端に接続される。これらのトランジスタ１、２の中点が過飽和リアクタトランス３のコイル３A、共振コンデンサ４を通じて電圧変換トランス５の１次側コイル５Aの一端に接続される。またこの１次側コイル５Aの他端がDC１００の－端に接続される。さらにトランジスタ１、２の中点がコンデンサ６を通じてDC１００の－端に接続される。

【００１６】また、トランジスタ１のコレクタが抵抗器７を通じてトランジスタ１のベースに接続され、このトランジスタ１のベースが順方向のツェナーダイオード８と逆方向のダイオード９の直列回路を通じてトランジスタ１のエミッタに接続される。さらにトランジスタ１のベースが抵抗器１０、コンデンサ１１と、過飽和リアクタトランス３のコイル３B及びコンデンサ１２の並列回路との直列回路を通じてトランジスタ１のエミッタに接続される。

【００１７】さらにトランジスタ２のコレクタが抵抗器１３を通じてトランジスタ２のベースに接続され、このトランジスタ２のベースが順方向のツェナーダイオード１４と逆方向のダイオード１５の直列回路を通じてトランジスタ２のエミックに接続される。さらにトランジスタ２のベースが抵抗器１６、コンデンサ１７と、過飽和リアクタトランス３のコイル３C及びコンデンサ１８の並列回路との直列回路を通じてトランジスタ２のエミッタに接続される。

【００１８】また、上述の電圧変換トランス５の２次側コイル５Bの一端及び他端が、それぞれNチャンネルのMOS－FET１９、２０のソース・ドレイン間を通じて互いに接続される。さらにこの接続点と２次側コイル５Bの中間タップとの間に平滑用のコンデンサ２１が接続される。そしてこのコンデンサ２１の両端から出力端子２２の＋端及び－端が導出される。さらにこの出力端子２２の＋端が制御回路２３を通じて過飽和リアクタトランス３の制御コイル３Dに接続される。

【００１９】そしてこの装置において、上述のスイッチングトランジスタ１、２が自励発振によって交互にオンオフされることによって、電圧変換トランス５の１次側コイル５Aには略正弦波の電流が流され、２次側コイル５Bには所望の電圧が取り出される。さらにこの取り出された電圧が、MOS－FET１９、２０を通じて互いに接続される。

【００２０】ここでこれらのMOS－FET１９、２０はそれぞれ駆動回路２４、２５によってオンオフが制御され、例えば図示の例ではコンデンサ２１側からコイル５Bに向かって電流が流れている期間にのみオンされるように同期制御される。これによって２次側コイル５Bに取り出された電圧が両波整流され、整流された電圧がコンデンサ２１で平滑されて出力端子２２に取り出される。

【００２１】また、出力端子２２の＋端に取り出された電圧の、所望の電圧からの変動分が制御回路２３で検出され、この変動分が過飽和リアクトランス３の制御コイル３Dに供給される。これによってこの過飽和リアクタトランス３のコイル３A～３Cに取り出される信号の波形が変化され、トランジスタ１、２のスイッチング周波数が変化されて、出力端子２２の＋端に取り出される電圧が所望の電圧に等しくなるように制御が行われる。

【００２２】このようにして、上述の装置において、安定化された所望の電圧を出力端子２２に取り出すことができる。さらにこの取り出された電圧は、例えばDCで駆動されるパーソナルコンピュータの電源として使用されるものである。

【００２３】そして上述の装置において、電圧変換トランス５の２次側の整流が、MOS－FET１９、２０のそれぞれ同期制御による同期整流によって行われてい

る。従ってこの場合には、２次側整流用のＭＯＳ－ＦＥＴ１９、２０のオン抵抗Ronによって損失が発生する。
【００２４】すなわちこのようなオン抵抗Ronは、例えば低オン抵抗のＭＯＳ－ＦＥＴでは７ｍΩ程度である。そしてこのオン抵抗Ronによって上述の装置では、
１．１１×Ｉo ×１．１１×Ｉo ×Ron〔W〕
の損失が発生する。
【００２５】そしてこのような２次側整流用のＭＯＳ－ＦＥＴ１９、２０による損失は、例えば出力電流Ｉo が１０〔Ａ〕では約０．８６〔Ｗ〕、２０〔Ａ〕では約３．４５〔Ｗ〕に留めることができ、特にパーソナルコンピュータのように低電圧、大電流が要求される電源で、出力に対する損失の割合を大幅に削減することができるものである。
【００２６】すなわち図２において、直線Ａは、従来の２次側整流用の素子に例えば順方向降下電圧Vf ＝０．４５Ｖのダイオードを用いた場合の、電流〔Ａ〕に対する損失〔Ｗ〕の発生の状況を示す。また、曲線Ｂは、２次側整流用の素子に例えばオン抵抗Ron＝７ｍΩのＭＯＳ－ＦＥＴを用いた場合の、電流〔Ａ〕に対する損失〔Ｗ〕の発生の状況を示している。
【００２７】従ってこの装置において、電圧変換用トランスの２次側整流としてＭＯＳ－ＦＥＴを用いて同期整流を行うことによって、特に低オン抵抗のＭＯＳ－ＦＥＴを用いることで、２次側整流での損失を大幅に減少させることができる。
【００２８】これによって、従来の装置では、２次側整流用ダイオードの順方向降下電圧によって、出力に対する損失の割合が大きくなっていたものを、本発明によれば、特にパーソナルコンピュータのように低電圧、大電流の電源が要求される場合に、２次側整流での損失を大幅に減少させ、効率の良いスイッチング電源を実現することができるものである。
【００２９】ところで上述の装置において、２次側整流素子は、本来は電圧変換用トランス５の２次側コイル５Ｂから平滑用コンデンサ２１を充電する方向のみに電流を流さなければならない。ところが上述の装置において、ＭＯＳ－ＦＥＴは、ゲートにオン電圧が印加されるとドレイン・ソース間は抵抗体と同等になるため、電流は双方向に流れることができる。
【００３０】従って上述の装置において、ＭＯＳ－ＦＥＴのゲートにオン電圧を印加するタイミングを悪くすると、コンデンサ２１から２次側コイル５Ｂへ放電電流が流れ、負荷側にエネルギーを有効に伝達できないばかりか、逆電流によるＭＯＳ－ＦＥＴの発熱やノイズの発生、１次側スイッチング損失の増大にもつながる恐れがある。
【００３１】そこで、このようなＭＯＳ－ＦＥＴのゲートにオン電圧を印加するタイミングを正確に制御するために、例えば図３に示すような回路が用いられる。なお以下の説明では、２次側整流用のＭＯＳ－ＦＥＴ１９、２０の下側の片方の回路についてのみ示すが、上下両方のＭＯＳ－ＦＥＴについての回路構成、及びその作用動作は同じである。
【００３２】この図３において、ＭＯＳ－ＦＥＴ２０に直列に電流検出用トランス３１の１次側コイル３１Ａが設けられる。そしてこの電流検出用トランス３１の２次側コイル３１Ｂの両端間に検出用の抵抗器３２が接続され、この抵抗器３２の電圧がコンパレータ３３で検出される。
【００３３】すなわち上述の抵抗器３２の一端が電圧源３４に接続され、この電圧源３４の電圧と抵抗器３２の他端の電圧がコンパレータ３３で比較されて、他端の電圧が所定値以上になったときに検出が行われる。そしてこの検出信号がバッファ回路３５を通じてＭＯＳ－ＦＥＴ２０のゲートに供給される。
【００３４】従ってこの回路において、例えば上述の１次側のトランジスタ１のコレクタ電流I_C が、図４のＡに示すようであった場合には、電圧変換用トランス５の２次側コイル５Ｂには図４のＢの電圧が誘起される。そしてこの電圧がコンデンサ２１の充電電圧より大きくなると、ＭＯＳ－ＦＥＴ２０の寄生ダイオード２０Ａを通じてコンデンサ２１に充電電流が流される。
【００３５】さらにこの充電電流が電流検出用トランス３１の１次側コイル３１Ａを流れることによって、２次側コイル３１Ｂには電圧が誘起される。そしてこの出力電圧がコンパレータ３３で検出され、この出力電圧が所定値以上になると、即座にバッファ回路３５を通じて例えば図４のＣに示すようなゲート電圧VgsがＭＯＳ－ＦＥＴ２０に印加される。
【００３６】また、上述の充電電流が減少すると、コンパレータ３３の出力が反転され、バッファ回路３５を通じてＭＯＳ－ＦＥＴ２０のゲート容量が放電されて、ＭＯＳ－ＦＥＴ２０がオフされる。なおこの時点でコンデンサ２１の充電電流はゼロにはなっていないが、この電流はＭＯＳ－ＦＥＴ２０の寄生ダイオード２０Ａを通じて流される。
【００３７】これによって、ＭＯＳ－ＦＥＴ２０には、例えば図４のＤに示すようなドレイン電流I_D が流される。すなわちこのＭＯＳ－ＦＥＴ２０は、コンデンサ２１への充電電流が流れ始めた後でオンされ、充電電流がゼロになる前にオフされる。そしてこのＭＯＳ－ＦＥＴ２０がオンされている期間に、低オン抵抗を介して損失の少ない充電が行われるものである。
【００３８】なお、上述のＭＯＳ－ＦＥＴ１９においても作用動作は全く同じに行われる。すなわち例えば図５のＡ、Ｂに示すＭＯＳ－ＦＥＴ２０の動作に反転した形で、図５のＣ、Ｄに示すようにＭＯＳ－ＦＥＴ１９の動作が行われる。そしてこの場合も、ＭＯＳ－ＦＥＴ１９は、コンデンサ２１への充電電流が流れ始めた後でオン

され、充電電流がゼロになる前にオフされるものである。

【0039】従ってこの回路において、MOS－FETは充電電流がゼロになる前にオフされるので、例えばターンオフのタイミングが遅れて逆電流が流されるようなことがない。これにより、いかなる動作条件でもMOS－FETのオン期間が充電電流の方向のみの電流だけ流せるようにでき、逆電流の発生による不具合を解消することができる。

【0040】さらに図6、図7は、MOS－FETのゲートにオン電圧を印加するタイミングを正確に制御するための回路の他の例を示す。すなわち図6は充電電流の検出方法として検出抵抗41を用いる場合であって、この検出抵抗41で検出された電圧をコンパレータ42で電圧源43の電圧と比較し、この比較出力をバッファ回路44を通じてMOS－FET20のゲートに印加している。

【0041】また、図7は検出抵抗としてMOS－FET20のオン抵抗を用いるものである。すなわちこの例では、MOS－FET20のオン抵抗で検出された電圧をコンパレータ51で電圧源52の電圧と比較し、この比較出力をバッファ回路53を通じてMOS－FET20のゲートに印加している。なおこの図7の回路は、もっとも損失が少なくなる構成である。

【0042】こうして上述の電源装置によれば、スイッチング素子を2石用いたハーフブリッジ構成を有し、2石のスイッチング素子の中点に共振コンデンサと電圧変換用トランスが設けられると共に、電圧変換用トランスの2次側整流としてMOS－FETを用いて同期整流を行うことにより、2次側整流での損失を大幅に減少させ、効率の良いスイッチング電源を実現することができるものである。

【0043】なお、上述の説明では、いずれも2次側整流用のMOS－FET19、20を電圧変換トランス5の2次側コイル5Bの－側に設ける場合について行ったが、例えば従来の装置で述べたダイオードのように＋側に設けても同様の作用効果を得ることができる。ただし、－側に設けた方がMOS－FETの駆動には適正である。

【0044】また、例えば図8に示すように1次側のスイッチング素子が他励発振によってオンオフ駆動される場合においても本発明を適用することができる。すなわち図8においては、コントロール回路60からの制御信号がドライブ回路61、62を通じてそれぞれスイッチング素子63、64に供給され、これらのスイッチング素子63、64がオンオフ駆動されて、上述の電圧変換トランス5の1次側コイル5Aに略正弦波の電流が流される。

【0045】さらにこの装置において、出力端子22の＋端に取り出された電圧の、所望の電圧からの変動分がフィードバック回路65を通じてコントロール回路60に供給され、これによってスイッチング素子63、64のスイッチング周波数が変化されて、出力端子22の＋端に取り出される電圧が所望の電圧に等しくなるように制御が行われる。

【0046】そしてさらにこの装置においても、電圧変換用トランスの2次側整流としてMOS－FETを用いて同期整流を行うことによって、特に低オン抵抗のMOS－FETを用いることで、2次側整流での損失を大幅に減少させることができ、効率の良いスイッチング電源を実現することができるものである。

【0047】

【発明の効果】この発明によれば、電圧変換用トランスの2次側整流としてMOS－FETを用いて同期整流を行うことによって、特に低オン抵抗のMOS－FETを用いることで、2次側整流での損失を大幅に減少させることができるようになった。

【0048】これによって、従来の装置では、2次側整流用ダイオードの順方向降下電圧によって、出力に対する損失の割合が大きくなっていたものを、本発明によれば、特にパーソナルコンピュータのように低電圧、大電流の電源が要求される場合に、2次側整流での損失を大幅に減少させ、効率の良いスイッチング電源を実現することができるものである。

【図面の簡単な説明】

【図1】本発明の適用される電源装置の一例の構成図である。

【図2】その説明のための図である。

【図3】本発明の適用される電源装置の要部の一例の構成図である。

【図4】その動作の説明のための図である。

【図5】その動作の説明のための図である。

【図6】本発明の適用される電源装置の要部の他の例の構成図である。

【図7】本発明の適用される電源装置の要部の他の例の構成図である。

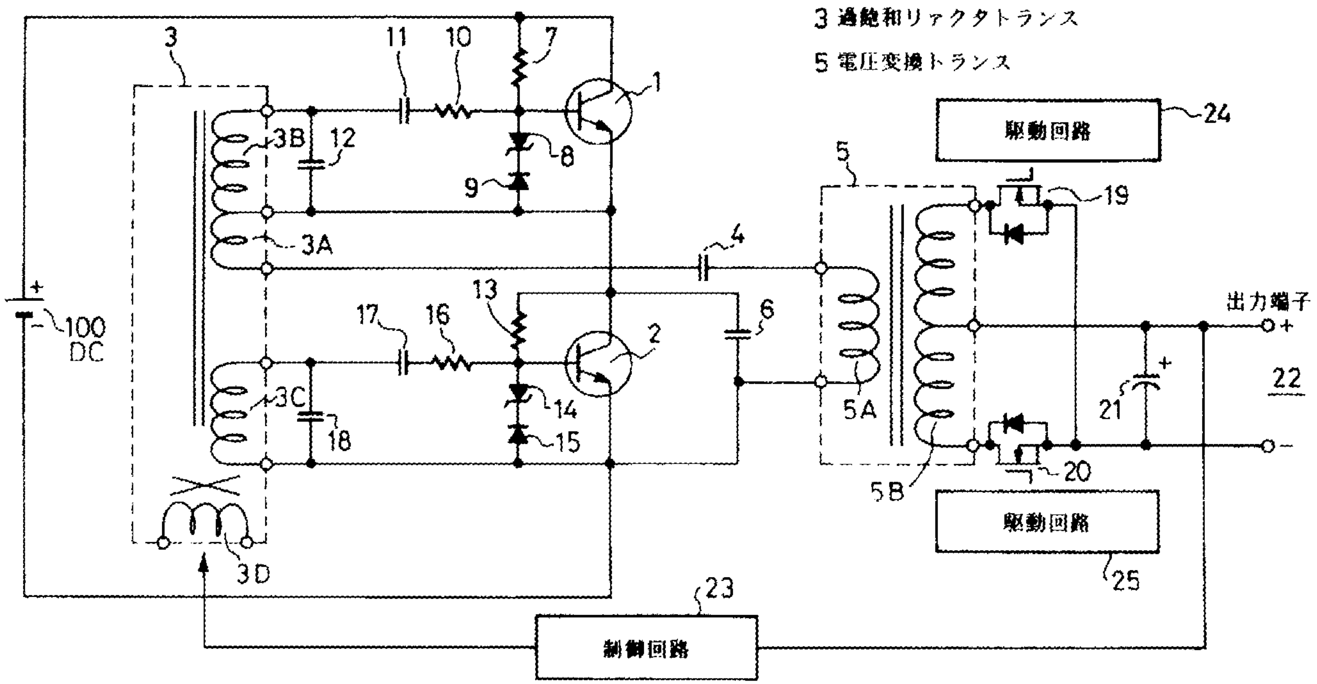
【図8】本発明の適用される電源装置の他の例の構成図である。

【図9】従来の電源装置の構成図である。

【符号の説明】

100　AC入力を整流したDC、1，2　スイッチングトランジスタ、3過飽和リアクタトランス、4　共振コンデンサ、5　電圧変換トランス、6　コンデンサ、7　抵抗器、8　ツェナーダイオード、9　ダイオード、10　抵抗器、11，12　コンデンサ、13　抵抗器、14　ツェナーダイオード、15ダイオード、16　抵抗器、17，18　コンデンサ、19，20　MOS－FET、21　コンデンサ、22　出力端子、23　制御回路、24，25　駆動回路

【図1】


3 過飽和リアクタトランス
5 電圧変換トランス
駆動回路
駆動回路
制御回路
出力端子
100 DC
3
3A
3B
3C
3D
5
5A
5B
1
2
4
6
7
8
9
10
11
12
13
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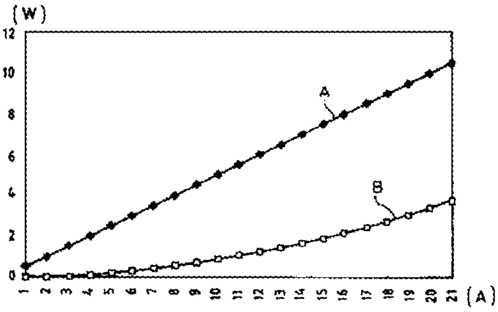
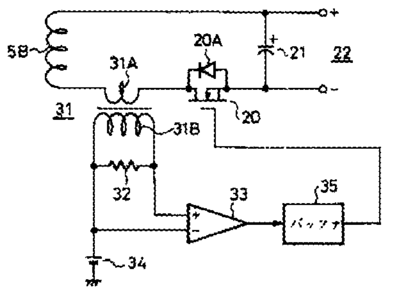
25

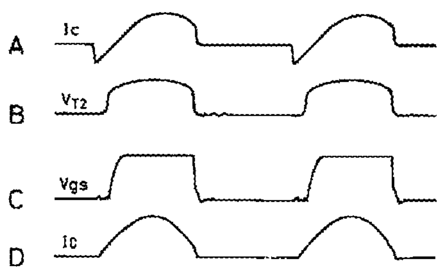
【図２】



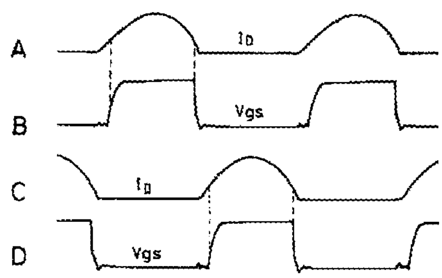
【図３】



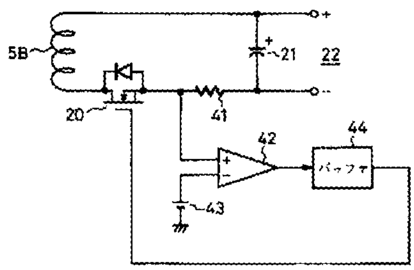
【図４】



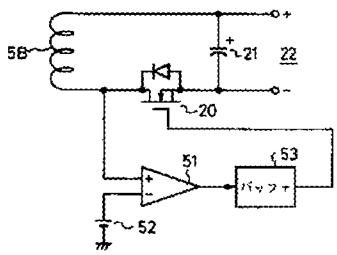
【図５】



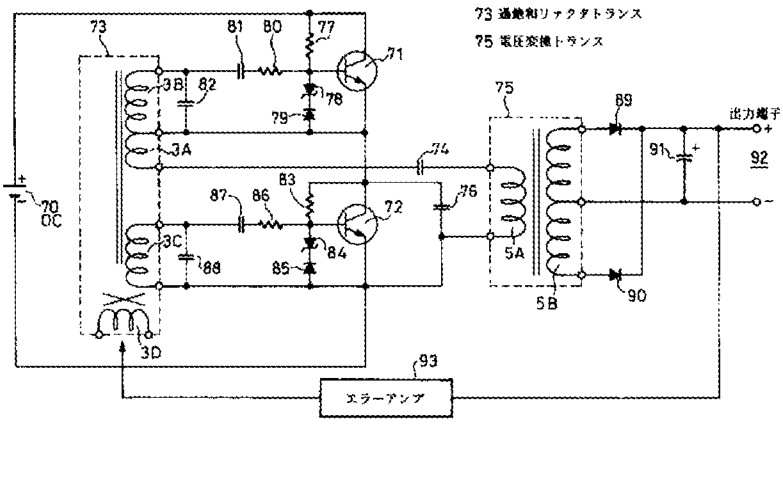
【図６】



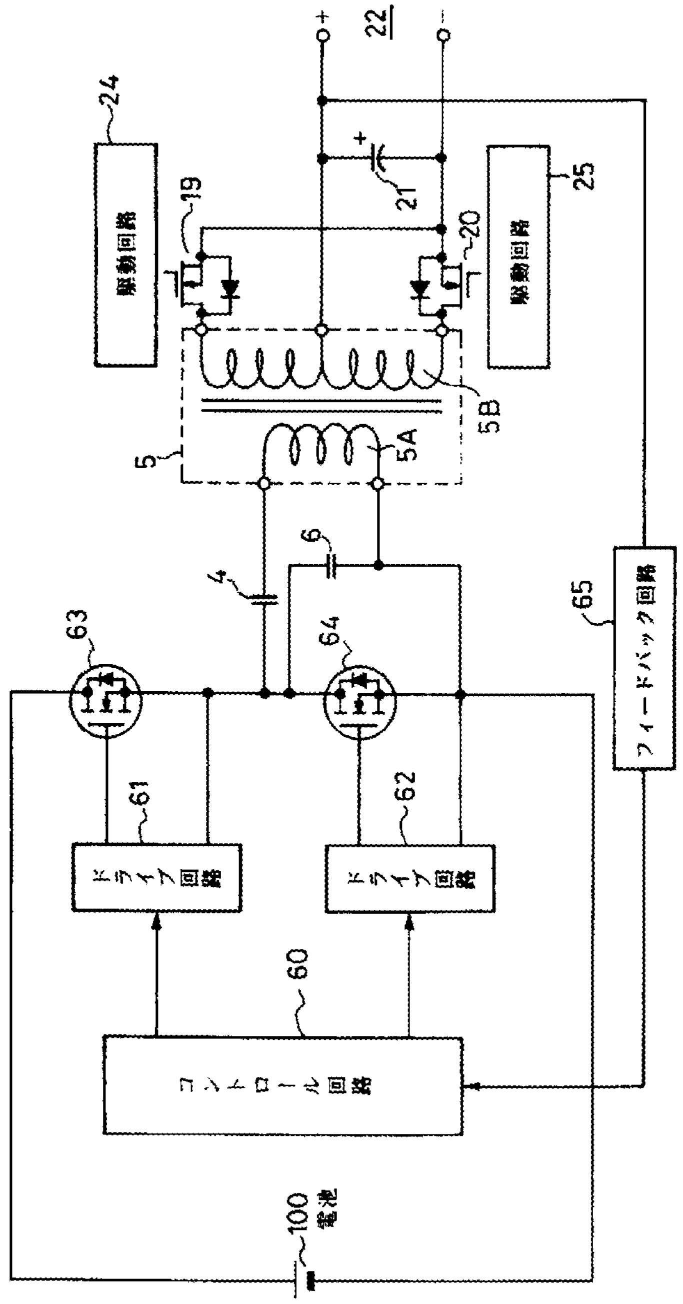
【図７】



【図９】



【図8】


22
+
−
24
駆動回路
19
20
21
25
駆動回路
5
5A
5B
4
6
63
64
65
フィードバック回路
61
62
ドライブ回路
ドライブ回路
60
コントロール回路
100
電池

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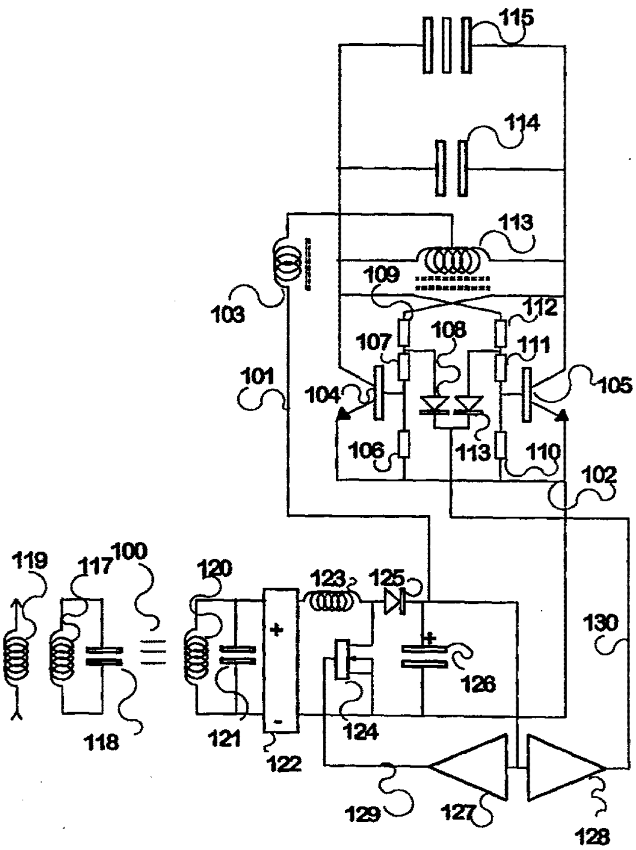
(54) **Title:** INDUCTIVE POWER TRANSFER ACROSS AN EXTENDED GAP

(57) **Abstract**

Inductive power transfer across an extended gap (100) from a primary conductor (119) is provided by means of a resonant intermediate loop comprised of capacitor (118) with inductor (117) – perhaps simply a non–coiled wire – carrying a larger resonating current, that can in turn generate an inductive field to be collected by a pickup coil (120). This loop may increase the transfer rate or reduce the alignment accuracy required of an IPT system, useful for vehicles as well as for lighting and display purposes, and also offers frequency–stabilising features. An electroluminescent advertising panel may be powered from a sine–wave oscillator at 1.2 kHz; its DC power at 50 volts collected by a controlled secondary pickup coil tuned to a system frequency of 15 kHz and placed near to an intermediate pickup coil; also resonant at the system frequency and which is driven by inductive coupling from a primary conductor fed with alternating current at the system frequency.



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Inductive power transfer across an extended gap

TECHNICAL FIELD OF THE INVENTION

This invention relates to the use of inductive power transfer to provide power across an extended gap between a primary inductive trackway and a secondary pickup device, for a range of purposes including motive power, battery charging and lighting including lighting using electroluminescent panels.

BACKGROUND

Inductive power transfer, although contactless, has in most applications in the prior art using primary pathways required that the configurations shall include ferromagnetic cores and that the secondary or pickup shall be quite closely placed in proximity to, or about the primary conductor. For example, Kelley in US 4833337 uses elongated ferrite inverted "U" cores and a ferrite member fixed to the primary pathway as well. Boys & Green (WO92/17929) use "E" cores with one primary conductor located inside each space between the three limbs of the "E". Bolger (US 3914562) teaches a 120 Hz primary inductive cable along a roadway; the cable having iron laminations along its entire length. These laminations face corresponding laminations within the moving vehicles that draw power from the tracks. These are expensive, heavy constructions which will exhibit magnetic attraction forces and any magnetostrictive effects within the cores will tend to cause noise. For transferring power to moving road vehicles, avoidance of core structures (at least in the primary pathway) and a wider tolerance in positioning is clearly useful.

Inductive power transfer systems in which various portions of the system are tuned to resonance are somewhat liable to instability should one or more resonant circuits assume a different resonant frequency to that of the system mean. Means to enhance stability are always useful, given that resonance is in most cases the preferred way to optimise the transfer of inductive power.

There are many applications in attention-gathering fields (i.e. advertising) in which it will be useful to extend the gap over which a useful field can be transmitted under inductive power transfer principles. Advantages of doing this include the concealment of the power sources so that panels appear to magically light up without a visible connection. Hence the use of inductive power transfer, which itself may involve higher frequencies, as a way of driving electroluminescent panels across a gap and without bare wires or contacts is a useful venture.

Electroluminescent panels have been available since at least 1957 as a source of lighting or of display and advertising material, yet they have proven to be difficult to drive at an acceptable level of brightness and at the same time retain a reasonably long life. Panels require a relatively high frequency (well above mains frequency) in order to glow at a useful level. Prior-art driving circuits such as dedicated chips rely on inverters to develop AC power at typically 800-1200 Hz, and up to typically 50 V peak-to-peak. Because the output of those inverters is substantially a square-wave waveform the phosphors of the panels are not excited optimally and brightness is not remarkable. Attempts to get more light with higher driving voltage usually results in breakdown of the dielectric and a failure of the panel, or a markedly curtailed life. There may be thermal runaway effects involved.

OBJECT

It is an object of this invention to provide an improved way to drive loads such as (but not limited to) electroluminescent panels across a gap using inductively transferred electric power, or at least to provide the public with a useful choice.

STATEMENT OF THE INVENTION

In a first broad aspect the invention provides means for inductive power transfer across an extended gap between a primary conductor and a secondary resonant pickup circuit, the means comprising an intermediate resonant loop, resonant at a system-wide resonant frequency and capable of being positioned within an inductive power transfer system so that inductive power is capable of being coupled inductively from the primary inductive conductor through the intermediate resonant loop to the at least one secondary resonant pickup circuit capable of collecting the inductive power.

Preferably the invention provides means for coupling inductive power as described in this section, wherein the intermediate resonant loop comprises a capacitance and an inductance, together resonant at the system-wide resonant frequency.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the inductance may comprise at least one lumped inductance and at least one extended inductance.

Optionally the at least one element having inductance within the intermediate resonant loop may comprise at least one intermediate lumped inductance comprised of a sub-loop having one or more turns and at least one extended intermediate inductance being the inductance of the loop itself.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the at least one lumped inductance is capable of receiving inductive power from a primary conductor.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the intermediate resonant loop is extended over a lateral distance so that one or more, spaced-apart, secondary resonant circuits may draw power from the intermediate resonant loop.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the intermediate resonant loop includes means to limit the amount of resonating current flowing.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the means to limit the amount of resonating current flowing includes means for at least partial decoupling of the intermediate loop from the primary conductor.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the secondary resonant circuit provides motive power to an electrically powered vehicle.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the intermediate resonant circuit is extended over a lateral distance beneath at least a part of a route taken by a vehicle, so that the intermediate resonant circuit is capable of providing power to the vehicle when the vehicle is situated adjacent to the position of the intermediate resonant circuit.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the intermediate resonant circuit provides a charging current to one or more battery units within a vehicle when the vehicle is situated adjacent to the position of the intermediate resonant circuit, such as at a bus stop.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the intermediate resonant circuit provides frequency stability to an inductively powered system.

Preferably the invention provides means for coupling inductive power as claimed in the preceding claim, wherein the intermediate resonant circuit includes active frequency-adjusting means or the like to overcome any system instability that may arise.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the intermediate resonant circuit provides a charging current to one or more battery units.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the secondary resonant circuit provides electric power to a light source.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the electrically powered light source is an electroluminescent panel driven with substantially sine-wave alternating current at an effective voltage and at an effective frequency.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the intermediate resonant loop comprises at least one element having inductance and at least one element having capacitance, together forming a circuit resonant substantially at the system-wide resonant frequency, and in which the intermediate resonant loop is capable of intercepting an inductive field from the primary inductive pathway and thereby having an effective resonating current induced within it, the inductive field developed about the intermediate resonant loop being in turn capable of inducing a current within the secondary resonant circuit.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the at least one element having inductance within the intermediate resonant loop comprises at least one lumped inductance comprised of a coil made from a fraction of a turn to a plurality of turns, the or each lumped inductance being situated at one position or, if the intermediate resonant loop has more than one lumped inductance, is situated at spaced-apart positions around the intermediate resonant loop, and at least one extended intermediate inductance is comprised of the inductance of the loop itself.

Preferably the invention provides means for coupling inductive power as described elsewhere in this section, wherein the orientation of the magnetic flux generated, when in use, about the intermediate lumped inductance is capable of enhancing the transfer of inductive power at that position. In another view, the inductive field developed, when in use, about the intermediate resonant loop may be caused to be concentrated at one or more predetermined positions by forming the intermediate resonant loop into a sub-loop having one or more turns at the or each position, so that the transfer of inductive power into or out of the inductive field developed, when in use, about the intermediate resonant loop is enhanced at the one or more predetermined positions.

Preferably the invention provides means for coupling inductive power over an extended distance from a primary, energised, inductive pathway having at least one conductor capable of carrying an alternating current having a system-wide consistent frequency, to a secondary resonant circuit capable of collecting the inductive power, the means comprising an intermediate resonant loop including at least one element having inductance and at least one element having a capacitance, together resonant at the system-wide resonant frequency, the intermediate resonant loop being capable of intercepting an inductive field from the primary inductive pathway and thereby having a current induced within it, the inductive field developed, when in use, about the intermediate resonant loop being in turn capable of inducing a current within the secondary resonant circuit so that in use it develops a substantial resonating current.

Preferably the lumped inductance is capable of receiving inductive power from a primary conductor, optionally connected to a primary lumped inductance adjacent to the intermediate lumped inductance.

Optionally the intermediate resonant loop may be extended over a lateral distance so that one or more, spaced-apart, secondary resonant circuits may draw power from the intermediate resonant loop.

Alternatively, the invention provides means to extend the distance between a source of changing magnetic fields and a magnetic field pickup means (including a secondary resonant circuit) over which an effective transfer of inductive power can take place, the means comprising a intermediate resonant circuit placed about the source of changing magnetic fields so that in use it develops a substantial resonating current.

Preferably the intermediate resonant loop of the invention is provided as an accessory to be overlaid upon a primary resonant pathway, so that it is capable of intercepting at least some of the magnetic flux surrounding one or more conductors of the primary pathway.

Alternatively the intermediate resonant loop of the invention may be provided as an accessory to be laid over or about a secondary resonant circuit or pathway so that the loop collects a magnetic flux and forwards it to the secondary resonant circuit or pathway.

Optionally the invention provides means to improve the frequency stability of an inductive power transfer system including a primary, energised, inductive pathway having at least one conductor capable of carrying an alternating current having a system-wide consistent frequency, and one or more secondary resonant circuits capable of collecting the inductive power, the means comprising an intermediate resonant loop including at least one element having inductance and at least one element having a capacitance, together resonant at the system-wide resonant frequency, the intermediate resonant loop being capable of intercepting an inductive field from the primary inductive pathway and thereby having a current induced within it, the inductive field developed, when in use, about the intermediate resonant loop being in turn capable of inducing a current within the secondary resonant circuit so that in use it develops a substantial resonating current, wherein the stabilising property depends on the reversal of the effect of a detuning or destabilising event as it crosses an inductive link between conductors, so that the addition of a second inductive link inherent in the use of an intermediate link between a primary and a secondary circuit causes the destabilising effect to be reversed twice.

In a second broad aspect the invention provides a power supply capable of receiving its electric power through an intermediate resonant loop as described elsewhere in this section, the power supply being capable of generating a substantially sine-wave alternating current at an effective voltage and an effective frequency for use with a capacitative load such as one or more electroluminescent panels; the power supply being itself supplied with electric power through an intermediate loop as described elsewhere in this section.

Preferably the invention provides a power supply as described elsewhere in this section, the power supply including a pair of switching devices driven in a complementary manner at the effective frequency, and includes an inductor capable of resonance at or about the effective frequency when connected to the capacitative load.

Preferably the invention provides a power supply as described elsewhere in this section, wherein the one or more electroluminescent panels are connected in parallel with a frequency-adjusting capacitance.

Preferably the invention provides a power supply as described elsewhere in this section, wherein the power supply includes a circuit comprising a first inductor of large inductance in series between a power supply and a centre tap of a second, resonating inductor of large inductance, the start and finish of the winding of the second inductor being connected to a second terminal of each of a pair of switches including current amplification properties, each first terminal of each switch being connected to the return line to the power supply, and each control terminal of each switch being connected via a resistor chain to the second terminal of the other switch, and the capacitative load being placed between the second terminals of the two switches.

Optionally the invention provides a power supply as described elsewhere in this section, wherein the circuit may be functionally enabled or disabled by connecting an intermediate point in one or both resistor chains to a potential capable of reversibly interrupting oscillation, thereby halting the supply of sine wave power.

Optionally the invention provides a beverage dispenser including one or more electroluminescent panels within valves capable of controlling the flow of the beverage, wherein the electroluminescent panels are provided with power by a power supply as described elsewhere in this section from an inductive power distribution system over a space, the width of the space being enhanced by the inclusion of an intermediate resonant circuit, so that the effective distance between the electroluminescent panel and the source of inductive power may be increased.

Preferably the invention provides a power supply wherein the power supply includes a circuit comprising a first inductor of large inductance in series between a power supply and a centre tap of a second, resonating inductor of large inductance, the start and finish of the winding of the second inductor being connected to a second terminal of each of a pair of switches including current amplification properties, each first terminal of each switch being connected to the return line to the power supply, and each control terminal of each switch being connected via a resistor chain to the second terminal of the other switch, and the capacitative load being placed between the second terminals of the two switches.

Preferably the invention provides a power supply as described elsewhere in this section, wherein the circuit may be functionally enabled or disabled by connecting an intermediate point in one or both resistor chains to a potential capable of reversibly interrupting oscillation, thereby halting the supply of sine wave power.

Optionally the power supply itself is supplied with electric power without the intervention of an intermediate loop as described elsewhere in this section.

Optionally the power supply itself is supplied with electric power from a utility rather than from an inductive power transfer system, in which case the power supply includes a circuit comprising a first inductor of large inductance in series between a power supply and a centre tap of a second, resonating inductor of large inductance, the start and finish of the winding of the second inductor being connected to a second terminal of each of a pair of switches including current amplification properties, each first terminal of each switch being connected to the return line to the power supply, and each control terminal of each switch being connected via a resistor chain to the second terminal of the other switch, and the capacitative load being placed between the second terminals of the two switches, but does not include a secondary resonant pickup circuit.

Optionally the invention provides a power supply as described elsewhere in this section, wherein the power supply itself is supplied with electric power from a conventional utility supply and the resonant secondary pickup aspect itself is absent.

Preferably the electric power is rectified.

DRAWINGS

The following is a description of a preferred form of the invention, given by way of example only, with reference to the accompanying diagrams.

Fig 1: is a circuit diagram used to drive an electroluminescent panel with inductively transferred power, using an intermediate loop.

Fig 2: is a circuit diagram showing the intermediate loop or circuit.

Fig 3: is a prior-art diagram of a self-illuminated roadway stud, in section, when attached to a roadway.

Fig 4: is a diagram of a self-illuminated roadway stud using an intermediate loop to continue the power supply connection after more layers of seal have been applied.

Fig 5: is a sectional diagram of a vehicle, driven with inductively transferred power and an intermediate loop as part of the trackway.

Fig 6: is a sectional diagram of a vehicle, driven with inductively transferred power and an intermediate loop included within the vehicle.

Fig 7: is a circuit diagram used to drive an electroluminescent panel with inductively transferred power, without using an intermediate loop.

PREFERRED EMBODIMENT

Application example 1: electroluminescent panel.

The invention will be described in relation to a particular application; driving an electroluminescent panel incorporated into a the handle of a beer tap as used in bars, where the panel serves as a background for advertising material. Clearly, the invention can be applied to other situations.

The circuit for driving an electroluminescent panel includes four sections:- (a) DC to AC conversion producing a sine wave output at an optimal frequency, capable of driving the panel more effectively, (b) power pickup means, (c) secondary control means operating on rectified power, and (d) panel disabling means. Refer to Fig 1.

Section (a) of the circuit is a DC to sine wave converter which is adapted for a capacitative load such as that of an electroluminescent panel 115; a device having usually one transparent conductive plane, a dielectric layer including one or more phosphors capable of emitting light when excited, and a second conductive plane, so comprising a capacitor. The light emitted from an energised panel could be regarded as a result of the existence of a "lossy dielectric" because a change in the voltage field between the planes is required to excite the phosphor. The panels used are made with flexible plastics materials by the New Zealand manufacturer of the advertising displays, using DuPont phosphors and chemicals. A typical panel has an area of about 50 cm^2 and a capacitance of about 10 nF.

We found that conventional excitation with approximately square wave waveforms from purpose-designed integrated-circuit (IC) excitation devices (e.g. the Supertex HV803) resulted in about 120 lux of emitted light, which is visible but not dramatic. Attempts to drive the panels harder, with more voltage, in order to get more light resulted in failure of either or both the panel and the IC driver and perhaps this is a result of the "impulse" nature of the step changes of a square wave drive being poorly matched to the requirements of the phosphor in terms of perceptible light. Perhaps thermal runaway effects occur during the failure process. In order to exercise the dielectric of a panel, and so excite the phosphors as efficiently as possible, it seems preferable to apply an AC waveform having a constant rate of change; a sine wave. We have confirmed that panels driven with a sine wave circuit according to this invention can radiate a considerably increased amount of light over apparently a long period before degradation or failure occurs. Accordingly we have constructed a sine-wave power supply circuit capable of producing a reasonably pure sine wave when used with a capacitative load (including electroluminescent panels) yet having high conversion efficiency and a low parts count.

Referring to Fig 1, 101 is a positive power input and 102 is a negative power input. 103 is an inductance of small physical size (total 13 x 13 x 9 mm) wound from 3500 turns of 0.05 mm insulated copper wire on an E-I ferrite coil former. It has an inductance of about 1.2 Henry. This part converts a voltage source such as our secondary pickup coil combination including a smoothing capacitor into a current source.

The active components in the circuit comprise 104 and 105, two NPN transistors in a cross-coupled type of circuit. Suitable transistors are rated for 200V V_{ceo}, 250 mA, and have a ß of about 40. (Steering diodes 108 and 113 simply provide for circuit disabling - see section (d)). The emitters of the transistors are connected to supply line 102; their bases are connected at the first junction (between 106 and 107) of a resistor chain comprising 106 (47K), 107 (82K), and 109 (330K); or 110, 111, and 112 for the other transistor. The top ends of these resistor chains are connected to the collectors of the opposite transistors. Also connected between the collectors are the ends of 113, a centre-tapped inductor otherwise like 103 which has the centre tap connected to 103, and optionally one or more capacitors such as 115, used for frequency-adjusting purposes to reach the about 1200 Hz desired frequency, and 116, one or more electroluminescent panels. 113 serves as a resonating inductance and as a DC feed or splitter.

Note that the desired frequency (the "second frequency" of our claims) is not related to the "first frequency" used for power distribution which is typically in the range of from 10 kHz up to perhaps 30 kHz, depending on switching device ratings, harmonic considerations, and the like.

The operating frequency is trimmed by adjustment of capacitor 115 to run at about 1200 Hz with the about 10 nF preferred electroluminescent panel. The magnetising inductance of the centre tapped inductor, which serves as a DC feed and as part of a resonant circuit, is about 1.2 Hy. In use the circuit is fed at about 50V DC which results in about 400 Lux of greenish light being emitted by the panel. For special effects such as flashing, the circuit can be switched off by disabling the base drives, actually by grounding the junction of the diodes 113 and 108 so interrupting signal and base current. On raising the diode voltage (above about 1.5V, so that the diodes become non-conducting) the circuit rapidly (in about 2-3 cycles) builds up to its full amplitude of oscillation. The controller 128 provides this output. (We have not discussed in detail any actual control signals for enabling or disabling the circuit. These may be internally generated by a simple free-running multivibrator, or may be picked up from an external source perhaps through the demodulation of control signals carried either though the primary conductor cable or as electromagnetic fields). Thus the circuit can be programmed to make the panel flash on and off, or be dimmed with a rapid enable/disable sequence. Brightness control is also possible by varying the applied voltage, as long as the ratings of the panel and other parts are not exceeded. The applied voltage could be varied by varying the reference voltage fed to the controller 127 for the shorting switch 124. Another mode of use of the comparator 128 is to inhibit the panel-driving converter when the bus voltage is under 40 volts, or enable it when the voltage is over 40 V. This has the effect in the target application of causing the panel to flash brightly and perhaps briefly, rather than fade into dimness, if the coupling to the pickup coil is reduced. In the target application this enhances human attention-gathering by the panel while in other applications this is a fail-safe feature for inadvertently reduced power transfer.

Power section: Integration of this circuit with an inductive pickup secondary circuit (sections (b) and (c)) is preferably as follows: A pickup coil 120, resonant with capacitor 121, can collect inductive power in the form of a changing magnetic field and convert it into AC. Typically we generate 10-40 kHz AC in a primary conductor or primary coil 119 to provide a changing magnetic field. The circulating current in the resonant tank circuit 120-121 is rectified in the bridge rectifier 122 and passed through an inductance 123 of typically 560 μH, intended to limit the peak current passing through a control switch 124 which is capable of shorting out the pickup coil (ignoring two diode voltage drops, of course). If the shorting switch is in a high-impedance state, rectified current flows through the steering diode 124 and along the bus 131 to charge up the smoothing capacitor 126, across which the supply voltage is developed. In this circuit, one comparator determines whether the bus 101 voltage is over 50 volts, in which case its output on line 129 goes high and turns ON the switch 124, or under 49 volts, when its output goes low. This output controls the switch 124. The negative bus is connected to the inductor 102.

Novel means for enhancing the gap length 100 over which inductively coupled inductive power transfer or ICIPT can be transferred are provided as follows (see both Fig 1 and Fig 2). An at least several times increase of the distance over which effective amounts of inductive power can be transferred is attainable. This aspect of the invention comprises placement of a simple intermediate resonant circuit 117, 118 having (in this example at least) no control means or active components or the like between a primary source of a changing magnetic field and the ultimate consumer or consumers. In Fig 1 this novel resonant circuit is represented by the capacitor 118 and the inductance 117. In Fig 2 the novel intermediate resonant circuit is represented by the capacitor 118, the lumped inductance 117, where power is transferred into the circuit from a source of inductive power passing through the inductor 119 which may be a straight conductor or a coil, and the elongated conductor 117A. In practice, the elongated conductor might energise a number of pickups such as the four tank circuits, one labelled 120 (inductor) and 121 (capacitor (each corresponding to a circuit such as that of Fig 1) and another labelled 120' and 121'. (See also Fig 5).

The physical configuration of the intermediate circuit may be varied according to the application. Electrically it may be represented as inductor 117 and capacitor 118 in Fig 1. The intermediate pickup coil can develop higher circulating currents or at least a higher magnetic flux than a primary energised conductor, and so transfer power over a greater gap length 100. An interesting observation about the intermediate resonant circuit 117/118 is that the overall stability of a system having extra resonant, tuned circuits of this type is improved. If one circuit (say 120,121) is detuned away from resonance, its power factor changes in use so that for example the current leads the voltage. In a second circuit (say 117 and 118) inductively coupled to the first the power factor is reversed so that the voltage now leads the current. In situations where one inductively coupled link exists, the reversal leads to instability, but in situations where a second inductively coupled link to a third circuit (119) also exists, the power factor relationship is again reversed and so the intermediate link leads to an improvement in frequency stability. Of course, this power supply may be used to drive an electroluminescent panel or similar device without the aid of an intermediate loop. Fig 7 shows such a power supply, practically identical to that of fig 1 but with the omission of the loop 117 and 118. Note that in Figs 1 and 7 the primary conductive pathway 119 need not have an actual discrete inductance, if sufficient current is flowing in a straight wire to provide an adequate flux.

Advantages of this power supply include that it renders an electroluminescent panel a much brighter, and hence more useful device. Furthermore, the increased brightness for a given peak voltage obtained with sine-wave driving seems to result in a greatly increased panel life, although the exact improvement of lifetime remains to be defined. We had been causing panels and drivers to fail when testing the prior-art square-wave driver circuit at higher voltages.

<u>Application example 2A: road studs.</u>

Fig 3 shows a prior-art view of a road stud (which is a device including a resonant secondary circuit, a control circuit to limit secondary current, and an array of light-emitting diodes intended as a self-lit "cat's eye" type of lane marker), in which the stud 300 is simply glued onto a road surface 303 above a previously cut slit containing primary inductive pathway conductors 304 and 305. Typically, the conductors are spread apart within the space 306 so that the magnetic field surrounding the upper conductor 304 is not partially cancelled out by the reverse field in 305. Inside the road stud there is a pickup inductor 301 (here shown side-on), resonating circuitry, power control and supply circuitry and a bank of light-emitting diodes 302 to provide a useful output.

One problem with this device is that after the road receives each of an often needed re-sealing, the distance over which the inductive field must travel to reach the stud becomes greater and may exceed the capability of a given field. (Studs can be hammered free of their adhesive and perhaps re-used if still functional). The principle of the intermediate loop of the invention is shown in Fig 4, in which a greater thickness of road surface 303B has been added to the original, 302A. One way in which this invention can be used in practice is to cut a further slit in the new seal 303B with a diamond saw or the like, and insert an intermediate loop 401 made of a good conductor such as a litz wire (which has a high surface area and hence reduced losses at high frequency) with its resonating capacitor 402. The capacitor may be made as a flat, card-like object rather than the usual cylinder so that it falls into a narrow slit.

In laboratory tests, an intermediate resonant circuit comprising a number of turns of wire wound over two ferrite strips together with appropriate tuning capacitors was made up. This circuit is resonant at a system frequency and can be placed over a single wire of a primary conductive pathway. When the circuit is close to the single wire, the road stud can be excited to a level at which the control circuit becomes operative (perceived as an upper brightness limit) when it is about 10 cm away from the single wire. Without the intermediate resonant circuit, this distance is limited to about 3 cm.

Advantages of this intermediate loop include that the road can be re-sealed more times before the original primary conductive trackway becomes useless. The "reach" of the magnetic flux can be extended with the aid of intermediate loops. We expect that a stack of more than one intermediate loop will also work although it is possible that current-limiting means, perhaps a saturable inductor, may be required.

<u>Application example 2B: two road studs.</u>

One road stud close to the primary conductor can act as a intermediate resonant circuit for another road stud; here the intermediate circuit is not a simple passive inductor/capacitor circuit but is controlled by a shorting switch arrangement for decoupling the circuit in the event of too high a circulating voltage. This illustrates use of an intermediate loop incorporating a current limiting feature. Such a feature is useful in permitting primary current to pass an un-loaded intermediate loop and so reach further consuming devices.

Application example 3A: vehicle powered through an intermediate loop attached to the trackway.

Fig 5 shows a vehicle 500, capable for example of running along an arrangement of rails 501, in which an electric motor 509 drives at last one wheel; the motor being fed from a set of motor control circuitry 508 which accepts AC power from a resonant pickup circuit comprised of a capacitor 506 and an inductor 507 preferably having a ferromagnetic core arranged so as to effectively intercept a flux from a supply. The primary conductor 503 running substantially parallel to the track has as an intermediate coupling arrangement a loop of wire (preferably a litz wire, because it may carry a high resonating current) including optionally one or more discrete inductances 504 and a tuning capacitor 505. The inductances 504 have two functions; they aid in causing the loop to be electrically resonant at a system-wide resonant frequency, and they act as concentrated sources of inductive fields to be picked up by the vehicle. In some transport systems there may be an arrangement wherein higher power levels are desirable at certain spots, such as for acceleration. Or, a vehicle may normally be powered by rechargeable batteries 510, to be charged at certain designated spots such as "bus stops" along a fixed route. Fig 5 could in fact be regarded as a sectional view through a bus stop having charging facilities. The intermediate loop allows effective charging to occur with an increased tolerance in the actual rest position.

Advantages of this invention include that power transfer may occur over greater distances. Thus a driver need not be so precise in positioning the bus over a charging conductor for recharging a bus battery. Reduced vertical positioning constraints allow a vehicle with a softer suspension. A product carrying conveyor device can supply increased power where the rails make an ascent. Incidentally, there may be simple battery charger applications where the increased gap distance is an advantage and, of course, the constant-current nature of loosely coupled inductive power transfer is an asset in changing batteries. The intermediate loop may allow increased power to be drawn from a primary conductor.

Application example 3B: vehicle powered through an on-board intermediate loop.

This version of the invention is similar to the arrangement shown in Fig 5, except that the intermediate loop (including 603 the resonating capacitor, 604; a part of a transformer, and 507;

a pickup inductor,) is now carried within (or upon) the vehicle and serves a different function. The capacitor 506 and the part-inductor 601 represent the original secondary pickup coil and resonating capacitor. We have included a ferromagnetic core 602 as a convenient way to produce a more economical transformer.

In this example the advantage of the intermediate loop is that it acts as a system frequency stabilising device. Suppose for example that the vehicle resonant pickup comprised of 506 and 601 has shifted away from the system-wide frequency and as a result the phase of the current within the pickup resonant circuit is leading the phase of the voltage. As is well-known, on the other side of a transformer device (including an inductive pickup device), the phase of the voltage will now tend to lead the phase of the current. This inversion of the order tends to cause system instability. If an intermediate loop is used, then within the primary conductor the original leading by the current is restored as a result of passage of the power through a second transformer device - or inductive coupling means in this case. Hence the detuning of the vehicle is less likely to cause system instability; and increased system stability is a resulting advantage.

Intermediate loops may be constructed and sold as separate accessories suitable for use with inductive power transfer systems of various types. One of the variables to be considered when ordering loops is the existing resonant frequency of the system with which the intermediate loops are to be used.

Application example 4: beer tap handles.

This example integrates all the inventions described in this specification. Electrically, the beer tap handle circuit is that shown in Fig 1, where the luminescent panel 114 is incorporated in the handle of a beer tap to act as an advertising accessory and attract the attention of consumers. In this instance, the reduced coupling that occurs when the handle is operated by being pulled away from a rest position has the effect of causing the hitherto steadily lit panel to not simply go dim, but enter a flashing mode wherein the brightness of each flash (which is of a reasonably long duration, depending on the size of capacitor 126) is comparable to the steady illumination (typically 400 lux using the circuit of this invention) of the handle in its rest position.

The components (apart from 119, 117, and 118) of Fig 1 are preferably installed in a concealed manner within each handle. Using surface-mount electronics size is not a problem. Refer to Fig 2 for the physical appearance of an illuminated beer-tap handle for use in a bar.

The pickup coil (120) comprises perhaps 20 turns on a C-shaped core which may be cut from a toroidal core. In the example this is oriented vertically (i.e. along the axis of the handle) in order to collect flux emanating from the intermediate resonant 118-117. In Fig 2, the rectangle 117A may be physically within a panel that passes close to each beer handle circuit (here suggested by the tank circuits 120, 121 etc). In one corner a concentration of flux pick-up means 117 is provided and this is in use oriented close to a source of magnetic field such as a coil 119 driven by a resonant power supply converter (not shown) with a sine wave at typically 40 kHz in this application. The tuning capacitor 118 is generally located close to this coil. The primary coil 119 may be incorporated in a clip over the holder for the panel. In this particular application it is useful to be able to detach the panel including the coil 117/117A/118 and as there are no direct connections to it, this can be done easily. In fact the componentry can be totally concealed. The panel can be detachable in this application to permit access to the tap mechanism and for cleaning. The detachable panel may be cleaned, for it has no active, sensitive parts or exposed electrical connections.

When in place, this panel is held so that its particular pickup area 117 is in proximity to the energising primary coil, and its border is near one or more pickup coils, 120, 120' and so on; one on each beer tap.

Advantages of this system containing a intermediate resonant circuit for powering electroluminescent panels in a consumer-accessible and often wet region include (1) that there is no need to place relatively obtrusive primary coils adjacent to each tap, with wiring, and rigidly held in close relationship to toroids around the beer handles, so affecting the ability to clean the taps, and (2) that the distance over which effective coupling occurs is greater, so that precise positioning is not required and so that electroluminescent panels remain lit during movement of the beer tap handles. Several beer taps may be driven from the one intermediate circuit.

VARIATIONS

For a vehicle, the intermediate loop may be mounted over the fixed primary trackway within the road surface, for gap-widening purposes, or it may be mounted within the vehicle in relationship with the secondary pickup coil or coils, where it serves to increase stability.

We have not yet explored the operation of a intermediate circuit under high power operating conditions or where several intermediate circuits are to be driven simultaneously from a single primary conductor. Intermediate resonant loops circuits may also need to include control circuits to limit the total circulating power. One possible example of a control "circuit" is a saturable ferrite core within the tuning inductance. Another is back-to-back Zener diodes connected across the tuning capacitor, selected so as to break down when the circulating voltage exceeds a predetermined limit.

INDUSTRIAL APPLICATION

(1) Improved drive circuitry for electroluminescent panels increases the range of possible applications for such panels. Prior-art drivers resulted in about 120 lux of emitted light, which is visible but not dramatic. 400 Lux was available with the circuit of this invention.

(2) Intermediate resonant circuits, by increasing the gap over which a given amount of power can be transferred inductively, can increase the number of applications for IPT. They can reduce the amount of primary current required, and/or reduce the size of a secondary pickup inductor, or they may reduce the requirements for precise alignment of the pickup coil with the primary conductor. For a road stud, which is an internally lit "cat's eye" device using light-emitting diodes, adequate function is obtained when it is about 10 cm away from the single wire. Without the intermediate resonant circuit, this distance is limited to about 3 cm. The intermediate resonant circuit itself is a simple and cheap device.

Finally, it will be appreciated that various alterations and modifications may be made to the foregoing without departing from the scope of this invention as set forth in the following claims.

CLAIMS

1. Means for coupling inductive power across an extended gap between a primary conductor and at least one secondary resonant pickup circuit capable of collecting the inductive power; the means comprising an intermediate resonant loop, resonant at a system-wide frequency and capable of being positioned within an inductive power transfer system so that inductive power is capable of being coupled inductively from the primary inductive conductor through the intermediate resonant loop to the at least one secondary resonant pickup circuit.

2. Means for coupling inductive power as claimed in claim 1, wherein the intermediate resonant loop comprises a capacitance and an inductance, together capable of resonance at the system-wide resonant frequency.

3. Means for coupling inductive power as claimed in claim 2, wherein the inductance within the intermediate resonant loop comprises at least one lumped inductance and at least one extended inductance.

4. Means for coupling inductive power as claimed in claim 3, wherein the at least one inductance is capable of transferring inductive power.

5. Means for coupling inductive power as claimed in claim 2, wherein the intermediate resonant loop is extended over a lateral distance so that one or more, spaced-apart, secondary resonant circuits may draw power from the intermediate resonant loop.

6. Means for coupling inductive power as claimed in claim 5, wherein the intermediate resonant loop includes means to limit the amount of resonating current flowing.

7. Means for coupling inductive power as claimed in claim 2, wherein the intermediate resonant circuit is extended over a lateral distance beneath at least a part of a route taken by a vehicle, so that the intermediate resonant circuit is capable of providing power to the vehicle when the vehicle is situated adjacent to the position of the intermediate resonant circuit.

8. Means for coupling inductive power as claimed in claim 7, wherein the intermediate resonant circuit provides a charging current to one or more battery units within a vehicle when the vehicle is situated adjacent to the position of the intermediate resonant circuit.

9. Means for coupling inductive power as claimed in claim 2 wherein the secondary resonant pickup circuit includes an electrically powered light source.

10. Means for coupling inductive power as claimed in claim 9, wherein the electrically powered light source is an electroluminescent panel and the secondary resonant pickup circuit includes means for generating an alternating current at an effective voltage and at an effective frequency.

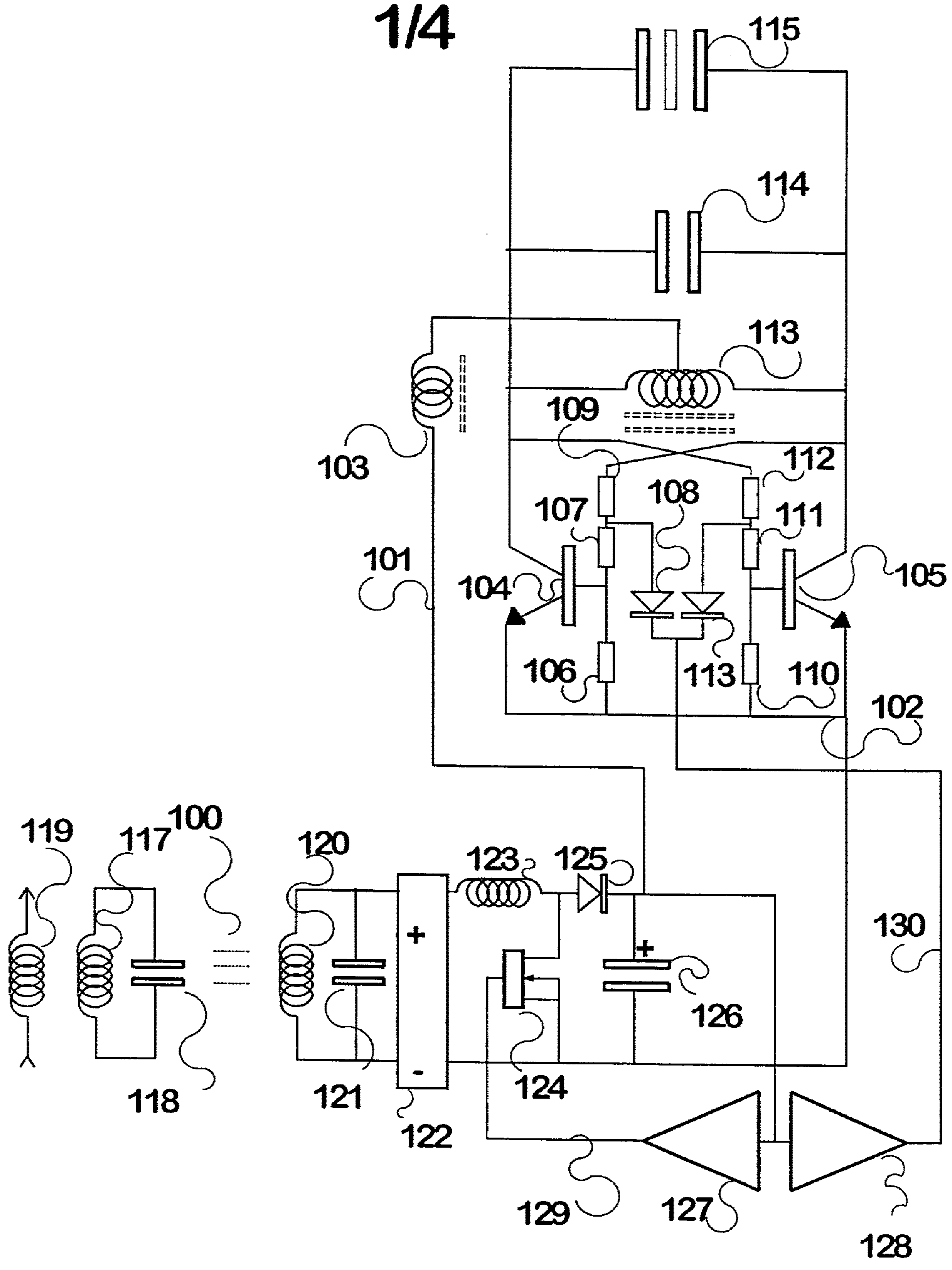
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Fig 1

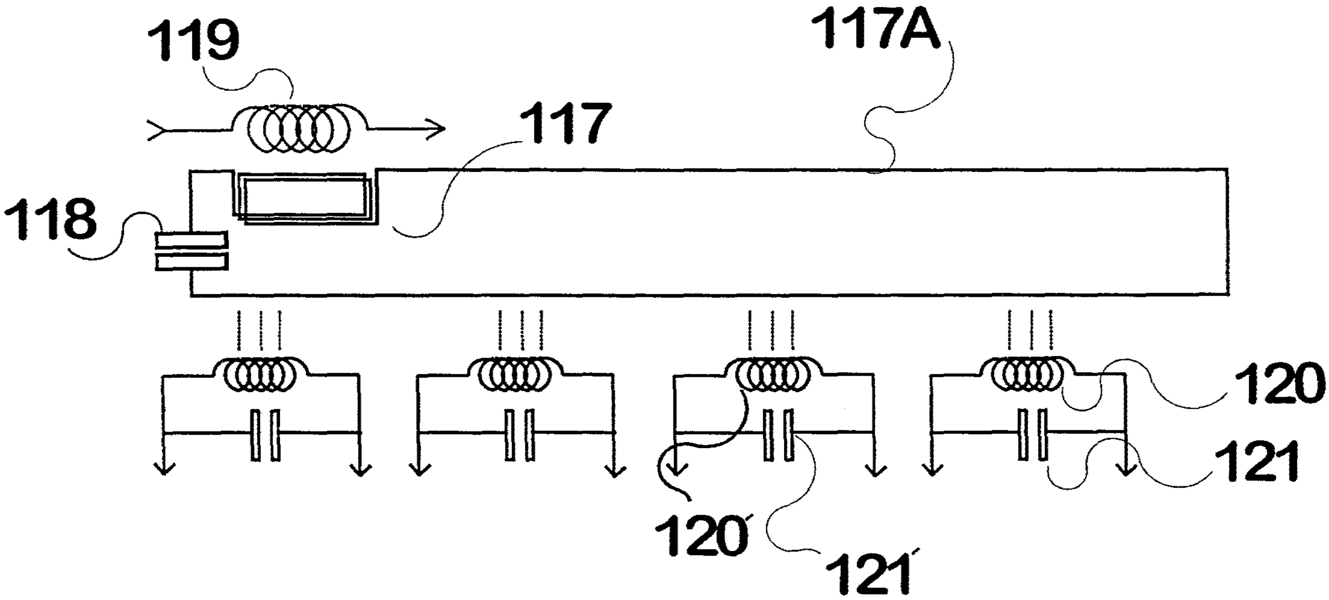

Fig 2

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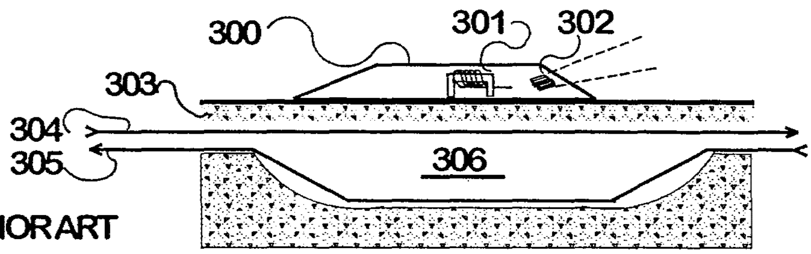

PRIOR ART

Fig 3

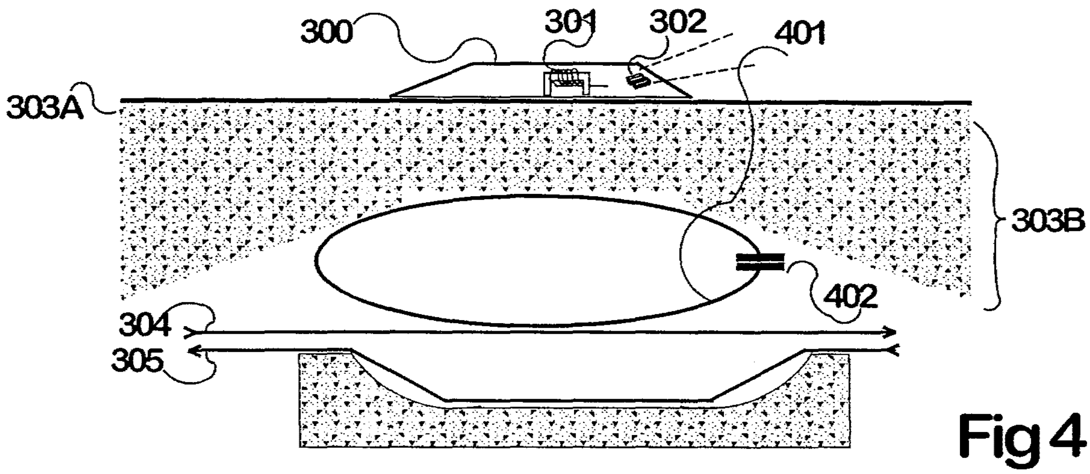

Fig 4

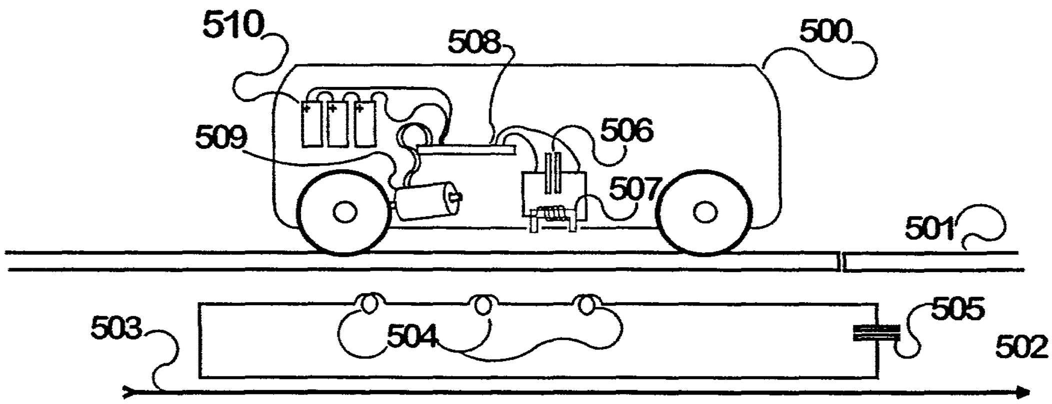

Fig 5

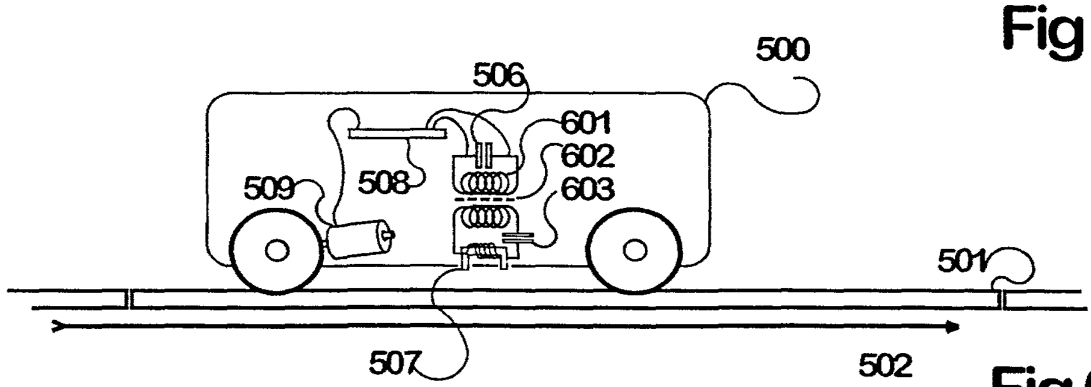

Fig 6

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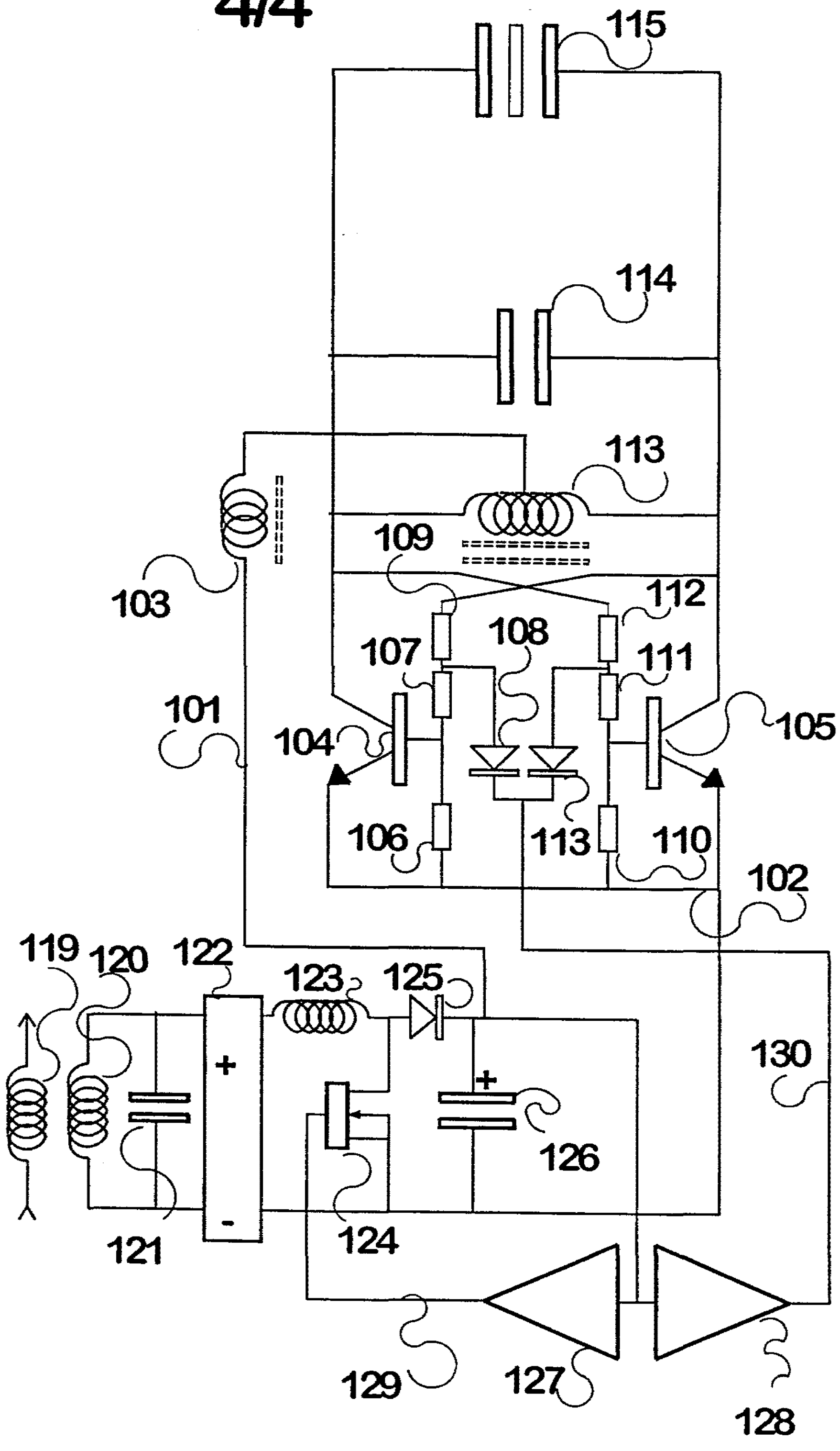
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Fig 7

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/NZ 98/00053

A.	**CLASSIFICATION OF SUBJECT MATTER**

Int Cl[6]: H02J 1/00, H02J 3/00, H01F 30/14, H01F 38/14

According to International Patent Classification (IPC) or to both national classification and IPC

B.	**FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
IPC H02J 1/00, H02J 3/00, H01F 30/14, H01F 38/14, B60L 9/IC

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU: IPC as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPAT: (Inductive() Power() Transfer) or [(INDUCTIVE: OR INDUCTION) AND RESONA:]
JAPIO: SAME AS ABOVE.

C.	**DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3914562 A (BOLGER) 21 October 1975 Abstract	1-10
A	US 4833337 A (KELLEY et al.) 23 May 1989 Abstract	1-10
A	WO 9217929 A1 (PIPER) 15 October 1992 Page 2 line 27 - Page 5 line 35	1-10

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier document but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 August 1998	-9 SEP 1998

Name and mailing address of the ISA/AU	Authorized officer
AUSTRALIAN PATENT OFFICE PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No.: (02) 6285 3929	**JUZER KHANBHAI** Telephone No.: (02) 6283 2176

Form PCT/ISA/210 (second sheet) (July 1992) copjhw

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/NZ 98/00053

C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 9425304 A1 (CADAC HOLDINGS LTD.) 10 November 1994 Page 1 line 28 - Page 3 line 26	1-10
A	WO 9511544 A1 (AUCKLAND UNISERVICES LTD.) 27 April 1995 Page 3 line 18 - Page 4 line 18	1-10
A	WO 9511545 A1 (AUCKLAND UNISERVICES LTD.) 27 April 1995 Page 3 line 18 - Page 6 line 12	1-10

Form PCT/ISA/210 (continuation of second sheet) (July 1992) copjhw

INTERNATIONAL SEARCH REPORT
Information on patent family members

International Application No.
PCT/NZ 98/00053

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	4833337	CA	1282010	EP	287645	WO	8802944
WO	9217929	AU	12373/92	CA	2106784	EP	577611
		EP	818868	MX	9201100	NZ	237572
		US	2593308				
WO	9425304	AU	40933/93				
WO	9511544	AU	80064/94	AU	80065/95	EP	727105
		JP	7170681	NZ	274939	US	5528113
		WO	9511545				
WO	9511545	AU	80064/94	AU	80065/94	EP	727105
		JP	7170681	NZ	274939	US	5528113
		WO	9511544				

END OF ANNEX

P80157.V01W01

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To: JOHN NORTRUP
STRATEGIC PATENTS, P.C.
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION

(PCT Rule 44.1)

Date of mailing *(day/month/year)* 05 JUL 2011

Applicant's or agent's file reference WTCY0053PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2011/027868	International filing date *(day/month/year)* 10 March 2011
Applicant WITRICITY CORPORATION	

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

Filing of amendments and statement under Article 19:
The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes 1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 82 70

For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 – 9.011.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

☐ the protest together with the decision thereon has been transmitted to the International Bureau together with any request to forward the texts of both the protest and the decision thereon to the designated Offices.

☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. Following the expiration of 30 months from the priority date, these comments will also be made available to the public.

Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 Telephone No. PCT OSP: 571-272-7774

Form PCT/ISA/220 (July 2010)

CPA GLOBAL
JUL 11 2011
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Verified

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To: JOHN NORTRUP
STRATEGIC PATENTS, P.C.
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION

(PCT Rule 44.1)

	Date of mailing *(day/month/year)* 05 JUL 2011
Applicant's or agent's file reference WTCY0053PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2011/027868	International filing date *(day/month/year)* 10 March 2011
Applicant WITRICITY CORPORATION	

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

   Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes 1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 82 70

   For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 – 9.011.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   ☐ the protest together with the decision thereon has been transmitted to the International Bureau together with any request to forward the texts of both the protest and the decision thereon to the designated Offices.

   ☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. Following the expiration of 30 months from the priority date, these comments will also be made available to the public.

   Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

   In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

   For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300
Facsimile No. 571-273-3201	Telephone No. PCT OSP: 571-272-7774

Form PCT/ISA/220 (July 2010)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference WTCY0053PWO	FOR FURTHER ACTION	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. PCT/US2011/027868	International filing date *(day/month/year)* 10 March 2011	(Earliest) Priority Date *(day/month/year)* 10 March 2010
Applicant WITRICITY CORPORATION		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 2 sheets.

☐ It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of:
      ☒ the international application in the language in which it was filed.
      ☐ a translation of the international application into ______ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).
   b. ☐ This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6*bis*(a)).
   c. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2. ☐ **Certain claims were found unsearchable** (see Box No. II).

3. ☐ **Unity of invention is lacking** (see Box No. III).

4. With regard to the **title**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. With regard to the **drawings**,
   a. the figure of the **drawings** to be published with the abstract is Figure No. 1
      ☒ as suggested by the applicant.
      ☐ as selected by this Authority, because the applicant failed to suggest a figure.
      ☐ as selected by this Authority, because this figure better characterizes the invention.
   b. ☐ none of the figures is to be published with the abstract.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/027868

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H04B 5/00 (2011.01)
USPC - 307/104
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - H04B 5/00; H01F 38/00; H02J 17/00; H01P 7/00, 7/06 (2011.01)
USPC - 307/104, 333/219, 230; 455/41.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
MicroPatent, Questel Orbit, USPTO EAST System (US-PGPUB; USPAT; USOCR; EPO; JPO; DERWENT), Google Patent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y	US 2009/0085408 A1 (BRUHN) 02 April 2009 (02.04.2009) entire document	1-4, 11-12, 14-15, 17 ----- 5-10, 13, 16, 18-19
Y	US 2009/0243397 A1 (COOK et al) 01 October 2009 (01.10.2009) entire document	5, 8-10, 16, 18
Y	US 2007/0021140 A1 (KEYES, IV et al) 25 January 2007 (25.01.2007) entire document	6-7
Y	US 2008/0266748 A1 (LEE) 30 October 2008 (30.10.2008) entire document	13, 19
A	US 2008/0036588 A1 (IVERSON et al) 14 February 2008 (14.02.2008) entire document	20-25
A	US 6,664,770 B1 (BARTELS) 16 December 2003 (16.12.2003) entire document	1-25
A	US 2004/0000974 A1 (ODENAAL et al) 01 January 2004 (01.01.2004) entire document	1-25

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 June 2011	05 JUL 2011

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To: JOHN NORTRUP
STRATEGIC PATENTS, P.C.
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

Date of mailing (*day/month/year*)	05 JUL 2011	
Applicant's or agent's file reference WTCY0053PWO	**FOR FURTHER ACTION** See paragraph 2 below	
International application No. PCT/US2011/027868	International filing date (*day/month/year*) 10 March 2011	Priority date (*day/month/year*) 10 March 2010
International Patent Classification (IPC) or both national classification and IPC IPC(8) - H04B 5/00 (2011.01) USPC - 307/104		
Applicant WITRICITY CORPORATION		

1. This opinion contains indications relating to the following items:

☒	Box No. I	Basis of the opinion
☐	Box No. II	Priority
☐	Box No. III	Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
☐	Box No. IV	Lack of unity of invention
☒	Box No. V	Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
☐	Box No. VI	Certain documents cited
☐	Box No. VII	Certain defects in the international application
☐	Box No. VIII	Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

3. For further details, see notes to Form PCT/ISA/220.

Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Date of completion of this opinion 27 June 2011	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (July 2009)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US2011/027868

Box No. I Basis of this opinion

1. With regard to the **language**, this opinion has been established on the basis of:
   - [x] the international application in the language in which it was filed.
   - [ ] a translation of the international application into ______________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).

2. [ ] This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing filed or furnished:

   a. (means)
   - [ ] on paper
   - [ ] in electronic form

   b. (time)
   - [ ] in the international application as filed
   - [ ] together with the international application in electronic form
   - [ ] subsequently to this Authority for the purposes of search

4. [ ] In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

Form PCT/ISA/237 (Box No. I) (July 2009)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY	International application No. PCT/US2011/027868

Box No. V **Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

1. Statement

Novelty (N)	Claims	3, 5-10, 13, 16, 18-19	YES
	Claims	1-2, 4, 11-12, 14-15, 17	NO
Inventive step (IS)	Claims	20-25	YES
	Claims	1-19	NO
Industrial applicability (IA)	Claims	1-25	YES
	Claims	None	NO

2. Citations and explanations:

Claims 1-2, 4, 11-12, 14-15, 17 lack novelty under PCT Article 33(2) as being anticipated by Bruhn.

Regarding claim 1, Bruhn discloses a wireless power converter (apparatus for wireless energy transmission, para 0017, Fig. 9) comprising at least one receiving magnetic resonator 130, 132 configured to capture electrical energy received wirelessly (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) through a first oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) characterized by a first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9); and at least one transferring magnetic resonator 126, 128 (Fig. 9) configured to generate (through resonance, para 0017-0018, Fig. 9) a second oscillating magnetic field (transferred to the secondary winding 20, para 0017-0018, 0031, Fig. 9) characterized by a second plurality of parameters different from the first plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), wherein the electrical energy from the at least one receiving magnetic resonator 130, 132 is used to energize the at least one transferring magnetic resonator 126, 128 (Fig. 9) to generate the second oscillating magnetic field (energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0018, Fig. 9).

Regarding claim 2, Bruhn discloses wherein the first plurality of parameters includes a first frequency (operating at the fundamental frequency, para 0017, 0031, Fig. 9) different from a second frequency of the second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018).

Regarding claim 4, Bruhn discloses wherein the second frequency is approximately an integer multiple of the first frequency (second resonator has twice the resonant frequency of first resonator, para 0018).

Regarding claim 11, Bruhn discloses wherein the at least one receiving magnetic resonator 130, 132 is configurable to capture energy from magnetic fields with different parameters (resonator 130 can receive energies with different frequencies, para 0017-0018, 0040, Fig. 9).

Regarding claim 12, Bruhn discloses wherein the at least one transferring magnetic resonator 126, 128 is configurable to generate magnetic fields with different parameters (resonator 126 can generate and transmit energy with different frequencies, para 0017-0018, 0040, Fig. 9).

Regarding claim 14, Bruhn discloses a system (para 0017, 0043) comprising a source resonator 126, 128 configured to generate a first oscillating magnetic field (transferred to the secondary winding 20, para 0017-0018, 0031, Fig. 9) characterized by a first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9); a device resonator 130, 132 configured to capture electrical energy received wirelessly (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) through a second oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) characterized by a second plurality of parameters different from the first plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018); and a wireless power converter (apparatus for wireless energy transmission, para 0017, Fig. 9) including conversion circuitry (circuits as seen in Fig. 9) configured to capture energy from the second oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) and to energize the source resonator 126, 128 to generate the first oscillating magnetic field (transferred to the secondary winding 20, energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0017-0018, 0031, Fig. 9).

Regarding claim 15, Bruhn discloses wherein the first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9) and the second plurality of parameters are different in at least a frequency (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018).

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Supplemental Box

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Regarding claim 17, Bruhn discloses wherein the wireless power converter (apparatus for wireless energy transmission, para 0017, Fig. 9) is powered by electrical energy captured by the device resonator 130, 132 (transferred to the secondary winding 20, energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0017-0018, 0031, Fig. 9).

Claim 3 lacks an inventive step under PCT Article 33(3) as being obvious over Bruhn.

Regarding claim 3, Bruhn discloses the invention above, the invention above, and discloses a first frequency (operating at the fundamental frequency, para 0017, 0031, Fig. 9) and a second frequency (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), but does not disclose wherein the first frequency is approximately an integer multiple of the second frequency. It would have been obvious to one of ordinary skill in the art at the time of the invention to provide a first frequency that is approximately an integer multiple of the second frequency, in order to provide a system that can handle different power levels for providing wireless energy to multiple devices, and because discovering the optimal value of a result effective variable involves only routine skill in the art.

Claims 5, 8-10, 16, 18 lack an inventive step under PCT Article 33(3) as being obvious over Bruhn in view of Cook et al. (hereinafter referred to as Cook).

Regarding claim 5, Bruhn discloses the invention above, but does not specifically disclose wherein the first plurality of parameters includes a first magnitude different from a second magnitude of the second plurality of parameters. Cook is in the field of wireless power systems (para 0044) and teaches wherein the first plurality of parameters includes a first magnitude different from a second magnitude of the second plurality of parameters (transmit power converter unit converts the supply voltage and frequency, such as 110V/60Hz, into another voltage [different voltage] and into another frequency, such as under 50Hz, that is more appropriate for wireless transmission, para 0155-0158). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the different magnitudes as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Regarding claim 8, Bruhn discloses the invention above, and further discloses electrical energy captured by the at least one receiving magnetic resonator 130 (resonator 130 captures energy developed by generator 16 and primary winding 18, Fig. 9, para 0034), but does not specifically disclose a first converter circuit configured to convert the electrical energy into a direct current signal. Cook teaches a first converter circuit 1550 configured to convert the electrical energy into a direct current signal (a DC/DC or DC/AC converter 1550 converts the electrical energy received by resonator antenna into direct current, para 0194-0195, Fig. 15). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the direct current conversion as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Regarding claim 9, Bruhn discloses the invention above, and further discloses wherein the alternating current signal (power source 16 provides AC current signal, Fig. 9, para 0040) is used to energize the at least one transferring magnetic resonator 126, 128 (energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0018, Fig. 9), but does not disclose a second converter circuit configured to convert the direct current signal from the first converter circuit into an alternating current signal. Cook teaches a second converter circuit (two converter circuits for converting current signals, para 0194-0195, as shown in Fig. 15) configured to convert the direct current signal from the first converter circuit into an alternating current signal (a DC/DC or DC/AC converter 1550 can convert the electrical energy received by resonator antenna into alternating current, para 0194-0195, Fig. 15). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the direct current conversion as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Regarding claim 10, Bruhn discloses the invention above, and further discloses at least one receiving magnetic resonator 130, 132 (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) and at least one transferring magnetic resonator 126, 128 (Fig. 9), but does not disclose wherein at least one of the resonators has a quality factor Q>100. Cook teaches a resonator with a quality factor Q>100 (magnetic resonant antennas used in system must provide a Q-factor as high as possible, and can provide Q-factors up to 300, para 0060-0061). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the high quality factor resonator as taught in Cook with the invention of Bruhn in order to provide a very efficient wireless power transmission system with minimal power losses (see Cook, para 0047).

Regarding claim 16, Bruhn discloses the invention above, but does not specifically disclose wherein the first plurality of parameters and the second plurality of parameters of the oscillating magnetic fields are different in at least a magnitude. Cook teaches wherein the first plurality of parameters and the second plurality of parameters of the oscillating magnetic fields are different in at least a magnitude (transmit power converter unit converts the supply voltage and frequency, such as 110V/60Hz, into another voltage [different voltage] and into another frequency, such as under 50Hz, that is more appropriate for wireless transmission, para 0155-0158). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the different magnitudes as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Supplemental Box

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Regarding claim 18, Bruhn discloses the invention above, and further discloses the source resonator 126, 128 and the device resonator 130, 132 (Fig. 9), but does not disclose wherein at least one of the resonators has a quality factor Q>100. Cook teaches a resonator with a quality factor Q>100 (magnetic resonant antennas used in system must provide a Q-factor as high as possible, and can provide Q-factors up to 300, para 0060-0061). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the high quality factor resonator as taught in Cook with the invention of Bruhn in order to provide a very efficient wireless power transmission system with minimal power losses (see Cook, para 0047).

Claims 6-7 lack an inventive step under PCT Article 33(3) as being obvious over Bruhn in view of Keyes, IV et al. (hereinafter referred to as Keyes).

Regarding claim 6, Bruhn discloses the invention above, and discloses wherein the first plurality of parameters includes a first frequency (operating at the fundamental frequency, para 0017, 0031, Fig. 9) different from a second frequency of the second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), but does not disclose a frequency hopping sequence. Keyes is in the field of wireless energy transfer systems (para 0008-0009, Fig. 43), and teaches a frequency hopping sequence (power transmitted wirelessly using frequency hopping technique, para 0056-0058). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the frequency hopping sequence as taught in Keyes with the invention of Bruhn in order to avoid wireless interference (see Keyes, para 0056).

Regarding claim 7, Bruhn discloses the invention above, and discloses wherein the first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9) includes a sequence different from a second sequence of the second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), but does not disclose an on/off sequence. Keyes teaches an on/off sequence (wireless reception of on or off control commands for wireless base units, para 0094). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the on/off sequence as taught in Keyes with the invention of Bruhn in order to provide a method of wirelessly powering devices on and off (see Keyes, para 0007-0008).

Claims 13, 19 lack an inventive step under PCT Article 33(3) as being obvious over Bruhn in view of Lee.

Regarding claim 13, Bruhn discloses the invention above, and discloses a loop inductor 130 (Fig. 9), but does not disclose wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor. Lee is in the field of wireless power converters (para 0001) and teaches wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor (transmitter and receiver are combined, para 0048, and constructed by winding transmission coil outputting power generated from electromagnetic wave generating source, para 0051, Fig. 10). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the shared loop as taught in Lee with the invention of Bruhn to provide a more efficient wireless power system for transferring power by maximizing generation and reception of electromagnetic waves in the resonance circuit (see Lee, para 0051).

Regarding claim 19, Bruhn discloses the invention above, and discloses a loop inductor 130 (Fig. 9), but does not disclose wherein the source resonator and the device resonator include a shared loop inductor. Lee teaches wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor (transmitter and receiver are combined, para 0048, and constructed by winding transmission coil outputting power generated from electromagnetic wave generating source, para 0051, Fig. 10). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the shared loop as taught in Lee with the invention of Bruhn to provide a more efficient wireless power system for transferring power by maximizing generation and reception of electromagnetic waves in the resonance circuit (see Lee, para 0051).

Claims 20-25 meet the criteria set out in PCT Article 33(2)-(3), because the prior art does not teach or fairly suggest:

Regarding claim 20, a method of wireless power conversion comprising: providing a configurable magnetic resonator; tuning the configurable magnetic resonator to capture a first oscillating magnetic field characterized by a first plurality of parameters; converting the oscillating magnetic field into electrical energy; storing the electrical energy as stored energy in an energy storage element; tuning the configurable magnetic resonator to generate a second oscillating magnetic field characterized by a second plurality of parameters; and energizing the configurable magnetic resonator using the stored energy to produce the second oscillating magnetic field.

Claims 21-25 meet the criteria due to their dependence on novel claim 20.

The prior art, as shown below, details some aspects of the invention, however, none of the prior art teaches all the missing limitations either alone or in combination as specified.

Electronic Acknowledgement Receipt

EFS ID:	15084910
Application Number:	13752169
International Application Number:	
Confirmation Number:	6134
Title of Invention:	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS
First Named Inventor/Applicant Name:	Andre B. Kurs
Customer Number:	87084
Filer:	John A. Monocello/Keisha Forsman
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0075-P01
Receipt Date:	28-FEB-2013
Filing Date:	28-JAN-2013
Time Stamp:	17:28:34
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Non Patent Literature	Tesla_HighFrequencyOscillators_TheElectricalEngineer.pdf	2381846 7a03d5f0f6d17b7b14ae93c808a07f47337ab6b9	no	5

Warnings:

Information:

2	Non Patent Literature	TexasInstruments_HFAntennaDesign.pdf	1144684 997315685f95e7a9dcd647397425b3eaf21d296e	no	47
Warnings:					
Information:					
3	Non Patent Literature	Thomsen_UltrahighSpeedAllOptical.pdf	529201 542e2e9d17593fa9c32761fa16f3160c6230f2ad	no	2
Warnings:					
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4	Non Patent Literature	60698442_APP_07-12-2005.pdf	884027 b740c85ff6a04e4cf442d747443bf33aa7974344	no	14
Warnings:					
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5	Non Patent Literature	60908666_APP_03-28-2007.pdf	7311096 15d3d207092f945c867cbc7ed55871fb6a480703	no	108
Warnings:					
Information:					
6	Non Patent Literature	60908383_APP_03-27-07.pdf	5404423 8e34727c5395b47ea3bd6cfc7c0c0c75a56597cc	no	80
Warnings:					
Information:					
7	Non Patent Literature	UPMRafsec_TutorialOverviewOfInductively.pdf	230316 7f989d147ade74feee08f2f71f27d44c5aec4e27	no	7
Warnings:					
Information:					
8	Non Patent Literature	Vandevoorde_WirelessEnergyTransfer.pdf	243393 560a73a66aab4942bb0f69d70fb3752089bd2f6a	no	7
Warnings:					
Information:					
9	Non Patent Literature	Vilkomerson_ImplantableDopplerSystem.pdf	729105 5c67a79a1355267a05d68e258097e54fa1c64d40	no	5
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10	Non Patent Literature	Wen_AMethodFor.pdf	523993 2c9391b420ddcbbe43178fc63ceaeb977306c78b	no	6
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11	Non Patent Literature	Yariv_CoupledResonatorOptical.pdf	359152 04f4207a7e7a441b1616b683de7d066dbb624784	no	3
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12	Non Patent Literature	Zierhofer_HighEfficiencyCouplingInsensitive.pdf	1104777 1267ac2574060e068faca20fb98f659fe16d447c	no	7
Warnings:					
Information:					
			Total Files Size (in bytes):	20846013	

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New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

Espacenet

Bibliographic data: JP11188113 (A) — 1999-07-13

POWER TRANSMISSION SYSTEM, POWER TRANSMISSION METHOD AND ELECTRIC STIMULATION DEVICE PROVIDED WITH THE POWER TRANSMISSION SYSTEM

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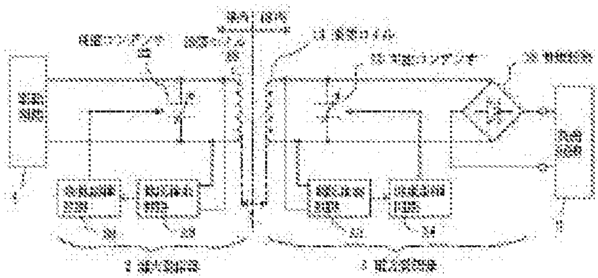
Applicant(s):	NEC CORP; JAPAN SCIENCE & TECH CORP; HOSHIMIYA NOZOMI; HANDA YASUNOBU; MATSUKI HIDETOSHI ±	
Classification:	**- international:**	***A61N1/378; H02J17/00;*** (IPC1-7): A61N1/378
	- European:	
Application number:	JP19970359519 19971226	
Priority number (s):	JP19970359519 19971226	

Abstract of JP11188113 (A)

PROBLEM TO BE SOLVED: To stably transmit power without destroying the resonance state of a coil even when the distance of transmission and reception coils fluctuates. SOLUTION: This system is provided with a transmission coil 21 and a reception coil 11 oppositely arranged holding skin between them, a variable capacitor 22 for constituting a resonance circuit by being connected to the transmission coil 21, a variable capacitor 12 for constituting the resonance circuit by being connected to the reception coil 11, voltage detection circuits 23 and 13 for respectively detecting voltage levels in the transmission coil 21 and the reception coil 11, a capacity control circuit 24 for inputting the voltage level detected in the voltage detection circuit 23 and varying the capacity of the variable capacitor 22 so that the detected voltage level takes a highest value at all times and a capacity control circuit 14 for inputting the voltage level detected in



the voltage detection circuit 13 and varying the capacity of the variable capacitor 12 so that the detected voltage level takes the highest value at all times.

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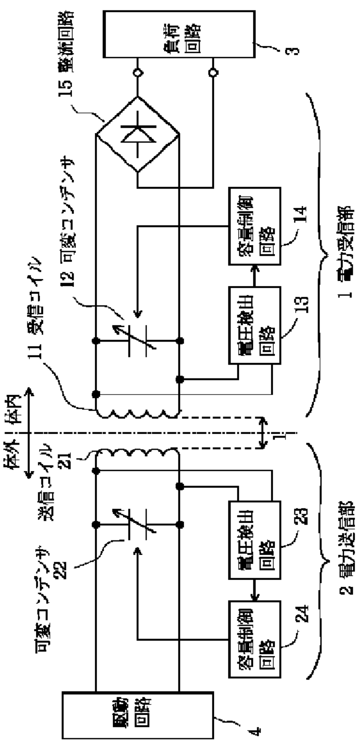
最終頁に続く

(54)【発明の名称】　電力伝送システムおよび電力伝送方法ならびにその電力伝送システムを備えた電気刺激装置

(57)【要約】

【課題】送受コイルの距離が変動しても、コイルの共振状態がくずれることがなく、安定した電力伝送を行うことができるようにする。

【解決手段】皮膚を挟んで対向配置された送信コイル２１、受信コイル１１と、送信コイル２１と接続されて共振回路を構成する可変コンデンサ２２と、受信コイル１１と接続されて共振回路を構成する可変コンデンサ１２と、送信コイル２１、受信コイル１１における電圧レベルをそれぞれ検出する電圧検出回路２３、１３と、電圧検出回路２３にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように可変コンデンサ２２の容量を可変する容量制御回路２４と、電圧検出回路１３にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように可変コンデンサ１２の容量を可変する容量制御回路１４とを有する。



【特許請求の範囲】

【請求項１】　対向配置された１対の電力供給コイルを備え、一方を送信コイル、他方を受信コイルとして電力が誘導的に伝送される電力伝送システムにおいて、
前記送信コイルと接続されて共振回路を構成する第１の可変コンデンサと、
前記受信コイルと接続されて共振回路を構成する第２の可変コンデンサと、
前記送信コイルにおける電圧レベルを検出する第１の電圧検出手段と、
前記受信コイルにおける電圧レベルを検出する第２の電圧検出手段と、
前記第１の電圧検出手段にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように前記第１の可変コンデンサの容量を可変する第１の容量制御手段と、
前記第２の電圧検出手段にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように前記第２の可変コンデンサの容量を可変する第２の容量制御手段と、を有することを特徴とする電力伝送システム。

【請求項２】　請求項１に記載の電力伝送システムにおいて、
前記第１の容量制御手段が、電力搬送波の周波数で前記送信コイルおよび第１の可変コンデンサからなる共振回路が共振するように制御し、
前記第２の容量制御手段が、電力搬送波の周波数で前記受信コイルおよび第２の可変コンデンサからなる共振回路が共振するように制御することを特徴とする電力伝送システム。

【請求項３】　対向配置された１対の電力供給コイルを備え、一方を送信コイル、他方を受信コイルとして電力が誘導的に伝送される電力伝送システムにおいて、
前記送信コイルと接続されて共振回路を構成する第１の可変コンデンサと、
前記受信コイルと接続されて共振回路を構成する第２の可変コンデンサと、
前記受信コイルにおける電圧レベルを検出する電圧検出手段と、
前記電圧検出手段にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように前記第１および第２の可変コンデンサの容量をそれぞれ可変する容量制御手段と、を有することを特徴とする電力伝送システム。

【請求項４】　請求項３に記載の電力伝送システムにおいて、
前記電力供給コイル対とは異なる、対向配置された送信コイルおよび受信コイルと、
前記送信コイルと接続されて第１の共振回路を構成する第１のコンデンサと、
前記受信コイルと接続されて第２の共振回路を構成する第２のコンデンサと、
前記容量制御手段から出力される制御信号を入力とし、該入力信号を前記第１の共振回路へ供給する信号送信手段と、
前記第２の共振回路を介して受信される前記制御信号を入力とし、該入力制御信号を前記第１の可変コンデンサへ出力する信号受信手段と、をさらに有することを特徴とする電力伝送システム。

【請求項５】　請求項１乃至請求項４のいずれかに記載の電力伝送システムを備える電気刺激装置であって、
前記受信コイルとともに体内に埋め込まれ、該受信コイルを介して電力供給を受けて生体の麻痺した部分を電気的に刺激する刺激手段と、
前記送信コイルに接続され、体外から前記刺激手段に電力を供給して刺激動作を制御する制御手段と、を有することを特徴とする電気刺激装置。

【請求項６】　対向配置された１対の電力供給コイル間で、一方を送信コイル、他方を受信コイルとして電力を誘導的に伝送する電力伝送方法において、
前記送信コイルおよび受信コイルにおける電圧レベルをそれぞれ検出し、それぞれの検出電圧レベルが常に最高値をとるように前記送信コイルおよび受信コイルの共振状態を制御することを特徴とする電力伝送方法。

【請求項７】　対向配置された１対の電力供給コイル間で、一方を送信コイル、他方を受信コイルとして電力を誘導的に伝送する電力伝送方法において、
前記受信コイルにおける電圧レベルを検出し、該検出電圧レベルが常に最高値をとるように前記送信コイルおよび受信コイルの共振状態を制御することを特徴とする電力伝送方法。

【請求項８】　請求項６または請求項７に記載の電力伝送方法において、
電力搬送波の周波数で前記送信コイルおよび受信コイルが共振するように制御することをことを特徴とする電力伝送方法。

【発明の詳細な説明】

【０００１】

【発明の属する技術分野】本発明は、対向配置された１対の電力供給コイルを用いて、両コイル間で電気エネルギーを伝送する電力伝送システムおよび電力伝送方法に関する。より具体的には、種々の生体機能の外的制御を行う装置、例えば脳卒中や脊髄損傷等、中枢性神経障害で麻痺した生体の機能を電気的刺激で治療、再建する電気刺激装置などに適用される電力伝送システムおよび電力伝送方法に関する。ここでいう電力伝送とは、電力の伝送だけでなく制御信号などの伝送をも含む。

【０００２】

【従来の技術】麻痺した身体の機能を電気的刺激で治療、再建する電気刺激装置は、基本的には、体内に埋め

込まれて生体の麻痺した部分を電気的に刺激する刺激装置と、体外に配置され、体内に埋め込まれた刺激装置に電力や信号を伝送して駆動する装置本体とから構成される。このような電気刺激装置において、装置本体側から体内に埋め込まれた刺激装置に電力や信号を伝送する電力伝送システムとしては、皮膚を挟んで対向配置された電力供給コイル対（例えば、空芯コイルや磁芯コイルなどにより構成される）を用い、体外の電力供給コイルから体内の電力供給コイルへ電力や信号を伝送することにより、体内に埋め込まれた刺激装置に電力や信号を伝送するようにしたものが知られている。その一例として、例えば特開平5-317434号公報には、非接触型電力供給コイルを備えたものが開示されている。

【０００３】上記公報に開示されたシステムは、電気刺激装置とともに体内に完全に埋め込まれる第１の電力供給コイルと、その第１の電力供給コイルと皮膚を介して平行に対向配置される第２の電力供給コイルとを備えており、体外に置かれた第２の電力供給コイルに高周波電力を供給することにより、その供給された高周波電力が体内の第１の電力供給コイルへ誘導的に伝送され、第１の電力供給コイルで所望の周波数に変換されるようになっている。

【０００４】この他、特開平4-285436号公報には、外部の送出コイルから、植え込まれた容量性要素に接続されているターゲットコイルへ電力を誘導的に伝送するシステムで、両コイル間の共振結合を維持できるようにしたものが開示されている。

【０００５】

【発明が解決しようとする課題】上述したような、対向配置された１対の電力供給コイル間で電力伝送が行われる電力伝送システムにおいては、両コイルを共振状態として電力伝送が誘導的に行われる。しかしながら、このような従来のシステムでは、送受側のコイルの共振パラメータは固定で一定とされるため、例えば両コイル間の距離が変わったり、あるいはコイルが横ずれしたりすると、両コイルの相互インダクタンスが変化してしまい、コイルの共振状態がくずれてしまう。この結果、受信側コイルにおける受信電圧が低くなり、受信コイルに接続された刺激装置などの負荷回路が動作しなくなるという問題が生じる。

【０００６】本発明の目的は、送受コイルの距離が変動しても、コイルの共振状態がくずれることがなく、安定した電力伝送を行うことができる電力伝送システムおよび電力伝送方法を提供することにある。さらには、その電力伝送システムを備えた電気刺激装置を提供することにある。

【０００７】

【課題を解決するための手段】上記目的を達成するため、本発明の第１の電力伝送システムは、対向配置された１対の電力供給コイルを備え、一方を送信コイル、他方を受信コイルとして電力が誘導的に伝送される電力伝送システムにおいて、前記送信コイルと接続されて共振回路を構成する第１の可変コンデンサと、前記受信コイルと接続されて共振回路を構成する第２の可変コンデンサと、前記送信コイルにおける電圧レベルを検出する第１の電圧検出手段と、前記受信コイルにおける電圧レベルを検出する第２の電圧検出手段と、前記第１の電圧検出手段にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように前記第１の可変コンデンサの容量を可変する第１の容量制御手段と、前記第２の電圧検出手段にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように前記第２の可変コンデンサの容量を可変する第２の容量制御手段と、を有することを特徴とする。

【０００８】本発明の第２の電力伝送システムは、対向配置された１対の電力供給コイルを備え、一方を送信コイル、他方を受信コイルとして電力が誘導的に伝送される電力伝送システムにおいて、前記送信コイルと接続されて共振回路を構成する第１の可変コンデンサと、前記受信コイルと接続されて共振回路を構成する第２の可変コンデンサと、前記受信コイルにおける電圧レベルを検出する電圧検出手段と、前記電圧検出手段にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように前記第１および第２の可変コンデンサの容量をそれぞれ可変する容量制御手段と、を有することを特徴とする。

【０００９】上記の場合、前記電力供給コイル対とは異なる、対向配置された送信コイルおよび受信コイルと、前記送信コイルと接続されて第１の共振回路を構成する第１のコンデンサと、前記受信コイルと接続されて第２の共振回路を構成する第２のコンデンサと、前記容量制御手段から出力される制御信号を入力とし、該入力信号を前記第１の共振回路へ供給する信号送信手段と、前記第２の共振回路を介して受信される前記制御信号を入力とし、該入力制御信号を前記第１の可変コンデンサへ出力する信号受信手段と、をさらに有するものとしてもよい。

【００１０】本発明の電気刺激装置は、上述のいずれかの電力伝送システムを備える電気刺激装置であって、前記受信コイルとともに体内に埋め込まれ、該受信コイルを介して電力供給を受けて生体の麻痺した部分を電気的に刺激する刺激手段と、前記送信コイルに接続され、体外から前記刺激手段に電力を供給して刺激動作を制御する制御手段と、を有することを特徴とする。

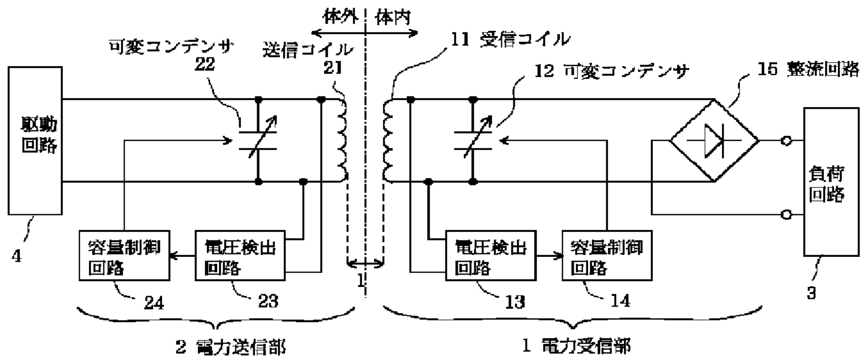
【００１１】本発明の第１の電力伝送方法は、対向配置された１対の電力供給コイル間で、一方を送信コイル、他方を受信コイルとして電力を誘導的に伝送する電力伝送方法において、前記送信コイルおよび受信コイルにおける電圧レベルをそれぞれ検出し、それぞれの検出電圧レベルが常に最高値をとるように前記送信コイルおよび

受信コイルの共振状態を制御することを特徴とする。
【００１２】本発明の第２の電力伝送方法は、対向配置された１対の電力供給コイル間で、一方を送信コイル、他方を受信コイルとして電力を誘導的に伝送する電力伝送方法において、前記受信コイルにおける電圧レベルを検出し、該検出電圧レベルが常に最高値をとるように前記送信コイルおよび受信コイルの共振状態を制御することを特徴とする。
【００１３】（作用）本発明によれば、送信コイルと第１の可変コンデンサにより共振回路が構成され、受信コイルと第２の可変コンデンサにより共振回路が構成されており、各共振回路の共振周波数はそれぞれの可変コンデンサの容量を可変することにより制御可能になっている。したがって、例えば送受コイル間の距離が変動して、送受コイルの相互インダクタンスが変化しても、その変化に応じて各共振回路の共振状態を制御することができ、送受コイル間における電力伝送を常に最適な状態で行うことができる。
【００１４】
【発明の実施の形態】次に、本発明の実施形態について図面を参照して説明する。
【００１５】（実施形態１）図１は、本発明の第１の実施形態の電力伝送システムの概略構成を示すブロック図である。この電力伝送システムは、生体の機能を電気的刺激で治療、再建する電気刺激装置に適用されるもので、生体の麻痺した部分を電気的に刺激する負荷回路３（刺激装置）が接続され、該負荷回路３とともに体内に埋め込まれる電力受信部１と、体内に埋め込まれた負荷回路３に電力や信号を伝送して刺激動作を制御する駆動回路４（装置本体）が接続され、該駆動回路４とともに体外に設置される電力送信部２とを有する。
【００１６】電力受信部１は、体外から供給される電力を受信するための受信コイル１１とこれに並列に接続された可変コンデンサ１２とからなるＬＣ回路（共振回路）と、受信コイル１１にて受信される電圧レベルを検出する電圧検出回路１３と、該電圧検出回路１３にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように可変コンデンサ１２の容量を可変する容量制御回路１４と、受信コイル１１にて受信される電圧を交流から直流に整流する整流回路１５とを有する。
【００１７】電力送信部２は、体内に埋め込まれた受信コイル１１と平行に対向して配置され、該受信コイル１１へ誘導的に電力を伝送する送信コイル２１とこれに並列に接続された可変コンデンサ２２とからなるＬＣ回路（共振回路）と、送信コイル２１にて伝送される電圧レベルを検出する電圧検出回路２３と、該電圧検出回路２３にて検出された電圧レベルを入力とし、該検出電圧レベルが常に最高値をとるように可変コンデンサ２２の容量を可変する容量制御回路２４とを有する。
【００１８】送受信コイル１１，２１は、両コイル間で誘導的に電力伝送が可能であればどのようなものを用いてもよく、例えば空芯コイル、磁芯コイルなど種々のコイルを使用することができる。
【００１９】上述のように構成された電力伝送システムでは、駆動回路４から負荷回路３を駆動するための電力が電力送信部２の送信コイル２１に供給されると、送信コイル２１から電力受信部１の受信コイル１１に誘導的に電力が伝送される。このとき、電力搬送波の周波数に電力受信部１および電力送信部２の各共振回路が共振した状態になっていれば、駆動回路４から供給される電力のほとんどが負荷回路３にて使用され、共振していない場合には、電力受信部１の受信コイル１１とこれに接続された各回路（電圧レギュレータ）で浪費される。受信コイル１１にて受信された電力は整流回路１５を介して負荷回路３へ供給される。
【００２０】いま、電力搬送波の周波数に電力受信部１および電力送信部２の各共振回路が共振した状態で電力伝送が行われている状態とする。ここで、送信コイル２１と受信コイル１１間の距離１が変化すると、これら送受コイルの相互インダクタンスが変化し、これにより共振パラメータも変化する。共振パラメータが変化すると、電力搬送波の電圧レベルが小さくなり、この電圧レベルの変化が電力受信部１および電力送信部２の各電圧検出回路１３，２３で検出される。
【００２１】電圧レベルが低下すると、容量制御回路１４は、電圧検出回路１３の出力を基に、その検出電圧レベルが最高値になるように可変コンデンサ１２の容量を可変する。同様に、容量制御回路２４は、電圧検出回路２３の出力を基に、その検出電圧レベルが最高値になるように可変コンデンサ２２の容量を可変する。これにより、送受コイルの相互インダクタンスが変化しても、常に電力搬送波の周波数に共振した状態で電力伝送を行うことができる。
【００２２】以上のように、本実施形態の電力伝送システムでは、送信電圧、受信電圧の検出をそれぞれ送信部、受信部個々に設けられた電圧検出部で行い、送信部、受信部の個々の共振回路のコンデンサの容量を共振状態を維持するように自動的に補正するようになっているので、最適の状態で電力伝送が行われる。
【００２３】なお、以上の説明では、生体機能の外的制御を行う装置に適用される例について説明したが、本発明はこれに限定されるものではなく、対向配置された１対の電力供給コイルを用いて、電気エネルギーを誘導的に伝送することにより電力供給を行うことが可能な装置であればどのようなものにも適用可能である。
【００２４】（実施形態２）上述した第１の実施形態では、送信部、受信部個々に独立して送受コイルの共振状態を制御するようになっているが、受信コイルの電圧レベルを検出して、その検出結果に基づいて送受コイルの

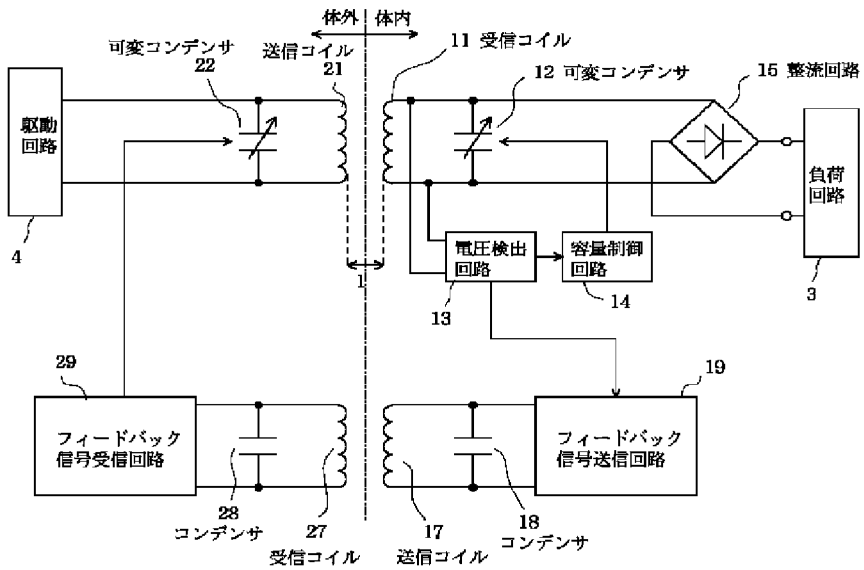
共振状態を制御することもできる。
【００２５】図２は、本発明の第２の実施形態の電力伝送システムの概略構成を示すブロック図である。同図中、図１に示した第１の実施形態の構成と同じ構成には同じ符号を付してある。
【００２６】本形態の電力伝送システムは、上述の第１の実施形態の電力送信部２側の電圧検出回路２３および容量制御回路２４を取り除き、電力受信部１側の容量制御回路１４が電圧検出回路１３にて検出された電圧レベルに基づいて、可変コンデンサ１２，２２の容量をそれぞれ制御するようになっている。そのための構成として、電力受信部１側に、送信コイル１７とコンデンサ１８からなる共振回路と、該共振回路に容量制御回路１４から送出された制御信号をフィードバック信号（電力送信部２側の可変コンデンサ２２の容量を制御するための制御信号）として供給するフィードバック信号送信回路１９とを備え、電力送信２側に、送信コイル１７に平行に対向して配置された受信コイル２７とコンデンサ２８からなる共振回路と、受信コイル２７を介して受信される容量制御回路１４から送出されたフィードバック信号を受け、該受信信号を制御信号として可変コンデンサ２２へ出力するフィードバック信号受信回路２９とを備える。
【００２７】上述のように構成された電力伝送システムでは、第１の実施形態の場合と同様に、駆動回路４から負荷回路３を駆動するための電力が電力送信部２の送信コイル２１に供給されると、送信コイル２１から電力受信部１の受信コイル１１に誘導的に電力が伝送される。受信コイル１１にて受信された電力は整流回路１５を介して負荷回路３へ供給される。
【００２８】いま、電力搬送波の周波数に電力受信部１および電力送信部２の各共振回路が共振した状態で電力伝送が行われている状態とする。ここで、送信コイル２１と受信コイル１１間の距離１が変化すると、これら送受コイルの相互インダクタンスが変化し、これにより共振パラメータも変化する。共振パラメータが変化すると、電力搬送波の電圧レベルが小さくなり、この電圧レベルの変化が電力受信部１の電圧検出回路１３で検出される。
【００２９】電圧レベルが低下すると、容量制御回路１４は、電圧検出回路１３の出力を基に、その検出電圧レベルが最高値になるように可変コンデンサ１２の容量を可変するとともに、可変コンデンサ２２の容量を可変するためフィードバック信号をフィードバック信号送信回路１９へ送出する。フィードバック信号を受けたフィードバック信号送信回路１９は、該フィードバック信号を所定の周波数で変調して各共振回路を介してフィードバック信号受信回路２９へ送信する。フィードバック信号受信回路２９は、受信した変調信号を復調して、これを制御信号として可変コンデンサ２２へ出力する。これにより、可変コンデンサ２２は電力受信部１の容量制御回路１４によって制御されることになる。
【００３０】上述のようにして、電力受信部１側の容量制御回路１４は、電圧検出回路１３にて検出された電圧レベルに基づいて、検出電圧レベルが最高値になるように可変コンデンサ１２，２２の容量を可変する。これにより、送受コイル１１，２１の相互インダクタンスが変化しても、常に電力搬送波の周波数に共振した状態で電力伝送を行うことができる。
【００３１】本実施形態では、送信コイル１７と受信コイル２７における信号伝送は、送信コイル２１と受信コイル１１間で行われる誘導的な電力伝送と同じ原理で行われるが、これら送受コイル１７，２７と接続されるコンデンサ１８，２８は変調周波数に応じて所定の容量のものが用いられる。このようなフィードバック系では、共振パラメータが固定であるため、送受コイル１７，２７間の距離が変動すると、受信されるフィードバック信号の電圧レベルが変動することが予想されるが、この変動は刺激装置への電力の供給に直接影響するものではないので問題とはならない。しかも、フィードバック信号を受信する部分は体外に設けられる装置本体側に設けられるので、増幅回路など付加することができ、これによりフィードバック信号の電圧レベルの変動を回避することもできる。
【００３２】
【発明の効果】以上説明したように構成される本発明によれば、送受コイルの相互インダクタンスの変化に応じてコイルの共振状態を制御することができるので、送受コイルの距離が変動しても、コイルの共振状態がくずれることがなく、安定した電力伝送を行うことができるという効果がある。
【００３３】受信コイルにおける電圧レベルを検出し、該電圧レベルが常に最高値をとるように送受コイルの共振状態を制御する発明においては、より確実に受信コイルを電力搬送波の周波数で共振するようにでき、より安定的に電力伝送を行うことができるという効果がある。
【００３４】本発明の電力伝送システムを備える電気刺激装置においては、体内に埋め込まれた刺激装置に安定して電力供給を行うことができるので、従来のような受信側コイルにおける受信電圧が低下して刺激装置などの負荷回路が動作しなくなるといった問題を防止でき、信頼性の高い電気刺激装置を提供することができる。
【図面の簡単な説明】
【図１】本発明の第１の実施形態の電力伝送システムの概略構成を示すブロック図である。
【図２】本発明の第２の実施形態の電力伝送システムの概略構成を示すブロック図である。
【符号の説明】
１　電力受信部
２　電力伝送部

３　負荷回路
４　駆動回路
１１，２７　受信コイル
１２，２２　可変コンデンサ
１３，２３　電圧検出回路
１４，２４　容量制御回路
１５　整流回路
１７，２１　送信コイル
１８，２８　コンデンサ
１９　フィードバック信号送信回路
２９　フィードバック信号受信回路

【図１】



【図２】



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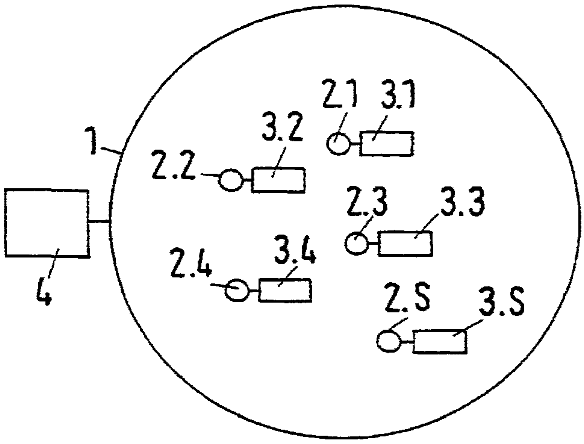
[Fortsetzung auf der nächsten Seite]

(54) Title: METHOD AND ASSEMBLY FOR THE WIRELESS SUPPLY OF ELECTRIC ENERGY TO A NUMBER OF ACTUATORS, ACTUATOR AND PRIMARY WINDING THEREFOR AND SYSTEM FOR A MACHINE WITH A NUMBER OF ACTUATORS

(54) Bezeichnung: VERFAHREN UND ANORDNUNG ZUR DRAHTLOSEN VERSORGUNG EINER VIELZAHL AKTOREN MIT ELEKTRISCHER ENERGIE, AKTOR UND PRIMÄRWICKLUNG HIERZU SOWIE SYSTEM FÜR EINE EINE VIELZAHL VON AKTOREN AUFWEISENDE MASCHINE



(57) Abstract: The invention relates to a method for the wireless supply of electric energy to a number of actuators (3.1 to 3.s). In said method, a medium-frequency, magnetic field, emitted by at least one primary winding (1, 1.1 to 1.p) is transmitted to each respective actuator which has at least one secondary winding (2.1 to 2.s) and is then converted into electric energy. The invention also relates to an assembly for the wireless supply of electric energy to a number of actuators (3.1 to 3.s), using at least one primary winding (1, 1.1 to 1.p), fed by a medium-frequency oscillator (4), whereby each actuator (3.1 to 3.s) has at least one secondary winding (2.1 to 2.s) which is suitable for absorbing energy from a medium-frequency magnetic field. The invention further relates to an actuator and a primary winding for said assembly and a system for a machine which has a number of actuators.

[Fortsetzung auf der nächsten Seite]

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Veröffentlicht:

— *Mit internationalem Recherchenbericht.*
— *Vor Ablauf der für Änderungen der Ansprüche geltenden Frist; Veröffentlichung wird wiederholt, falls Änderungen eintreffen.*

Zur Erklärung der Zweibuchstaben-Codes, und der anderen Abkürzungen wird auf die Erklärungen ("Guidance Notes on Codes and Abbreviations") am Anfang jeder regulären Ausgabe der PCT-Gazette verwiesen.

(57) Zusammenfassung: Es wird ein Verfahren zur drahtlosen Versorgung einer Vielzahl Aktoren (3.1 bis 3.s) mit elektrischer Energie vorgeschlagen, wobei ein von mindestens einer Primärwicklung (1, 1.1 bis 1.p) abgestrahltes, mittelfrequentes magnetisches Feld zu jedem mindestens eine Sekundärwicklung (2.1 bis 2.s) aufweisenden Aktor übertragen und dort in elektrische Energie umgewandelt wird. Des weiteren wird eine Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren (3.1 bis 3.s) mit elektrischer Energie unter Einsatz mindestens einer von einem mittelfrequenten Oszillator (4) gespeisten Primärwicklung (1, 1.1 bis 1.p) vorgeschlagen, wobei jeder Aktor (3.1 bis 3.s) mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung (2.1 bis 2.s) aufweist. Ausserdem werden ein Aktor und eine Primärwicklung hierzu sowie ein System für eine eine Vielzahl von Aktoren aufweisende Maschine vorgeschlagen.

Verfahren und Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie, Aktor und Primärwicklung hierzu sowie System für eine eine Vielzahl von Aktoren aufweisende Maschine

Beschreibung

Die Erfindung bezieht sich auf ein Verfahren und eine Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie, auf einen Aktor und eine Primärwicklung hierzu sowie auf ein System für eine eine Vielzahl von Aktoren aufweisende Maschine. Die Erfindung kann beispielsweise zur elektrischen Energieversorgung von mikromechanischen, piezoelektrischen, elektrochemischen, magnetostriktiven, elektrostriktiven, elektrostatischen oder elektromagnetischen Aktoren verwendet werden, wie sie in Aktoren-Systemen oder Maschinen, beispielsweise bei Steuer/Regelsystemen, in Fernsteuersystemen, in der Robotertechnik, bei Herstellungsautomaten bzw. Fertigungsautomaten, als Anzeigeelemente und in Schutz- und Sicherheitssystemen (beispielsweise bei Freiluft- oder Innenraum-Schaltanlagen) zum Einsatz gelangen.

Aus der DE 44 42 677 A1 sind ein Verfahren und eine Anordnung zum Versorgen eines elektrischen Verbrauchers mit einer elektrischen Versorgungsspannung oder einem elektrischen Versorgungsstrom bekannt, wobei Funkwellen eines Funksenders zu einem mit dem Verbraucher elektrisch verbundenen Funkempfänger übertragen werden und vom Funkempfänger in die elektrische Versorgungsspannung bzw. den elektrischen Versorgungsstrom umgewandelt werden. Die Funkwellen können aus dem elektromagnetischen Hochfrequenzbereich (Radiowellen) oder auch aus dem Mikrowellenbereich (Richtfunk) kommen.

Dabei ist es von Nachteil, daß aufgrund der hohen Frequenzen und dementsprechend kleinen Antennen einerseits und der durch EMV-Vorschriften und Regeln für Sicherheit und Gesundheitsschutz an Arbeitsplätzen mit Exposition durch elektrische, magnetische oder elektromagnetische Felder beschränkten zulässigen Sendeleistung andererseits nur sehr unzureichend geringe Abstände zwischen Funksender und Funkempfänger erzielbar sind. Das gleiche trifft für die erzielbaren Leistungen zu, welche im Bereich weniger μW liegen, was meist unzureichend für Aktoren ist.

Der Erfindung liegt die Aufgabe zugrunde, ein kostengünstiges und zuverlässiges Verfahren zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie anzugeben.

Des weiteren ist eine kostengünstige und zuverlässige Anordnung zur Durchführung dieses Verfahrens anzugeben.

Ferner soll ein hierzu geeigneter Aktor vorgeschlagen werden.

Des weiteren soll eine hierzu geeignete Primärwicklung vorgeschlagen werden.

Außerdem soll ein System für eine eine Vielzahl von Aktoren aufweisende Maschine angegeben werden.

Diese Aufgabe wird bezüglich des Verfahrens erfindungsgemäß durch ein Verfahren zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie gelöst, wobei ein von mindestens einer Primärwicklung abgestrahltes, mittelfrequentes magnetisches Feld zu jedem mindestens eine Sekundärwicklung aufweisenden Aktor übertragen und dort in elektrische Energie umgewandelt wird.

Unter den in diesem Zusammenhang interessierenden mittelfrequenten Schwingungen wird der Bereich von etwa 15 kHz bis etwa 15 MHz verstanden.

Diese Aufgabe wird bezüglich der Vorrichtung erfindungsgemäß durch eine Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie unter Einsatz mindestens einer von einem mittelfrequenten Oszillator gespeisten Primärwicklung gelöst, wobei jeder Aktor mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung aufweist.

Die Aufgabe wird bezüglich des Aktors durch einen Aktor mit mehreren zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeigneten, orthogonalen Sekundärwicklungen gelöst.

Die Aufgabe wird bezüglich der Primärwicklung durch eine Primärwicklung, bestehend aus mehreren separaten Wicklungsabschnitten gelöst, welche jeweils aus mehreren parallelen Leitern aufgebaut sind, wobei die einzelnen Wicklungsabschnitte über Verbindungselemente mechanisch und elektrisch miteinander verbunden sind und wobei bei einem Verbindungselement zwei Wicklungsabschnitte versetzt gegeneinander elektrisch miteinander verbunden sind, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

Die Aufgabe wird alternativ bezüglich der Primärwicklung durch eine Primärwicklung, bestehend aus einem flexiblen, aus mehreren parallelen Leitern aufgebauten Kabel und einem Verbindungselement gelöst, welches die beiden Kabelenden versetzt gegeneinander elektrisch und mechanisch miteinander verbindet, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

Die Aufgabe wird bezüglich des Systems durch ein System für eine eine Vielzahl von Aktoren aufweisende Maschine, insbesondere Fertigungsautomat, gelöst, wobei jeder Aktor mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung aufweist, wobei mindestens eine von einem mittelfrequenten Oszillator gespeiste Primärwicklung zur drahtlosen Versorgung der Aktoren mit elektrischer Energie vorgesehen ist und wobei jeder Aktor mit einer Empfangseinrichtung ausgestattet ist, welche Funksignale einer mit einem Prozeßrechner der Maschine verbundenen zentralen Sendeeinrichtung empfängt.

Die mit der Erfindung erzielbaren Vorteile bestehen insbesondere darin, daß im Vergleich zu konventionellen Lösungen mit Kabelanschluß zur elektrischen Energieversorgung der Aktoren der durch Planung, Material, Installation, Dokumentation und Wartung bedingte relativ hohe Kostenfaktor eines Kabelanschlusses entfällt. Es können keine Ausfälle aufgrund von Kabelbrüchen oder schlechten, beispielsweise korrodierten Kontakten auftreten.

Im Vergleich zur Verwendung von Batterien zur Energieversorgung von Aktoren entfällt der Wartungsaufwand und Kostenaufwand, der durch den erforderlichen Austausch von Batterien – zumal an schwer zugänglichen Stellen – bedingt ist.

Im angegebenen Mittelfrequenz-Bereich von etwa 15 kHz bis etwa 15 MHz sind die sich durch Skineffekte ergebenden Nachteile, beispielsweise die auftretenden Verluste, noch handhabbar. Die elektromagnetischen Wellen werden aufgrund der im Vergleich zu den auftretenden Wellenlängen zu kleinen und deshalb als Antennen unwirksamen Primärwicklungen nicht abgestrahlt, wodurch ein einfacher Aufbau der Anordnungen ermöglicht wird. Eine EMV-Messung von eventuell abgestrahlten Störungen muß nicht erfolgen. Günstig wirkt sich zudem aus, daß mittelfrequente Magnetfelder durch metallische Maschinen-Komponenten nur in geringem Ausmaß abgeschirmt werden, so daß vorteilhaft auch an unzugänglichen Stellen eines Aktoren-Systems bzw. einer Maschine ein zur Energieversorgung ausreichend starkes Magnetfeld auftritt.

Weitere Vorteile sind aus der nachstehenden Beschreibung ersichtlich.

Vorteilhafte Ausgestaltungen der Erfindung sind in den Unteransprüchen gekennzeichnet.

Die Erfindung wird nachstehend anhand der in der Zeichnung dargestellten Ausführungsbeispiele erläutert. Es zeigen:

Fig.1 ein Prinzipschaltbild der Anordnung zur drahtlosen elektrischen Versorgung von Aktoren,

Fig. 2 ein Schaltbild zur Erläuterung des verwendeten Transformatorprinzips,

Fig.3 eine erste praktische Ausführungsform,

Fig.4 eine zweite praktische Ausführungsform,

Fig.5 eine dritte Ausführungsform mit orthogonalen Primärwicklungen,

Fig.6 eine vierte Ausführungsform mit unterschiedlich gestalteten Primärwicklungen,

Fig.7 eine fünfte Ausführungsform mit bandförmiger Primärwicklung,

Fig.8 ein Ersatzschaltbild mit primärseitigen und sekundärseitigen Weiterbildungen,

Fig.9 eine Primärwicklung gemäß sechster Ausführungsform,

Fig. 10 eine Detailansicht einer Ecke einer Primärwicklung gemäß sechster Ausführungsform,

Fig. 11 eine Detailansicht der Wicklungseinspeisung bei der sechsten Ausführungsform,

Fig. 12 eine Primärwicklung gemäß siebter Ausführungsform,

Fig. 13 eine Detailansicht der Wicklungseinspeisung bei der siebten Ausführungsform,

Fig. 14 eine Detailansicht einer Ecke einer Primärwicklung gemäß siebter Ausführungsform,

Fig. 15 eine Primärwicklung gemäß achter Ausführungsform.

In Fig. 1 ist ein Prinzipschaltbild der Anordnung zur drahtlosen elektrischen Versorgung von Aktoren dargestellt. Es ist eine kreisförmige, vorzugsweise aus mehreren

Windungen aufgebaute Primärwicklung 1 zu erkennen, welche eine Vielzahl – gegebenenfalls bis zu einigen Hundert - von Sekundärwicklungen 2.1, 2.2, 2.3....2.s (s = beliebige ganze Zahl) umfaßt, wobei jede Sekundärwicklung 2.1 bzw. 2.2 bzw. 2.3....2.s mit einem Aktor 3.1 bzw. 3.2 bzw. 3.3....3.s verbunden ist. Die Primärwicklung 1 ist an einen Oszillator 4 (Mittelfrequenz-Oszillator) angeschlossen. Der Oszillator 4 speist die Primärwicklung 1 mit einer mittelfrequenten Schwingung im Bereich von etwa 15 kHz bis etwa 15 MHz. Diese Mittelfrequenz würde zur Abstrahlung von elektromagnetischen Feldern führen, deren Wellenlängen größer als 22 m bis 22 km sind und damit wesentlich größer als die Abmessungen der eingesetzten Primärwicklung – kleiner als 2 m - , so daß die Primärwicklung nicht als Antenne für derartige elektromagnetische Strahlung wirkt. Es liegt also eine rein magnetische Kopplung (und keine wirksame elektromagnetische Kopplung) zwischen der Primärwicklung und den Sekundärwicklungen im Sinne eines Mittelfrequenz-Transformators vor.

Als Aktoren werden beispielsweise mikromechanische, piezoelektrische, elektrochemische, magnetostriktive, elektrostriktive, elektrostatische oder elektromagnetische Aktoren eingesetzt.

In Fig. 2 ist ein Schaltbild zur Erläuterung des verwendeten Transformatorprinzips dargestellt. Es sind wiederum die Primärwicklung 1 mit einspeisendem Oszillator 4 und die Aktoren 3.1....3.s mit den angeschlossenen Sekundärwicklungen 2.1....2.s zu erkennen.

In Fig. 3 ist eine erste praktische Ausführungsform dargestellt. Es ist ein Aktoren-System 5 – insbesondere eine Maschine bzw. ein Industrieroboter bzw. Herstellungsautomat bzw. Fertigungsautomat - gezeigt, welches mit zahlreichen an unterschiedliche, zumindest teilweise bewegliche Systemkomponenten montierten Aktoren 3.1....3.s versehen ist. Die Aktoren 3.1...3.s dienen beispielsweise als Anzeigeelemente, als Steuer/Regelelemente und als Schutz/Sicherheitselemente. Das Aktoren-System 5 befindet sich zwischen zwei horizontal angeordneten Primärwicklungen 1.1 und 1.2. Diese beiden Primärwicklungen 1.1, 1.2 liegen elektrisch parallel am Oszillator 4 (Generator) oder werden alternativ von zwei separaten Oszillatoren gespeist. Zwischen beiden Primärwicklungen tritt ein relativ gleichmäßiges Magnetfeld auf. Von Wichtigkeit ist es dabei, daß sich die Aktoren stets im sich zwischen beiden

Primärwicklungen 1.1, 1.2 ausbildenden magnetischen Feld befinden, so daß über ihre Sekundärwicklungen eine magnetische Ankopplung wirksam und demzufolge eine Energieeinspeisung möglich ist.

Jeder Aktor ist mit einer Empfangseinrichtung und Sendeeinrichtung ausgestattet, die Funksignale hinsichtlich der Befehle an die Aktoren zur Ausführung bestimmter Handlungen empfängt und Funksignale hinsichtlich aktueller Aktor-Informationen, wie die Rückmeldungen "gewünschte Handlung erfolgreich/nicht erfolgreich ausgeführt" abgibt. Die Funksignale zu allen Aktoren bzw. von allen Aktoren werden von einer zentralen Sende/Empfangseinrichtung 9 abgegeben bzw. empfangen und von einem Prozeßrechner 10 (speicherprogrammierbare Steuerung) vorgegeben bzw. an diesen weitergeleitet. Vorzugsweise befindet sich die Sende/Empfangseinrichtung in unmittelbarer Nähe des Aktoren-Systems 5, um eine optimale Funkverbindung mit den Aktoren zu gewährleisten, während der die Maschine steuernde Prozeßrechner 10 auch entfernt vom Aktoren-System 5 angeordnet sein kann. Wie leicht erkennbar ist, ergibt sich durch das vorgeschlagene System eine kabellose Konfiguration der Aktoren sowohl hinsichtlich ihrer elektrischen Energieversorgung als auch hinsichtlich der Informationsübertragung vom und zum Prozeßrechner 10.

In Fig. 4 ist eine zweite praktische Ausführungsform dargestellt. Bei dieser Ausführungsform ist lediglich eine einzige Primärwicklung 1 vorgesehen, welche das Aktoren-System 5 – insbesondere ein Industrieroboter bzw. Herstellungsautomat bzw. Fertigungsautomat - mit den zahlreichen, an ihm montierten Aktoren 3.1....3.s global umfaßt.

In Fig. 5 ist eine dritte Ausführungsform mit drei orthogonal zueinander angeordneten Primärwicklungen dargestellt. Es ist ein Aktoren-System 5 gezeigt, welches von einer ersten vertikalen Primärwicklung 1.1, einer hierzu orthogonalen zweiten vertikalen Primärwicklung 1.2 und einer horizontalen dritten Primärwicklung 1.2 umschlossen ist. Bei dieser Ausführungsform mit drei orthogonalen Primärwicklungen ergibt sich eine besonders gleichmäßige und nicht gerichtete Ausbildung des magnetischen Feldes. Alternativ bzw. ergänzend hierzu ist es auch möglich, jeden Aktor mit zwei oder drei orthogonalen Sekundärwicklungen auszurüsten.

Des weiteren ist auch eine Ausführungsform realisierbar, bei der lediglich zwei orthogonale Primärwicklungen vorgesehen sind. Selbstverständlich sind auch Ausführungsformen realisierbar, welche mehrere Primärwicklungen 1.1 bis 1.p aufweisen, die nicht orthogonal angeordnet sind.

In Fig. 6 ist eine vierte Ausführungsform mit mehreren unterschiedlich gestalteten Primärwicklungen dargestellt. Es handelt sich um ein relativ ausgedehntes Aktoren-System 5, bei dem die einzelnen Aktoren 3.1....3.s nicht einigermaßen homogen über das System verteilt angeordnet sind, sondern lediglich an einigen bestimmten Bereichen des Systems gehäuft auftreten. Bei einer derartigen ausgedehnten Konfiguration ist aus Gründen der zu erzielenden magnetischen Feldstärke der Einsatz mehrerer, gezielt angeordneter Primärwicklungen vorteilhaft, welche jeweils mindestens eine Sekundärwicklung eines Aktors lokal beeinflussen.

Ein erster mit Aktoren bestückter Systembereich liegt dabei im Magnetfeld zwischen zwei horizontalen, rechteckförmigen, sich einander gegenüberliegenden Primärwicklungen 1.1, 1.2. Ein zweiter, hierzu benachbarter, mit Aktoren bestückter Systembereich liegt im Magnetfeld zwischen zwei horizontalen, kreisringförmigen oder ovalen, sich einander gegenüberliegender Primärwicklungen 1.3, 1.4. Ein dritter mit Aktoren bestückter Systembereich wird vom Magnetfeld einer Primärwicklung 1.5 beeinflußt, wobei diese Primärwicklung um den Mittelschenkel eines E-förmigen Ferritkernes angeordnet ist, wodurch sich teilweise eine Abschirmung des Magnetfeldes und sich teilweise eine Verstärkung im interessierenden, lokal begrenzten Bereich ergibt ("Spot-Wirkung"). Ein vierter mit Aktoren bestückter Systembereich liegt im Einflußbereich einer Primärwicklung 1.6. Die Magnetfelder der einzelnen Primärwicklungen 1.1 bis 1.6 in den einzelnen Systembereichen sind jeweils gestrichelt angedeutet.

In Fig. 7 ist eine fünfte Ausführungsform mit bandförmiger Primärwicklung dargestellt. Die bandförmige Primärwicklung 1 ist an ihrem einen Ende am Oszillator 4 angeschlossen, während das weitere Ende zusammengeschaltet ist. Auf diese Weise ergibt sich eine Doppelleitung mit zwei vom gleichen Strom mit entgegengesetzter Richtung durchflossenen Leitern, was das Magnetfeld zwischen beiden Leitern in gewünschter Weise verstärkt und das Magnetfeld im Bereich außerhalb der beiden Leiter abschwächt. Vorteilhaft wird die bandförmige Primärwicklung 1 an der Maschine derart installiert, daß sich die einzelnen Aktoren 3.1 bis 3.n im Bereich zwischen beiden Leitern der Doppelleitung befinden.

Selbstverständlich kann dabei jede Leitung der Doppelleitung aus mehreren Einzelleitern bestehen, wobei die Einzelleiter beider Leitungen im Sinne einer Wicklung miteinander verbunden sind, so daß sich quasi eine Primärwicklung 1 wie unter Fig. 4 beschrieben ergibt, welche extrem flach ausgebildet ist.

In Fig. 8 ist ein Ersatzschaltbild mit primärseitigen und sekundärseitigen Weiterbildungen dargestellt. Wie zu erkennen ist, liegt die Primärwicklung 1 über einem Kompensationskondensator 6 am Oszillator 4, wodurch ein resonanter Betrieb des Oszillators erzielt wird. Lediglich beispielhaft ist die magnetische Kopplung zwischen Primärwicklung 1 und Sekundärwicklung 2.1 angedeutet. An die Sekundärwicklung 2.1 ist ein AC/DC-Steller 7 angeschlossen, der einen zur Energieversorgung des Aktors 3.1 dienenden Energiespeicher 8 speist.

In Erweiterung des in Fig. 8 dargestellten Schaltbildes ist es auch möglich, einen Kompensationskondensator in der Anschlußleitung zwischen Sekundärwicklung 2.1 und AC/DC-Steller 7 vorzusehen.

Wicklungen werden üblicherweise durch Wickeln eines Leiters in mehreren Windungen gewünschter Anzahl hergestellt. Bei großflächig auszubildenden Wicklungen kann dies Schwierigkeiten bereiten, beispielsweise bei nachträglicher Integration einer relativ großen Primärwicklung in einem Herstellungs- bzw. Fertigungsautomaten oder allgemein in einer Maschine. Unter "relativ groß" ist zu verstehen, daß die Primärwicklung etwa die Größe des Herstellungsautomaten selbst aufweist.

Nachstehend werden Primärwicklungen gemäß sechster, siebter und achter Ausführungsform angegeben, die ohne Schwierigkeiten auch nachträglich in einer Anlage oder Maschine integriert werden können.

Dabei kann die Primärwicklung aus mehreren separaten, jeweils aus mehreren parallelen Leitern aufgebauten Wicklungsabschnitten bestehen, wobei die einzelnen Wicklungsabschnitte über Verbindungselemente mechanisch und elektrisch miteinander verbunden sind und wobei bei einem Verbindungselement zwei Wicklungsabschnitte versetzt gegeneinander elektrisch miteinander verbunden sind, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

Alternativ hierzu kann die Primärwicklung aus einem flexiblen, aus mehreren parallelen Leitern aufgebauten Kabel und einem Verbindungselement bestehen, welches die beiden Kabelenden versetzt gegeneinander elektrisch und mechanisch miteinander verbindet, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

Die mit der sechsten, siebten und achten Ausführungsform erzielbaren Vorteile bestehen insbesondere darin, daß die Primärwicklung auftrennbar ist und deshalb ein nachträglicher Einbau der vorgeschlagenen Primärwicklung in einer Maschine in einfacher Art möglich ist. Die Primärwicklung wird erst in der Maschine selbst durch Verbinden der einzelnen Wicklungsabschnitte bzw. des flexiblen Kabels unter Einsatz des mindestens einen Verbindungselementes hergestellt, wobei eine exakte Anpassung an die Maschine durch die Anzahl und Lage der Verbindungselemente und durch flexible Ausgestaltung der Wicklungsabschnitte, bestehend vorzugsweise aus flexiblem Flachbandkabel, ermöglicht wird. Der Einsatz von Flachbandkabel hat den weiteren Vorteil, daß das von der Primärwicklung produzierte Magnetfeld axial relativ breit ausgebildet ist, was die magnetische Ankopplung an weitere Wicklungen verbessert.

In Fig. 9 ist eine Primärwicklung gemäß sechster Ausführungsform dargestellt. Diese sechste Ausführungsform ist insbesondere für eine vertikale Anordnung der Primärwicklung geeignet. Die rechteckförmige Primärwicklung weist vier separate Wicklungsabschnitte 1a´, 1b´, 1c´, 1d´ auf, die an den vier Ecken über Verbindungselemente 2a´, 2b´, 2c´, 2d´ elektrisch und mechanisch miteinander verbunden sind. Für die Wicklungsabschnitte 1a´ bis 1d´ wird vorzugsweise flexibles mehradriges Flachbandkabel mit mehreren parallelen Leitern eingesetzt.

In Fig. 10 ist eine Detailansicht einer Ecke einer Primärwicklung gemäß sechster Ausführungsform dargestellt. Das gezeigte Verbindungselement 2a´ weist sieben winkelförmig ausgebildete, in einer Reihe nebeneinander angeordnete und gegenseitig elektrisch isolierte Kontaktstellen mit jeweils zwei Anschlüssen für die beiden Wicklungsabschnitte 1a´, 1b´ auf. Die Abwinkelung der nebeneinander angeordneten Kontaktstellen erfolgt in zwei Ebenen. Zur elektrischen Kontaktierung weisen diese Kontaktstellen beispielsweise Öffnungen mit Kontaktzungen auf, in welche die elektrischen Leiter der Wicklungsabschnitte eingesteckt werden.

In Fig. 11 ist eine Detailansicht der Wicklungseinspeisung bei der sechsten Ausführungsform dargestellt. Wie zu erkennen ist, sind die beiden Wicklungsabschnitte 1a´, 1d´ versetzt gegeneinander in das Verbindungselement 2d´ eingesteckt. Die jeweils freien Enden des Wicklungsabschnittes 1a´ bzw. des Wicklungsabschnittes **1**d´ bilden die Wicklungsenden und sind mit einer Verbindungsleitung 3´ bzw. 4´ kontaktiert, welche andererseits mit einem Generator bzw. Oszillator verbunden sind. Die Kontaktierung zwischen der Verbindungsleitung 4´ und dem Wicklungsabschnitt 1d´ erfolgt über das Verbindungselement 2d´. Die weitere elektrische Verbindung zwischen der Verbindungsleitung 3´ und dem Wicklungsabschnitt 1a´ erfolgt beispielsweise durch Verlöten.

Alternativ kann auch an der Wicklungseinspeisung ein Verbindungselement eingesetzt sein, das eine Kontaktstelle mehr aufweist, als dies der Anzahl der parallelen Leiter eines Wicklungsabschnittes entspricht. Dann können beide Kontaktierungen zwischen den Verbindungsleitungen 3´, 4´ und den Wicklungsabschnitten über das Verbindungselement selbst erfolgen.

Die weiteren Verbindungselemente 2b´, 2c´der Primärwicklung sind in der gemäß Fig. 10 dargestellten Art und Weise mit den Wicklungsabschnitten verbunden. Insgesamt ergibt sich eine Primärwicklung mit sieben Windungen.

In Fig. 12 ist eine Primärwicklung gemäß siebter Ausführungsform dargestellt. Diese siebte Ausführungsform ist insbesondere für eine horizontale Anordnung der Primärwicklung geeignet. Die rechteckförmige Primärwicklung weist vier separate Wicklungsabschnitte 5a´, 5b´, 5c´, 5d´ auf, die an den vier Ecken über Verbindungselemente 6a´, 6b´, 6c´, 6d´ elektrisch und mechanisch miteinander verbunden sind. Für die Wicklungsabschnitte 5a´ bis 5d´ wird vorzugsweise mehradriges Flachbandkabel eingesetzt.

In Fig. 13 ist eine Detailansicht der Wicklungseinspeisung bei der siebten Ausführungsform dargestellt. Zur elektrischen Kontaktierung weisen die Verbindungselemente wiederum Öffnungen mit Kontaktzungen auf, in welche die elektrischen Leiter der Wicklungsabschnitte eingeführt werden. Wie zu erkennen ist, sind die beiden Wicklungsabschnitte 5a´, 5d´ versetzt gegeneinander in das Verbindungselement 6d´ eingesteckt. Die jeweils freien Enden des Wicklungsabschnittes 5a´ bzw. des Wicklungsabschnittes 5d´ bilden die Wicklungsenden und sind mit einer Verbindungsleitung 8´ bzw. 7´ kontaktiert, welche andererseits mit einem Generator bzw. Oszillator verbunden sind. Da ein Verbindungselement 6d´ eingesetzt ist, welches ein Kontaktpaar mehr aufweist als dies der Anzahl der parallelen Leiter der Wicklungsabschnitte entspricht, erfolgt die Kontaktierung zwischen der Verbindungsleitung 7´ und dem Wicklungsabschnitt 5d´ sowie die Kontaktierung zwischen der Verbindungsleitung 8´ und dem Wicklungsabschnitt 5a´ über das Verbindungselement 6d´.

In Fig. 14 ist eine Detailansicht einer Ecke einer Primärwicklung gemäß siebter Ausführungsform dargestellt. Das gezeigte Verbindungselement 6a´ weist fünf winkelförmig ausgebildete, in einer Reihe nebeneinander angeordnete und gegenseitig elektrisch isolierte Kontaktstellen für die beiden Wicklungsabschnitte 5a´, 5b´ auf, wobei die Abwinkelungen der nebeneinander angeordneten Kontaktstellen in einer Ebene erfolgen. Die elektrische und mechanische Verbindung der weiteren Wicklungsabschnitte über die Verbindungselemente 6b´ und 6c´ erfolgt in gleicher Art und Weise.

Vorstehend ist ausgeführt, daß für die Wicklungsabschnitte 1a´ bis 1d´ und 5a´ bis 5d´ vorzugsweise mehradriges, flexibles Flachbandkabel eingesetzt wird. Alternativ hierzu ist es insbesondere zur Bildung einer sehr leistungsstarken Primärwicklung mit relativ hohem Stromdurchgang möglich, die Wicklungsabschnitte aus mehreren nebeneinander anzuordnenden, elektrisch gegeneinander zu isolierenden, starren Leiterstäben aufzubauen.

Vorstehend werden rechteckförmige Konfigurationen der Primärwicklung beschrieben, welche den Einsatz von Verbindungselementen mit rechtwinklig abgebogenen Kontaktstellen erfordern. Abweichend hiervon können selbstverständlich auch andere Wicklungs-Konfigurationen (dreieckig, fünfeckig usw.) realisiert werden.

Im einfachsten Fall ist eine aus einem flexiblen Kabel 9´, insbesondere Flachbandkabel und einem einzigen Verbindungselement 10´ bestehende Primärwicklung herstellbar, wobei die beiden Enden des Kabels über das einzige Verbindungselement 10´ versetzt gegeneinander elektrisch miteinander verbunden sind, wodurch sich freie, zum Anschluß von Verbindungsleitungen 11´, 12´ zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben. Eine derartige Primärwicklung ist in Fig. 15 gezeigt.

Patentansprüche

1. Verfahren zur drahtlosen Versorgung einer Vielzahl Aktoren (3.1 bis 3.s) mit elektrischer Energie, wobei ein von mindestens einer Primärwicklung (1, 1.1 bis 1.p) abgestrahltes, mittelfrequentes magnetisches Feld zu jedem mindestens eine Sekundärwicklung (2.1 bis 2.s) aufweisenden Aktor übertragen und dort in elektrische Energie umgewandelt wird.

2. Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren (3.1 bis 3.s) mit elektrischer Energie unter Einsatz mindestens einer von einem mittelfrequenten Oszillator (4) gespeisten Primärwicklung (1, 1.1 bis 1.p), wobei jeder Aktor (3.1 bis 3.s) mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung (2.1 bis 2.s) aufweist.

3. Anordnung nach Anspruch 2, gekennzeichnet durch eine einzige, die Sekundärwicklungen (2.1 bis 2.s) der Aktoren (3.1 bis 3.s) global umfassende Primärwicklung (1).

4. Anordnung nach Anspruch 2, gekennzeichnet durch mindestens zwei parallel nebeneinander angeordnete Primärwicklungen (1.1, 1.2), zwischen denen die Sekundärwicklungen (2.1 bis 2.s) der Aktoren (3.1 bis 3.s) angeordnet sind.

5. Anordnung nach Anspruch 2, gekennzeichnet durch zwei orthogonal zueinander angeordnete Primärwicklungen (1.1, 1.2).

6. Anordnung nach Anspruch 2, gekennzeichnet durch drei orthogonal zueinander angeordnete Primärwicklungen (1.1, 1.2, 1.3).

7. Anordnung nach Anspruch 2, gekennzeichnet durch mindestens eine, mindestens eine Sekundärwicklung (2.1 bis 2.s) eines Aktors (3.1 bis 3.s) lokal beeinflussende Primärwicklung (1.1 bis 1.p).

8. Anordnung nach Anspruch 2, gekennzeichnet durch eine in Form einer Doppelleitung ausgeführte Primärwicklung (1), wobei die Sekundärwicklungen (2.1 bis 2.s) der Aktoren (3.1 bis 3.s) zwischen der Doppelleitung angeordnet sind.

9. Anordnung nach einem der Ansprüche 2 bis 8, dadurch gekennzeichnet, daß mindestens eine Primärwicklung mit einem Ferritkern versehen ist.

10. Anordnung nach einem der Ansprüche 2 bis 9, dadurch gekennzeichnet, daß die mindestens eine Primärwicklung mit einem Kompensationskondensator (6) beschaltet ist.

11. Aktor mit mehreren zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeigneten, orthogonalen Sekundärwicklungen (2.1 bis 2.s).

12. Aktor nach Anspruch 11, dadurch gekennzeichnet, daß die Sekundärwicklungen (2.1 bis 2.s) mit einem Kompensationskondensator (6) beschaltet sind.

13. Aktor nach Anspruch 11 oder 12, dadurch gekennzeichnet, daß die Sekundärwicklungen (2.1 bis 2.s) mit einem AC/DC-Steller beschaltet sind, welcher einen Energiespeicher (8) auflädt.

14. System für eine eine Vielzahl von Aktoren aufweisende Maschine, insbesondere Fertigungsautomat,

- wobei jeder Aktor (3.1 bis 3.s) mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung (2.1 bis 2.s) aufweist,
- wobei mindestens eine von einem mittelfrequenten Oszillator (4) gespeiste Primärwicklung (1, 1.1 bis 1.p) zur drahtlosen Versorgung der Aktoren (3.1 bis 3.s) mit elektrischer Energie vorgesehen ist,

- wobei jeder Aktor mit einer Empfangseinrichtung ausgestattet ist, welche Funksignale einer mit einem Prozeßrechner der Maschine verbundenen zentralen Sendeeinrichtung empfängt.

15. System nach Anspruch 14, dadurch gekennzeichnet, daß die Aktoren mit Sendeeinrichtungen versehen sind, welche interessierende Aktor-Informationen beinhaltende Funksignale an eine zentrale, mit dem Prozeßrechner verbundene Empfangseinrichtung abgeben, so daß ein bidirektionaler Informationsaustausch zwischen dem Prozeßrechner und den Aktoren möglich ist.

16. Primärwicklung, bestehend aus mehreren separaten Wicklungsabschnitten (1a´ bis 1d´, 5a´ bis 5d´), welche jeweils aus mehreren parallelen Leitern aufgebaut sind, wobei die einzelnen Wicklungsabschnitte über Verbindungselemente (2a´ bis 2d´, 6a´ bis 6d´) mechanisch und elektrisch miteinander verbunden sind und wobei bei einem Verbindungselement zwei Wicklungsabschnitte versetzt gegeneinander elektrisch miteinander verbunden sind, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen (3´, 4´, 7´, 8´) zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

17. Primärwicklung, bestehend aus einem flexiblen, aus mehreren parallelen Leitern aufgebauten Kabel (9´) und einem Verbindungselement (10´), welches die beiden Kabelenden versetzt gegeneinander elektrisch und mechanisch miteinander verbindet, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen (11´, 12´) zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

18. Primärwicklung nach Anspruch 16 und/oder 17, dadurch gekennzeichnet, daß ein Verbindungselement (2a´ bis 2d´, 6a´ bis 6d´) aus mehreren in einer Reihe nebeneinander angeordneten, elektrisch gegeneinander isolierten Kontaktstellen mit jeweils zwei Anschlüssen besteht.

19. Primärwicklung nach Anspruch 18, dadurch gekennzeichnet, daß eine Abwinkelung der nebeneinander angeordneten Kontaktstellen in einer Ebene erfolgt.

20. Primärwicklung nach Anspruch 18, dadurch gekennzeichnet, daß eine Abwinkelung der nebeneinander angeordneten Kontaktstellen in zwei Ebenen erfolgt.

21. Primärwicklung nach Anspruch 19 oder 20, dadurch gekennzeichnet, daß die Abwinkelungen rechtwinklig erfolgen.

22. Primärwicklung nach Anspruch 16, dadurch gekennzeichnet, daß die Anzahl der Kontaktstellen eines Verbindungselementes (2a´ bis 2c´, 6a´ bis 6c´) gleich der Anzahl der parallelen Leiter eines Wicklungsabschnittes ist, mit Ausnahme des Verbindungselementes (2d´, 6d´) für den Anschluß der gegeneinander zu versetzenden Wicklungsabschnitte (1a´ und 1d´, 5a´ und 5d´), welches eine Kontaktstelle mehr aufweist als dies der Anzahl der parallelen Leiter eines Wicklungsabschnittes entspricht.

Fig.1

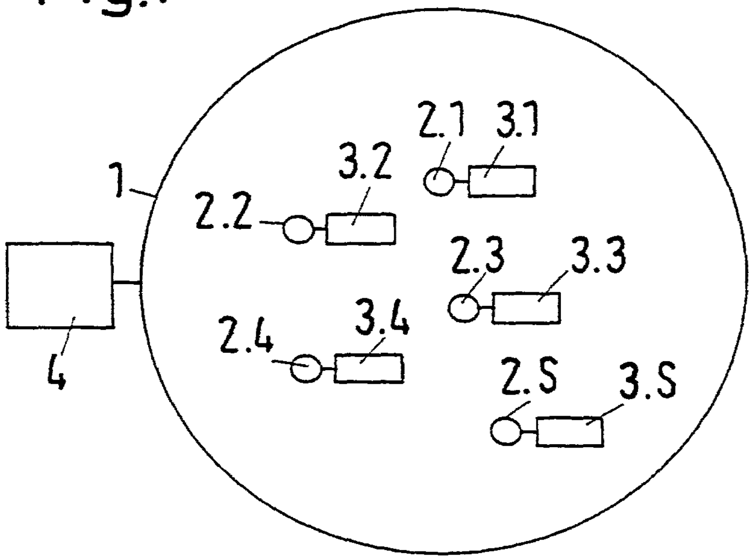


Fig.2

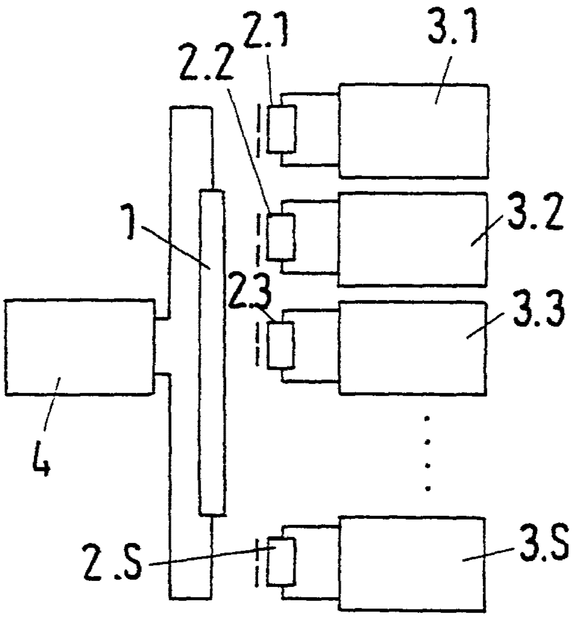


Fig.3

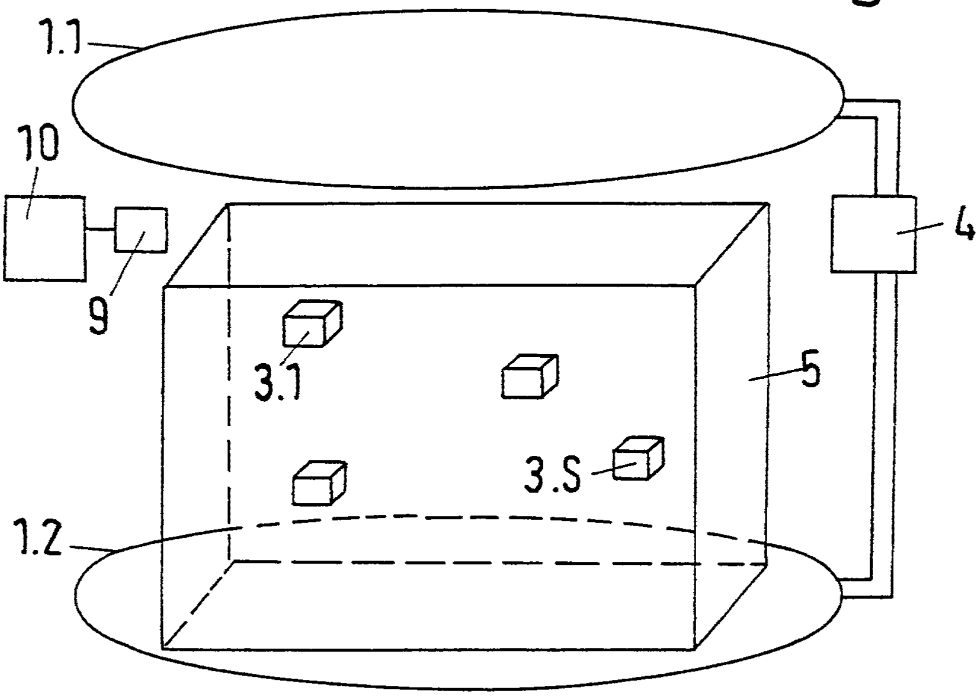


Fig.4

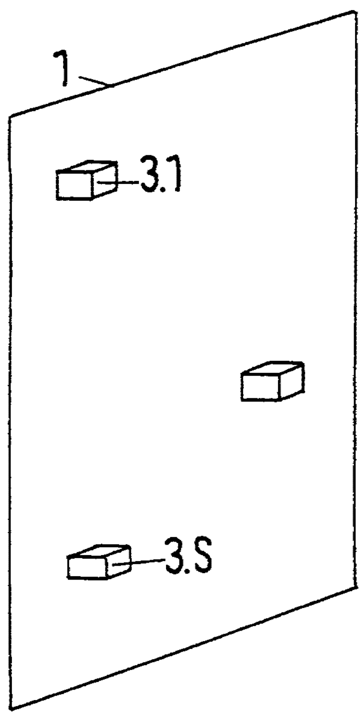


Fig.5

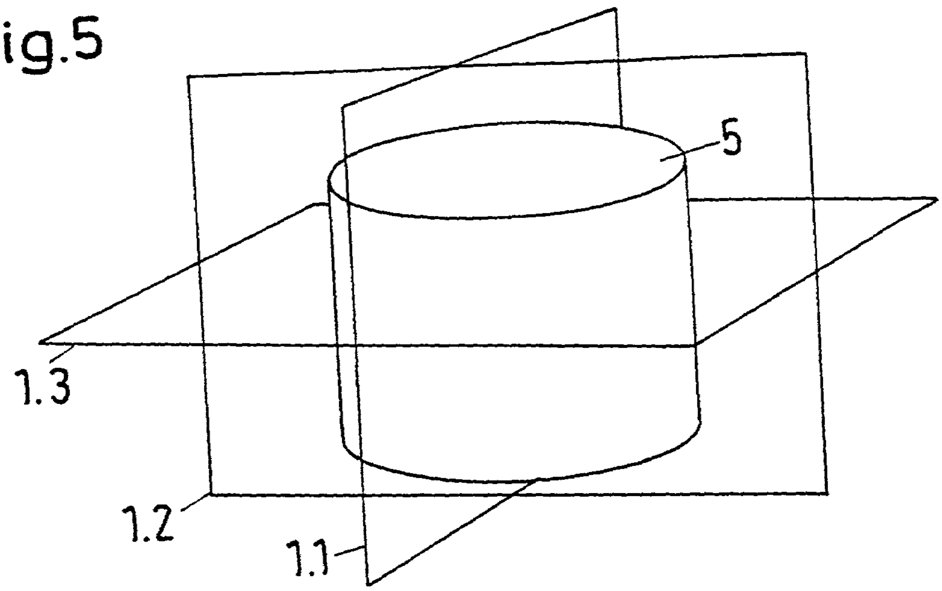


Fig. 6

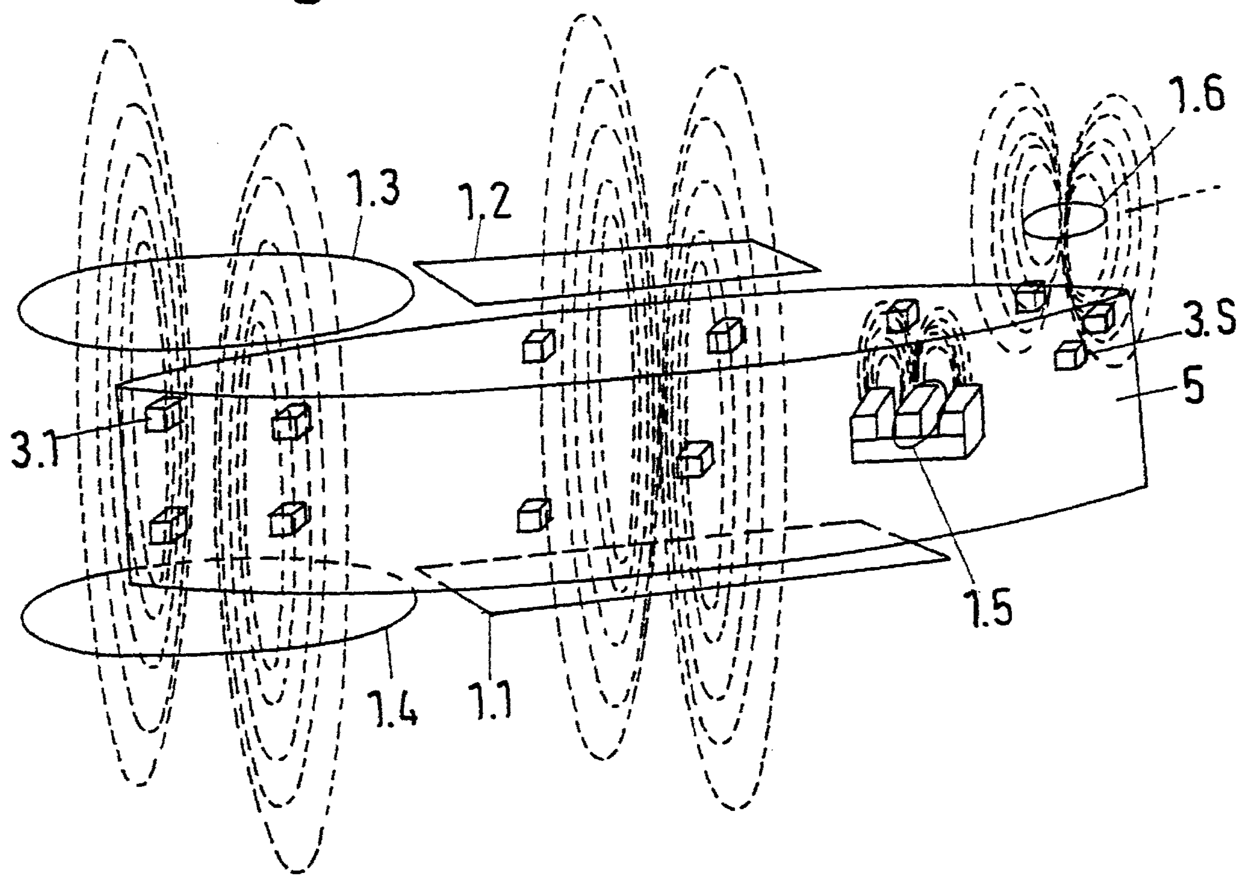


Fig.7

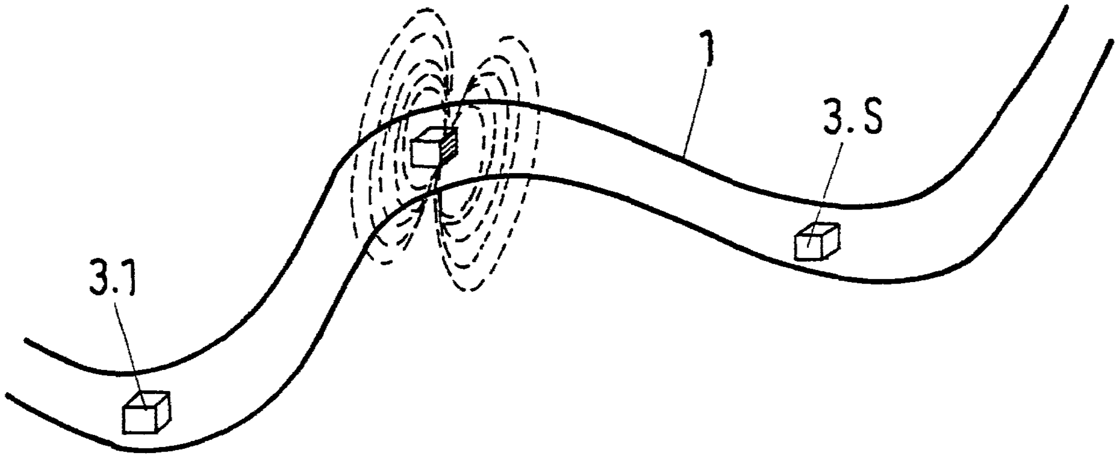


Fig. 8

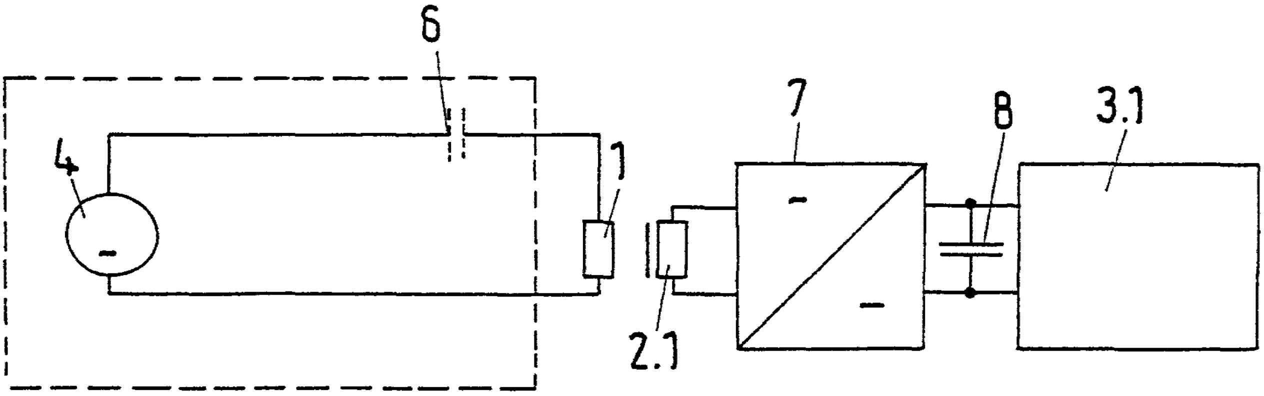


Fig.9

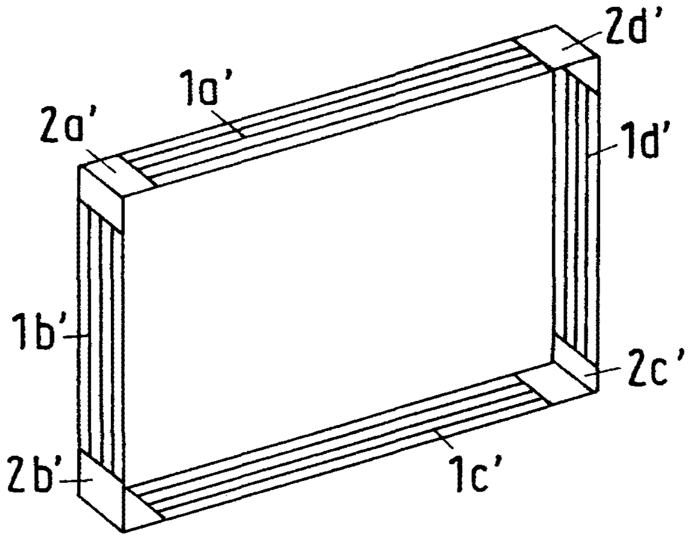


Fig.10

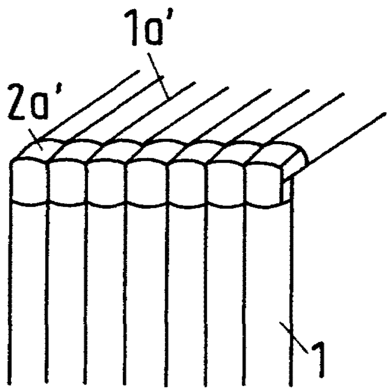


Fig.11

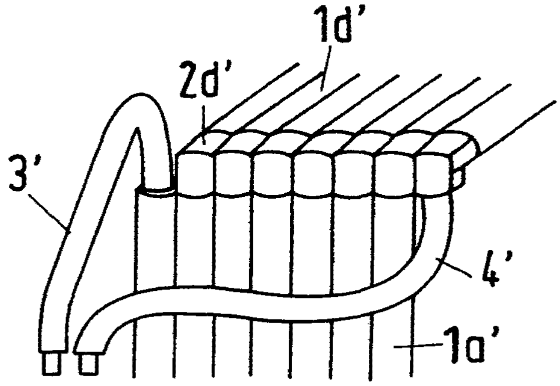


Fig.12

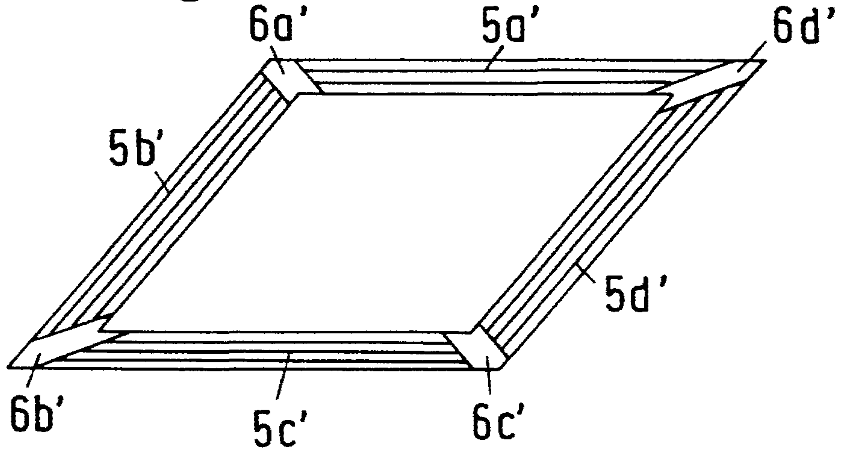


Fig.13

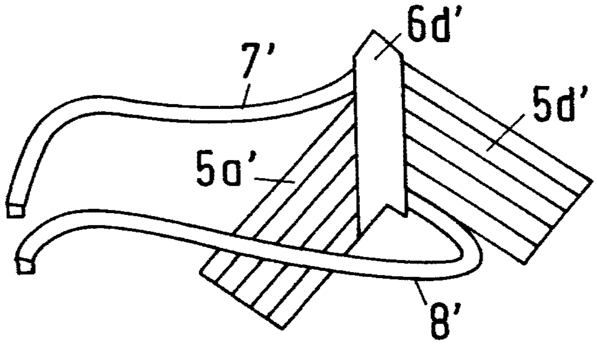


Fig.14

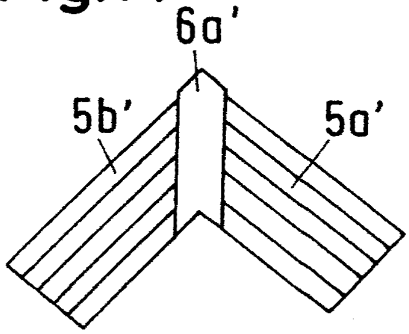
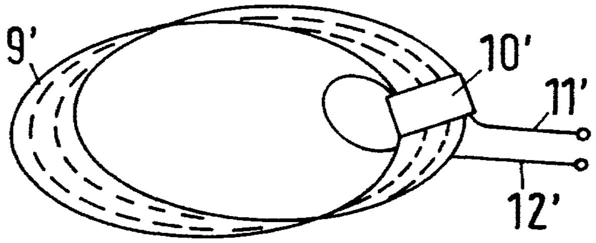


Fig.15



ERSATZBLATT (REGEL 26)

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/05138

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H02J5/00 G05B19/042

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H02J G05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 89 10030 A (MAGELLAN TECH PTY LTD ;UNISCAN LTD (AU)) 19 October 1989 (1989-10-19) page 9, line 7 - line 33; figures 1A,2,3 ---	1,11,12, 14,15
Y	DE 195 28 341 C (ILG GMBH) 10 October 1996 (1996-10-10) claim 3; figure 1 ---	1,11,12, 14,15
Y	DE 197 35 624 C (DAIMLER BENZ AG) 10 December 1998 (1998-12-10) page 2, paragraph 4; figure 1 ---	1,11,12, 14,15
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
8 September 2000	01 12 2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	MOYLE, J

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/05138

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KAWAMURA A ET AL: "WIRELESS TRANSMISSION OF POWER AND INFORMATION THROUGH ONE HIGH FREQUENCY RESONANT AC LINK INVERTER FOR ROBOT MANIPULATOR APPLICATIONS" RECORD OF THE INDUSTRY APPLICATIONS CONFERENCE (IAS),US,NEW YORK, IEEE, vol. CONF. 30, 8 October 1995 (1995-10-08), pages 2367-2372, XP000547151 ISBN: 0-7803-3009-9 abstract -----	1-15

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP00/05138

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See supplemental sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-15

Remark on Protest
☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

International application No.
PCT/EP 00/05138

Additional Matter PCT/ISA/210

The International Searching Authority found that this application contains multiple inventions, as follows :

1. Claims Nos. 1-15
Transportation of inductive energy and data to machine tool actuators

2. Claims Nos. 16-22
Structural inductive transmission coil units

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 00/05138

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 8910030 A	19-10-1989	AT 115792 T	15-12-1994
		AU 624377 B	11-06-1992
		AU 3429889 A	03-11-1989
		CA 1338675 A	22-10-1996
		CA 1340489 A	06-04-1999
		DE 68920038 D	26-01-1995
		DE 68920038 T	03-08-1995
		EP 0409880 A	30-01-1991
		EP 0609964 A	10-08-1994
		JP 3505148 T	07-11-1991
		US 5701121 A	23-12-1997
		ZA 8902468 A	27-12-1989
DE 19528341 C	10-10-1996	NONE	
DE 19735624 C	10-12-1998	AU 9159798 A	08-03-1999
		WO 9909634 A	25-02-1999
		EP 0968559 A	05-01-2000

Form PCT/ISA/210 (patent family annex) (July 1992)

INTERNATIONALER RECHERCHENBERICHT

Ii ıationales Aktenzeichen
PCT/EP 00/05138

A. KLASSIFIZIERUNG DES ANMELDUNGSGEGENSTANDES
IPK 7 H02J5/00 G05B19/042

Nach der Internationalen Patentklassifikation (IPK) oder nach der nationalen Klassifikation und der IPK

B. RECHERCHIERTE GEBIETE

Recherchierter Mindestprüfstoff (Klassifikationssystem und Klassifikationssymbole)
IPK 7 H02J G05B

Recherchierte aber nicht zum Mindestprüfstoff gehörende Veröffentlichungen, soweit diese unter die recherchierten Gebiete fallen

Während der internationalen Recherche konsultierte elektronische Datenbank (Name der Datenbank und evtl. verwendete Suchbegriffe)

EPO-Internal

C. ALS WESENTLICH ANGESEHENE UNTERLAGEN

Kategorie°	Bezeichnung der Veröffentlichung, soweit erforderlich unter Angabe der in Betracht kommenden Teile	Betr. Anspruch Nr.
Y	WO 89 10030 A (MAGELLAN TECH PTY LTD ;UNISCAN LTD (AU)) 19. Oktober 1989 (1989-10-19) Seite 9, Zeile 7 - Zeile 33; Abbildungen 1A,2,3 ---	1,11,12, 14,15
Y	DE 195 28 341 C (ILG GMBH) 10. Oktober 1996 (1996-10-10) Anspruch 3; Abbildung 1 ---	1,11,12, 14,15
Y	DE 197 35 624 C (DAIMLER BENZ AG) 10. Dezember 1998 (1998-12-10) Seite 2, Absatz 4; Abbildung 1 ---	1,11,12, 14,15
	-/--	

[X] Weitere Veröffentlichungen sind der Fortsetzung von Feld C zu entnehmen

[X] Siehe Anhang Patentfamilie

° Besondere Kategorien von angegebenen Veröffentlichungen :

"A" Veröffentlichung, die den allgemeinen Stand der Technik definiert, aber nicht als besonders bedeutsam anzusehen ist

"E" älteres Dokument, das jedoch erst am oder nach dem internationalen Anmeldedatum veröffentlicht worden ist

"L" Veröffentlichung, die geeignet ist, einen Prioritätsanspruch zweifelhaft erscheinen zu lassen, oder durch die das Veröffentlichungsdatum einer anderen im Recherchenbericht genannten Veröffentlichung belegt werden soll oder die aus einem anderen besonderen Grund angegeben ist (wie ausgeführt)

"O" Veröffentlichung, die sich auf eine mündliche Offenbarung, eine Benutzung, eine Ausstellung oder andere Maßnahmen bezieht

"P" Veröffentlichung, die vor dem internationalen Anmeldedatum, aber nach dem beanspruchten Prioritätsdatum veröffentlicht worden ist

"T" Spätere Veröffentlichung, die nach dem internationalen Anmeldedatum oder dem Prioritätsdatum veröffentlicht worden ist und mit der Anmeldung nicht kollidiert, sondern nur zum Verständnis des der Erfindung zugrundeliegenden Prinzips oder der ihr zugrundeliegenden Theorie angegeben ist

"X" Veröffentlichung von besonderer Bedeutung; die beanspruchte Erfindung kann allein aufgrund dieser Veröffentlichung nicht als neu oder auf erfinderischer Tätigkeit beruhend betrachtet werden

"Y" Veröffentlichung von besonderer Bedeutung; die beanspruchte Erfindung kann nicht als auf erfinderischer Tätigkeit beruhend betrachtet werden, wenn die Veröffentlichung mit einer oder mehreren anderen Veröffentlichungen dieser Kategorie in Verbindung gebracht wird und diese Verbindung für einen Fachmann naheliegend ist

"&" Veröffentlichung, die Mitglied derselben Patentfamilie ist

Datum des Abschlusses der internationalen Recherche	Absendedatum des internationalen Recherchenberichts
8. September 2000	01.12.2000
Name und Postanschrift der Internationalen Recherchenbehörde Europäisches Patentamt, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Bevollmächtigter Bediensteter MOYLE, J

Formblatt PCT/ISA/210 (Blatt 2) (Juli 1992)

INTERNATIONALER RECHERCHENBERICHT

I. nationales Aktenzeichen
PCT/EP 00/05138

C.(Fortsetzung) ALS WESENTLICH ANGESEHENE UNTERLAGEN		
Kategorie°	Bezeichnung der Veröffentlichung, soweit erforderlich unter Angabe der in Betracht kommenden Teile	Betr. Anspruch Nr.
A	KAWAMURA A ET AL: "WIRELESS TRANSMISSION OF POWER AND INFORMATION THROUGH ONE HIGH FREQUENCY RESONANT AC LINK INVERTER FOR ROBOT MANIPULATOR APPLICATIONS" RECORD OF THE INDUSTRY APPLICATIONS CONFERENCE (IAS),US,NEW YORK, IEEE, Bd. CONF. 30, 8. Oktober 1995 (1995-10-08), Seiten 2367-2372, XP000547151 ISBN: 0-7803-3009-9 Zusammenfassung -----	1-15

Formblatt PCT/ISA/210 (Fortsetzung von Blatt 2) (Juli 1992)

Internationales Aktenzeichen
PCT/EP 00/05138

INTERNATIONALER RECHERCHENBERICHT

Feld I Bemerkungen zu den Ansprüchen, die sich als nicht recherchierbar erwiesen haben (Fortsetzung von Punkt 2 auf Blatt 1)

Gemäß Artikel 17(2)a) wurde aus folgenden Gründen für bestimmte Ansprüche kein Recherchenbericht erstellt:

1. ☐ Ansprüche Nr.
weil sie sich auf Gegenstände beziehen, zu deren Recherche die Behörde nicht verpflichtet ist, nämlich

2. ☐ Ansprüche Nr.
weil sie sich auf Teile der internationalen Anmeldung beziehen, die den vorgeschriebenen Anforderungen so wenig entsprechen, daß eine sinnvolle internationale Recherche nicht durchgeführt werden kann, nämlich

3. ☐ Ansprüche Nr.
weil es sich dabei um abhängige Ansprüche handelt, die nicht entsprechend Satz 2 und 3 der Regel 6.4 a) abgefaßt sind.

Feld II Bemerkungen bei mangelnder Einheitlichkeit der Erfindung (Fortsetzung von Punkt 3 auf Blatt 1)

Die internationale Recherchenbehörde hat festgestellt, daß diese internationale Anmeldung mehrere Erfindungen enthält:

siehe Zusatzblatt

1. ☐ Da der Anmelder alle erforderlichen zusätzlichen Recherchengebühren rechtzeitig entrichtet hat, erstreckt sich dieser internationale Recherchenbericht auf alle recherchierbaren Ansprüche.

2. ☐ Da für alle recherchierbaren Ansprüche die Recherche ohne einen Arbeitsaufwand durchgeführt werden konnte, der eine zusätzliche Recherchengebühr gerechtfertigt hätte, hat die Behörde nicht zur Zahlung einer solchen Gebühr aufgefordert.

3. ☐ Da der Anmelder nur einige der erforderlichen zusätzlichen Recherchengebühren rechtzeitig entrichtet hat, erstreckt sich dieser internationale Recherchenbericht nur auf die Ansprüche, für die Gebühren entrichtet worden sind, nämlich auf die Ansprüche Nr.

4. ☒ Der Anmelder hat die erforderlichen zusätzlichen Recherchengebühren nicht rechtzeitig entrichtet. Der internationale Recherchenbericht beschränkt sich daher auf die in den Ansprüchen zuerst erwähnte Erfindung; diese ist in folgenden Ansprüchen erfaßt:
1-15

Bemerkungen hinsichtlich eines Widerspruchs

☐ Die zusätzlichen Gebühren wurden vom Anmelder unter Widerspruch gezahlt.

☐ Die Zahlung zusätzlicher Recherchengebühren erfolgte ohne Widerspruch.

Formblatt PCT/ISA/210 (Fortsetzung von Blatt 1 (1))(Juli 1998)

WEITERE ANGABEN PCT/ISA/ 210

Die internationale Recherchenbehörde hat festgestellt, daß diese internationale Anmeldung mehrere (Gruppen von) Erfindungen enthält, nämlich:

1. Ansprüche: 1-15

   Induktive Energie- und Daten- Transport zu Werkzeugmaschinenaktoren

2. Ansprüche: 16-22

   Strukturelle Einzelheiten von induktiven Übertragungsspulen

INTERNATIONALER RECHERCHENBERICHT

Angaben zu Veröffentlichungen, die zur selben Patentfamilie gehören

I ationales Aktenzeichen
PCT/EP 00/05138

Im Recherchenbericht angeführtes Patentdokument	Datum der Veröffentlichung	Mitglied(er) der Patentfamilie	Datum der Veröffentlichung
WO 8910030 A	19-10-1989	AT 115792 T	15-12-1994
		AU 624377 B	11-06-1992
		AU 3429889 A	03-11-1989
		CA 1338675 A	22-10-1996
		CA 1340489 A	06-04-1999
		DE 68920038 D	26-01-1995
		DE 68920038 T	03-08-1995
		EP 0409880 A	30-01-1991
		EP 0609964 A	10-08-1994
		JP 3505148 T	07-11-1991
		US 5701121 A	23-12-1997
		ZA 8902468 A	27-12-1989
DE 19528341 C	10-10-1996	KEINE	
DE 19735624 C	10-12-1998	AU 9159798 A	08-03-1999
		WO 9909634 A	25-02-1999
		EP 0968559 A	05-01-2000

Formblatt PCT/ISA/210 (Anhang Patentfamilie)(Juli 1992)

No documents available for this priority number.

Espacenet

Bibliographic data: JP2001309580 (A) — 2001-11-02

NON-CONTACT POWER TRANSFER APPARATUS

Inventor(s): MUTO MOTOHARU; ABE HIDEAKI + (MUTO MOTOHARU, ; ABE HIDEAKI)

Applicant(s): MATSUSHITA ELECTRIC WORKS LTD + (MATSUSHITA ELECTRIC WORKS LTD)

Classification: **- international:** ***H02J17/00; H02M3/28; H02M7/12; H02M7/21;*** (IPC1-7): H02J17/00; H02M3/28; H02M7/12; H02M7/21
- cooperative:

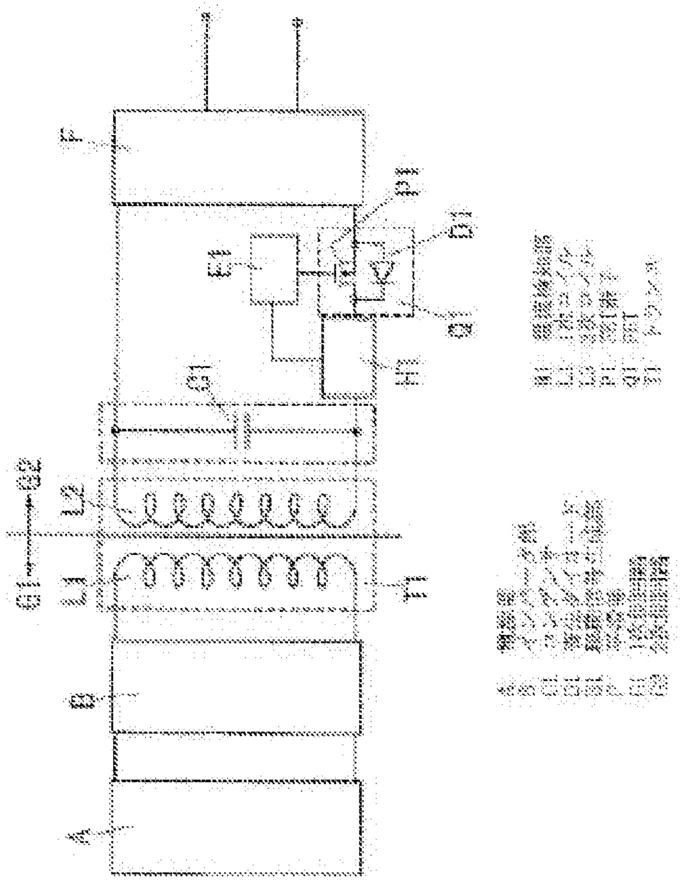
Application number: JP20000124565 20000425

Priority number(s): JP20000124565 20000425

Also published as: JP4140169 (B2)

Abstract of JP2001309580 (A)

PROBLEM TO BE SOLVED: To provide a non-contact power transfer apparatus which has improved the rectifying efficiency of a secondary side circuit. SOLUTION: A power supply section A supplies a DC power to an inverter section B, the DC power is converted to a high frequency power in the inverter section B, and the high frequency power is supplied to a primary coil L1 of a transformer T1. A secondary coil L2 of the transformer T1 receives the power from the primary coil L1 through electro-magnetic coupling, the voltage across the secondary coil L2 is half-wave rectified with FETQ1, and the half-wave rectified voltage is smoothed in a smoothing section F to output a DC voltage. A current detecting section H1connected in series to FETQ1 detects a current flowing into the FETQ1 and outputs the detected signal to a drive signal generating section E1.; The drive signal generating section E1outpts a drive signal to turn ON the FET element P1when the detected signal from the current detecting section H1is the predetermined threshold value or higher, and also outputs a drive signal to turn OFF the FET element P1 when the signal from the current detecting section H1is a predetermined threshold or lower.



(19)日本国特許庁（ＪＰ）　　(12) **公 開 特 許 公 報**（Ａ）

(11)特許出願公開番号
特開2001－309580
（P2001－309580A）

(43)公開日　平成13年11月２日(2001.11.2)

(51)Int.Cl.⁷	識別記号	ＦＩ	テーマコード（参考）
Ｈ０２Ｊ　17/00		Ｈ０２Ｊ　17/00	Ｂ　５Ｈ００６
Ｈ０２Ｍ　3/28		Ｈ０２Ｍ　3/28	Ｆ　５Ｈ７３０
7/12		7/12	Ａ
7/21		7/21	Ａ

審査請求　未請求　請求項の数13　ＯＬ　（全 16 頁）

(21)出願番号　特願2000－124565(P2000－124565)

(22)出願日　平成12年４月25日(2000.4.25)

(71)出願人　000005832
松下電工株式会社
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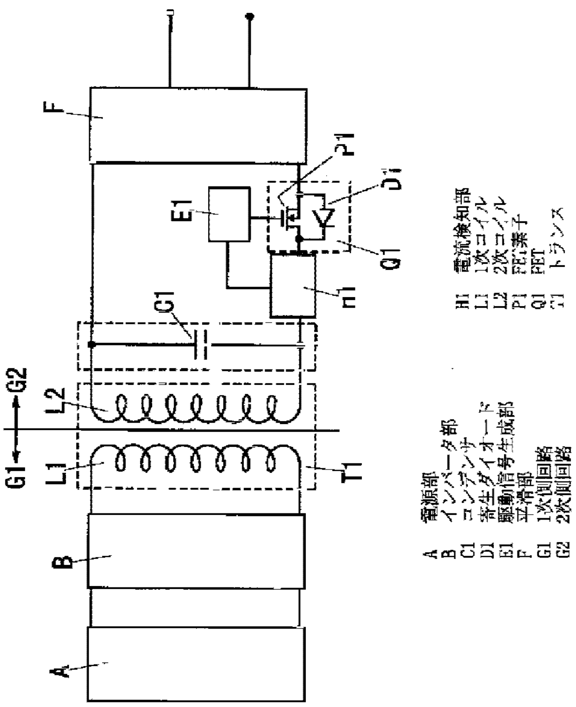
大阪府門真市大字門真1048番地松下電工株式会社内

(74)代理人　100087767
弁理士　西川　惠清　（外１名）

最終頁に続く

(54)【発明の名称】　非接触電力伝達装置

(57)【要約】
【課題】　２次側回路の整流効率を上げた非接触電力伝達装置を提供する。
【解決手段】　電源部Ａは直流電力をインバータ部Ｂに供給し、インバータ部Ｂで高周波電力に変換され、前記高周波電力はトランスＴ１の１次コイルＬ１に供給される。トランスＴ１の２次コイルＬ２は、電磁結合により１次コイルＬ１より電力を受電し、２次コイルＬ２両端の電圧はＦＥＴＱ１で半波整流され、半波整流された電圧は平滑部Ｆで平滑されて直流電圧を出力する。ＦＥＴＱ１に直列に接続された電流検知部Ｈ１はＦＥＴＱ１に流れる電流を検出し、前記検出信号を駆動信号生成部Ｅ１に出力する。駆動信号生成部Ｅ１は、電流検知部Ｈ１からの検出信号が所定のしきい値以上であればＦＥＴ素子Ｐ１をオンにする駆動信号を出力し、電流検知部Ｈ１からの信号が所定のしきい値以下であればＦＥＴ素子Ｐ１をオフにする駆動信号を出力する。



【特許請求の範囲】

【請求項１】　直流電源を供給する電源部と、前記直流電源を高周波電源に変換するインバータ部と、前記インバータ部から高周波電力を供給される１次コイルと１次コイルから受電した電力を出力する２次コイルとが分離可能なトランスの前記１次コイルとで構成される１次側回路と、前記２次コイルと、前記２次コイルに並列に接続される負荷整合用コンデンサ及び前記２次コイルの出力電圧を整流する整流部とで構成される２次側回路とを有する非接触電力伝送装置において、スイッチング素子及び前記スイッチング素子に並列に逆接続されたダイオードとからなる同期整流要素を前記２次コイルに直列に接続して構成された前記整流部と、前記同期整流要素に流れる電流を検出する電流検知部と、前記電流検知部の検出信号に基づいて前記同期整流要素のスイッチング素子の駆動信号を生成する駆動信号生成部とからなることを特徴とする非接触電力伝送装置。

【請求項２】　前記トランスの２次コイルはセンタータップを備え、前記整流部は、前記トランスの２次コイルのセンタータップではない両出力端に直列に且つ互いに逆方向に接続する第１及び第２の前記同期整流要素の前記トランスの２次コイルに接続していない各他端同士を接続して全波整流部を構成することを特徴とする請求項１記載の非接触電力伝送装置。

【請求項３】　一つの前記電流検知部の検出信号より前記第１の同期整流要素のスイッチング素子の駆動信号を生成し、前記第２の同期整流要素のスイッチング素子の駆動信号は前記第１の同期整流要素のスイッチング素子の駆動信号の反転信号とすることを特徴とする請求項２記載の非接触電力伝送装置。

【請求項４】　前記電流検知部は、前記同期整流要素に直列に接続した電流検出用抵抗からなり、前記電流検出用抵抗の両端に発生する電圧に基づいて前記駆動信号生成部にて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とする請求項１乃至３いづれか記載の非接触電力伝送装置。

【請求項５】　前記電流検出用抵抗の抵抗値は、前記電流検出用抵抗に流れる電流に対して発生する前記電流検出用抵抗の両端の電圧が前記駆動信号生成部にて前記同期整流要素のスイッチング素子を駆動できる電圧にまで増幅できる最小の電圧になる抵抗値であることを特徴とする請求項４記載の非接触電力伝送装置。

【請求項６】　前記電流検知部は、前記同期整流要素に直列に接続した１次コイル及び２次コイルとからなるカレントトランスと、前記カレントトランスの２次コイルの両端に並列に接続した抵抗と、前記抵抗の両端間の電圧を整流するために前記カレントトランスの２次コイルに直列に接続した整流ダイオードとから構成され、前記整流ダイオードから出力される前記電流検知部の出力に基づいて駆動信号生成部にて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とする請求項１乃至３いづれか記載の非接触電力伝送装置。

【請求項７】　前記駆動信号生成部は、前記電流検知部の出力と基準電圧とを比較し、前記比較結果に基づいて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とする請求項１乃至６いづれか記載の非接触電力伝送装置。

【請求項８】　前記同期整流要素を複数有する非接触電力伝送装置において、先に導通し整流を終了しつつある前記第１の同期整流要素を流れる電流値と、次の整流のために導通を行うべき前記第２の同期整流要素のダイオードに流れ始める電流値とが相等しくなる時刻に、前記第１の同期整流要素のスイッチング素子をオフにする駆動信号を出力する第１の駆動信号生成部と、前記第２の同期整流要素のスイッチング素子をオンにする駆動信号を出力する第２の駆動信号生成部とを有することを特徴とする請求項２乃至７いづれか記載の非接触電力伝送装置。

【請求項９】　前記第１及び第２の駆動信号生成部は、先に導通し整流を終了しつつある第１の同期整流要素を流れる電流値と、次の整流のために導通を行うべき第２の同期整流要素のダイオードに流れ始める電流値とが相等しくなる時刻における前記電流検知部の出力電圧と同じ電圧である基準電圧と、前記電流検知部の検出信号とを比較し、前記比較結果に基づいて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とする請求項８記載の非接触電力伝送装置。

【請求項１０】　前記第２の駆動信号生成部は、先に導通し整流を終了しつつある第１の同期整流要素を流れる電流値と、次の整流のために導通を行うべき第２の同期整流要素のダイオードに流れ始める電流値とが相等しくなる時刻に、前記第２の同期整流要素のスイッチング素子をオンにできる電圧にまで増幅した駆動信号を出力することを特徴とする請求項８記載の非接触電力伝送装置。

【請求項１１】　前記整流部は前記同期整流要素を前記トランスの２次コイルに直列に１つ接続した半波整流部を構成し、前記駆動信号生成部は前記電流検知回路の検出信号と基準電圧とを比較して前記比較出力を前記同期整流要素のスイッチング素子の駆動信号とする比較器からなり、前記基準電圧は、前記同期整流要素のスイッチング素子に前記スイッチング素子に並列に逆接続されたダイオードの順電流方向と同じ方向の電流が最大時間流れ且つ前期同期整流要素のスイッチング素子に前記ダイオードの順電流と逆方向の電流が流れない電圧であることを特徴とする請求項７記載の非接触電力伝送装置。

【請求項１２】　前記整流部は前記同期整流要素を前記トランスの２次コイルに直列に１つ接続した半波整流部を構成し、前記駆動信号生成部は前記同期整流要素のダイオードに順電流が流れ始める時刻に、前記同期整流要

素のスイッチング素子をオンにできる電圧にまで増幅した駆動信号を出力する駆動信号生成部を有することを特徴とする請求項１，４，５，６いづれか記載の非接触電力伝送装置。

【請求項１３】　前記インバータ部は、スイッチング素子を有するハーフブリッジのインバータからなり、前記スイッチング素子はゼロボルトスイッチングを行うことを特徴とする請求項１乃至１２いづれか記載の非接触電力伝送装置。

【発明の詳細な説明】

【０００１】

【発明の属する技術分野】本発明は、非接触電力伝達装置に関するものである。

【０００２】

【従来の技術】非接触電力技術を応用して実用化されている例は、シェーバーや電動歯ブラシ等の充電用途であり、数Ｗ程度の低出力に限られていた。そして、２次側回路の整流方式としては、ダイオード整流方式が用いられてきた。

【０００３】

【発明が解決しようとする課題】分離着脱式トランスによる磁気誘導を利用した非接触 無接点の電力伝送技術は、その金属接点レスという特徴により感電の根本的対策を施せることから、水まわりの電源としての用途が注目されつつある。安全で安心できる電源として使用するために、出力電圧が低電圧であるとともに機器の効率も低下せず、車用において既に実績のある１２Ｖ程度の電源でなおかつ、いろいろな機器が使用できるよう５０Ｗ以上の高出力化が必要となった。しかし、低電圧で高出力化を行うに従い出力電流も大きくなり、従来非接触給電装置の２次側回路で使用されているダイオード整流方式では整流損失が大きくなりダイオード等の放熱板のサイズも大きくなり実用的なサイズに収められないという問題が発生した。

【０００４】そこで従来から出力電圧が５Ｖ以下のスイッチング電源の整流部の損失低減に使用されている同期整流技術を非接触電力伝達装置に適用することを検討した。同期整流技術とは、同期整流用スイッチング素子としてＦＥＴのスイッチング素子とＦＥＴの寄生ダイオードを使い、整流するサイクルに応じてＦＥＴのスイッチング素子をスイッチングさせてＦＥＴのスイッチング素子を介して整流電流を流すことで、ＦＥＴの低いオン抵抗を利用して整流部の損失を低減させる技術である。勿論、寄生ダイオードを内蔵しているＦＥＴの代わりに、スイッチング素子とスイッチング素子に並列に逆方向のダイオードを接続しても同じ動作をする。

【０００５】非接触電力伝達装置は、直流電源を供給する電源部と、直流電源を高周波電源に変換するインバータ部と、インバータ部から高周波電力を供給される１次コイルと１次コイルから受電した電力を出力する２次コイルとが分離可能な分離着脱式トランスの１次コイルとで構成される１次側回路と、２次コイルと、２次コイルに並列に接続される負荷整合用コンデンサ及び２次コイルの出力電圧を整流する整流部とで構成される２次側回路とからなっている。この時２次側に取り出せる有効電力を最大にして回路全体の効率を上げ、分離着脱式トランスの小型化を図るために、分離着脱式トランスの１次コイルと２次コイルとの間の漏れ磁束による漏れインダクタンスと２次コイルに並列に接続する負荷整合用コンデンサとにより回路全体の力率を改善している。

【０００６】ところが、前記負荷整合用コンデンサによる負荷整合を行うと、前記２次コイルの出力波形はスイッチング電源の２次コイル出力波形とは異なり、正弦波状あるいはさらに歪んだ波形となる、そのために、巻線間電圧あるいは補助巻線を利用した従来の同期整流用スイッチング素子の駆動信号生成方式では同期整流用スイッチング素子のオン時間が短いため整流効率が悪く、ダイオード整流方式より効率を上げることができなかった。

【０００７】本発明は、上記事由に鑑みてなされたものであり、その目的は、２次側回路の整流効率を上げた非接触電力伝達装置を提供することにある。

【０００８】

【課題を解決するための手段】請求項１の発明は、直流電源を供給する電源部と、前記直流電源を高周波電源に変換するインバータ部と、前記インバータ部から高周波電力を供給される１次コイルと１次コイルから受電した電力を出力する２次コイルとが分離可能なトランスの前記１次コイルとで構成される１次側回路と、前記２次コイルと、前記２次コイルに並列に接続される負荷整合用コンデンサ及び前記２次コイルの出力電圧を整流する整流部とで構成される２次側回路とを有する非接触電力伝送装置において、スイッチング素子及び前記スイッチング素子に並列に逆接続されたダイオードとからなる同期整流要素を前記２次コイルに直列に接続して構成された前記整流部と、前記同期整流要素に流れる電流を検出する電流検知部と、前記電流検知部の検出信号に基づいて前記同期整流要素のスイッチング素子の駆動信号を生成する駆動信号生成部とからなることを特徴とし、２次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができる。

【０００９】請求項２の発明は、請求項１の発明において、前記トランスの２次コイルはセンタータップを備え、前記整流部は、前記トランスの２次コイルのセンタータップではない両出力端に直列に且つ互いに逆方向に接続する第１及び第２の前記同期整流要素の前記トランスの２次コイルに接続していない各他端同士を接続して全波整流部を構成することを特徴とし、全波整流することで半波整流よりも損失が少なく効率の良い整流を行える。

【0010】請求項3の発明は、請求項2の発明において、一つの前記電流検知部の検出信号より前記第1の同期整流要素のスイッチング素子の駆動信号を生成し、前記第2の同期整流要素のスイッチング素子の駆動信号は前記第1の同期整流要素のスイッチング素子の駆動信号の反転信号とすることを特徴とし、駆動信号生成部の簡素化を図ることができ、低コスト化、小型化ができる。
【0011】請求項4の発明は、請求項1乃至3のいづれかの発明において、前記電流検知部は、前記同期整流要素に直列に接続した電流検出用抵抗からなり、前記電流検出用抵抗の両端に発生する電圧に基づいて前記駆動信号生成部にて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とし、簡単な回路構成で電流検知部を構成できる。
【0012】請求項5の発明は、請求項4の発明において、前記電流検出用抵抗の抵抗値は、前記電流検出用抵抗に流れる電流に対して発生する前記電流検出用抵抗の両端の電圧が前記駆動信号生成部にて前記同期整流要素のスイッチング素子を駆動できる電圧にまで増幅できる最小の電圧になる抵抗値であることを特徴とし、電流検知部での損失を減らすことができる。
【0013】請求項6の発明は、請求項1乃至3いづれかの発明において、前記電流検知部は、前記同期整流要素に直列に接続した1次コイル及び2次コイルとからなるカレントトランスと、前記カレントトランスの2次コイルの両端に並列に接続した抵抗と、前記抵抗の両端間の電圧を整流するために前記カレントトランスの2次コイルに直列に接続した整流ダイオードとから構成され、前記整流ダイオードから出力される前記電流検知部の出力に基づいて駆動信号生成部にて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とし、2次側回路の整流損失を減らすことができる。
【0014】請求項7の発明は、請求項1乃至6いづれかの発明において、前記駆動信号生成部は、前記電流検知部の出力と基準電圧とを比較し、前記比較結果に基づいて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とし、2次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができる。
【0015】請求項8の発明は、請求項2乃至7いづれかの発明において、前記同期整流要素を複数有する非接触電力伝送装置において、先に導通し整流を終了しつつある前記第1の同期整流要素を流れる電流値と、次の整流のために導通を行うべき前記第2の同期整流要素のダイオードに流れ始める電流値とが相等しくなる時刻に、前記第1の同期整流要素のスイッチング素子をオフにする駆動信号を出力する第1の駆動信号生成部と、前記第2の同期整流要素のスイッチング素子をオンにする駆動信号を出力する第2の駆動信号生成部とを有することを特徴とし、2次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができる。
【0016】請求項9の発明は、請求項8記載の発明において、前記第1及び第2の駆動信号生成部は、先に導通し整流を終了しつつある第1の同期整流要素を流れる電流値と、次の整流のために導通を行うべき第2の同期整流要素のダイオードに流れ始める電流値とが相等しくなる時刻における前記電流検知部の出力電圧と同じ電圧である基準電圧と、前記電流検知部の検出信号とを比較し、前記比較結果に基づいて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とし、2次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができる。
【0017】請求項10の発明は、請求項8記載の発明において、前記第2の駆動信号生成部は、先に導通し整流を終了しつつある第1の同期整流要素を流れる電流値と、次の整流のために導通を行うべき第2の同期整流要素のダイオードに流れ始める電流値とが相等しくなる時刻に、前記第2の同期整流要素のスイッチング素子をオンにできる電圧にまで増幅した駆動信号を出力することを特徴とし、2次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができる。
【0018】請求項11の発明は、請求項7記載の発明において、前記整流部は前記同期整流要素を前記トランスの2次コイルに直列に1つ接続した半波整流部を構成し、前記駆動信号生成部は前記電流検知回路の検出信号と基準電圧とを比較して前記比較出力を前記同期整流要素のスイッチング素子の駆動信号とする比較器からなり、前記基準電圧は、前記同期整流要素のスイッチング素子に前記スイッチング素子に並列に逆接続されたダイオードの順電流方向と同じ方向の電流が最大時間流れ且つ前期同期整流要素のスイッチング素子に前記ダイオードの順電流と逆方向の電流が流れない電圧であることを特徴とし、2次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができる。
【0019】請求項12の発明は、請求項1、4、5、6いづれか記載の発明において、前記整流部は前記同期整流要素を前記トランスの2次コイルに直列に1つ接続した半波整流部を構成し、前記駆動信号生成部は前記同期整流要素のダイオードに順電流が流れ始める時刻に、前記同期整流要素のスイッチング素子をオンにできる電圧にまで増幅した駆動信号を出力する駆動信号生成部を有することを特徴とし、2次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができる。
【0020】請求項13の発明は、請求項1乃至12いづれか記載の発明において、前記インバータ部は、スイッチング素子を有するハーフブリッジのインバータから

なり、前記スイッチング素子はゼロボルトスイッチングを行うことを特徴とし、２次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができる。

【００２１】

【発明の実施の形態】以下、本発明の実施の形態を図面に基づいて説明する。

【００２２】（実施形態１）図１は実施形態１の回路構成を示す。電源部Ａとインバータ部ＢとトランスＴ１の１次コイルＬ１とで１次側回路Ｇ１を構成し、トランスＴ１の２次コイルＬ２と負荷整合用コンデンサＣ１と同期整流要素を構成するＦＥＴＱ１と電流検知部Ｈ１と駆動信号生成部Ｅ１と平滑部Ｆとで２次回路Ｇ２を構成する。

【００２３】電源部Ａは直流電力をインバータ部Ｂに供給し、インバータ部Ｂで高周波電力に変換され、前記高周波電力はトランスＴ１の１次コイルＬ１に供給される。トランスＴ１の２次コイルＬ２は、電磁結合により１次コイルＬ１より電力を受電し、２次コイルＬ２両端の電圧はＦＥＴＱ１で半波整流され、半波整流された電圧は平滑部Ｆで平滑されて直流電圧を出力する。

【００２４】トランスＴ１の１次コイルＬ１と２次コイルＬ２とはお互いに絶縁物により所定のギャップ長だけ離間し、分離脱着できる構成になっている。

【００２５】２次コイルＬ２に並列に接続されるコンデンサＣ１は負荷整合用であり、２次側回路Ｇ２で取り出せる有効電力を最大にして１次側回路Ｇ１から２次側回路Ｇ２への電力伝達の効率を上げている。

【００２６】次に本実施形態１の同期整流動作について説明する。

【００２７】ＦＥＴＱ1は、ＦＥＴ素子Ｐ１とＦＥＴ素子Ｐ１に並列に逆方向に接続された寄生ダイオードＤ１とからなっている。ＦＥＴＱ１に直列に接続された電流検知部Ｈ１はＦＥＴＱ１に流れる電流を検出し、前記検出信号を駆動信号生成部Ｅ１に出力する。駆動信号生成部Ｅ１は、電流検知部Ｈ１からの検出信号が所定のしきい値以上であればＦＥＴ素子Ｐ１をオンにする駆動信号を出力し、電流検知部Ｈ１からの信号が所定のしきい値以下であればＦＥＴ素子Ｐ１をオフにする駆動信号を出力する。

【００２８】電磁誘導によって１次コイルＬ１から２次コイルＬ２に誘導された起電力の極性が、ＦＥＴＱ１の寄生ダイオードＤ１の順方向と合致した時に寄生ダイオードＤ１には順方向電流が流れ、前記順方向電流を電流検知部Ｈ１で検出し、駆動信号生成部Ｅ１は電流検知部Ｈ１からの検出信号が前記しきい値を超えるとＦＥＴ素子Ｐ１にオン信号を出力してＦＥＴ素子Ｐ１はオンする。

【００２９】ＦＥＴ素子Ｐ１がオンすると当初寄生ダイオードＤ１を流れていた電流は寄生ダイオードＤ１に比べてＦＥＴ素子Ｐ１のほうが抵抗が小さいので、ＦＥＴ素子Ｐ１のオン抵抗を介してＦＥＴＱ１のソースからドレイン方向に流れる。この時、ＦＥＴＱ１に整流電流が流れるサイクル中にＦＥＴ素子のオン時間をできるだけ長くしたほうが、ＦＥＴＱ１での損失を小さくでき、整流損失を減らすことができる。

【００３０】電磁誘導によって１次コイルＬ１から２次コイルＬ２に誘導される起電力が変化して２次コイルＬ２に誘導される起電力が小さくなると電流検知部Ｈ１から出力される検出信号も小さくなり、駆動信号生成部Ｅ１は電流検知部Ｈ１からの検出信号が前記しきい値より下がるとＦＥＴ素子Ｐ１にオフ信号を出力してＦＥＴ素子Ｐ１はオフする。

【００３１】さらに、２次コイルＬ２に誘導される起電力の極性が反転するとＦＥＴ素子Ｐ１の寄生ダイオードＤ１には逆方向の電圧がかかるため、再び２次コイルＬ２に誘導された起電力の極性が反転するまでは寄生ダイオードＤ１には電流は流れず、平滑部Ｆの入力は半波整流波形となる。半波整流出力は平滑部Ｆで平滑される。

【００３２】図２は、本実施形態１のＦＥＴＱ１に流れる電流波形Ｓ１を示し、前記電流波形Ｓ１はなだらかに立ち上がり歪んだ波形となる。

【００３３】この同期整流時の損失は、前記電流波形Ｓ１がＦＥＴ素子Ｐ１のオンしきい値Ｋを超えてＦＥＴ素子Ｐ１がオフからオンになる時間をｔ１、前記電流波形Ｓ１がＦＥＴ素子Ｐ１のオンしきい値Ｋより下がりＦＥＴ素子Ｐ１がオンからオフになる時間をｔ２、前記電流波形Ｓ１が0になる時間をｔ３、前記同期整流時のＦＥＴ素子Ｐ１のオン抵抗をＲｏｎ、ＦＥＴＱ１を流れる電流をＩ、寄生ダイオードＤ１の順方向電圧をＶｆとすると、一周期での総損失Wは、下記数１のように表される。

【００３４】

【数１】

$$W=\int_{0}^{t_1} I \cdot Vf\,dt+\int_{t_1}^{t_2} I^2 \cdot Ron\,dt+\int_{t_2}^{t_3} I \cdot Vf\,dt$$

【００３５】このように、ＦＥＴＱ１に流れる電流を検出し、前記検出信号に同期した信号でＦＥＴ素子Ｐ１を駆動すれば、ＦＥＴＱ１の寄生ダイオードＤ１に電流が流れる時間を短くすることができ、ＦＥＴＱ１での損失を低減できる。その結果、放熱板のサイズを小さくできるため、２次側回路Ｇ２を小型化できる。

【００３６】（実施形態２）図３は実施形態２の回路構成を示す。電源部Ａ、インバータ部Ｂ、トランスＴ１の１次コイルＬ１からなる１次側回路Ｇ１の構成、動作は実施形態１と同様なので省略する。

【００３７】トランスＴ１の2次コイルＬ２は出力端子が3つあるセンタータップ方式となっており、２次コイルＬ２両端の端子1及び3とセンタータップ端子2の３つの端子を有し、２次コイルＬ２の端子１－端子3間に

並列に負荷整合用のコンデンサＣ１を接続する。２次コイルＬ２の端子１に直列に電流検知部Ｈ１を介して同期整流要素を構成するＦＥＴＱ１のドレインを接続し、２次コイルＬ２の端子３に直列に電流検知部Ｈ３を介して同期整流要素を構成するＦＥＴＱ２のドレインを接続する。ＦＥＴＱ１、Ｑ２の各ソースは互いに接続し、平滑コンデンサＣ８の負極側に接続し、２次コイルＬ２の端子3は、チョークコイルＬ３を介して平滑コンデンサＣ８の正極側に接続する。

【００３８】次に、本実施形態２の動作について説明する。ＦＥＴＱ1は、ＦＥＴ素子Ｐ１とＦＥＴ素子Ｐ１に並列に逆方向の接続された寄生ダイオードＤ１とからなっている。ＦＥＴＱ１に直列に接続された電流検知部Ｈ１はＦＥＴＱ１に流れる電流を検出し、前記検出信号を駆動信号生成部Ｅ１に出力する。駆動信号生成部Ｅ１は、電流検知部Ｈ１からの検出信号が所定のしきい値以上であればＦＥＴ素子Ｐ１をオンにする駆動信号を出力し、電流検知部Ｈ１からの信号が所定のしきい値以下であればＦＥＴ素子Ｐ１をオフにする駆動信号を出力する。

【００３９】同様にＦＥＴＱ２は、ＦＥＴ素子Ｐ２とＦＥＴ素子Ｐ２に並列に逆方向の接続れた寄生ダイオードＤ２とからなっている。ＦＥＴＱ２に直列に接続された電流検知部Ｈ２はＦＥＴＱ２に流れる電流を検出し、前記検出信号を駆動信号生成部Ｅ２に出力する。駆動信号生成部Ｅ２は、電流検知部Ｈ２からの検出信号が所定のしきい値以上であればＦＥＴ素子Ｐ２をオンにする駆動信号を出力し、電流検知部Ｈ２からの信号が所定のしきい値以下であればＦＥＴ素子Ｐ２をオフにする駆動信号を出力する。

【００４０】電磁誘導によって１次コイルＬ１から２次コイルＬ２の端子２－１間に誘導される起電力の極性が、ＦＥＴＱ１の寄生ダイオードＤ１の順方向と合致した時に寄生ダイオードＤ１に順方向電流が流れ、前記順方向電流を電流検知部Ｈ１にて検出し、駆動信号生成部Ｅ１は電流検知部Ｈ１の検出信号が前記しきい値を超えるとＦＥＴ素子Ｐ１にオン信号を出力してＦＥＴ素子Ｐ１はオンする。ＦＥＴ素子Ｐ１がオンすると当初寄生ダイオードＤ１を流れていた電流は寄生ダイオードＤ１に比べてＦＥＴ素子Ｐ１のほうが抵抗が小さいので、ＦＥＴ素子Ｐ１のオン抵抗を介してＦＥＴＱ１のソースからドレイン方向に流れる。この時、実施形態１同様、ＦＥＴＱ１に整流電流が流れるサイクル中にＦＥＴ素子のオン時間をできるだけ長くしたほうが、ＦＥＴＱ１での損失を小さくでき、整流損失を減らすことができる。

【００４１】電磁誘導によって１次コイルＬ１から２次コイルＬ２に誘導される起電力が変化して２次コイルＬ２に誘導される起電力が小さくなると電流検知部Ｈ１から出力される検出信号も小さくなり、駆動信号生成部Ｅ１は電流検知部Ｈ１からの検出信号が前記しきい値より下がるとＦＥＴ素子Ｐ１にオフ信号を出力してＦＥＴ素子Ｐ１はオフする。

【００４２】さらに、２次コイルＬ２に誘導された起電力の極性が反転するとＦＥＴ素子Ｐ１の寄生ダイオードＤ１には逆方向の電圧がかかるため、再び２次コイルＬ２に誘導された起電力の極性が反転するまで寄生ダイオードＤ１には電流は流れない。

【００４３】一方この時、電磁誘導によって１次コイルＬ１から２次コイルＬ２の端子２－３間に誘導された起電力の極性は、ＦＥＴＱ２の寄生ダイオードＤ２の順方向と合致しているため、寄生ダイオードＤ２に順方向電流が流れ、ＦＥＴＱ２、ＦＥＴ素子Ｐ２、寄生ダイオードＤ２、電流検知部Ｈ２、駆動信号生成部Ｅ２は前記ＦＥＴＱ１、ＦＥＴ素子Ｐ１、寄生ダイオードＤ１、電流検知部Ｈ１、駆動信号生成部Ｅ１と同様の前記動作を行う。

【００４４】前記動作を繰り返して、ＦＥＴＱ１、Ｑ２のソースと２次コイルＬ２の端子２間の電圧には全波整流された電圧が生じ、チョークコイルＬ３と平滑コンデンサＣ８とで平滑される。

【００４５】図4は、２次コイルＬ２の端子１－３間の誘導起電力波形Ｓ２と、２次コイルＬ２を流れる電流波形Ｓ３と、ＦＥＴＱ１、Ｑ２のオンしきい値Ｋとを示している。負荷整合用のコンデンサＣ１の影響で、２次コイルＬ２の電流波形Ｓ３は歪んだ波形になり、２次コイルＬ２の端子１－３間に誘起する電圧波形Ｓ２は一定区間０Ｖである区間を挟んで正負に振動した波形となる。そのため、従来の補助巻線や２次コイル間電圧を利用したＦＥＴの駆動方式ではＦＥＴＱ１、Ｑ２のオンしきい値Ｋと前記電圧波形Ｓ２とを比較すると、ＦＥＴの駆動信号は波形Ｓ４のようになり、ＦＥＴＱ１及びＱ２をオンする時間が短いため整流効率が上がらない。

【００４６】しかし、図５に示す様にＦＥＴＱ１を流れる電流波形Ｓ５とＦＥＴＱ１、Ｑ２のオンしきい値Ｋとを比較し、またＦＥＴＱ２を流れる電流波形Ｓ６とＦＥＴＱ１、Ｑ２のオンしきい値Ｋとを比較することで、ＦＥＴＱ１、Ｑ２の駆動信号は各々波形Ｓ７、Ｓ８のようになり、図４の波形Ｓ４に比べてＦＥＴＱ１、Ｑ２のＦＥＴ素子Ｐ１、Ｐ２のオン時間が長くなる。したがって、ＦＥＴ素子Ｐ１、Ｐ２に整流電流が流れる時間が長くなり、整流効率が上がる。

【００４７】また本実施形態２に示す２次コイルがセンタータップ方式であるトランスＴ１を用いた全波整流回路と実施形態１に示す半波整流回路とを比較すると、同じ出力電流を流す場合、全波整流回路は半波整流回路に比べてＦＥＴに流す電流の最大値を小さくできる。ＦＥＴ素子Ｐ１，Ｐ２がオンした時の損失は電流の２乗に比例するので、本実施形態２では、ＦＥＴ素子Ｐ１，Ｐ２に流す電流を半波整流回路に比べて小さくでき、損失を減らすことができる。

【００４８】なお、図６に示す回路構成の様に、負荷整合用のコンデンサＣ１を２次コイルＬ２の端子１－端子２間に並列に接続し、負荷整合用のコンデンサＣ９を２次コイルＬ２の端子２－端子３間に並列に接続した場合も図４の負荷整合用のコンデンサＣ１と同様の効果が得られる。さらに、前記コンデンサＣ１をＦＥＴＱ１に並列に接続し、前記コンデンサＣ９をＦＥＴＱ２並列に接続しても同様の効果が得られる。

【００４９】なお、図１において負荷整合用コンデンサＣ１をＦＥＴＱ１に並列に接続しても同様の効果が得られる。

【００５０】（実施形態３）図７は実施形態３の回路構成を示し、交流電源を直流電源に変換する電源部Ａと電源部Ａからの直流入力を高周波電源に変換するインバータ部Ｂと、インバータ部Ｂの制御回路Ｊと、インバータ部Ｂから高周波電源を供給されるトランスＴ１の１次コイルＬ１とから１次側回路Ｇ１は構成され、トランスＴ１のセンタータップ式の２次コイルＬ２と、負荷整合用コンデンサＣ１と、電流検知部Ｈ１，Ｈ２と、駆動信号生成部Ｅ１，Ｅ２と、ＦＥＴＱ１，Ｑ２とチョークコイルＬ３と、平滑コンデンサＣ８とで構成される２次側回路Ｇ２とからなっている。

【００５１】２次側回路Ｇ２の構成、動作は実施形態２の図３と同様なので説明は省略する。

【００５２】１次側回路Ｇ１の構成、動作について説明する。電源部Ａは、交流電源Ｖｓと交流電源Ｖｓを全波整流する整流器Ｄ３とから構成され、インバータ部Ｂは整流器Ｄ３の出力端に並列に接続されたコンデンサＣ２、Ｃ３の直列回路と、整流器Ｄ３の出力端に並列に接続されたスイッチング素子Ｑ３、Ｑ４の直列回路と、スイッチング素子Ｑ３、Ｑ４に各々並列に接続されたコンデンサＣ４，Ｃ５とからなるハーフブリッジインバータ回路で構成され、制御回路Ｊはスイッチング素子Ｑ３，Ｑ４のスイッチング動作を制御するための電子回路から構成され、トランスＴ１の１次コイルＬ１の一端はコンデンサＣ１、Ｃ２の中点に接続され、他端はスイッチング素子Ｑ１、Ｑ２の中点に接続される。

【００５３】整流器Ｄ３で全波整流された電圧はコンデンサＣ２、Ｃ３で分圧され、スイッチング素子Ｑ３，Ｑ４は制御回路Ｊからの一定のデッドタイムを持った駆動信号により交互にオン オフして１次コイルＬ１に高周波電圧を印加する。

【００５４】また、スイッチング素子Ｑ３、Ｑ４に並列に接続されたコンデンサＣ４，Ｃ５により、スイッチング素子Ｑ３，Ｑ４のスイッチング動作をゼロ電圧スイッチング動作とすることができ、スイッチング素子Ｑ３、Ｑ４でのスイッチング損失を減少させることができる。

【００５５】またスイッチング素子Ｑ３、Ｑ４の駆動信号は一定のデッドタイムを持っているので、トランスＴ１の２次コイルＬ２の端子１－端子３間の電圧は図４の波形Ｓ２のようになるため、実施形態２と同様に電流検出回路Ｈ１、Ｈ２の検出信号から生成した駆動信号でＦＥＴＱ１、Ｑ２による同期整流を行えば、実施形態２同様に２次側回路Ｇ２の整流損失も減少できる。

【００５６】また、図８に示す回路構成のようにトランスＴ１の１次コイルＬ１に並列にコンデンサＣ４を接続した場合も、図７の回路同様にゼロ電圧スイッチングを行える。前記以外の図８の回路の構成、動作は図７の回路の構成、動作と同様なので説明は省略する。

【００５７】このように本実施形態３によれば、２次側回路Ｇ２だけでなく、１次側回路Ｇ１での損失を減らして、回路全体の効率を上げて回路全体の小型化ができる。

【００５８】（実施形態４）図９は実施形態４の回路構成を示す。基本的な回路構成、動作は実施形態３の図７と同様で、ＦＥＴ素子Ｐ１の駆動信号生成部Ｅ１の駆動信号を反転器ＩＮＶ１を介して反転させた信号をＦＥＴ素子Ｐ２の駆動信号とした点が図７に示す回路構成と異なる。前記以外の回路構成、動作については実施形態３の図７と同様なので省略する。

【００５９】図９に示す回路構成図のように、トランスＴ１の２次コイルＬ２にセンタータップ方式を用いた同期整流回路では、ＦＥＴＱ１、Ｑ２に交互に電流が流れるようにＦＥＴＱ１、Ｑ２の駆動信号を制御するため、ＦＥＴＱ１、Ｑ２の各駆動信号は、一方の駆動信号の反転信号となる。そこで、ＦＥＴＱ１の駆動信号生成部Ｅ１の駆動信号を反転器ＩＮＶ１を介して反転させた信号をＦＥＴＱ２の駆動信号としてＦＥＴＱ２を駆動することで、ＦＥＴＱ２の駆動回路の簡素化を図ることができ、低コスト化、小型化ができる。

【００６０】なお、２次側回路Ｇ２の整流回路として、同期整流を用いたフォワード方式を採用した場合にも、２つの整流及び転流用スイッチング素子にたいしても同様に応用できる。

【００６１】（実施形態５）図１０は実施形態５の回路構成図を示す。基本的な回路構成、動作は実施形態３の図７とほぼ同様で、図１０では、図７の電流検知部Ｈ１、Ｈ２を、各々ＦＥＴＱ１、Ｑ２に直列に接続した抵抗Ｒ１、Ｒ２からなる電流検知部Ｈ３、Ｈ４に置き換えた点が異なる。前記以外の回路構成、動作については実施形態３の図７と同様なので省略する。

【００６２】本実施形態５では、ＦＥＴＱ１、Ｑ２に各々直列に接続された抵抗Ｒ１、Ｒ２の両端には各々ＦＥＴＱ１、Ｑ２に流れる電流に比例した電圧が発生する。前記抵抗Ｒ１、Ｒ２の各両端電圧を駆動信号生成部Ｅ１、Ｅ２に各々入力し、駆動信号生成部Ｅ１、Ｅ２は、抵抗Ｒ１、Ｒ２の各両端電圧が所定のしきい値以上であればＦＥＴ素子Ｐ１、Ｐ２を各々オンにする駆動信号を出力し、抵抗Ｒ１、Ｒ２の各両端電圧が所定のしきい値以下であればＦＥＴ素子Ｐ１、Ｐ２を各々オフにする駆

動信号を出力する。
【0063】このように本実施形態5によれば、簡単な方法でFETQ1、Q2の電流を検出でき、前記検出信号を用いてFETQ1、Q2の駆動信号を生成することで実施形態2同様にFETQ1、Q2に電流が流れる各整流サイクル中にできるだけ長い間FET素子P1、P2をオンにして、整流損失を減らすことができる。
【0064】（実施形態6）図11は本実施形態6の回路構成図を示し、基本的な回路構成、動作は実施形態5の図10と同様で、図11では、図10の抵抗R1、R2を各々微小な抵抗値（例えば10mΩ）を有する抵抗R3、R4からなる電流検出部H5、H6に置き換え、駆動信号生成部E1、E2を各々オペアンプOP1、OP2からなる駆動信号生成部E3、E4に置き換えた点が異なる。前記以外の回路構成、動作については実施形態5の図10と同様なので省略する。
【0065】本実施形態5では、FETQ1、Q2に各々直列に接続された抵抗R3、R4の抵抗値を微小な抵抗値（例えば10mΩ）とすることで、実施形態5に比べて抵抗R3、R4での損失を減らしている。しかし抵抗R3、R4の抵抗値を小さくしたことで抵抗R3、R4両端の電圧も小さくなるため、抵抗R3、R4両端の電圧を各々オペアンプOP1、OP2の反転入力端子と非反転入力端子とに入力し、オペアンプOP1、OP2で抵抗R3、R4の各両端電圧を、FETQ1、Q2を十分駆動できる電圧にまで差動増幅し、前記差動増幅したオペアンプOP1、OP2の出力をFET素子P1、P2の駆動信号とする。
【0066】このように本実施形態6では、電流検知部H5、H6での損失を下げることができる。
【0067】（実施形態7）図12は実施形態7の回路構成図を示す。基本的な回路構成、動作は実施形態3の図7とほぼ同様で、図12では図7の電流検知部H1、H2を各々、1次コイルL4、L5と2次コイルL6、L7からなるカレントトランスCT1、CT2の2次コイルL6、L7に並列に抵抗R5、R6を各々接続し、前記2次コイルL6、L7に直列にダイオードD3、D4を各々接続し、ダイオードD3、D4を介して抵抗R5、R6に並列にコンデンサC6、C7、抵抗R7、R8及び定電圧ダイオードZD1、ZD2を各々接続した電流検知部H7、H8に置き換えた点と、図7の駆動信号生成部E1、E2を各々ダイオードD3、D4に直列に接続した増幅器AMP1、AMP2からなる駆動信号生成部E5、E6に置き換えた点とが異なる。前記以外の回路構成、動作については実施形態3の図7と同様なので省略する。
【0068】カレントトランスCT1、CT2の各1次コイルL4、L5に流れる電流をカレントトランスCT1、CT2の各2次コイルL6、L7で検出し、抵抗R5、R6の両端に各々電圧を発生させ、前記電圧はダイオードD3、D4で各々半波整流される。コンデンサC6、C7はノイズカット用であり、抵抗R7、R8はコンデンサC6、C7に蓄積された電荷を放出してAMP1、2の入力信号の立下りを急峻にする。また、定電圧ダイオードZD1、ZD2は増幅器AMP1、2の入力に増幅器AMP1、2の定格電圧を超えた電圧が入力されないように半波整流した電圧を一定電圧でクランプする。
【0069】そして、カレントトランスCT1、CT2の2次コイルL6、L7の出力電流は小さいためにFET素子P1、P2を駆動できないので、増幅器AMP1、AMP2で増幅し、前記増幅した駆動信号でFETQ1、Q2を駆動する。
【0070】このように本実施形態7によれば、FETQ1、Q2を流れる電流を検出でき、前記検出信号を用いてFETQ1、Q2の駆動信号を生成することで実施形態2同様にFETQ1、Q2に電流が流れる各整流サイクル中にできるだけ長い間FET素子P1、P2をオンにして、整流損失を減らすことができる。
【0071】（実施形態8）図13の回路構成図を用いて実施形態8を説明する。基本的な回路構成、動作は実施形態7の図12とほぼ同様で、図13では、図12の増幅器AMP1、AMP2を、比較器CP1、CP2と比較器CP1、CP2の反転入力端子に基準電圧源E1、E2を各々接続した比較回路に置き換えた点が異なる。前記以外の回路構成、動作については実施形態7の図12と同様なので省略する。
【0072】本実施例8では、ダイオードD3、D4で半波整流されたカレントトランスCT1、CT2の各2次コイルL6、L7の出力を各々比較器CP1、CP2の非反転入力端子に接続し、基準電圧源E1、E2を各々比較器CP1、CP2の反転入力端子に接続して、基準電圧源E1、E2の基準電圧を適切に設定することで、FETQ1、Q2に電流が流れる各整流サイクル中にできるだけ長い間FET素子P1、P2をオンにして、整流損失を減らすことができる。
【0073】図14は、本実施形態8におけるFETQ1を流れる電流波形S9と、基準電圧源E1の基準電圧M1と、比較器CP1の出力波形S10を示しており、前記波形S9が前記基準電圧M1を超えると前記波形S10はHレベルとなり、前記波形S9が前記基準電圧M1より下がると前記波形S10はLレベルとなる。したがって、基準電圧M1を適切に設定することで比較器CP1の出力波形S10がHレベルの区間を広くできる。FETQ2についても同様である。
【0074】即ちFETQ1、Q2に電流が流れる各整流サイクル中にできるだけ長い間FET素子P1、P2をオンにして、整流損失を減らすことができる。
【0075】（実施形態9）図13の回路構成図を用いて実施形態9を説明する。基本的な回路構成、動作につ

いては実施形態８と同様なので省略する。

【００７６】同期整流を行うためにオンしていたＦＥＴ素子Ｐ１を有するＦＥＴＱ１の電流は、負荷整合用コンデンサＣ６のために２次コイルＬ２に発生する誘導起電力に応じてなめらかに電流値が減少していく。また次の半サイクルの同期整流を行うためにオンするＦＥＴ素子Ｐ２を有するＦＥＴＱ２も同様にコンデンサＣ６のために、ＦＥＴＱ１に流れる電流がゼロになる前に寄生ダイオードＤ２を介して電流が流れ始める。そのため、ＦＥＴ素子Ｐ１、Ｐ２が同時にオンする可能性があり、整流が行われなくなる可能性がある。

【００７７】そこで本実施形態９では、ＦＥＴＱ１、Ｑ２に流れる各電流が等しくなった時にそれまでオンしていたＦＥＴ素子Ｐ１をオフにする駆動信号を比較器ＣＰ１から出力し、それまでオフしていたＦＥＴ素子Ｐ２をオンにする駆動信号を比較器ＣＰ２から出力する。また、逆の半サイクルも同様にＦＥＴＱ１、Ｑ２に流れる各電流が等しくなった時にそれまでオンしていたＦＥＴ素子Ｐ２をオフにする駆動信号を比較器ＣＰ２から出力し、それまでオフしていたＦＥＴ素子Ｐ１をオンにする駆動信号を比較器ＣＰ１から出力する。

【００７８】このように、本実施形態９によれば、ＦＥＴ素子Ｐ１、Ｐ２が同時にオンすることがなくなり、整流損失を減らせて放熱板を含む２次側回路Ｇ２を小型化できる。

【００７９】（実施形態１０）図１３の回路構成図を用いて実施形態１０を説明する。基本的な回路構成、動作については実施形態９と同様なので省略する。

【００８０】実施形態９で説明したように、ＦＥＴＱ１、Ｑ２に流れる各電流が等しくなった時にそれまでオンしていたＦＥＴ素子Ｐ１をオフにする駆動信号を比較器ＣＰ１から出力し、それまでオフしていたＦＥＴ素子Ｐ２をオンにする駆動信号を比較器ＣＰ２から出力する。また、逆の半サイクルも同様にＦＥＴＱ１、Ｑ２に流れる各電流が等しくなった時にそれまでオンしていたＦＥＴ素子Ｐ２をオフにする駆動信号を比較器ＣＰ２から出力し、それまでオフしていたＦＥＴ素子Ｐ１をオンにする駆動信号を比較器ＣＰ１から出力すれば、ＦＥＴ素子Ｐ１、Ｐ２が同時にオンすることなくなり、整流損失を減らせる。

【００８１】そこで、本実施形態１０では図１３の回路構成においてカレントトランスＣＴ１、ＣＴ２で検出した各検出信号をダイオードＤ３、Ｄ４で半波整流した出力電圧、即ち定電圧ダイオードＺＤ１、ＺＤ２の各出力電圧を比較器ＣＰ１、ＣＰ２の非反転入力端子に入力し、ＦＥＴＱ１、Ｑ２に流れる各電流が等しくなった時の定電圧ダイオードＺＤ１、ＺＤ２の各出力電圧を基準電圧とする基準電圧源Ｅ１、Ｅ２を比較器ＣＰ１、ＣＰ２の反転入力端子に入力に各々接続して、比較器ＣＰ１、ＣＰ２の出力をＦＥＴ素子Ｐ１、Ｐ２の各駆動信号とすることで、ＦＥＴ素子Ｐ１、Ｐ２が同時にオンすることがなくなり、整流損失を減らせて放熱板を含む２次側回路Ｇ２を小型化できる。

【００８２】図１５は、本実施形態１０におけるＦＥＴＱ１を流れる電流波形Ｓ１１、基準電圧源Ｅ１の基準電圧Ｍ２、比較器ＣＰ１の出力波形Ｓ１２と、ＦＥＴＱ２を流れる電流波形Ｓ１３、基準電圧源Ｅ２の基準電圧Ｍ３、比較器ＣＰ２の出力波形Ｓ１４とを示す。ＦＥＴＱ１を流れる電流波形Ｓ１１の大きさとＦＥＴＱ２を流れる電流波形Ｓ１３の大きさとが等しくなる時間ｔ４において比較器ＣＰ１の出力をＬにしてＦＥＴ素子Ｐ１をオフにし、比較器ＣＰ２の出力をＨにしてＦＥＴ素子Ｐ２をオンにすることでＦＥＴ素子Ｐ１、Ｐ２が同時にオンすることがなくなり、整流損失を減らせて放熱板を含む２次側回路Ｇ２を小型化できる。

【００８３】（実施形態１１）図１２の回路構成図を用いて実施形態１１を説明する。基本的な回路構成、動作については実施形態７と同様なので省略する。

【００８４】実施形態９で説明したように、ＦＥＴＱ１、Ｑ２に流れる各電流が等しくなった時にそれまでオンしていたＦＥＴＱ１をオフにする駆動信号を比較器ＣＰ１から出力し、それまでオフしていたＦＥＴＱ２をオンにする駆動信号を比較器ＣＰ２から出力する。また、逆の半サイクルも同様にＦＥＴＱ１、Ｑ２に流れる各電流が等しくなった時にそれまでオンしていたＦＥＴＱ２をオフにする駆動信号を比較器ＣＰ２から出力し、それまでオフしていたＦＥＴＱ１をオンにする駆動信号を比較器ＣＰ１から出力すれば、ＦＥＴＱ１、Ｑ２が同時にオンすることがなくなり、整流損失を減らせる。

【００８５】そこで、本実施形態１１では図１２の回路構成においてＦＥＴＱ１、Ｑ２に流れる電流が等しくなるときに、カレントトランスＣＴ１、ＣＴ２で検出した各検出信号をダイオードＤ３、Ｄ４で半波整流した出力電圧、即ち定電圧ダイオードＺＤ１、ＺＤ２の各出力電圧を増幅器ＡＭＰ１、２で各々増幅したＦＥＴ素子Ｐ１、Ｐ２の各駆動信号が、ＦＥＴ素子Ｐ１、Ｐ２を十分オンできる電圧になるように、カレントトランスＣＴ１の１次コイルＬ４と２次コイルＬ６との巻線比及び、カレントトランスＣＴ２の１次コイルＬ５と２次コイルＬ７との巻線比を設定する。

【００８６】図１６は、本実施形態１１におけるＦＥＴ素子Ｐ１の駆動信号波形Ｓ１５、ＦＥＴＱ１を流れる電流波形Ｓ１６、定電圧ダイオードＺＤ１のクランプ電圧Ｎ１と、ＦＥＴ素子Ｐ２の駆動信号波形Ｓ１７、ＦＥＴＱ２を流れる電流波形Ｓ１８、定電圧ダイオードＺＤ２のクランプ電圧Ｎ２と、ＦＥＴ素子Ｐ１、Ｐ２を十分オンできる電圧Ｋとを示している。ＦＥＴＱ１を流れる電流波形Ｓ１６の大きさとＦＥＴＱ２を流れる電流波形Ｓ１８の大きさとが等しくなる時間ｔ５において、ＦＥＴ素子Ｐ１の駆動信号波形Ｓ１５がＦＥＴ素子Ｐ１、Ｐ２

を十分オンできる電圧Kより下がってFET素子P1はオフになり、FET素子P2の駆動信号波形S17がFET素子P1、P2を十分オンできる電圧Kを超えてFET素子P2はオンになることでFET素子P1、P2が同時にオンすることがなくなり、整流損失を減らせて放熱板を含む2次側回路G2を小型化できる。

【0087】なお、前記波形S15、S17は定電圧電圧ダイオードZD1、ZD2のクランプ電圧N1、N2にクランプされる。

【0088】（実施形態12）図1に示す回路構成図のように、1つの同期整流用FETQ1を用いて半波整流を行う場合、FETQ1での整流損失を小さくするためにはFETQ1に電流が流れる整流サイクル中にできるだけ長い間FETQ1のFET素子P1をオンにする必要がある。

【0089】図1の電流検出部H1と駆動信号生成部E1とを、図13の電流検出部H9と駆動信号生成部E7に各々置き換えて、駆動信号生成部E7の比較器CP1の反転入力端子に接続している基準電圧源E1の基準電圧を0V付近にすることで、比較器CP1は前記整流サイクル中にできるだけ長い間FET素子P1をオンにする駆動信号を出力して、FETQ1での整流損失を減らせて放熱板を含む2次側回路G2を小型化できる。

【0090】上記以外の回路構成、動作については、実施形態1及び8で説明しているので省略する。

【0091】（実施形態13）図1に示す回路構成図のように、1つの同期整流用FETQ1を用いて半波整流を行う場合、FETQ1での整流損失を小さくするためにはFETQ1に電流が流れる整流サイクル中にできるだけ長い間FETQ1のFET素子P1をオンにする必要がある。

【0092】図1の電流検出部H1と駆動信号生成部E1とを、図12の電流検出部H7と駆動信号生成部E5に各々置き換えて、電流検出部H7のカレントトランスCT1の1次コイルL4と2次コイルL5の巻数比を大きくすることで、カレントトランスCT1の1次コイルL4に流れる電流が小さい時でも2次コイルL5の誘起電圧が大きくなり、FETQ1のFET素子P1をオンできる駆動信号が増幅器AMP1から出力される。したがって、整流素子P1は前記整流サイクル中にできるだけ長い間オンになり、FETQ1での整流損失を減らせて放熱板を含む2次側回路G2を小型化できる。

【0093】上記以外の回路構成、動作については、実施形態1及び7で説明しているので省略する。

【0094】

【発明の効果】請求項1の発明は、直流電源を供給する電源部と、前記直流電源を高周波電源に変換するインバータ部と、前記インバータ部から高周波電力を供給される1次コイルと1次コイルから受電した電力を出力する2次コイルとが分離可能なトランスの前記1次コイルとで構成される1次側回路と、前記2次コイルと、前記2次コイルに並列に接続される負荷整合用コンデンサ及び前記2次コイルの出力電圧を整流する整流部とで構成される2次側回路とを有する非接触電力伝送装置において、スイッチング素子及び前記スイッチング素子に並列に逆接続されたダイオードとからなる同期整流要素を前記2次コイルに直列に接続して構成された前記整流部と、前記同期整流要素に流れる電流を検出する電流検知部と、前記電流検知部の検出信号に基づいて前記同期整流要素のスイッチング素子の駆動信号を生成する駆動信号生成部とからなることを特徴とし、2次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができるという効果がある。

【0095】請求項2の発明は、請求項1の発明において、前記トランスの2次コイルはセンタータップを備え、前記整流部は、前記トランスの2次コイルのセンタータップではない両出力端に直列に且つ互いに逆方向に接続する第1及び第2の前記同期整流要素の前記トランスの2次コイルに接続していない各他端同士を接続して全波整流部を構成することを特徴とし、全波整流することで半波整流よりも損失が少なく効率の良い整流を行えるという効果がある。

【0096】請求項3の発明は、請求項2の発明において、一つの前記電流検知部の検出信号より前記第1の同期整流要素のスイッチング素子の駆動信号を生成し、前記第2の同期整流要素のスイッチング素子の駆動信号は前記第1の同期整流要素のスイッチング素子の駆動信号の反転信号とすることを特徴とし、駆動信号生成部の簡素化を図ることができ、低コスト化、小型化ができるという効果がある。

【0097】請求項4の発明は、請求項1乃至3のいづれかの発明において、前記電流検知部は、前記同期整流要素に直列に接続した電流検出用抵抗からなり、前記電流検出用抵抗の両端に発生する電圧に基づいて前記駆動信号生成部にて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とし、簡単な回路構成で電流検知部を構成できるという効果がある。

【0098】請求項5の発明は、請求項4の発明において、前記電流検出用抵抗の抵抗値は、前記電流検出用抵抗に流れる電流に対して発生する前記電流検出用抵抗の両端の電圧が前記駆動信号生成部にて前記同期整流要素のスイッチング素子を駆動できる電圧にまで増幅できる最小の電圧になる抵抗値であることを特徴とし、電流検知部での損失を減らすことができるという効果がある。

【0099】請求項6の発明は、請求項1乃至3いづれかの発明において、前記電流検知部は、前記同期整流要素に直列に接続した1次コイル及び2次コイルとからなるカレントトランスと、前記カレントトランスの2次コイルの両端に並列に接続した抵抗と、前記抵抗の両端間

の電圧を整流するために前記カレントトランスの２次コイルに直列に接続した整流ダイオードとから構成され、前記整流ダイオードから出力される前記電流検知部の出力に基づいて駆動信号生成部にて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とし、２次側回路の整流損失を減らすことができるという効果がある。

【０１００】請求項７の発明は、請求項１乃至６いづれかの発明において、前記駆動信号生成部は、前記電流検知部の出力と基準電圧とを比較し、前記比較結果に基づいて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とし、２次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができるという効果がある。

【０１０１】請求項８の発明は、請求項２乃至７いづれかの発明において、前記同期整流要素を複数有する非接触電力伝送装置において、先に導通し整流を終了しつつある前記第１の同期整流要素を流れる電流値と、次の整流のために導通を行うべき前記第２の同期整流要素のダイオードに流れ始める電流値とが相等しくなる時刻に、前記第１の同期整流要素のスイッチング素子をオフにする駆動信号を出力する第１の駆動信号生成部と、前記第２の同期整流要素のスイッチング素子をオンにする駆動信号を出力する第２の駆動信号生成部とを有することを特徴とし、２次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができるという効果がある。

【０１０２】請求項９の発明は、請求項８記載の発明において、前記第１及び第２の駆動信号生成部は、先に導通し整流を終了しつつある第１の同期整流要素を流れる電流値と、次の整流のために導通を行うべき第２の同期整流要素のダイオードに流れ始める電流値とが相等しくなる時刻における前記電流検知部の出力電圧と同じ電圧である基準電圧と、前記電流検知部の検出信号とを比較し、前記比較結果に基づいて前記同期整流要素のスイッチング素子の駆動信号を生成することを特徴とし、２次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができるという効果がある。

【０１０３】請求項１０の発明は、請求項８記載の発明において、前記第２の駆動信号生成部は、先に導通し整流を終了しつつある第１の同期整流要素を流れる電流値と、次の整流のために導通を行うべき第２の同期整流要素のダイオードに流れ始める電流値とが相等しくなる時刻に、前記第２の同期整流要素のスイッチング素子をオンにできる電圧にまで増幅した駆動信号を出力することを特徴とし、２次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができるという効果がある。

【０１０４】請求項１１の発明は、請求項７記載の発明において、前記整流部は前記同期整流要素を前記トランスの２次コイルに直列に１つ接続した半波整流部を構成し、前記駆動信号生成部は前記電流検知回路の検出信号と基準電圧とを比較して前記比較出力を前記同期整流要素のスイッチング素子の駆動信号とする比較器からなり、前記基準電圧は、前記同期整流要素のスイッチング素子に前記スイッチング素子に並列に逆接続されたダイオードの順電流方向と同じ方向の電流が最大時間流れ且つ前期同期整流要素のスイッチング素子に前記ダイオードの順電流と逆方向の電流が流れない電圧であることを特徴とし、２次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができるという効果がある。

【０１０５】請求項１２の発明は、請求項１、４、５、６いづれか記載の発明において、前記整流部は前記同期整流要素を前記トランスの２次コイルに直列に１つ接続した半波整流部を構成し、前記駆動信号生成部は前記同期整流要素のダイオードに順電流が流れ始める時刻に、前記同期整流要素のスイッチング素子をオンにできる電圧にまで増幅した駆動信号を出力する駆動信号生成部を有することを特徴とし、２次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができるという効果がある。

【０１０６】請求項１３の発明は、請求項１乃至１２いづれか記載の発明において、前記インバータ部は、スイッチング素子を有するハーフブリッジのインバータからなり、前記スイッチング素子はゼロボルトスイッチングを行うことを特徴とし、２次側回路の整流損失を減らして、整流部の放熱板のサイズを小さくでき、回路全体の効率を上げることができるという効果がある。

【図面の簡単な説明】

【図１】本発明の実施形態１、１２、１３の回路構成を示す図である。

【図２】本発明の実施形態１のＦＥＴに流れる電流波形を示す図である。

【図３】本発明の実施形態２の回路構成を示す図である。

【図４】本発明の実施形態２の回路動作を示す図である。

【図５】本発明の実施形態２のＦＥＴ素子のスイッチング動作を示す図である。

【図６】本発明の実施形態２の回路構成を示す図である。

【図７】本発明の実施形態３の回路構成を示す図である。

【図８】本発明の実施形態３の回路構成を示す図である。

【図９】本発明の実施形態４の回路構成を示す図である。

【図１０】本発明の実施形態５の回路構成を示す図であ

る。

【図１１】本発明の実施形態６の回路構成を示す図である。

【図１２】本発明の実施形態７、１１の回路構成を示す図である。

【図１３】本発明の実施形態８、９、１０の回路構成を示す図である。

【図１４】本発明の実施形態８のスイッチング動作を示す図である。

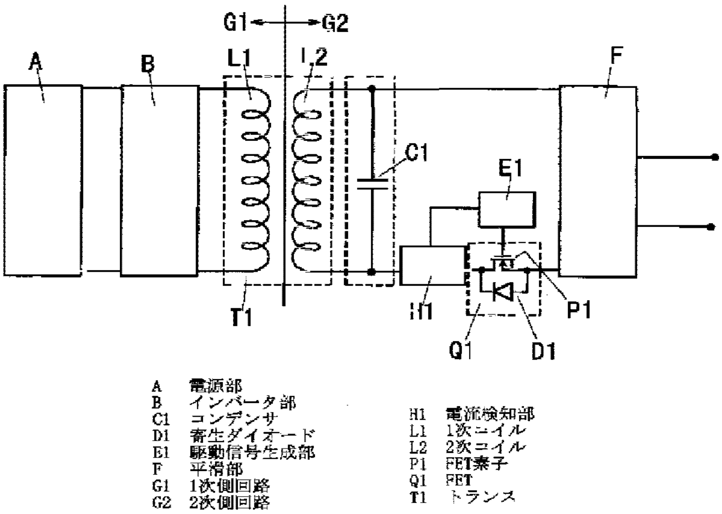
【図１５】本発明の実施形態１０のスイッチング動作を示す図である。

【図１６】本発明の実施形態１１のスイッチング動作を示す図である。

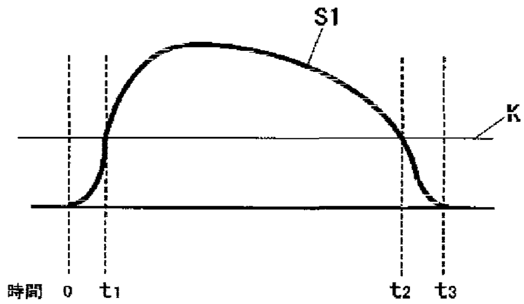
【符号の説明】

Ａ　電源部
Ｂ　インバータ部
Ｃ１　コンデンサ
Ｄ１　寄生ダイオード
Ｅ１　駆動信号生成部
Ｆ　平滑部
Ｇ１　１次側回路
Ｇ２　２次側回路
Ｈ１　電流検知部
Ｌ１　１次コイル
Ｌ２　２次コイル
Ｐ１　ＦＥＴ素子
Ｑ１　ＦＥＴ
Ｔ１　トランス

【図１】



【図２】



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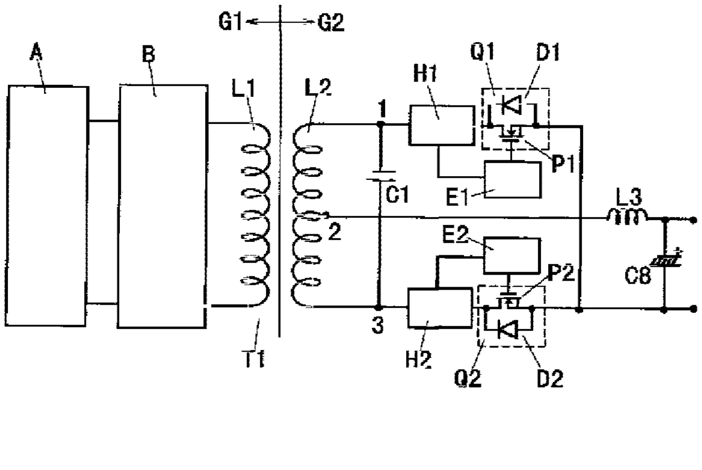

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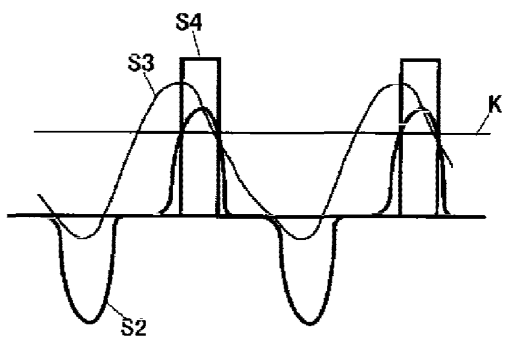

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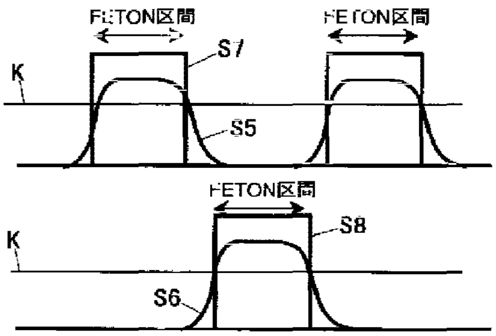

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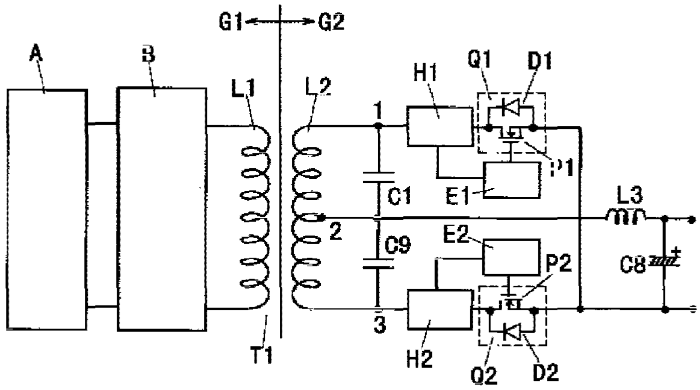

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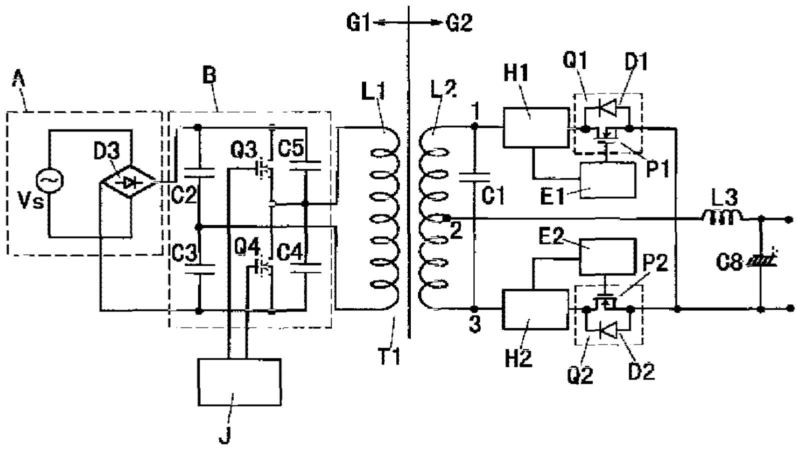

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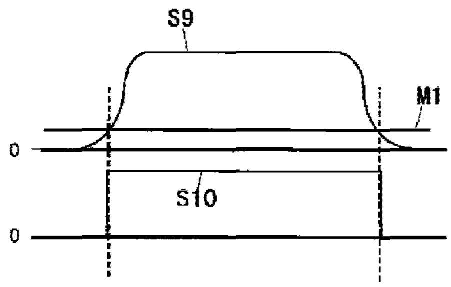

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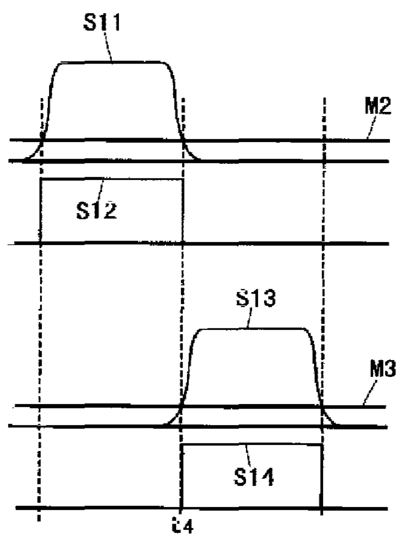

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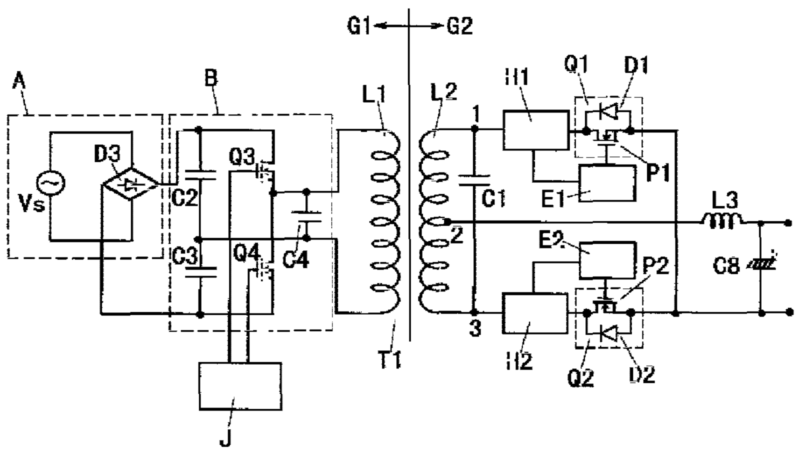

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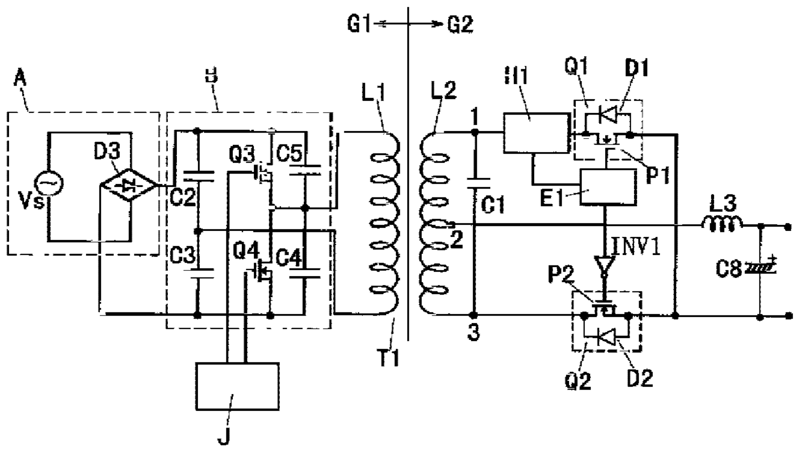

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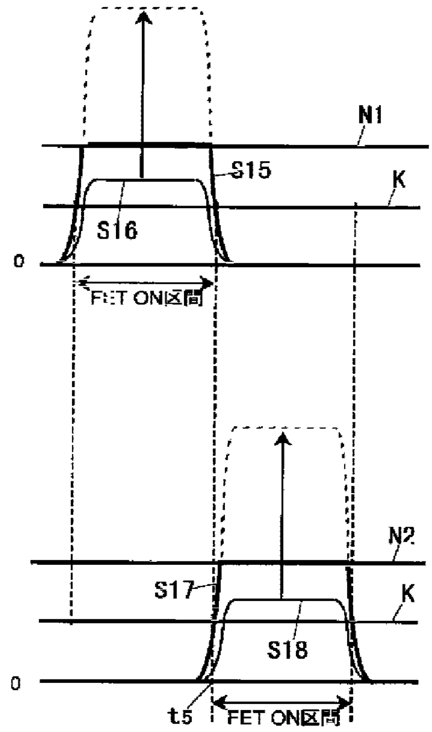
【図16】



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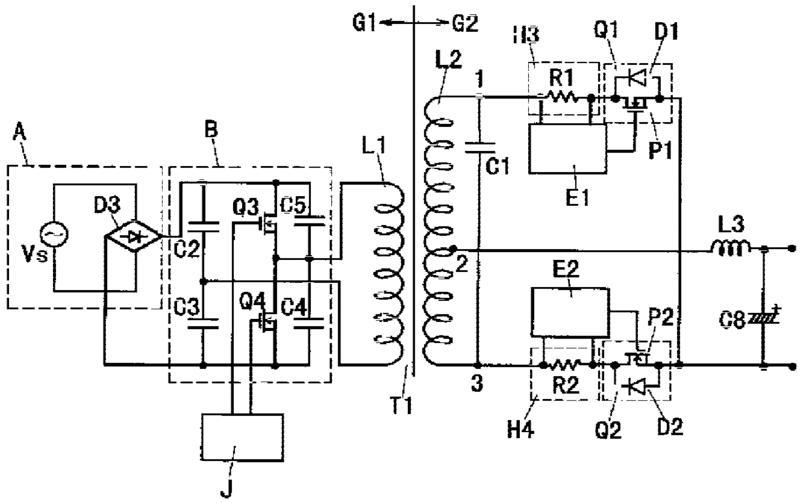
【図10】



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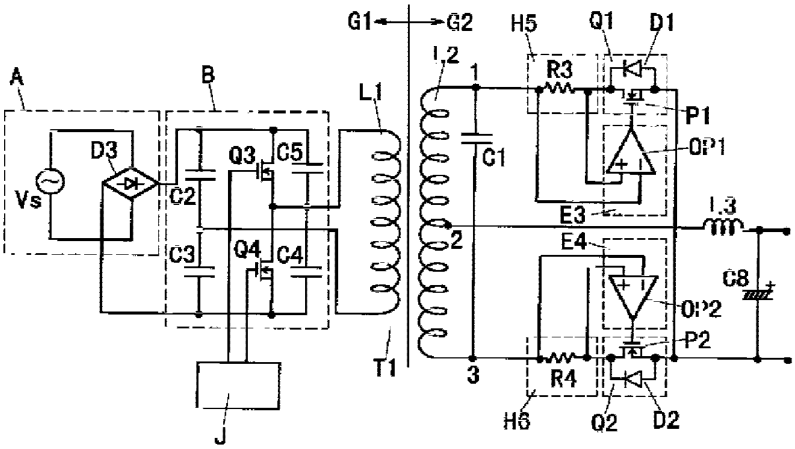
【図11】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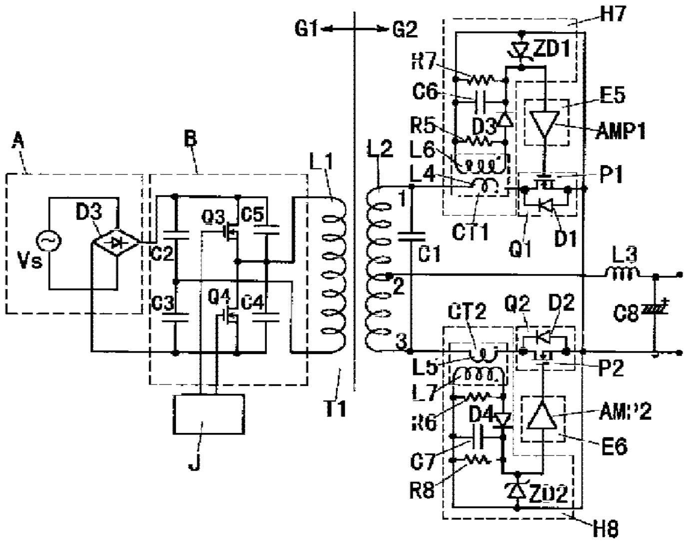
【図12】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D3
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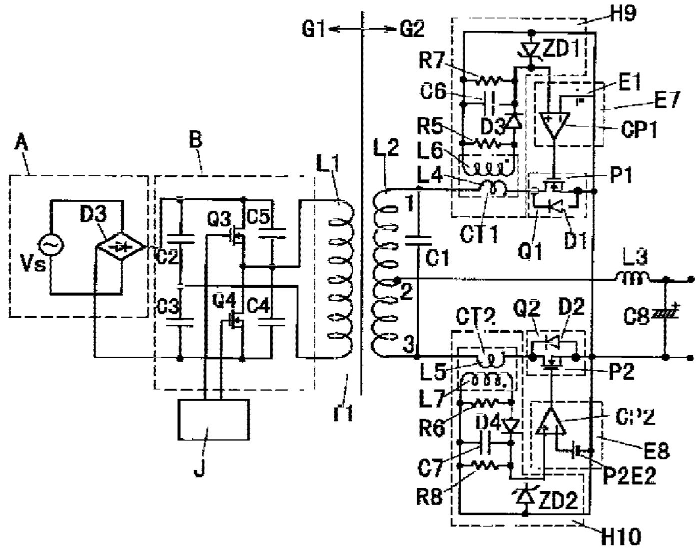
【図１３】



フロントページの続き

Ｆターム(参考）　5H006 CA02 CB01 CB07 CC01 DB03
　　　　　　　　　　　DC02 HA09
　　　　　　　　5H730 BB25 BB26 CC01 DD04 DD21
　　　　　　　　　　　EE02 EE03 EE13 FD31

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

PCT

To: JOHN MONOCELLO III GTC LAW GROUP LLP & AFFILIATES C/O CPA GLOBAL P.O. BOX 52050 MINNEAPOLIS, MN 55402	NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION (PCT Rule 44.1)
	Date of mailing *(day/month/year)* 06 JAN 2012
Applicant's or agent's file reference WTCY-0048-PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2011/051634	International filing date *(day/month/year)* 14 September 2011
Applicant WITRICITY CORPORATION	

LTC

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

   Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes 1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 82 70

   For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 – 9.011.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   ☐ the protest together with the decision thereon has been transmitted to the International Bureau together with any request to forward the texts of both the protest and the decision thereon to the designated Offices.

   ☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. Following the expiration of 30 months from the priority date, these comments will also be made available to the public.

   Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

   In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

   For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 Telephone No. PCT OSP: 571-272-7774

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Coded ______ Verified ______

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To: JOHN MONOCELLO III GTC LAW GROUP LLP & AFFILIATES C/O CPA GLOBAL P.O. BOX 52050 MINNEAPOLIS, MN 55402	**PCT** NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION (PCT Rule 44.1)
	Date of mailing *(day/month/year)* **06 JAN 2012**
Applicant's or agent's file reference WTCY-0048-PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2011/051634	International filing date *(day/month/year)* 14 September 2011
Applicant WITRICITY CORPORATION	

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

   Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes 1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 82 70

   For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 – 9.011.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   ☐ the protest together with the decision thereon has been transmitted to the International Bureau together with any request to forward the texts of both the protest and the decision thereon to the designated Offices.

   ☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. Following the expiration of 30 months from the priority date, these comments will also be made available to the public.

   Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

   In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

   For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 Telephone No. PCT OSP: 571-272-7774

Form PCT/ISA/220 (July 2010)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference WTCY-0048-PWO	**FOR FURTHER ACTION**	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. PCT/US2011/051634	International filing date *(day/month/year)* 14 September 2011	(Earliest) Priority Date *(day/month/year)* 14 September 2010
Applicant WITRICITY CORPORATION		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 2 sheets.

☐ It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of:
      ☒ the international application in the language in which it was filed.
      ☐ a translation of the international application into ______ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).
   b. ☐ This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6*bis*(a)).
   c. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.
2. ☐ **Certain claims were found unsearchable** (see Box No. II).
3. ☐ **Unity of invention is lacking** (see Box No. III).
4. With regard to the **title**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established by this Authority to read as follows:
5. With regard to the **abstract**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.
6. With regard to the **drawings**,
   a. the figure of the **drawings** to be published with the abstract is Figure No. 30
      ☒ as suggested by the applicant.
      ☐ as selected by this Authority, because the applicant failed to suggest a figure.
      ☐ as selected by this Authority, because this figure better characterizes the invention.
   b. ☐ none of the figures is to be published with the abstract.

Form PCT/ISA/210 (first sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/051634

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H02J 17/00 (2011.01)
USPC - 307/104
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - H01F 27/42; H01F 38/00, 38/14; H01P 7/08; H02J 7/02; H02J 17/00 (2011.01)
USPC - 307/104; 320/108, 109; 333/219, 219.2; 336/92

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase, Google Scholar, Google Patents

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2010/0181843 A1 (SCHATZ et al) 22 July 2010 (22.07.2010) entire document	1-27
Y	US 2009/0134712 A1 (COOK et al) 28 May 2009 (28.05.2009) entire document	1-27
A	US 2008/0211320 A1 (COOK et al) 04 September 2008 (04.09.2008) entire document	1-27
A	US 2010/0109445 A1 (KURS et al) 06 May 2010 (06.05.2010) entire document	1-27

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 December 2011	06 JAN 2012

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To: JOHN MONOCELLO III
GTC LAW GROUP LLP & AFFILIATES
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

Date of mailing *(day/month/year)* **06 JAN 2012**		
Applicant's or agent's file reference WTCY-0048-PWO	**FOR FURTHER ACTION** See paragraph 2 below	
International application No. PCT/US2011/051634	International filing date *(day/month/year)* 14 September 2011	Priority date *(day/month/year)* 14 September 2010
International Patent Classification (IPC) or both national classification and IPC IPC(8) - H02J 17/00 (2011.01) USPC - 307/104		
Applicant WITRICITY CORPORATION		

1. This opinion contains indications relating to the following items:

- [x] Box No. I Basis of the opinion
- [ ] Box No. II Priority
- [ ] Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- [ ] Box No. IV Lack of unity of invention
- [x] Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
- [ ] Box No. VI Certain documents cited
- [ ] Box No. VII Certain defects in the international application
- [ ] Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

Name and mailing address of the ISA/US	Date of completion of this opinion	Authorized officer:
Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	22 December 2011	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (July 2011)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US2011/051634

Box No. I Basis of this opinion

1. With regard to the **language**, this opinion has been established on the basis of:
   - [X] the international application in the language in which it was filed.
   - [ ] a translation of the international application into ______________________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).

2. [ ] This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing filed or furnished:

   a. (means)
   - [ ] on paper
   - [ ] in electronic form

   b. (time)
   - [ ] in the international application as filed
   - [ ] together with the international application in electronic form
   - [ ] subsequently to this Authority for the purposes of search

4. [ ] In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

Box No. V **Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

1. Statement

Novelty (N)	Claims	1-27	YES
	Claims	None	NO
Inventive step (IS)	Claims	None	YES
	Claims	1-27	NO
Industrial applicability (IA)	Claims	1-27	YES
	Claims	None	NO

2. Citations and explanations:

Claims 1-27 lack an inventive step under PCT Article 33(3) as being obvious over Schatz et al., hereinafter referred to as Schatz, in view of Cook et al., hereinafter referred to as Cook.

Regarding claim 1, Schatz disclose a system (par. 10, system) for wireless energy distribution over a defined area (par. 9, wireless energy transfer scheme the is capable of transmitting power over mid-range distance; abstract, wireless power transfer within refrigerator; par. 645-646, wireless power transfer system integrated in the refrigerator door), the system (par. 10, system) comprising: a source resonator (par. 10, source resonator) coupled to an energy source (par. 10, resonator connected to power source) and generating an oscillating magnetic field with a frequency (par. 23, generate an oscillating magnetic field; par. 29-30, generating magnetic field with resonant frequency), at least one repeater resonator (par. 14, designed as repeater resonators; par. 141, multiple resonators daisy chained together) in proximity to the source resonator (par. 141, resonators maybe positioned in daisy chain fashion for exchanging energy from source in particular area); and at least two other repeater resonators (par. 14, designed as repeater resonators, which plurality implies multiple or at least two; par. 396, multiple repeaters; par. 141, multiple resonators daisy chained together) in proximity to at least one of the repeater resonators (par. 141, multiple resonators are daisy chained together, which implies in proximity to one another), wherein the repeater resonators provide an effective wireless energy transfer area (par. 141-142, repeater resonators transfer energy over a distances; par. 646-647, additional resonators within the refrigerator provide for wireless energy transfer within the area), but is silent on the particulars of at least one repeater positioned in a defined area and in proximity to the source, and having a resonant frequency; and at least two other repeater with a resonant frequency positioned in the defined area and in proximity to at least one of the repeater resonators, wherein the repeater resonators provide an effective wireless energy transfer area at least one of within or equal to the defined area.
However, Cook in discussing wireless power range increase using parasitic antennas (title) disclose at least one repeater (120, parasitic antenna; par. 28, parasitic antenna that re-radiates) positioned in a defined area (par. 23, antennas are positioned within a room) and in proximity to a source (100, main antenna; fig. 1, depicts 120 in proximity to 100), and having a resonant frequency (par. 26, antenna 100 having a resonant frequency); and at least two repeaters (120, 130) positioned in a defined area (par. 23, antennas are positioned within a room) and in proximity to at least one of a repeater resonators (fig. 1, depicts 120 and 130 within proximity of each other), wherein a repeater provides an effective wireless energy transfer area at least one of within or equal to the defined area (par. 29-32, parasitic antennas 120, 130 transmit within area). Therefore, it would have been obvious to one of ordinary skill in the art at the time of the invention to incorporate the aforementioned improvements of Cook with the invention of Schatz for the purpose of providing a local areas where power is more efficiently received (abstract – Cook).

Regarding claim 2, modified Schatz disclose the system of claim 1, Schatz further disclose wherein the defined area covered is at least 2 square meters (par. 483, the defined area could be a floor, which inherently is greater in size that 2 square meters).

Regarding claim 3, modified Schatz disclose the system of claim 1, Schatz further disclose wherein the defined area covered is at least 10 square centimeters (par. 646, the defined area is refrigerator, which inherently is greater in size than 10 centimeters).

Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

Regarding claim 4, modified Schatz disclose the system of claim 1, Schatz further disclose comprising at least one additional source resonator (par. 519, utilize source resonators; par. 600, source resonators; par. 646, another source resonator) that generates an oscillating magnetic field with the frequency (par. 23, generating an oscillating magnetic field; par. 113, inherently a resonator oscillates with a frequency), wherein the at least one additional source resonator is positioned in proximity to defined area (par. 646, additional source resonator can be integrated into the body of the refrigerator; par. 519, source resonators that are arranged in various configurations within an area).

Regarding claim 5, modified Schatz disclose the system of claim 4, Schatz further disclose wherein the frequency and relative phase of the oscillating fields generated by the sources of the system are synchronized (par. 594, oscillating magnetic fields of resonators are driven in-phase).

Regarding claim 6, modified Schatz disclose the system of claim 4, Schatz further disclose wherein the relative phase of the oscillating fields generated by the different sources of the system is adjustable (par. 594, oscillating field of multiple resonators can be adjusted either in-phase or out of phase).

Regarding claim 7, modified Schatz disclose the system of claim 4, Schatz further disclose wherein at least one repeater resonator, comprises a capacitively loaded conducting loop (par. 166, capacitively-loaded loop inductor; par. 179, capacitively-loaded conductive loops).

Regarding claim 8, modified Schatz disclose the system of claim 4, Schatz further disclose wherein at least one of the repeater resonators have an adjustable resonant frequency (par. 113, angular resonant frequency, varies based on resonant period; par. 173, resonant frequency of the resonator is tunable by changing the inductance or capacitor of the resonator).

Regarding claim 9, modified Schatz disclose the system of claim 8, Schatz further disclose wherein the resonant frequency of the repeater resonators may be detuned from the frequency of the magnetic fields generated by the source resonators to change the distribution of the magnetic fields in the defined area (par. 593, resonators may be detuned from other resonators).

Regarding claim 10, modified Schatz disclose the system of claim 9, Schatz further disclose wherein some repeaters are detuned to maximize the magnetic fields in a region of the defined area (par. 593-594, detuned resonators in order to create specific hotspot areas of concentrated magnetic energy).

Regarding claim 11, modified Schatz disclose the system of claim 10, Schatz further disclose wherein the detuning of repeaters is performed according to a network routing algorithm (par.593-597, detuning performed based on the drive signal to appropriately tune the resonator as it is activated in the bank, adjustments are also made based on a sharing algorithm; par. 387, power levels, frequencies and input impedances for resonators may be adjusted based on algorithm; par. 403, processor adjusts the resonator through algorithms).

Regarding claim 12, modified Schatz disclose the system of claim 10, Schatz further disclose comprising a communication channel (4204, wireless communication channel) between the resonators of the system (par. 431, wireless communication channel may allow resonators 102 to exchange information).

Regarding claim 13, modified Schatz disclose the system of claim 12, Schatz further disclose wherein the communication channel is used to coordinate detuning of the repeater resonators of the system to achieve a specific magnetic field distribution (par. 431-433, communication channel communicates controls to the resonator, which could include detuning of the resonator to achieve specific distribution).

Regarding claim 14, modified Schatz disclose the system of claim 1, Schatz further disclose wherein the repeater resonators have a quality factor Q>100 (par. 19, Q sub1 and sub2 are greater than 100; par. 26, resonator with quality factor Q greater than one hundred; par. 235, quality factor, Q, of 100 or higher and even Q of 1000 or higher; par. 239, quality factor, Q, of order of 1000 or higher).

Regarding claim 15, modified Schatz disclose the system of claim 10, modified Schatz further disclose wherein the repeater resonators further comprise pressure sensors (par. 533, pressure sensors) and wherein the information from the pressure sensors is used to change the magnetic field distribution (par. 533-534, information from sensors, such as pressure sensors, help to optimize magnetic field direction and resonator alignment).

Regarding claim 16, modified Schatz disclose the system of claim 1, wherein the defined area is a floor (par. 17, applications could include under the floor; par. 232-233, active area on the floor).

Regarding claim 17, modified Schatz disclose the system of claim 16, wherein the resonators are integrated into flooring material (par. 233, integrated into a floor).

Regarding claim 18, modified Schatz disclose the system of claim 1, modified Schatz further disclose wherein the defined area is a wall (par. 17, applications could include in the walls of a room; par. 232, walls).

Regarding claim 19, modified Schatz disclose the system of claim 1, Schatz further disclose wherein the defined area is a ceiling (par. 17, applications could include on the ceiling; par. 232, ceilings).

Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

Regarding claim 20, Schatz disclose a wireless energy transfer flooring system (par. 483, wireless energy transfer may be integrated into the floor) comprising: at least one source resonator (par. 10, source resonator) coupled to an energy source (par. 10, resonator connected to power source) and generating an oscillating magnetic field with a frequency (par. 23, generate an oscillating magnetic field; par. 29-30, generating magnetic field with resonant frequency), at least one repeater resonator (par. 14, designed as repeater resonators; par. 141, multiple resonators daisy chained together) in proximity to the source resonator (par. 141, resonators maybe positioned in daisy chain fashion for exchanging energy from source in particular area); and at least two other repeater resonators (par. 14, designed as repeater resonators, which plurality implies multiple or at least two; par. 396, multiple repeaters; par. 141, multiple resonators daisy chained together) in proximity to at least one of the repeater resonators (par. 141, multiple resonators are daisy chained together, which implies in proximity to one another), wherein the resonant frequency of at least one of resonators is detuned from the frequency of the oscillating magnetic field of the at least one source to change the distribution of magnetic fields in the defined area (par. 589, in order to maximize distribution of magnetic fields around source operating parameters of resonators is adjusted, which implies detuned), but is silent on the particulars of at least one repeater positioned in a defined area and in proximity to the source, and having a resonant frequency; and at least two other repeater with a resonant frequency positioned in the defined area and in proximity to at least one of the repeater resonators, wherein the resonant frequency of at least one of the repeater resonators is detuned from the frequency of the oscillating magnetic field of the at least one source to change the distribution of magnetic fields in the defined area.
However, Cook in discussing wireless power range increase using parasitic antennas (title) disclose at least one repeater (120, parasitic antenna; par. 28, parasitic antenna that re-radiates) positioned in a defined area (par. 23, antennas are positioned within a room) and in proximity to a source (100, main antenna; fig. 1, depicts 120 in proximity to 100), and having a resonant frequency (par. 26, antenna 100 having a resonant frequency); and at least two repeaters (120, 130) positioned in a defined area (par. 23, antennas are positioned within a room) and in proximity to at least one of a repeater resonators (fig. 1, depicts 120 and 130 within proximity of each other), wherein the resonant frequency of at least one of the repeaters is detuned from a frequency of an oscillating magnetic field of a source (par. 68, detuning of resonant frequency of antennas, including parasitic antenna; par. 78, detuning of antenna to influence resonant frequency). Therefore, it would have been obvious to one of ordinary skill in the art at the time of the invention to incorporate the aforementioned improvements of Cook with the invention of Schatz for the purpose of providing a local areas where power is more efficiently received (abstract – Cook).

Regarding claim 21, modified Schatz disclose the system of claim 20, Schatz further disclose comprising a communication channel (4204, wireless communication channel) between the resonators of the system (par. 431, wireless communication channel may allow resonators 102 to exchange information).

Regarding claim 22, modified Schatz disclose the system of claim 21, Schatz further disclose wherein the communication channel is used to coordinate detuning of the repeater resonators of the system to achieve a specific magnetic field distribution (par. 431-433, communication channel communicates controls to the resonator, which could include detuning of the resonator to achieve specific distribution).

Regarding claim 23, modified Schatz disclose the system of claim 20, Schatz further disclose wherein the resonators are integrated into flooring material (par. 233, resonators maybe integrated into a floor).

Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

Regarding claim 24, Schatz disclose a method of distributing wireless energy from at least one source resonator to a specific location within an area (abstract, source resonator distributing wireless energy to a refrigerator) having tunable repeater resonators (par. 20, resonators are tunable), the method comprising: determining a closest resonator to a specific location (par. 533, based on position and location information finding a nearby wireless power transmission source); tuning the resonant frequency of the repeater resonators to provide for an energy transfer path from the source (par. 538, the frequency is tuned to resonant frequency in order in order to transmit wireless power; par. 582-583, the source and device resonators are adjusted as move closer to each other), but is silent on determining a closest repeater resonators, and tuning the resonant frequency of the repeater resonators to provide for an energy transfer path to the closest repeater resonators.
However, Cook in discussing wireless power range increase using parasitic antennas (title) disclose determining a closest repeater (par. 28-30, parasitic antennas radiate within certain area based on location; fig. 1, depicts receivers 125-128 receiving power from there respective antennas), and tuning the resonant frequency of a repeater to provide for an energy transfer path to closest repeater (par. 26, parasitic, repeaters, are tuned to create areas of maximum power). Therefore, it would have been obvious to one of ordinary skill in the art at the time of the invention to incorporate the aforementioned improvements of Cook with the invention of Schatz for the purpose of providing a local areas where power is more efficiently received (abstract – Cook) .

Regarding claim 25, modified Schatz disclose the method of claim 24, Schatz further disclose comprising detuning resonators (par. 250, detuning resonators; par. 593, detune resonators) that are not in the energy transfer path (par. 593, detune non-active resonators, which implies those not in energy path).

Regarding claim 26, modified Schatz disclose the method of claim 24, Schatz further disclose wherein the energy transfer path is determined by a shortest path algorithm (par. 582, close to each other, power transfer efficiency; par. 596, devices are powered by resonators which are closer to them).

Regarding claim 27, modified Schatz disclose the method of claim 24, wherein the energy transfer path is determined by a central control (par. 533, central station or database is in communication with source, which guides the user to the source; par. 537, central authority authenticates sources and devices).

Claims 1-27 meet the criteria set out in PCT Article 33(4), and thus have industrial applicability because the subject matter claimed can be made or used in industry.

PCT Application No.: PCT-US2011-51634
Date of Search: 22 December 2011

Search History:

Limited Classification Search

The Patent Analyst performed a limited classification search within the following US, IPC, ECLA, or F-Term classification areas:

U.S. Class/Subclass(es): 307/104; 320/108, 109; 333/219, 219.2; 336/92

IPC (8) Class/Subclass(es): H01F 27/42; H01F 38/00, 38/14; H01P 7/08; H02J 7/02; H02J 17/00 (2011.01)

See Global Search Results.

Global Patent Literature Text Search

The Patent Analyst performed the following global text search, which was not limited by classification but may or may not have been limited by other criteria:

PATBASE

- 1) pn=(us20100181843 or us20100109445) (1)
- 2) (PA=(witricity corp)) (2)
- 3) (TAC=((wireless energy) or (wireless power))) (1512)
- 4) (TAC=((wireless energy) or (wireless power)) and defined w2 area) (3)
- 5) PN=(US2008278264 OR WO10093964) (2)
- 6) ctb 2 or ctf 2 (230)
- 7) pn=us2010/0259108 (1)
- 8) PA=(LOU_HERBERT_T OR LOU_HERBERT_TOBY OR FELDSTEIN_MICHAEL_A OR SCHATZ_DAVID_A OR GANEM_STEVEN_J OR GANEM_STEVEN_JOSEPH OR GILER_ERIC_R OR PERGAL_FRANK_J OR KURS_ANDRE_B OR CAMPANELLA_ANDREW_J OR EFE_VOLKAN OR SOLJACIC_MARIN OR FIORELLO_RON OR LI_QIANG OR HALL_KATHERINE_L OR KESLER_MORRIS_P OR KARALIS_ARISTEIDIS OR KULIKOWSKI_KONRAD OR KULIKOWSKI_KONRAD_J OR MACDONALD_MATTHEW_J) (472)
- 9) 8 and 3 (4)
- 10) (((wireless energy) or (wireless power))) and 8 (4)
- 11) 3 and (repeater w3 reson*) (10)
- 12) pd<20100914 (100000)
- 13) 11 and 12 (8)
- 14) 3 and 12 (966)
- 15) 14 and (resonator*) (60)
- 16) IC=("H01F27/42") (1671)
- 17) IC=("H01F38/00") (11012)
- 18) IC=("H01F38/14") (3896)
- 19) IC=("H01P7/08") (1831)
- 20) IC=("H02J17/00") (6354)
- 21) IC=("H02J7/02") (10622)
- 22) 16 or 17 or 18 or 19 or 20 or 21 (33311)
- 23) 22 and (repeat* w2 resonat*) (6)
- 24) 22 and (relay* w2 reson*) (11)
- 25) (repeat* w2 resona*) or (relay* w2 resona*) (767)

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
26 May 2011 (26.05.2011)

PCT

(10) International Publication Number
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(54) Title: WIRELESS POWER UTILIZATION IN A LOCAL COMPUTING ENVIRONMENT

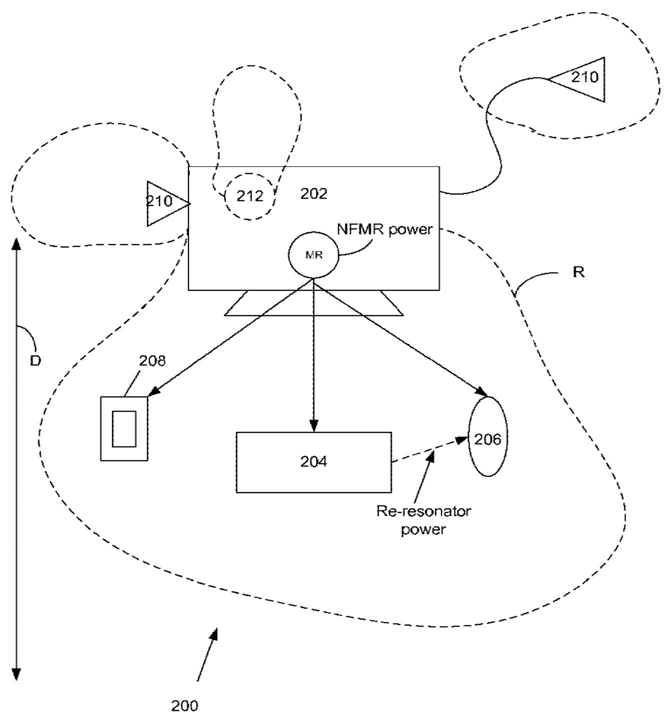

Fig. 2

(57) Abstract: Various embodiments of a wirelessly powered local computing environment are described. The wireless powered local computing environment includes at least a near field magnetic resonance (NFMR) power supply arranged to wirelessly provide power to any of a number of suitably configured devices. In the described embodiments, the devices arranged to receive power wirelessly from the NFMR power supply must be located in a region known as the near field that extends no further than a distance D of a few times a characteristic size of the NFMR power supply transmission device. Typically, the distance D can be on the order of 1 meter or so.

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WIRELESS POWER UTILIZATION IN A LOCAL COMPUTING ENVIRONMENT

TECHNICAL FIELD

[0001] The described embodiments relate generally to utilizing a wireless power transmission in a portable computing environment.

BACKGROUND

[0002] Historically, transferring power wirelessly has been successful for fairly limited applications. In particular, only those applications where a wireless power source and a wireless power receiver are located very close to each other have been successful. In this arrangement, the wireless power source and the wireless power receiver are typically coupled inductively by way of a magnetic field that can entangle both the power source and receiver. Although well suited for applications requiring relatively low power (on the order of mW), this same process is not suitable for those applications requiring either more power (on the order of at least a few watts to hundreds of watts) or where the power source and power receiver are located further apart from each other, such as a few inches to a few feet.

[0003] However, it has been discovered (see "Efficient wireless non-radiative mid-range energy transfer" by Karalis et al., Annals of Physics 323 (2008) pgs. 34 - 38) that useable power can be transferred wirelessly from a power source to a receiver located within a distance referred to as a near field. By near field it is meant that within a distance a few times larger than that of both objects involved in the transfer (about one meter or so for most applications) a relatively large amount of power (at least on the order of a few watts) can be transferred between a wireless source device and a receiver with an acceptable efficiency. In this way, a realistic and practical approach to wireless transferring useable amounts of power over distances suitable for limited applications can be realized. Typically, each battery powered device such as a wireless electronic device requires its own charger and power source, which is usually an alternating current (AC) power outlet. Such a wired configuration becomes unwieldy when many devices need charging.

[0004] Various over-the-air or wireless power transmission between a transmitter and a receiver coupled to the electronic device to be charged have been carried out that generally fall into two categories. One category is based on the coupling of plane wave radiation between a transmit antenna and a receive antenna on the device to be charged. The receive antenna collects the radiated power and rectifies it for charging the battery. Antennas are generally of resonant length in order to improve the coupling efficiency. This approach suffers from the fact that the power coupling falls off quickly with distance between the antennas, so charging over reasonable distances (e.g., less than 1 to 2 meters) becomes difficult.

[0005] Other techniques rely upon inductive coupling between a transmit antenna embedded, for example, in a "charging" mat or surface and a receive antenna (plus a rectifying circuit) embedded in the electronic device to be charged. This approach has the disadvantage that the spacing between transmit and receive antennas must be very close (e.g., within thousandths of meters). Though this approach does have the capability to simultaneously charge multiple devices in the same area, this area is typically very small and requires the user to accurately locate the devices to a specific area.

[0006] With wireless power transmission there is a need for apparatuses and methods for transmitting and relaying wireless power at varying power levels and multiplexed times to increase power transmission efficiency.

[0007] Furthermore, what is desired are methods, systems, and apparatus for efficient and user friendly interaction between peripheral devices in a wirelessly powered local computing environment. In particular, in order to enhance the user's experience and provide efficient power utilization, cooperation between the plurality of peripheral devices in the context of the wireless power environment is desired.

SUMMARY

[0008] The present invention provides a system and method for utilizing wireless near field magnetic resonance (NFMR) power transmission in a computing environment.

[0009] In various embodiments, methods, systems, and apparatus for interacting between a plurality of peripheral devices receiving power wirelessly from a wireless power supply is described. In one embodiment, a virtual charging area can be created. The virtual charging area can extend to about about one (1) meter from a central station that incorporates a NFMR power supply. The virtual charging area can define a region in which suitably configured peripheral devices, such as a mouse, keyboard, and so on can receive power by way of a NFMR channel formed between the NFRM power supply and a NFMR resonator circuit included in the peripheral device. In this way, when both the NFMR power supply and the NFMR resonator circuit are tuned to each other, then useable power can be transferred over a power conduction channel formed between the two resonant devices.

[0010] In some embodiments, at least one of the peripheral devices can have a tunable resonator circuit having at least one circuit element (such as a resistor, inductor, or capacitor) having a value that can be changed. In this way, the tunable resonator circuit can be de-coupled from the NFMR power supply by de-tuning the tunable resonator circuit in relation to the resonance frequency of the NFMR power supply. In this way, the effective Q value of the tunable circuit is reduced to the point that essentially no power is transferred. In one embodiment, at least one of the plurality of peripheral devices can include a secondary NFMR resonator circuit adapted to re-resonant power to another one of the plurality of peripheral devices by establishing a NFMR channel to the other peripheral device over which useable power can be transferred. In some embodiments, the NFMR power supply can eliminate any voids in the virtual charging area by modifying resonance characteristics such as frequency.

[0011] A method of wirelessly transmitting power can be performed by creating a first coupling mode region of an electromagnetic field within a near field of a power supply transmit antenna, coupling the electromagnetic field and a receiver antenna of a first receiver device within the coupling mode region, creating a second coupling mode region of the electromagnetic field different from the first coupling mode region within a near field of a transmit antenna of the first receiver device, coupling the electromagnetic field to a receive antenna of second receiver device in the near field of the transmit antenna of the first receiver device, wirelessly delivering power from the power supply to the first receiver device by way of the power supply transmit antenna using the first coupling mode region of the electromagnetic field; and wirelessly delivering at least some of the power wirelessly delivered to the first receiver device is wirelessly by re-transmitting the at least some power to the second receiver device by way of the first receiver transmit antenna using the second coupling mode region of the electromagnetic field.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The included drawings are for illustrative purposes and serve only to provide examples of possible structures and arrangements for the disclosed embodiments. These drawings in no way limit any changes in form and detail that may be made to the described embodiments by one skilled in the art without departing from the spirit and scope of the embodiments.

[0013] Fig. 1 illustrates representative tunable resonator circuits in accordance with the described embodiments.

[0014] Fig. 2 shows representative virtual charging area in accordance with the described embodiments.

[0015] Fig. 3 shows representative hybrid power circuit in accordance with the described embodiments.

[0016] Fig. 4 shows representative time multiplexing for distributing power in accordance with the described embodiments.

[0017] Fig. 5 illustrates a wireless transmission or charging system, in accordance with various exemplary embodiments.

[0018] Fig. 6 shows a simplified schematic diagram of a wireless power transfer system.

[0019] Fig. 7 shows an antenna used in exemplary embodiments configured as a "loop" antenna that can also be referred to herein as a "magnetic" antenna.

[0020] Fig. 8 shows a flowchart detailing process 800 in accordance with the described embodiments.

DETAILED DESCRIPTION

[0021] Various embodiments of a wirelessly powered local computing environment are described. The wireless powered local computing environment includes at least a near field magnetic resonance (NFMR) power supply arranged to wirelessly provide power to any of a number of suitably configured devices. In the described embodiments, the devices arranged to receive power wirelessly from the NFMR power supply can be located in a region known as the near field that extends no further than a distance D that can be a few times a characteristic size of the NFMR power supply transmission device. Typically, the distance D can be on the order of 1 meter or so.

[0022] Fig. 1 shows various representative tunable circuits in accordance with the described embodiments. The representative tunable circuits can include series RLC (resistor (R), inductor (L), capacitor(C)) circuit 102. In this arrangement, a resonant frequency can be tuned (i.e., changed) by changing any of the component values. For example, circuit 102, capacitor C can be a variable capacitor used to tune circuit 102. Similarly, circuit 104 (known as a Hartlely oscillator) can be used as a tunable circuit in the described embodiments as can tuned LC circuit 106.

[0023] Fig. 2 shows representative virtual charging area 200 in accordance with the described embodiments. Virtual charging area 200 provides region R of charging for suitably configured devices placed within the region R. NFMR power supply can be placed in central unit such as desktop computer. In this way, the desktop computer can provide the NFMR power supply with computing resources. It should be noted that the near field magnetic resonance (NFMR) power supply can include high Q circuit that relies upon near field magnetic coupling by way of a resonance channel formed between resonances of the power source and sink to transfer power. The NFMR power supply can be a standalone unit such as, for example, included in a desk top computer, laptop computer, tablet computer, and so on. In other embodiments, the NFMR power supply can take the form of a portable type unit such as a dongle that can be connected to a legacy device such as a desktop computer thereby providing the ability to retrofit devices. In still other embodiments, housing or a portion of a housing used to enclose the NFMR power source can act to extend a useful range of the NFMR power supply.

[0024] In this way, suitably configured peripheral devices can be powered directly from the NFMR power supply. In so doing, the peripheral devices when tuned to the appropriate frequency can receive power wirelessly from the NFMR power supply. In so doing, the appropriately tuned peripheral device can be considered to be part of a resonance circuit that can include the NFMR power supply and any other peripheral devices so tuned. As part of such a circuit, each device has associated with it a corresponding load that can be sensed by the NFMR power supply. As such, the resonance circuit can have a characteristic load that can change by the addition or deletion of devices from the resonance circuit. For example, if a suitably configured device such as a portable media player is brought within range of the NFMR power supply, then the load associated with the portable media player can be sensed by the NFMR power supply when (and if) the portable media player is appropriately tuned. It should be noted that in some cases, the device being brought into the range of the NFMR power supply can communicate its initial presence using a standard communication protocol such as WiFi or Bluetooth. However, once incorporated into the resonance circuit, the device can use a communication back channel described in detail below. Accordingly, any change in the characteristic load factor of the resonance circuit can convey information that can be used by the NFMR power supply to control the various devices in the resonance circuit by, for example, distributing power, and so on.

[0025] In some embodiments, certain of the peripheral devices can be configured to include a re-resonator circuit that can receive power directly from the NFMR power supply. Such devices can also transfer a portion of the power received to other of the peripheral devices. For example, as shown in Fig. 2 virtual charging area 200 includes central unit 202 (desktop computer) that can include the NFMR power supply, keyboard 204, mouse 206, and portable media player 208. In one embodiment, keyboard 204 can be configured to receive power directly from the NFMR power supply included in desktop computer 202 as can mouse 206 and portable media player 208 (when located within range R).

[0026] In some cases, the ability of desktop computer 202 to provide power directly to mouse 206, for example, can be reduced due to any number of factors. Such factors can include, for example, the addition of other devices into region R that require power from the NFMR power supply, obstacles interfering with the direct power channel formed between the NFMR and mouse 206, and so on. In this case, keyboard 204 can act as a re-resonator such that a portion of the power delivered to keyboard 204 from the NFMR power supply can be passed on by way of a re-resonator transmission unit (not shown) in keyboard 204. In this way, any power loss experienced by mouse 206 can be ameliorated by the power received from keyboard 204. This arrangement can be transitory or can last for as long as mouse 206 is not able to receive adequate power directly from the NFMR power supply. In other cases, the locating of portable media player 208 within region R can reduce the amount of power available to keyboard 204 and mouse 206. In this case, if a battery in keyboard 206 is fully charged (or additional charge is not necessary) then keyboard 206 can decouple a charging circuit while still maintaining a re-resonator circuit providing power to mouse 206.

[0027] In some embodiments, dongle 210 can be connected to desktop computer 202 (by way of a USB port or cable, for example). So connected, dongle 210 can, in turn, act as a range extender for the NFMR power supply. In this way, dongle 210 can extend a range that power can be provided by the NFMR power supply included in desktop computer 202. In some cases, dongle 210 can re-resonate power already received from the NFMR power supply while in other cases, dongle 210 can include its own NFMR power supply. By having its own NFMR power supply, dongle 210 can provide additional power wirelessly to those devices within virtual charging region 200 separate from the power provided by the NFMR power supply included in desktop 202. It should be noted that in some embodiments, the housing of desktop computer 202 (or a portion thereof) can be used as a resonator as part of the NFMR power supply.

[0028] Fig. 3 shows representative hybrid power circuit 300 in accordance with the described embodiments. As described, hybrid power circuit 300 can match the low power delivery capability of the NFMR power supply to a large power requirement of required for long term storage devices, such as lithium ion polymer (LiPO) battery. Batteries in such devices as portable phones, portable media players, and so on, can require relatively large amount of power to charge that can be greater than that available from the NFMR power supply. Therefore, it is difficult to charge these high capacity batteries such as LiPO using the NFMR power supply. However, a short term charge storage device (such as a capacitor, ultra capacitor, and so on) that can be charged up by power delivered by the NFMR power supply can be used to temporarily store charge prior to being passed to the battery. In this way, once sufficient charge is stored in the short term charge storage device, the stored charge can be used to charge a long term charge storage device (such as a LiPO battery). For example, Fig. 3 shows representative hybrid power circuit 300 having capacitor 302, capacitor charging circuit 304 (that can receive power P from the NFMR power supply), long term power storage unit 306 (that can take the form of battery 306), and battery charging circuit 308. In the described embodiment, power P provided by the NFMR power supply can "trickle" charge capacitor 302. Once sufficient charge is stored in capacitor 302, capacitor charging circuit 304 can sense capacitor voltage VC and switch fully charged capacitor 302 to battery 306 by way of battery charging circuit 308. In this way, charge Q stored in capacitor 302 can be used to increase the charge of battery 306. Once capacitor 302 is discharged (as determined by capacitor charging circuit 304), capacitor 302 can again receive power P from the NFMR power supply.

[0029] One of the advantages of a wirelessly powered local computing environment is the potential to provide an enhanced user experience. For example, by doing away with clumsy and annoying cables and eliminating the need to replace batteries, an easy to use and efficient local computing environment can be provided to the user. However, in order to provide this enhanced user experience, it would be advantageous for the various devices that make up the wirelessly powered local computing environment to be able to interact with each other as well as with the NFMR power supply. Such interaction can include, for example, providing power by the NFMR power supply to any of the devices within range in whatever amount is required. For example, an amount of power transferred between the NFMR power supply (having a first resonator circuit) and receiving device (having a second resonator circuit) can be controlled by tuning (or de-tuning) the second resonator circuit along the lines described above. It should be noted that when a device is tuned, the tuned device can become part of the resonance circuit. As part of the resonance circuit, a load associated with the device can be “seen” by the NFMR power supply. This load can, in turn, be used by the NFMR power supply to determine the power requirements of the resonance circuit as well as how the required power must be distributed amongst the various devices included in the resonance circuit. On the other hand, when a device “de-tunes”, then the device no longer resonates with the NFMR power supply and is effectively removed from the resonance circuit and receives little or no additional power.

[0030] It should be noted that various environmental factors can have an effect on the efficiency of power transfer from the NFMR power supply to those devices included in the resonance circuit. For example, any object (metallic, for example) that can interfere with the magnetic coupling between the NFMR power supply and those device wirelessly receiving power can adversely affect both the amount of power supplied and the efficiency of the power transfer. This reduction in power transferred or power transfer efficiency can put an undue strain on the NFMR power supply as well as increase the likelihood that particular devices may not have sufficient power to operate at peak efficiency, to execute important functions, or in some cases, not be able to operate at all. In one embodiment, feedback provided by a device to the NFMR power supply indicating that the device requires more power or has experienced a reduction in power can cause the NFMR power supply to try to ascertain the reason or reasons why the device has experienced this reduction in power. For example, if the device is moving within a void region (a void being defined as that region having a substantially reduced power transmission or efficiency factor), then the NFMR power supply can attempt to move the void region by modifying selected resonance factors (such as resonance frequency) thereby having the effect of moving the void region (hopefully beyond the range of the operating region of the devices wirelessly coupled to the NFMR power supply). In one embodiment, the NFMR power supply can determine that the power transfer efficiency has dropped below a threshold for a device(s) based upon, for example, feedback from the affected device(s). In response, the NFMR power supply can respond by modifying the frequency of the magnetic resonance signal until the power efficiency has recovered to above the threshold, by increasing power, or by, in some cases, causing less important or less used devices, to de-tune themselves (thereby removing themselves from the resonance circuit) so as to free up power that can be provided to those devices requiring more power. It should be noted that these operations can be carried out in the background in such a way that the user is unaware of the operations taking place. In still another embodiment, the power source can alter phase, frequency and or signal amplitude relative to other links in order to optimize power delivery.

[0031] In order to provide more robust communication between the various devices coupled with the NFMR power supply, each device can provide affirmative feedback to the NFMR power supply using a direct communication channel such as Bluetooth or WiFi. It should be noted, however, that an indirect communication channel can also be used. Such an indirect communication channel can be formed using the resonance circuit load factor mediated by the number (and type) of devices wirelessly coupled with the NFMR power supply. Since each device has an associated resonance load (i.e., load perceived by the NFMR power supply when a device is tuned to the proper resonance frequency), an indirect communication channel mediated by load state of the device, or devices in the resonance circuit can be established with the NFMR power supply. For example, the NFMR power supply can characterize a particular load state of a resonance circuit by ascertaining the overall resonance load (i.e., sense load on resonant circuit). Any changes to the load state can indicate a change in the status of the resonance circuit which, in turn, can infer that one or more of the devices previously included in the resonance circuit (i.e., tuned to the NFMR power supply resonant frequency) has dropped out, or de-tuned. In some cases, a Morse code like communication protocol can be established between the NFRM power supply and each of the devices. This Morse code like communication protocol can be based upon a device tuning and de-tuning itself using an identifiable pattern. In this way, a simple device identifier, for example, can be communicated to the NFMR power supply. Using this arrangement, a device that has determined to de-tune itself and to remove itself from the resonance circuit, can signal the NFMR power supply its intent as well as identify itself. In this way, the NFRM power supply can have a more clear understanding of the condition of the resonance circuit and the devices included therein. This device to device communication channel (also referred to as a back channel) can be capable of communicating simple information. Such information can include, for example, a device identifier, a synchronization flag, and so on. It should be noted that this communication channel is independent and separate from other communication channels provided by, for example, WiFi or Bluetooth.

[0032] For example, if keyboard is using power wirelessly provide by the NFMR power supply to charge its battery, when the keyboard determines that the battery is substantially fully charged, then the keyboard can determine that power from the NFMR power supply is no longer required (at least until the battery discharges to a pre-set level). In this case, the keyboard can notify the NFMR power supply that it no longer requires power (or at least until it signals that it requires power at some future point in time). In this case, the NFMR can redirect power away from the keyboard (using, for example, a different resonant frequency when the NFMR power supply is equipped to transmit power on a number of frequency ranges, or bands) or the keyboard can remove itself from the resonance circuit (either on its own or as directed) by de-tuning itself. In this way, the load of the resonance circuit can be reduced allowing more power to be wirelessly delivered to the other devices in the resonance circuit. It should be noted that for efficiency and environmental reasons, the NFMR power supply will provide only as much power as is needed. For example, as battery charges up then less power is required. In this way, the charge state of the battery can be communicated to the NFMR power supply that can respond by reducing, or throttling back, the power provided to the keyboard.

[0033] It should be noted that while a device can be removed from the resonance circuit by the process of de-tuning, the device can be added to the resonance circuit by tuning it. By tuning (and conversely de-tuning) it is meant that circuit characteristics (such as resistance) can be changed resulting in the circuit Q increasing in the case of tuning or decreasing in the case of de-tuning. It should be noted that the relative increase or decrease in Q for a circuit can be dependent upon the circuit and applications to which the circuit is used.

[0034] When a device is brought within range R of the power supply, then the load experienced by the power supply increases by that amount corresponding to the device. In this way, proximity detection can be thought as having taken place that can trigger an action to be taken. For example, if a portable media player is brought within range R of a desktop computer, then the proximity signal generated by the change in load experienced by the power supply can cause the desktop computer to initiate a synchronization process, for example, between the portable media player and the desktop computer.

[0035] The communication channels established between the various devices in the resonance circuit can be used for the devices to determine amongst themselves which device takes priority with regards to power supplied by the NFMR power supply. In other cases, a host device (that includes the NFMR power supply and any associated computing resources) can act as aggregator. By aggregator, it is meant that the host device can determine the priority of those devices for receiving power, how much power to receive, and for how long. It should be noted that some devices and or some operations performed by a device can have a higher priority than other devices and or operations. For example, a high priority device(s) may require guaranteed power for operation (such as using a mouse vs charging a portable media player). The host device can use any suitable priority mechanism (round robin, for example).

[0036] In another embodiment, the devices receiving power can communicate amongst themselves to determine which device has priority. The devices understand their own operating points, such as a minimum amount of power to perform certain function, maximum power required to perform all functions. In this way, each device can provide a desired amount of power, a list of functions that can be performed, and a minimum amount of power required for operation. The source can determine how much power can be delivered and which device can get the power it needs. In some cases, the devices themselves set the priority, in other cases, the host device sets the priority. When a device is not receiving power, it removes itself from the resonance circuit by de-tuning, and returns to the circuit by re-tuning.

[0037] It should be noted that the NFMR power supply can use any number of protocols to wirelessly provide power to the various devices included in the resonance circuit. For example, the NFMR power supply can include a plurality of resonator circuits each arranged to resonate at a particular frequency. In this way, the NFMR power supply can provide power orthogonally using different frequency bands. In this way, a device can have multiple resonant frequencies in order to take advantage of the frequency bands provided by the NFMR power supply. For example, the NFMR power supply can wirelessly provide power using multiple frequency bands where a number of devices can each tune themselves to a particular frequency. In this way, frequency shifting techniques can be used to more efficiently transfer power to the plurality of devices within range of the NFMR power supply.

[0038] Other mechanisms for a single NFMR power supply to independently transmit power to more than one device includes time multiplexing as shown in Fig. 4. As illustrated, devices 400, 402 and 404 can each take turns tuning and de-tuning themselves such that at any one time only one of the devices if receiving power. For example, during a period 1, device 400 receives power by tuning itself to at least one of the available resonant frequencies while devices 402 and 404 are de-tuned. Once device 400 has completed its power cycle, device 400 de-tunes itself and device 402 tunes itself and receives power wirelessly from the NFMR power supply. Once device 402 completes its power cycle, device 402 de-tunes itself and device 404 tunes itself to at least one of the resonance frequencies to receive power from the NFMR power supply. In other embodiments, the NFMR power supply can use frequency multiplexing in which the NFMR can toggle amongst a number of frequencies each one tuned to a particular device. The device can receive power only when the device resonates with a current frequency of the power supply.

[0039] The closed loop control can also affect the modes of operation of the devices in the resonance circuit. For example, a keyboard can determine an amount of power received from the source which will depend upon the distance between the source and the keyboard (as well as the presence of any interfering objects). If the power received falls below a threshold, then the keyboard can use more battery power or request that the source increase power. In some cases, if the power provided can not be increased to meet the current operating requirements of the keyboard, then the keyboard can take action to reduce its power requirements by, for example, reducing backlight, etc. It should be noted that as discussed above, the reduction on power received by the keyboard can be caused by many other factors other than an increase in distance. Such factors can include, for example, the presence of voids, objects, other devices added to the circuit, and so on.

[0040] Fig. 5 illustrates a wireless transmission or charging system 500, in accordance with various exemplary embodiments. Input power 502 is provided to a transmitter 504 for generating a radiated field 506 for providing energy transfer. A receiver 508 couples to the radiated field 506 and generates an output power 510 for storing or consumption by a device (not shown) coupled to the output power 510. Both the transmitter 504 and the receiver 508 are separated by a distance 512. In one exemplary embodiment, transmitter 504 and receiver 508 are configured according to a mutual resonant relationship and when the resonant frequency of receiver 508 and the resonant frequency of transmitter 504 are very close, transmission losses between the transmitter 504 and the receiver 508 are minimal when the receiver 508 is located in the "near-field" of the radiated field 506.

[0041] Transmitter 504 further includes a transmit antenna 514 for providing a means for energy transmission and receiver 508 further includes a receive antenna 518 for providing a means for energy reception. The transmit and receive antennas are sized according to applications and devices to be associated therewith. As stated, an efficient energy transfer occurs by coupling a large portion of the energy in the near-field of the transmitting antenna to a receiving antenna rather than propagating most of the energy in an electromagnetic wave to the far field. When in this near-field a coupling mode may be developed between the transmit antenna 514 and the receive antenna 518. The area around the antennas 514 and 518 where this near-field coupling may occur is referred to herein as a coupling-mode region.

[0042] Fig. 6 shows a simplified schematic diagram of a wireless power transfer system. The transmitter 604 includes an oscillator 622, a power amplifier 624 and a filter and matching circuit 626. The oscillator is configured to generate a desired frequency, which may be adjusted in response to adjustment signal 623. The oscillator signal may be amplified by the power amplifier 624 with an amplification amount responsive to control signal 625. The filter and matching circuit 626 may be included to filter out harmonics or other unwanted frequencies and match the impedance of the transmitter 604 to the transmit antenna 514.

[0043] The receiver 608 may include a matching circuit 632 and a rectifier and switching circuit 634 to generate a DC power output to charge a battery 636 as shown in FIG. 6 or power a device coupled to the receiver (not shown). The matching circuit 632 may be included to match the impedance of the receiver 508 to the receive antenna 518. The receiver 508 and transmitter 504 may communicate on a separate communication channel 619 (e.g., Bluetooth, zigbee, cellular, etc).

[0044] As illustrated in Fig. 7, antennas used in exemplary embodiments may be configured as a "loop" antenna 750, which may also be referred to herein as a "magnetic" antenna. Loop antennas may be configured to include an air core or a physical core such as a ferrite core. Air core loop antennas may be more tolerable to extraneous physical devices placed in the vicinity of the core. Furthermore, an air core loop antenna allows the placement of other components within the core area. In addition, an air core loop may more readily enable placement of the receive antenna 518 (FIG. 5, 6) within a plane of the transmit antenna5 (FIG. 5, 6) where the coupled-mode region of the transmit antenna 514 (FIG. 5, 6) may be more powerful.

[0045] As stated, efficient transfer of energy between the transmitter 104 and receiver 508 occurs during matched or nearly matched resonance between the transmitter 504 and the receiver 508. However, even when resonance between the transmitter 504 and receiver 508 are not matched, energy may be transferred at a lower efficiency. Transfer of energy occurs by coupling energy from the near-field of the transmitting antenna to the receiving antenna residing in the neighborhood where this near-field is established rather than propagating the energy from the transmitting antenna into free space.

[0046] The resonant frequency of the loop or magnetic antennas is based on the inductance and capacitance. Inductance in a loop antenna is generally simply the inductance created by the loop, whereas, capacitance is generally added to the loop antenna's inductance to create a resonant structure at a desired resonant frequency. As a non-limiting example, capacitor 752 and capacitor 754 may be added to the antenna to create a resonant circuit that generates resonant signal 756. Accordingly, for larger diameter loop antennas, the size of capacitance needed to induce resonance decreases as the diameter or inductance of the loop increases. Furthermore, as the diameter of the loop or magnetic antenna increases, the efficient energy transfer area of the near-field increases. Of course, other resonant circuits are possible. As another non-limiting example, a capacitor may be placed in parallel between the two terminals of the loop antenna. In addition, those of ordinary skill in the art will recognize that for transmit antennas the resonant signal 756 may be an input to the loop antenna 750.

[0047] Exemplary embodiments of the invention include coupling power between two antennas that are in the near-fields of each other. As stated, the near-field is an area around the antenna in which electromagnetic fields exist but may not propagate or radiate away from the antenna. They are typically confined to a volume that is near the physical volume of the antenna. In the exemplary embodiments of the invention, magnetic type antennas such as single and multi-turn loop antennas are used for both transmit (Tx) and receive (Rx) antenna systems since magnetic near-field amplitudes tend to be higher for magnetic type antennas in comparison to the electric near-fields of an electric-type antenna (e.g., a small dipole). This allows for potentially higher coupling between the pair. Furthermore, "electric" antennas (e.g., dipoles and monopoles) or a combination of magnetic and electric antennas is also contemplated.

[0048] The Tx antenna can be operated at a frequency that is low enough and with an antenna size that is large enough to achieve good coupling (e.g., >-4 dB) to a small Rx antenna at significantly larger distances than allowed by far field and inductive approaches mentioned earlier. If the Tx antenna is sized correctly, high coupling levels (e.g., -1 to -4 dB) can be achieved when the Rx antenna on a host device is placed within a coupling-mode region (i.e., in the near-field) of the driven Tx loop antenna.

[0049] Fig. 8 shows a flowchart detailing process 800 in accordance with the described embodiments. Process 800 can begin at 802 by creating a first coupling mode region of an electromagnetic field within a near field of a power supply transmit antenna. Next at 804, the electromagnetic field and a receiver antenna of a first receiver device are coupled with the coupling mode region. At 806, a second coupling mode region of the electromagnetic field different from the first coupling mode region is created with a near field of a transmit antenna of the first receiver device. At 808, the electromagnetic field is coupled to a receive antenna of second receiver device in the near field of the transmit antenna of the first receiver device. At

810, power is wirelessly delivered from the power supply to the first receiver device by way of the power supply transmit antenna using the first coupling mode region of the electromagnetic field. At 812, at least some of the power wirelessly delivered to the first receiver device is wirelessly re-transmitted to the second receiver device by way of the first receiver transmit antenna using the second coupling mode region of the electromagnetic field.

WHAT IS CLAIMED IS:

1. A wirelessly powered local computing environment, the local computing environment including a near field magnetic resonance wireless power supply arranged to use a resonance channel to transfer useable energy to resonance circuits within a near field distance D, the distance D defining an outermost range of the NFMR power supply, comprising:

a central processing unit, the central processing unit providing processing resources to the NFMR power supply; and

a plurality of peripheral devices each having a tunable resonance circuit suitably adapted to receive power wirelessly from the NFMR power supply, wherein when at least one of the plurality of devices is within range of the NFMR power supply, the device tunes the resonance circuit to at least one of the resonance frequencies of the NFMR power supply and subsequently de-tunes the resonance circuit to provide a device identification to the NFMR power supply using a change in a resonance circuit load factor.

2. The local computing environment as recited in claim 1, wherein at least one of the peripheral devices includes a re-resonator circuit, the re-resonator circuit arranged to wirelessly provide a portion of the power received by the peripheral device from the NFMR power supply to at least one other peripheral client device.

3. A battery charging circuit, comprising:

a first node arranged to receive wirelessly provided power;

a short term charge storage device having a first charge capacity; and

a long term storage device having a second charge capacity, wherein the second charge capacity is substantially greater than the first charge capacity, wherein the long term storage device is charged by,

(A) storing charge corresponding to the power wirelessly received at the first node into the short term charge storage device,

(B) when the stored charge is equal to about the first charge capacity, then passing the stored charge from the short term storage device to the long term storage device, and

(C) repeating (A) and (B) until the charge stored in the long term storage device is about equal to the second charge capacity.

4. The circuit as recited in claim 3, wherein the short term charge storage device is an ultracapacitor and wherein the long term charge storage device is a LiPO battery.

5. A method of wirelessly transmitting power, comprising:

creating a first coupling mode region of an electromagnetic field within a near field of a power supply transmit antenna;

coupling the electromagnetic field and a receiver antenna of a first receiver device within the coupling mode region;

creating a second coupling mode region of the electromagnetic field different from the first coupling mode region within a near field of a transmit antenna of the first receiver device;

coupling the electromagnetic field to a receive antenna of second receiver device in the near field of the transmit antenna of the first receiver device;

wirelessly delivering power from the power supply to the first receiver device by way of the power supply transmit antenna using the first coupling mode region of the electromagnetic field; and

wirelessly delivering at least some of the power wirelessly delivered to the first receiver device is wirelessly by re-transmitting the at least some power to the second receiver device by way of the first receiver transmit antenna using the second coupling mode region of the electromagnetic field.

6. The method as recited in claim 5, wherein the first receiver device is a keyboard.

7. The method as recited in claim 6, wherein the second receiver device is a mouse.

8. The method as recited in claim 7, wherein the power supply is included in a host computing device.

9. The method as recited in claim 8, wherein the second coupling mode region is between the keyboard and the mouse.

10. The method as recited in claim 9, wherein the first coupling mode region is between the host computing device and the keyboard.

11. The method as recited in claim 9, wherein the first coupling mode region is between the host computing device and the mouse.

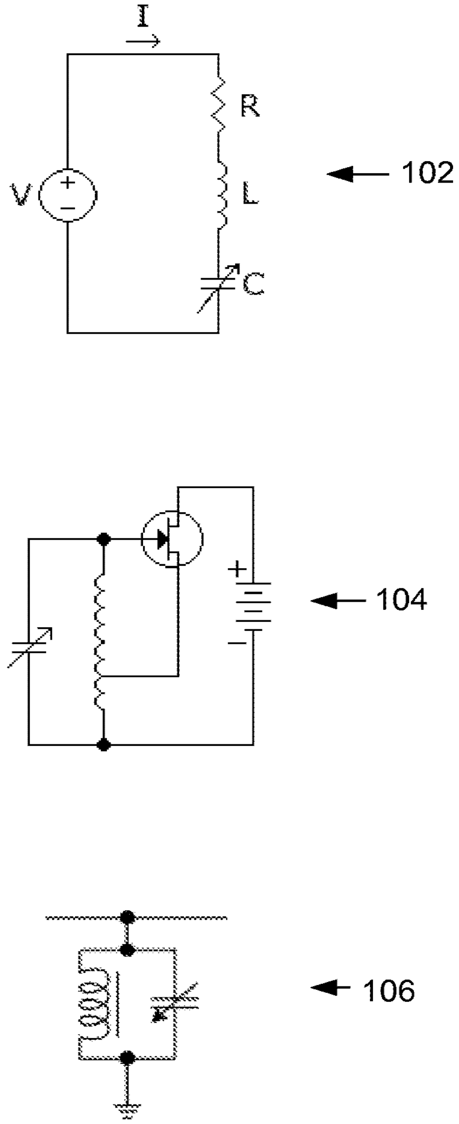

Fig. 1

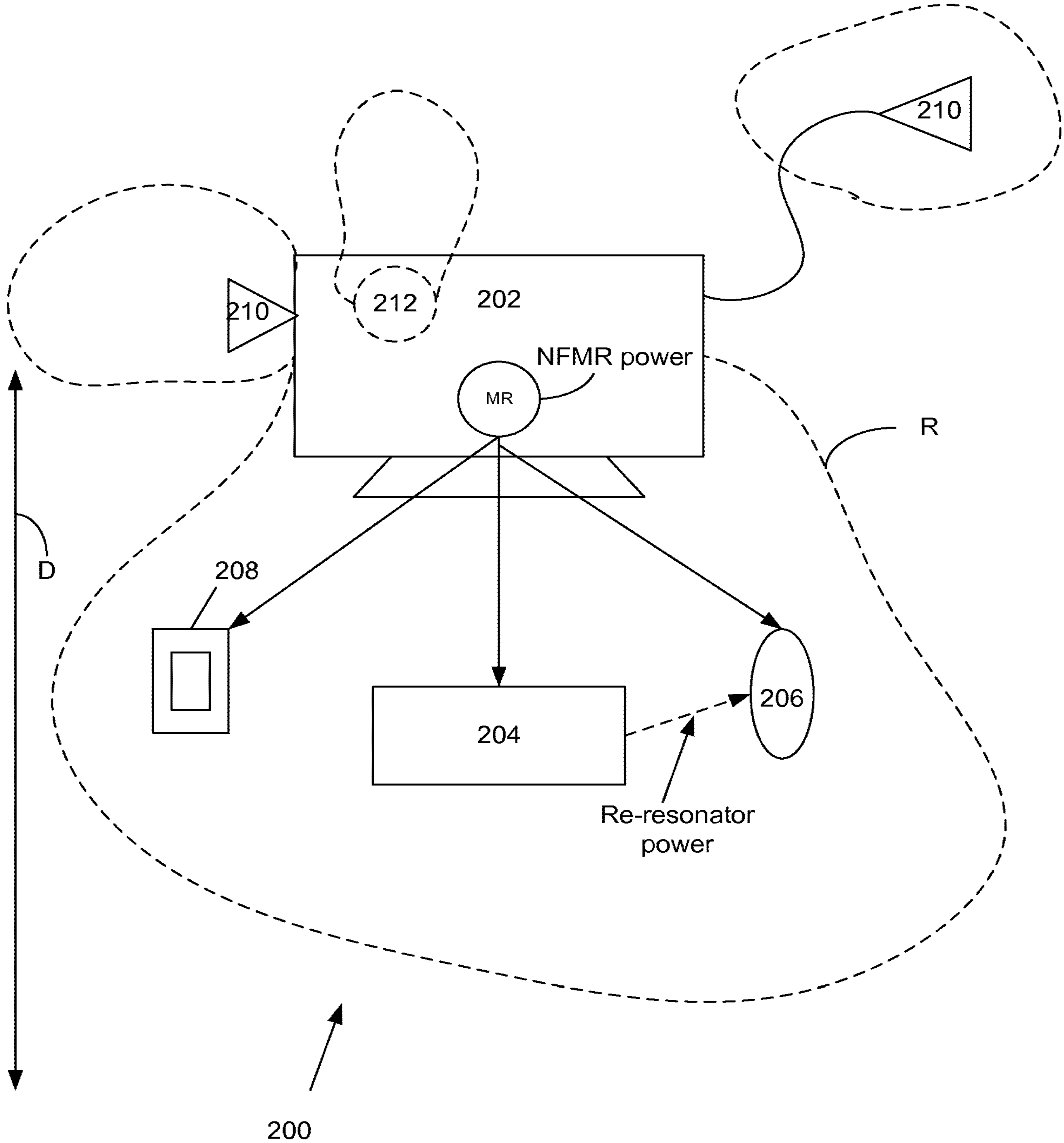
210
210
212
202
NFMR power
MR
R
D
208
204
206
Re-resonator
power
200

Fig. 2

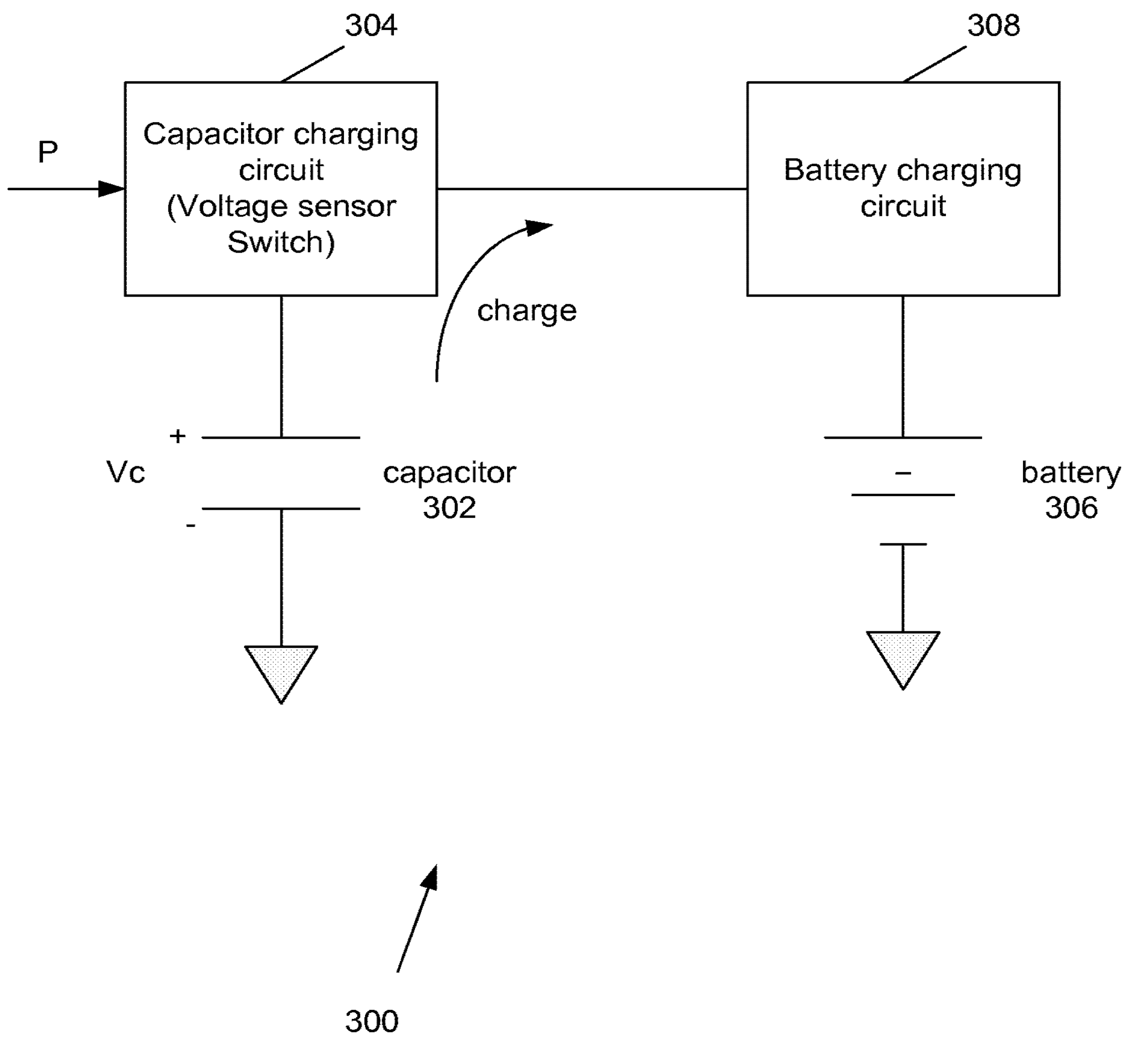
304
308
P
Capacitor charging circuit (Voltage sensor Switch)
Battery charging circuit
charge
+
Vc
-
capacitor 302
–
battery 306
300

Fig. 3

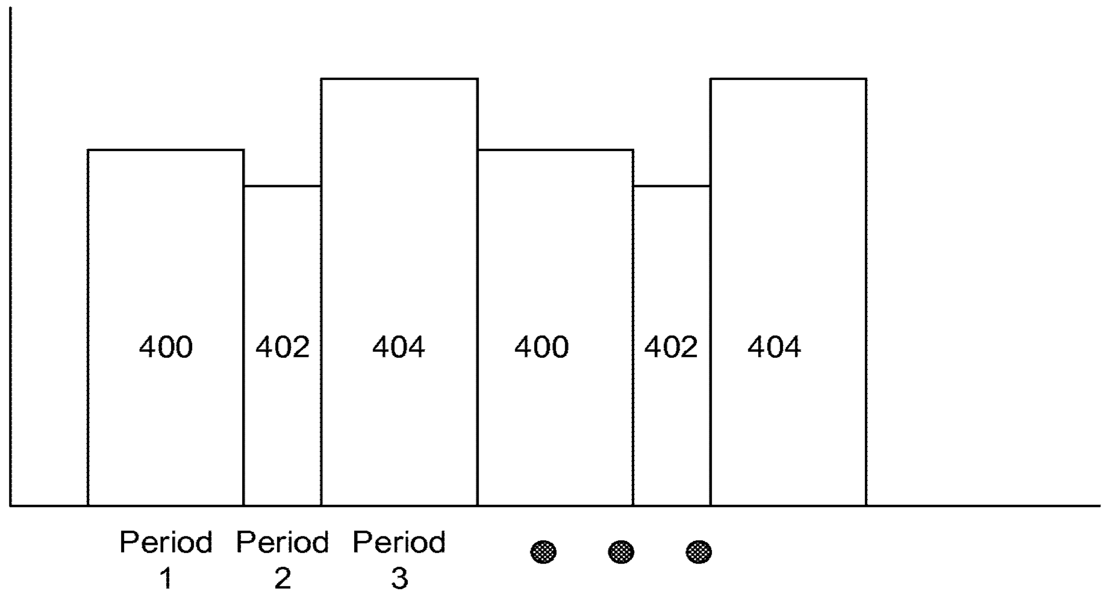

Fig. 4

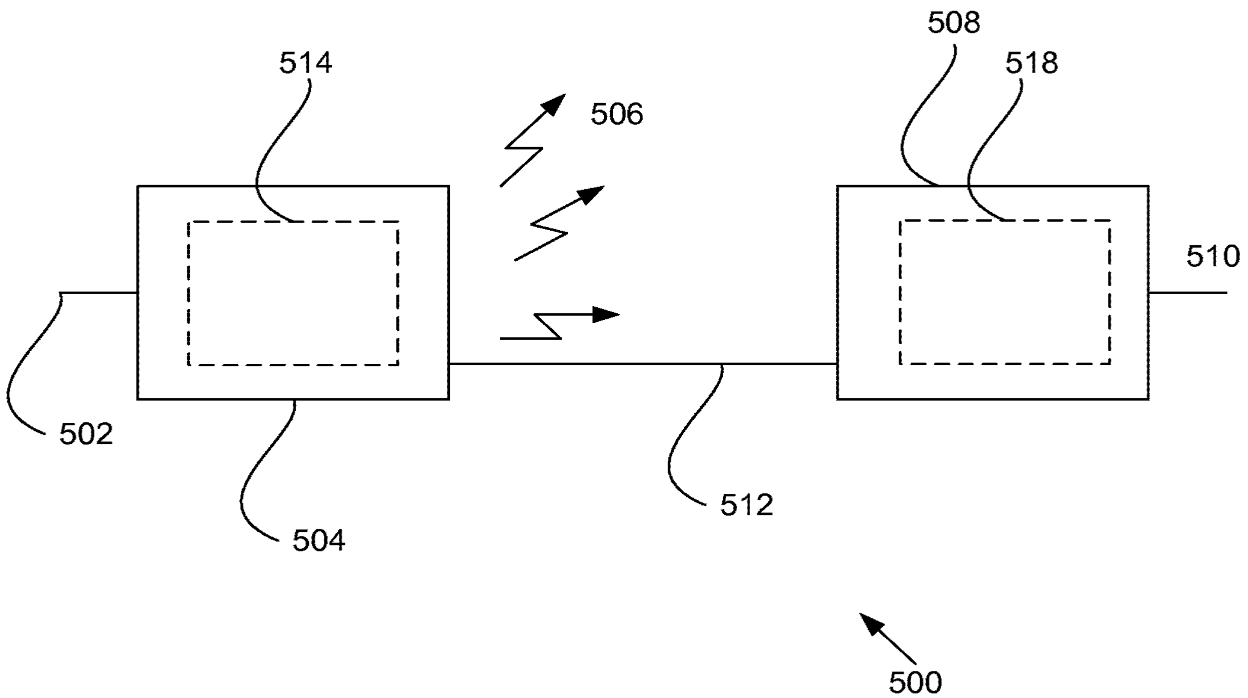

Fig. 5

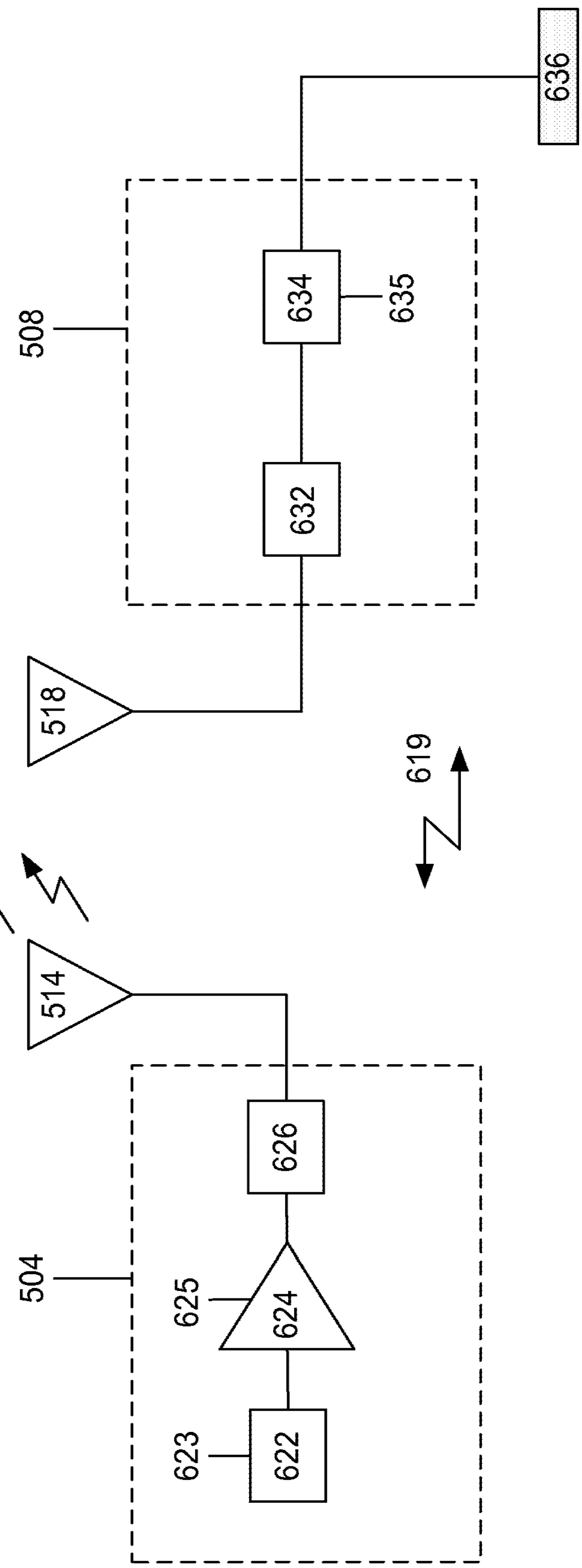

Fig. 6

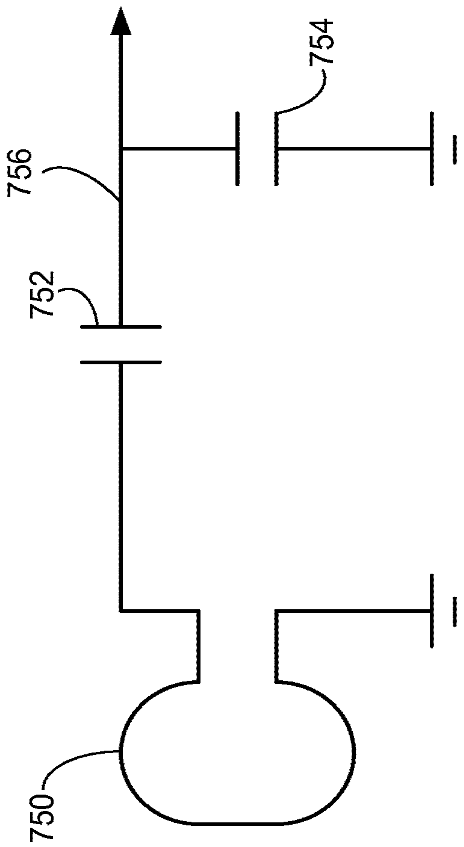

Fig. 7

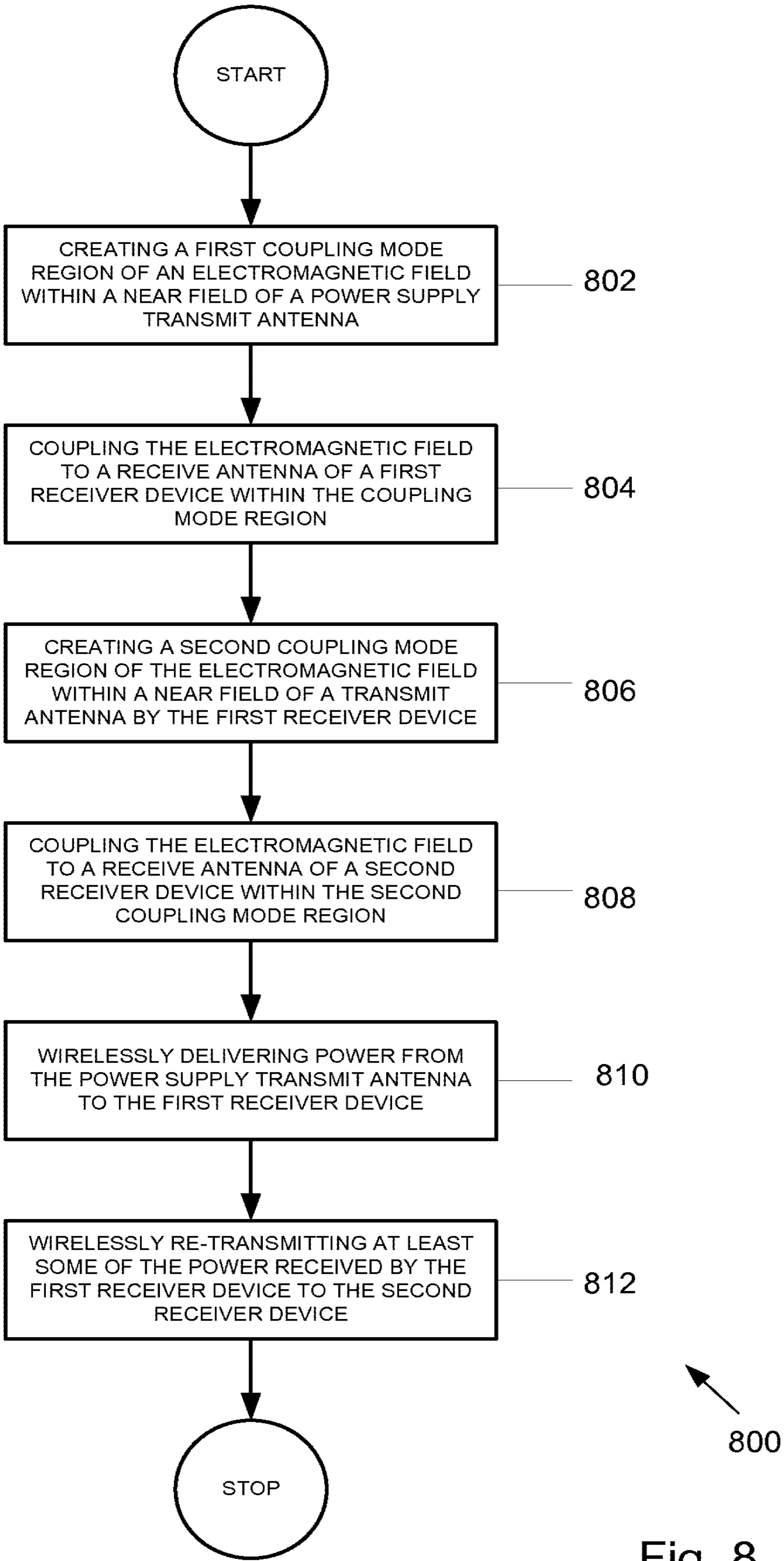
START
CREATING A FIRST COUPLING MODE REGION OF AN ELECTROMAGNETIC FIELD WITHIN A NEAR FIELD OF A POWER SUPPLY TRANSMIT ANTENNA
802
COUPLING THE ELECTROMAGNETIC FIELD TO A RECEIVE ANTENNA OF A FIRST RECEIVER DEVICE WITHIN THE COUPLING MODE REGION
804
CREATING A SECOND COUPLING MODE REGION OF THE ELECTROMAGNETIC FIELD WITHIN A NEAR FIELD OF A TRANSMIT ANTENNA BY THE FIRST RECEIVER DEVICE
806
COUPLING THE ELECTROMAGNETIC FIELD TO A RECEIVE ANTENNA OF A SECOND RECEIVER DEVICE WITHIN THE SECOND COUPLING MODE REGION
808
WIRELESSLY DELIVERING POWER FROM THE POWER SUPPLY TRANSMIT ANTENNA TO THE FIRST RECEIVER DEVICE
810
WIRELESSLY RE-TRANSMITTING AT LEAST SOME OF THE POWER RECEIVED BY THE FIRST RECEIVER DEVICE TO THE SECOND RECEIVER DEVICE
812
STOP
800

Fig. 8

Espacenet

Bibliographic data: DE10029147 (A1) — 2001-12-20

Installation for supplying toys with electrical energy, preferably for production of light, comprises a sender of electromagnetic waves which is located at a small distance above a play area with the toys

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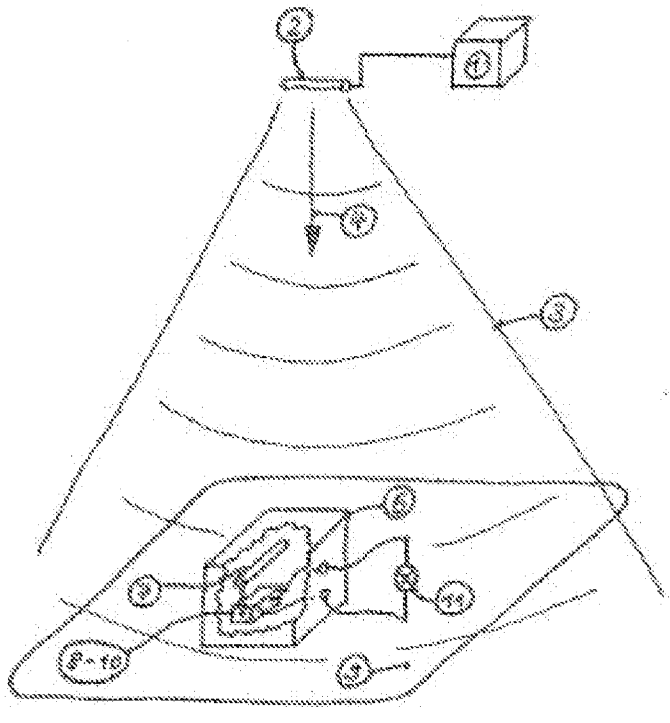
Classification:
- **international:** ***A63H17/28; A63H19/20; H02J17/00;*** (IPC1-7): A63H17/00; A63H17/28; A63H19/20; H02J17/00
- **Euro:** A63H17/28; A63H19/20; H02J17/00

Application number: DE20001029147 20000614

Priority number(s): DE20001029147 20000614

Abstract of DE10029147 (A1)

The installation for supplying toys with electrical energy, preferably for production of light, comprises a sender of electromagnetic waves which is located at a small distance above a play area with the toys provided with appropriate receiver antennas and electronic energy conversion circuits.



Last updated: 24.09.2012 Worldwide Database 5.7.44.2; 92p

(19) BUNDESREPUBLIK DEUTSCHLAND

DEUTSCHES PATENT- UND MARKENAMT

(12) **Offenlegungsschrift**

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A 63 H 17/00

(21) Aktenzeichen: 100 29 147.3
(22) Anmeldetag: 14. 6. 2000
(43) Offenlegungstag: 20. 12. 2001

DE 100 29 147 A 1

(71) Anmelder:
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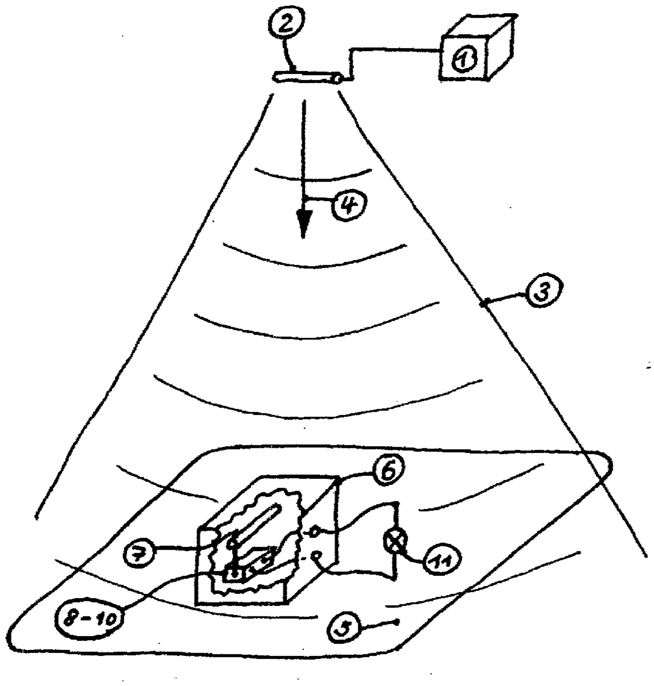
(72) Erfinder:
gleich Anmelder

Die folgenden Angaben sind den vom Anmelder eingereichten Unterlagen entnommen

(54) Anlage zur Versorgung von Spielzeugen mit elektrischer Energie mit Hilfe eines Senders, der elektromagnetische Wellen aussendet, und eines Empfängers mit Antenne

(57) Mit einem Generator 1 und einer Antenne 2 wird ein Sendesignal erzeugt, das eine Modellfläche 5 bestrahlt. Auf der Modellfläche stehen Spielzeuge, in denen sowohl die Empfangsantennen 7 als auch je eine nachgeschaltete Elektronik integriert sind. Die Sendeenergie wird von der Empfangsantenne empfangen und entweder direkt an Glühlampen 11 weitergeleitet, um diese zum Leuchten zu bringen, oder über die nachgeschaltete Elektronik, bestehend aus dem Empfänger-Eingangskreis 8, dem Gleichrichter 9 und der Anpaßelektronik 10, an die Licht emittierenden Dioden 11 weitergegeben, um diese zum Leuchten anzuregen.



DE 100 29 147 A 1

Beschreibung

[0001] Die Erfindung betrifft eine Anlage zur drahtlosen Versorgung von Spielzeugen mit elektrischer Energie, die mit Hilfe eines Senders elektromagnetische Wellen überträgt, die von einem Empfänger mit einer Antenne empfangen wird, und die eine Lichtquelle zum Leuchten bringt. Wichtig bei dieser Art der Versorgung ist, dass die Spielzeuge selbst keine eigene Stromversorgung, wie Batterien, Akkumulatoren o. ä., benötigen, und dass die Versorgung ortsunabhängig erfolgt. Eine weitere wesentliche Besonderheit dieser Versorgungsart ist die einfache Erzeugung des Sendesignals durch einen Funktionsgenerator mit einer einstellbaren Frequenz. Der Antenneneingang des Empfängers ist auf die vorgegebene Frequenz optimiert.

[0002] Die drahtlose Energieübertragung mittels eines Wechselfeldes ist grundsätzlich aus EP-B1-91-971 bekannt. Bei einer derartigen Anlage wird das Magnetfeld in parallel zu einer Fahrstrecke geführten Stableitern erzeugt, wodurch Fahrspielzeuge geleitet werden können.

[0003] Es wird ein weiteres Verfahren beschrieben, in dem "Steuersignale" über ein Sender/Empfänger-System übertragen werden (DE 39 03 535 A1). Diese Steuersignale werden über eine Luftspule als Sender und einer Empfängerspule auf das Spielzeug übertragen, dann aber mit relativ aufwendigen Mitteln (Bandfilter, Mikroprozessor, Signalformer usw.) für die Steuerung des Spielzeuges genutzt. Die Spielzeuge ihrerseits werden mit externen Spannungsquellen betrieben.

[0004] Ein weiteres Verfahren der drahtlosen Energieübertragung mittels induzierter Spannungen wird in der Patentanmeldung 100 24 648.6 beschrieben.

[0005] Alle diese Verfahren nutzen für die Übertragung von Energie oder Informationen das Prinzip der Induktion.

[0006] Der Erfindung liegt daher die Aufgabe zugrunde, in einem abgegrenzten Spielbereich, der Modellfläche, mit Hilfe eines in der räumlichen Nähe (im Meter-Bereich) des Spielbereiches angeordneten Senders über eine Sendeantenne Energie zu den in einem Spielzeug integrierten elektrischen Verbraucher zu übertragen. Die Spielzeuge brauchen dabei nicht über eigene Spannungsquellen zu verfügen. Die Energie wird vorzugsweise für die Beleuchtung der Spielzeuge genutzt.

[0007] Bei Nutzung heutiger Technik, z. B. low-current-LEDs (lichtemittierende Dioden), werden für den Betrieb einer LED nur noch ca. 2 mW benötigt. Bei einer erzielten Spannung von nur ca. 2 V kann eine low-current-LED schon mit einem Strom von 1 mA betrieben werden. Wenn es sich um eine rote LED handelt, kann diese Licht z. B. in einem Miniaturauto als Rücklicht genutzt werden. Das Licht kann mit einem passiven Lichtleiter (z. B. bestehend aus Acrylglas) an jeden gewünschten Ort gelenkt werden.

[0008] Zur Lösung dieser Aufgabe werden die mit Anspruch 1–11 gekennzeichneten Merkmale und Maßnahmen vorgeschlagen. Der Gegenstand der Erfindung ist nachstehend anhand eines Ausführungsbeispieles, das in der Zeichnung schematisch veranschaulicht ist, erläutert. In der Zeichnung zeigen:

[0009] **Fig.** 0 Übersicht, Prinzipbild;

[0010] **Fig.** 1 Anordnung des Senders relativ zur Spielfläche;

[0011] **Fig.** 2 Schematische Darstellung des Empfängers;

[0012] **Fig.** 3 Ausführungsbeispiel der Umsetzung der empfangenen Energie in Licht.

[0013] Bei dem nachstehend aufgeführten Ausführungsbeispiel dient die erfindungsgemäße Anordnung der drahtlosen Versorgung eines Spielzeuges mit Energie, die z. B. zum Betreiben einer Lichtquelle genutzt wird.

[0014] Dazu wird nach **Fig.** 1 eine Antenne **2** voh einem Generator **1** mit einem Sendestrom mit einer vorgegebenen Frequenz betrieben, so dass eine Modellfläche **5** gleichmäßig aus Richtung **4** bestrahlt wird. Auf der Modellfläche **5** wird wie in **Fig.** 2 angedeutet, ein Spielzeug **6** angeordnet, in dem eine komplette Empfängereinheit eischließlich der Empfangsantenne **7**, integriert ist. Diese Empfängereinheit besteht aus einer Empfangsantenne **7**, und einer nachgeschalteten Elektronik, die wiederum aus dem Antennen-Eingangskreis **8**, dem Gleichrichter **9** und der Anpaßelektronik **10** besteht. An dieser Anpaßelektronik sind die Lichtquellen **11** angeschlossen. In **Fig.** 3 wird noch einmal gezeigt, wie in dem Ausführungsbeispiel die Umwandlung Sendeenergie in Licht erfolgt. Die in der Antenne **7** aufgenommenen Energie wird an die nachgeschaltete Elektronik weitergegeben. Eine Anpaßelektronik **8** mit Schwingkreis (L1, L2, C) sorgt dafür, dass die Spannung bzw. der Strom die angeschlossene Lichtquelle **11** nicht überlastet. In einem einfachen Fall reicht für das Betreiben einer Licht emittierenden Diode ein angepaßter Vorwiderstand aus. Dazu muß die Sendeleistung des Generators **1** aus **Fig.** 1 so geregelt werden, daß die empfangene Energie gleichgerichtet wird und an den Anschlüssen des Gleichrichters **9** konstant bleibt. Es sind aber auch weitere Ausführungen der Anpaßelektronik denkbar, wie z. B. das Einführen einer Zenerdiode zur Spannungsstabilisierung und/oder das Einführen eines Speicherkondensators zum Überbrücken von Spannungsschwankungen.

[0015] Bei ausreichender Leistungsübertragung reicht auch der direkte Anschluß einer Glühlampe an die Kontakte des Antennen-Eingangskreises **8** aus. In diesem Falle wird der Gleichrichter **9** und die Anpaßelektronik **10** nicht gebraucht.

Figurenlegende

1 Generator zur Versorgung der Sendeantenne
2 Sendeantenne
3 Durch den Sender verursachter Strahlenkegel und bestrahlte Fläche
4 Abstrahlrichtung des Senders
5 Spielfläche/Modellfläche
6 Spielzeug
7 Empfangsantenne
8 Gleichrichter
9 Anpaßelektronik
10 Lichtquelle

Patentansprüche

1. Anlage zur Versorgung von Spielzeugen mit elektrischer Energie, vorzugsweise zur Erzeugung von Licht, bestehend aus einem Sender, der ein Signal mit einer bestimmten Frequenz aussendet und mdst. einem mit einen Empfänger ausgerüsteten Spielzeug, **dadurch gekennzeichnet**, dass der Sender aus einem geringen Abstand (vorzugsweise im Meter-Bereich) auf eine Modellfläche gerichtet wird, und dass die auf dieser Fläche positionierten und mit je einem Empfänger versehenen Spielzeuge die vom Sender abgestrahlte Energie über eine Antenne aufnehmen und diese aufgenommene Sendeenergie mittels einer elektronischen Schaltung in Licht umwandeln.

2. Anlage nach Anspruch 1, dadurch gekennzeichnet, dass das Sendesignal eine in der Frequenz einstellbare Schwingung mit regelbarer Amplitude ist, die von einem Generator erzeugt wird.

3. Anlage nach Anspruch 1, dadurch gekennzeichnet, dass die Schwingung vorzugsweise eine Sinusschwin-

gung ist.

4. Anlage nach Anspruch 1 und einem der folgenden, dadurch gekennzeichnet, dass die Sendefrequenz abhängig von der Größe der mechanischen Ausmaße der Spielzeuge, in die die Empfangsantenne integriert ist, gewählt wird.

(Bei Spielzeugen, die eine Größe von wenigen cm haben, ist wegen der optimalen Antennengröße eine Sendefrequenz im GHz-Bereich notwendig).

5. Anlage nach Anspruch 1 und einem der folgenden, dadurch gekennzeichnet, dass die Empfindlichkeit des Empfängers auf das Sendesignal maximal abgestimmt ist.

6. Anlage nach Anspruch 1 und einem der folgenden, dadurch gekennzeichnet, dass der Sender so dimensioniert ist, dass er im wesentlichen nur an die auf der Modellfläche gestellten Spielzeuge Energie sendet.

7. Anlage nach Anspruch 1 und einem der folgenden, dadurch gekennzeichnet, dass der komplette Empfänger, einschließlich der Antenne mit nachgeschalteter Elektronik, im Spielzeug integriert wird.

8. Anlage nach Anspruch 1 bis 7, dadurch gekennzeichnet, dass die aufgenommene Energie mit einem Speicher (z. B. Speicherkondensatoren, sog. gold caps, oder Akkumulatoren) zwischengespeichert, bzw. gepuffert wird, so dass kurzzeitige Unterbrechungen der Energieübertragung überbrückt werden können.

9. Anlage nach Anspruch 1 bis 7, dadurch gekennzeichnet, dass durch Ein- und Ausschalten des Sendesignals der Eindruck einer blinkenden Lichtquelle entsteht.

10. Anlage nach Anspruch 1 und einem der folgenden, dadurch gekennzeichnet, dass das Licht der Lichtquelle mit Lichtleitern (z. B. speziell gewinkeltes Acrylglas) an die Stellen des Spielzeuges gelenkt wird, an denen das Licht erscheinen soll.

11. Anlage nach Anspruch 1 und einem der folgenden, dadurch gekennzeichnet, dass auch andere Aggregate/Komponenten als eine Lichtquelle, z. B. Relais, Motoren usw., mit Hilfe der übertragenen elektrischen Energie betrieben werden.

Hierzu 2 Seite(n) Zeichnungen

- Leerseite -

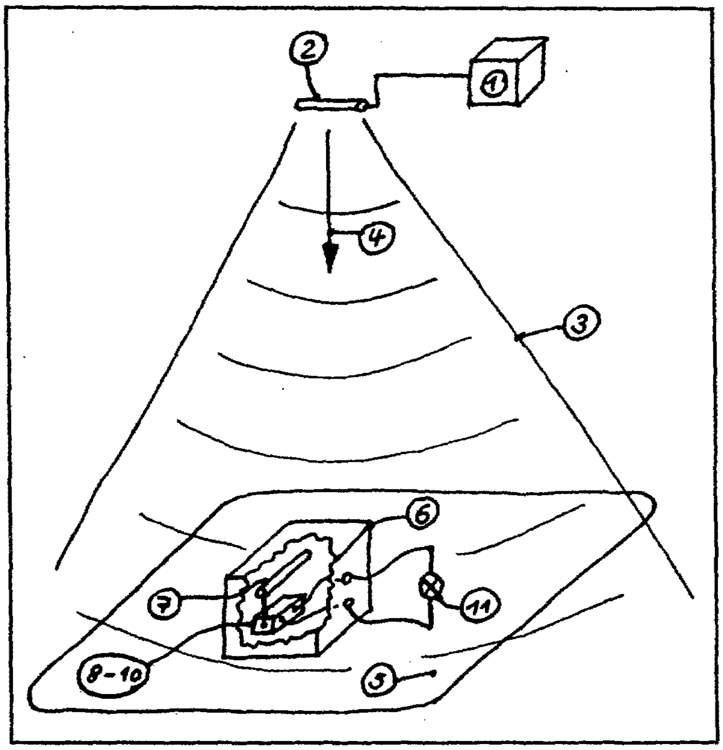


Fig. 0 Übersicht, Prinzipbild

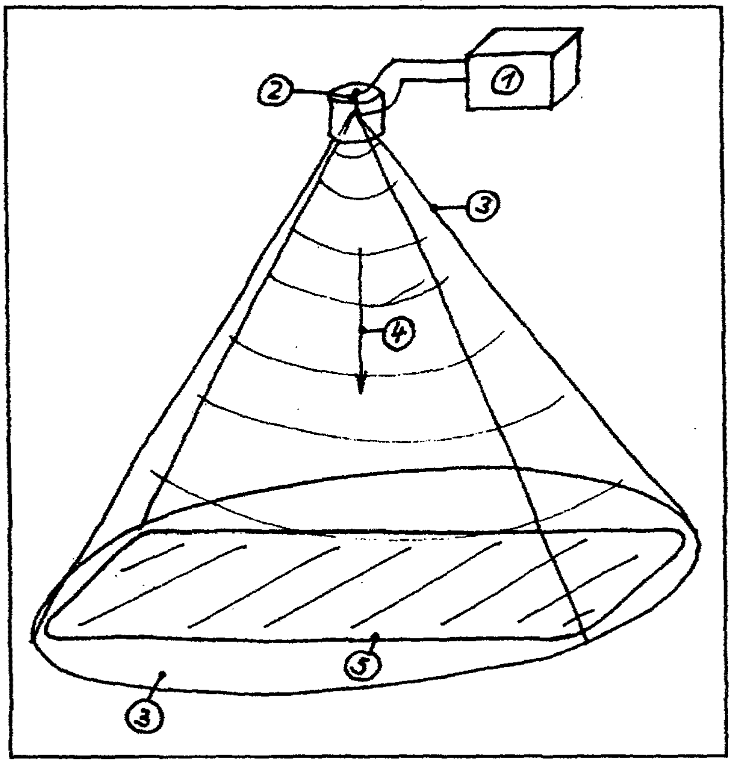


Fig. 1 Anordnung des Senders relativ zur Spielfläche

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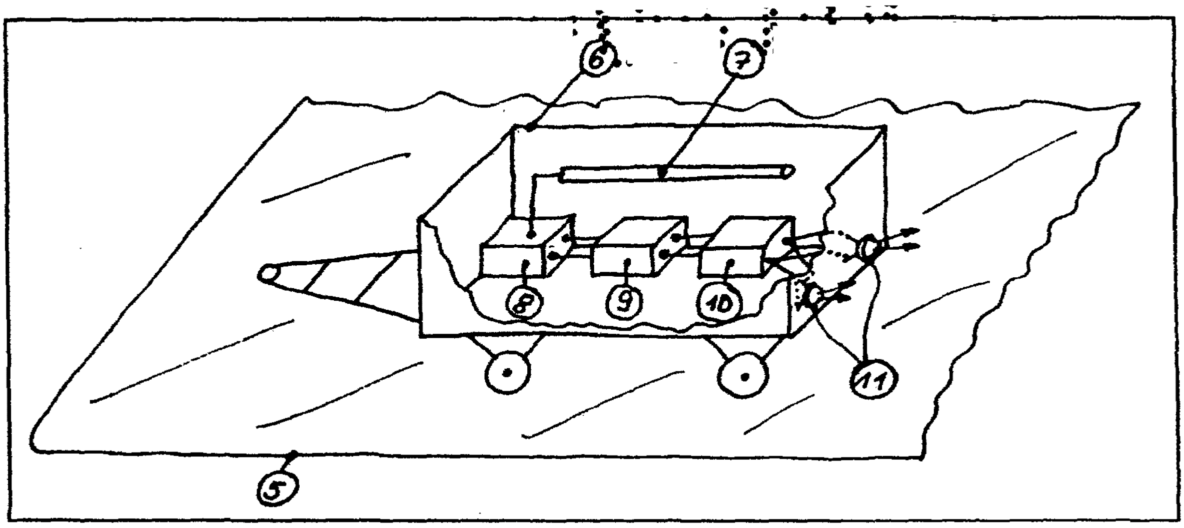


Fig.2 Schematische Darstellung eines Empfängers

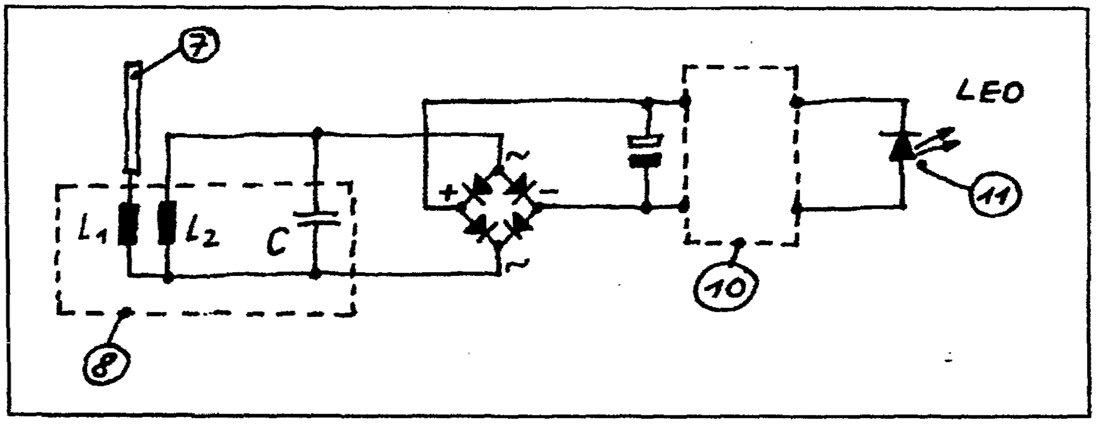


Fig. 3 Ausführungsbeispiel der Umsetzung der empfangenen Energie in Licht

Espacenet

Bibliographic data: JP2002010535 (A) — 2002-01-11

NON-CONTACT POWER TRANSMISSION DEVICE

Inventor(s): ABE HIDEAKI; KAWAMOTO MINORU; MUTO MOTOHARU ± (ABE HIDEAKI, ; KAWAMOTO MINORU, ; MUTO MOTOHARU)

Applicant(s): MATSUSHITA ELECTRIC WORKS LTD ± (MATSUSHITA ELECTRIC WORKS LTD)

Classification: - **international:** ***H01F38/14; H02J1/00; H02J17/00; H02M3/28; H02M3/335;*** (IPC1-7): H01F38/14; H02J1/00; H02J17/00; H02M3/28; H02M3/335
- **cooperative:**

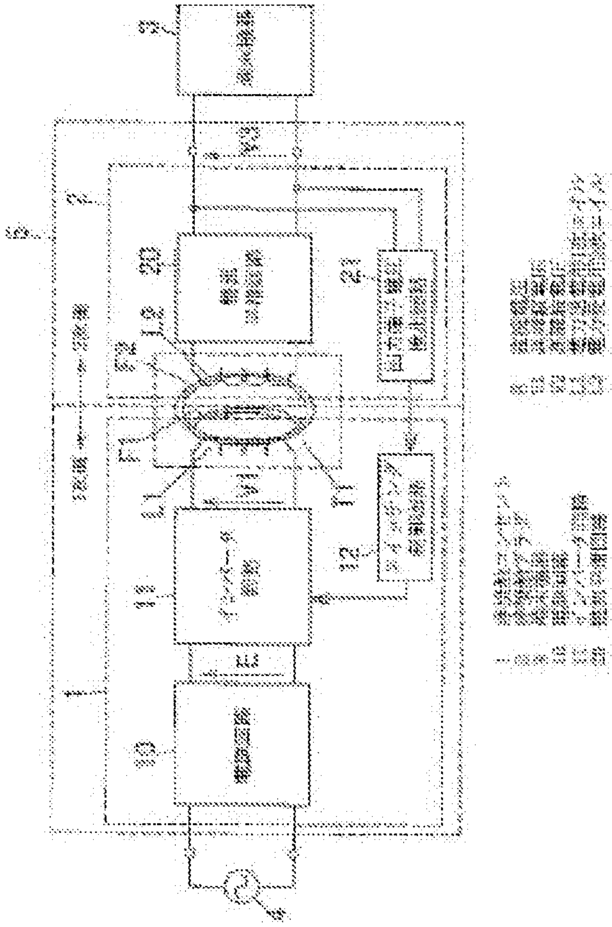
Application number: JP20000193404 20000627

Priority number(s): JP20000193404 20000627

Also published as: JP4135299 (B2)

Abstract of JP2002010535 (A)

PROBLEM TO BE SOLVED: To provide a non-contact power transmission device capable of stabilizing output terminal voltage to a constant value in a wide load range. SOLUTION: This non-contact power transmission device consists of a non- contact receptacle 1 including, a power circuit 10 outputting a DC voltage E and an inverter circuit 11 generating a const frequency high-frequency voltage V1 by inputting the DC voltage E and switching a semiconductor switch and a primary coil L1 for power transmission to which is supplied the high-frequency voltage V1 from the inverter circuit 11,; a non-contact plug 2 including a secondary coil L2 for receiving power in which a high-frequency voltage V2 is induced by the primary coil L1 for power transmission and a rectifying and smoothing circuit 20 rectifying and smoothing the high frequency voltage V2 induced in the secondary coil L2 for receiving power, and a terminal apparatus 3 connected to the output terminal of the non-contact plug 2 to server as a load, and conducts thinning-out control for thinning out the high-frequency voltage V1 of constant frequency supplied to the primary coil L1 for power transmission from the inverter circuit 11.



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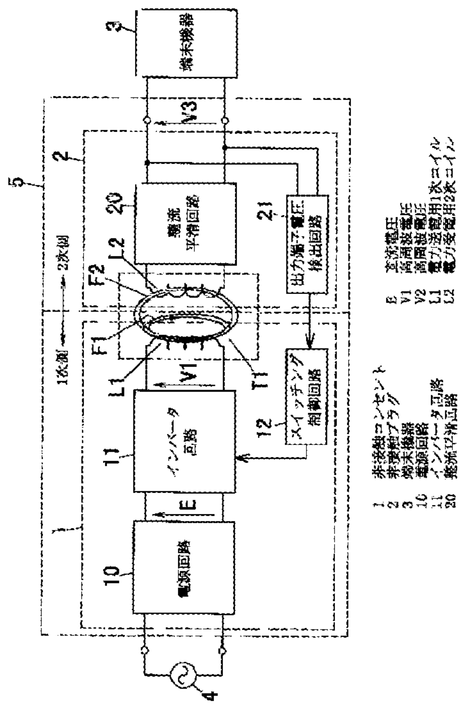
(54)【発明の名称】　非接触電力伝達装置

(57)【要約】
【課題】　広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供する
【解決手段】直流電圧Ｅを出力する電源回路１０と直流電圧Ｅを入力して半導体スイッチをスイッチングさせることで一定周波数の高周波電圧Ｖ１を発生させるインバータ回路１１とインバータ回路１１から高周波電圧Ｖ１を供給される電力送電用１次コイルＬ１とを含む非接触コンセント１と、電力送電用１次コイルＬ１から高周波電圧Ｖ２を誘起される電力受電用２次コイルＬ２と電力受電用２次コイルＬ２に誘起される高周波電圧Ｖ２を整流平滑する整流平滑回路２０とを含む非接触プラグ２と、非接触プラグ２の出力端子に接続され負荷となる端末機器３とから構成し、インバータ回路１１より電力送電用１次コイルＬ１に供給される一定周波数の高周波電圧Ｖ１を間引く間引き制御を行う。



【特許請求の範囲】
【請求項１】　直流電圧を出力する電源回路と前記直流電圧を一定周波数の高周波電圧に変換するインバータ回路と前記インバータ回路から前記高周波電圧を供給される電力送電用１次コイルとから構成される非接触コンセントと、前記電力送電用１次コイルと分離着脱自在なトランス構造を構成して高周波電圧を誘起される電力受電用２次コイルと前記電力受電用２次コイルに誘起される高周波電圧を整流平滑する整流平滑回路とから構成される非接触プラグと、前記非接触プラグの出力端子に接続され負荷となる端末機器とから構成される非接触電力伝達装置において、前記非接触コンセントは、対象としている負荷領域に対する前記非接触プラグの出力端子電圧を、前記インバータ回路より前記電力送電用１次コイルに供給される高周波電圧を間引いて安定化させる間引き制御を行う制御手段を備えることを特徴とする非接触電力伝達装置。
【請求項２】　前記制御手段は、非接触プラグの出力端子電圧が所定の電圧を上回った場合には、インバータ回路から電力送電用１次コイルへの高周波電圧の供給を一定時間間引き、前記一定時間間引きを行った後非接触プラグの出力端子電圧が前記所定の電圧を上回っていれば再び電力送電用１次コイルへの前記高周波電圧の供給を一定時間間引くことを繰り返し、前記各一定時間間引きを行った後で非接触プラグの出力端子電圧が所定の電圧を下回った場合には、非接触プラグの出力端子電圧が所定の電圧を上回るまで電力送電用１次コイルへの前記高周波電圧の供給を連続的に行う動作を継続させることを特徴とする請求項１記載の非接触電力伝達装置。
【請求項３】　非接触プラグは、非接触プラグ内部の電気状態を表す情報を磁気信号に変換して非接触コンセントに伝送し、前記制御手段は、前記磁気信号に基づいて間引き制御のための制御信号を形成し、前記制御信号によりインバータ回路を間引き制御することを特徴とする請求項１または２記載の非接触電力伝達装置。
【請求項４】　インバータ回路は、ハーフブリッジ型の部分共振インバータであることを特徴とする請求項１乃至３いずれか記載の非接触電力伝達装置。
【請求項５】　電力受電用２次コイルはセンタータップを備え、整流平滑回路は、電力受電用２次コイルのセンタータップではない両出力端に直列に且つ互いに逆方向に接続する整流素子の電力受電用２次コイルに接続していない各他端同士を接続した全波整流部を有し、前記整流素子の接続中点にチョークコイルを接続することを特徴とする請求項４記載の非接触電力伝達装置。
【請求項６】　電力受電用２次コイルに並列にコンデンサを接続することを特徴とする請求項１乃至５いずれか記載の非接触電力伝達装置。
【請求項７】　前記コンデンサの静電容量値は、対象とする負荷領域の最大負荷時において、電力送電用１次コイルに供給される高周波電圧の極性反転時期と、前記コンデンサの両端に発生する振動電圧が極大値または極小値となる時期とが一致する静電容量値であることを特徴とする請求項６記載の非接触電力伝達装置。
【請求項８】　非接触コンセントに１次側信号受信コイルを設け、非接触プラグには前記１次側信号受信コイルに対向配置され前記１次側信号受信コイルと分離着脱自在なトランス構造を構成する２次側信号送信コイルを設け、前記２次側信号送信コイルは非接触プラグの内部の電気状態を表す情報を交流電圧に変換した信号を入力され、磁気信号として磁束信号を発生し、前記１次側信号受信コイルは前記磁束信号により電圧を誘起され、前記制御手段はインバータ回路を前記誘起された電圧に基づいた制御信号により前記間引き制御することを特徴とする請求項３乃至７いずれか記載の非接触電力伝達装置。
【請求項９】　電力送電用１次コイルと１次側信号受信コイルとの間、及び電力受電用２次コイルと２次側信号送信コイルとの間の少なくとも一方の間に磁性体からなる磁気シールド用隔壁を設けたことを特徴とする請求項８記載の非接触電力伝達装置。
【請求項１０】　電力送電用１次コイルと電力受電用２次コイルとを、磁性体からなるコアに巻装し、前記コアを互いに前記コアの軸方向に対向配置させたことを特徴とする請求項９記載の非接触電力伝達装置。
【請求項１１】　電力送電用１次コイルと電力受電用２次コイルとを、前記コイルの軸方向に垂直な方向に開口部を有する有底筒型の磁性体からなるコアに巻装し、前記コアを互いに前記コアの軸方向に対向配置させ、前記コアの非開口部の近傍に１次側信号受信コイルと２次側信号送信コイルとを配置したことを特徴とする請求項９記載の非接触電力伝達装置。
【請求項１２】　２次側信号送信コイルは、非接触プラグの内部の電気状態を表す情報を交流電圧に変換した信号を入力されて、電力送電用１次コイルが発生させる磁束とは逆位相の位相を有する磁束信号を発生することを特徴とする請求項８乃至１１いずれか記載の非接触電力伝達装置。
【請求項１３】　２次側信号送信コイルの一方の端子は、電力受電用２次コイルのどちらか一方の端子に接続していることを特徴とする請求項１２記載の非接触電力伝達装置。
【請求項１４】　非接触コンセントは、電力送電用１次コイルの近傍に電力送電用１次コイルと電力受電用２次コイルとの間に発生する磁束を検出する磁束検出用コイルを設け、前記磁束検出用コイルは、磁気信号として電力送電用１次コイルで発生する磁束を検出し、前記磁束検出用コイルから前記検出する磁束に応じて出力される電圧に基づいて前記制御手段は、インバータ回路を間引き制御することを特徴とする請求項３乃至７いずれか記載の非接触電力伝達装置。

【請求項15】 電力送電用1次コイルと電力受電用2次コイルとを、前記コイルの軸方向に垂直な方向に開口部を有する有底筒型の磁性体からなるコアに設けて前記コアを互いに前記コアの軸方向に対向配置させ、前記電力送電用1次コイルのコアの開口部の近傍に前記磁束検出用コイルを配置したことを特徴とする請求項14記載の非接触電力伝達装置。

【請求項16】 一つの非接触コンセントは、出力電圧の異なる複数の非接触プラグに適合し、各非接触プラグが対象としている負荷領域を含む全領域において前記各非接触プラグの出力電圧を所定の電圧範囲内に収める前記制御手段を有することを特徴とする請求項1乃至15いずれか記載の非接触電力伝達装置。

【請求項17】 非接触プラグの出力端子に並列に抵抗を接続することを特徴とする請求項1乃至16いずれか記載の非接触電力伝達装置。

【請求項18】 非接触プラグが非接触コンセントの所定の位置に結合していない場合は、前記制御手段は、インバータ回路から電力送電用1次コイルへ供給する出力を制限することを特徴とする請求項1乃至17いずれか記載の非接触電力伝達装置。

【請求項19】 非接触コンセントはインバータ回路から電力送電用1次コイルへの高周波電圧の供給の制限を制御するスイッチ機能を備え、非接触プラグは前記スイッチ機能のオン オフ状態を制御する駆動体を備え、非接触プラグが非接触コンセントの所定の位置に結合すると前記スイッチ機能を動作させることで前記制御手段はインバータ回路から電力送電用1次コイルへの高周波電圧の供給を可能にすることを特徴とする請求項18記載の非接触電力伝達装置。

【請求項20】 非接触コンセントの前記スイッチ機能が機械接点からなり、非接触プラグが備える駆動体は磁石からなり、非接触プラグが非接触コンセントの所定の位置に結合すると前記磁石の磁力によって前記機械接点が動作して、前記制御手段はインバータ回路から電力送電用1次コイルへの高周波電圧の供給を可能にすることを特徴とする請求項19記載の非接触電力伝達装置。

【請求項21】 非接触プラグが非接触コンセントの所定の位置に結合すると、非接触プラグ及び非接触コンセントの少なくともどちらか一方に使用可能を報知する表示を行うことを特徴とする請求項1乃至20いずれか記載の非接触電力伝達装置。

【請求項22】 非接触コンセント及び非接触プラグの少なくともどちらか一方は、非接触プラグの出力端子に接続された端末機器の負荷電力、及び非接触プラグの出力電圧の少なくともどちらか一方を表示する表示部を付加したことを特徴とする請求項1乃至21いずれか記載の非接触電力伝達装置。

【請求項23】 非接触プラグの出力端子に接続される端末機器は前記非接触プラグに対して、分離着脱自在なことを特徴とする請求項1乃至22いずれか記載の非接触電力伝達装置。

【請求項24】 非接触プラグの出力端子から端末機器への電力の供給は、磁気結合によって供給されることを特徴とする請求項23記載の非接触電力伝達装置。

【請求項25】 非接触プラグの出力端子間に、電圧クランプ素子を接続することを特徴とする請求項1乃至24いずれか記載の非接触電力伝達装置。

【発明の詳細な説明】

【0001】

【発明の属する技術分野】本発明は、非接触電力伝達装置に関するものである。

【0002】

【従来の技術】近年、電磁誘導を利用した非接触電力伝達の実用化が盛んに行われている。これらは負荷が特定されているものが大半であり、複数の負荷を対象としたり、単独負荷であってもその負荷電流が大きく変わる場合の実用化例は見当たらない。非接触電力伝達では電力供給側となる1次側と負荷を持つ2次側との間に電気的絶縁物があり、電力供給側の1次側コイルと負荷側の2次側コイルとで分離着脱できる構造を有するトランスを介して電力を伝達する。図27に前記トランスによる非接触電力伝達装置の従来例1の概略構成図を示す。1次側は、電力供給側の1次側コイルL1の両端に、インバータ回路（本従来例では省略）で生成された可聴域周波数以上である約20KHz以上の高周波電圧V1が印加されて構成され、2次側は、1次側コイルL1との間に磁気結合度Mを有する負荷側の2次側コイルL2と、2次側コイルL2に誘起された電圧を整流する平滑整流回路20と、平滑整流回路20の出力端に接続される負荷である負荷3aとから構成され、1次側コイルL1と2次側コイルL2とで分離着脱できる構造を有する電力送受用トランスT1を構成している。図28は、電力送受用トランスT1の構造を示す。電力を供給する1次側は、磁性材料からなるE型コアA4に設けられた1次側コイルL1を有し、1次側から電力を供給される2次側も同様に磁性材料からなるE型コアA4に設けられた2次側コイルL2を有し、互いに電気的絶縁GAP116を介して対向設置されている。このような分離着脱できる電力送受用トランスT1においては、漏れ磁束F1が生じ、1次側コイルL1と2次側コイルL2との磁気結合度Mは低下する。ここで図29に、図27の回路を2次側に換算した等価回路を示す。2次側コイルL2の誘起電圧を有する電圧源E2の出力に直列に漏れインダクタンスL4が接続され、平滑整流回路20を介して負荷3aに接続される。前述のように磁気結合度Mが低下して1次コイルL1で生じる総磁束の内2次側コイルL2の鎖交磁束F2が少なくなると、漏れ磁束F1による漏れインダクタンスL4が生じる。また、1次側コイルL1の両端に印可される電圧V1は可聴域周波数以上であ

る約２０ＫＨｚ以上の高周波で駆動されるため、磁気結合度Ｍが低く漏れインダクタンスＬ４を有する電力送受用トランスＴ１を介して負荷３ａへ電力を伝達する場合、２次コイルＬ２の誘起電圧即ち、電圧源Ｅ２の電圧は低下し、漏れインダクタンスＬ４による誘導リアクタンスのために電圧降下を起こし、結果として出力端子電圧Ｖ３は低下する。図３０は図２９に示す負荷電流Ｉ３に対する出力端子電圧Ｖ３の特性１１７ａ及び負荷電力Ｐの特性１１８ａを示した図である。出力端子電圧Ｖ３は漏れインダクタンスＬ４による交流インピーダンスのために線形的に低下する。また、負荷電力Ｐは、負荷電流Ｉ３が所定の電圧以下では負荷電流Ｉ３が増加するにしたがって負荷電力Ｐも増加するが、負荷電流Ｉ３が所定の電圧以上になると負荷電流Ｉ３が増加するにしたがって負荷電力Ｐは低下する。このような特性を持つ場合には、一定電圧入力で動作する異なる負荷電流の機器を負荷３ａとして設けた場合、負荷電流Ｉ３が所定の電流値以上では増加するほど、出力端子電圧Ｖ３は低下し、負荷７の定電圧入力条件を外れてしまい、本来の性能を発揮できなくなる。

【０００３】また、非接触電力伝達において非接触充電の場合には２次コイルＬ２に並列または直列にコンデンサを接続して負荷整合による力率改善を行い、前記漏れインダクタンスＬ４の影響を補い２次側で取り出すことのできる有効電力を増加させる場合が多い。図３１の回路図は前記図２７の２次側コイルＬ２に並列にコンデンサＣ２を接続したもので、図３２は図３１の回路を２次側に換算した等価回路を示し、２次側コイルＬ２の誘起電圧を有する電圧源Ｅ２の出力に直列に漏れインダクタンスＬ４が接続され、漏れインダクタンスＬ４を介して電圧源Ｅ２に並列にコンデンサＣ２が接続され、コンデンサＣ２の両端は整流平滑回路２０を介して負荷３ａに接続される。前記コンデンサＣ２を接続することにより電力伝送効率が大幅に向上し、小型化ができる。負荷３ａに充電を行う場合には出力端子電圧Ｖ３は例えば電池電圧となりほぼ一定である。しかし、負荷３ａが定電圧負荷ではない例えば抵抗のような負荷に対しては、図３３の負荷電流Ｉ３に対する出力端子電圧Ｖ３の特性１１７ｂ及び負荷電力Ｐの特性１１８ｂに示すようにコンデンサＣ２が接続されている場合には接続されていない場合に比べて、負荷電流Ｉ３が増加すると出力端子電圧Ｖ３の低下が顕著に見られる。また負荷電力Ｐがピークとなる点Ｋ付近の出力端子電圧Ｖ３の時に最適な負荷整合が行われ、負荷電流Ｉ３がこのＫ点での負荷電流より大きい領域では、出力端子電圧Ｖ３が急速に低下する。負荷電流Ｉ３がＫ点での負荷電流よりも小さい領域でも負荷電流Ｉ３に反比例して出力端子電圧Ｖ３は低下している。そして、負荷電流Ｉ３が非常に小さい領域では出力端子電圧Ｖ３は急に大きくなっている。

【０００４】前述のような特性や特徴を持つ非接触電力伝送において図３４の負荷電流Ｉ３に対する出力端子電圧Ｖ３の特性１１７ｃ及び負荷電力Ｐの特性１１８ｃに示すように、出力端子電圧Ｖ３を、負荷電流Ｉ３の異なる負荷に対して出力端子電圧Ｖ３を対象とする全ての負荷領域で一定として安定化させる方法が望まれる。この安定した特性を得るために通常のスイッチング電源の電圧制御で行われるように、２次側の出力端子電圧Ｖ３を検出し、基準電圧と比較、誤差増幅し、１次側に誤差増幅した信号を非接触で伝送して１次側の駆動電圧振幅、周波数、デューティ及び間引き率を制御するフィードバック制御方法を検討したところ、いずれも従来技術では不都合を生じることが判明した。

【０００５】

【発明が解決しようとする課題】非接触伝送では、通常のスイッチング電源に比べて、漏れ磁束Ｆ１によるノイズが少し多くなることと、負荷整合を施しても回路効率が少し低下することから、１次コイルＬ１に印可される高周波電圧Ｖ１を生成するためのインバータ回路は共振型インバータを採用することが最適である。そして、安定化したい電圧領域で、対象とする最大負荷電流時において最適負荷整合を行うこと、即ち２次側に接続されるコンデンサＣ２の静電容量を、負荷整合を行うのに最適な値に設定することが最良である。

【０００６】ところが、前述の回路方式において無負荷時から全負荷時にわたって出力端子電圧Ｖ３を一定にする安定化を行う場合、不都合がある。２次側に接続した負荷整合用のコンデンサＣ２は、全ての負荷電流領域において接続されているため１次コイルＬ１に印可される高周波電圧Ｖ１を生成するためのインバータ回路が、ＰＷＭ方式及び周波数可変方式では、周波数やデューティ比の変化幅が大きいと回路動作が不安定になる場合がある。これは図３２に示す２次側等価回路に示すように２次側コイルＬ２の誘起電圧を有する電圧源Ｅ２には、漏れインダクタンスＬ４とコンデンサＣ２とが直列に接続された直列共振回路が接続されているため、１次コイルＬ１に印可される高周波電圧Ｖ１の周波数やデューティ比が大きく変化して２次側コイルＬ２に誘起する電圧の周波数やデューティ比が大きく変化すると、前記直列共振回路の動作も大きく変化するためであると考えられる。もし、この影響が無視できたとしても、負荷電流Ｉ３を非常に大きく変化させなければならない時（例えば１００倍の変化幅がある時）には、１次コイルＬ１に印可される高周波電圧Ｖ１の周波数やデューティ比も非常に大きく変化させなければならないため、特に軽負荷、無負荷近辺での制御が回路動作の実用限界を超えて制御不能になる場合がある。

【０００７】また１次コイルＬ１に印可される高周波電圧Ｖ１を生成するためのインバータ回路が、従来の間引き制御を行った場合には、従来の間引き制御は、１次コイルＬ１に印可される高周波電圧Ｖ１を固定周波数で

連続駆動させる中で、出力端子電圧の検出電圧が安定化したい目標電圧を超えた場合にインバータを休止させる制御方法であり、この方法も軽負荷、無負荷近辺において、目標電圧付近で、駆動周波数の1周期にも満たないオン オフ動作が頻繁に行われ、共振型インバータのメリットである低損失のソフトスイッチングが行われず、ハードスイッチングを行ってスイッチング損失が増加すると共に、強いノイズ源となる。

【0008】そしてこれらの制御方式は、従来技術では、2次側の出力端子電圧V3などの情報は光信号を利用したフォトカプラを介して、1次側のインバータ回路の駆動電圧振幅、周波数、デューティ比及び間引き率を制御するフィードバック制御であった。しかし、非接触電力伝達装置においては、浴室や屋外などの水まわりや汚れの多いところ悪環境で使われる場合にそのメリットが出るため、まわりの明るさや、汚れ等の影響を受ける光信号を利用する技術手段は採用が難しい。

【0009】本発明は、上記事由に鑑みてなされたものであり、その目的は、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することにある。

【0010】

【課題を解決するための手段】請求項1の発明は、直流電圧を出力する電源回路と前記直流電圧を一定周波数の高周波電圧に変換するインバータ回路と前記インバータ回路から前記高周波電圧を供給される電力送電用1次コイルとから構成される非接触コンセントと、前記電力送電用1次コイルと分離着脱自在なトランス構造を構成して高周波電圧を誘起される電力受電用2次コイルと前記電力受電用2次コイルに誘起される高周波電圧を整流平滑する整流平滑回路とから構成される非接触プラグと、前記非接触プラグの出力端子に接続され負荷となる端末機器とから構成される非接触電力伝達装置において、前記非接触コンセントは、対象としている負荷領域に対する前記非接触プラグの出力端子電圧を、前記インバータ回路より前記電力送電用1次コイルに供給される高周波電圧を間引いて安定化させる間引き制御を行う制御手段を備えることを特徴とし、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができる。

【0011】請求項2の発明は、請求項1の発明において、前記制御手段は、非接触プラグの出力端子電圧が所定の電圧を上回った場合には、インバータ回路から電力送電用1次コイルへの高周波電圧の供給を一定時間間引き、前記一定時間間引きを行った後非接触プラグの出力端子電圧が前記所定の電圧を上回っていれば再び電力送電用1次コイルへの前記高周波電圧の供給を一定時間間引くことを繰り返し、前記各一定時間間引きを行った後で非接触プラグの出力端子電圧が所定の電圧を下回った場合には、非接触プラグの出力端子電圧が所定の電圧を上回るまで電力送電用1次コイルへの前記高周波電圧の供給を連続的に行う動作を継続させることを特徴とし、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができる。

【0012】請求項3の発明は、請求項1または2の発明において、非接触プラグは、非接触プラグ内部の電気状態を表す情報を磁気信号に変換して非接触コンセントに伝送し、前記制御手段は、前記磁気信号に基づいて間引き制御のための制御信号を形成し、前記制御信号によりインバータ回路を間引き制御することを特徴とし、電圧安定化のためのフィードバック信号に磁気信号を使うため、まわりの明るさや汚れの影響を受けずに、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができる。

【0013】請求項4の発明は、請求項1乃至3いずれかの発明において、インバータ回路は、ハーフブリッジ型の部分共振インバータであることを特徴とし、故障時の出力電圧の上昇を抑えることができる。

【0014】請求項5の発明は、請求項4の発明において、電力受電用2次コイルはセンタータップを備え、整流平滑回路は、電力受電用2次コイルのセンタータップではない両出力端に直列に且つ互いに逆方向に接続する整流素子の電力受電用2次コイルに接続していない各他端同士を接続した全波整流部を有し、前記整流素子の接続中点にチョークコイルを接続することを特徴とし、整流部を小型化することができる。

【0015】請求項6の発明は、請求項1乃至5いずれかの発明において、電力受電用2次コイルに並列にコンデンサを接続することを特徴とし、負荷整合をとることで1次側から2次側へ伝達できる有効電力を増加させることができる。

【0016】請求項7の発明は、請求項6の発明において、前記コンデンサの静電容量値は、対象とする負荷領域の最大負荷時において、電力送電用1次コイルに供給される高周波電圧の極性反転時期と、前記コンデンサの両端に発生する振動電圧が極大値または極小値となる時期とが一致する静電容量値であることを特徴とし、最適な負荷整合を行って回路効率を向上させることができる。

【0017】請求項8の発明は、請求項3乃至7いずれかの発明において、非接触コンセントに1次側信号受信コイルを設け、非接触プラグには前記1次側信号受信コイルに対向配置され前記1次側信号受信コイルと分離着脱自在なトランス構造を構成する2次側信号送信コイルを設け、前記2次側信号送信コイルは非接触プラグの内部の電気状態を表す情報を交流電圧に変換した信号を入力され、磁気信号として磁束信号を発生し、前記1次側信号受信コイルは前記磁束信号により電圧を誘起され、前記制御手段はインバータ回路を前記誘起された電圧に基づいた制御信号により前記間引き制御することを特徴

とし、電圧安定化のためのフィードバック信号に磁束信号を使うため、まわりの明るさや汚れの影響を受けずに、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができる。

【0018】請求項9の発明は、請求項8の発明において、電力送電用1次コイルと1次側信号受信コイルとの間、及び電力受電用2次コイルと2次側信号送信コイルとの間の少なくとも一方の間に磁性体からなる磁気シールド用隔壁を設けたことを特徴とし、信号送受用トランスに鎖交する電流送授用トランスで発生する磁束を低減させて、正確な電圧安定化のための磁束信号を送受信することができる。

【0019】請求項10の発明は、請求項9の発明において、電力送電用1次コイルと電力受電用2次コイルとを、磁性体からなるコアに巻装し、前記コアを互いに前記コアの軸方向に対向配置させたことを特徴とし、信号送受用トランスに鎖交する電流送授用トランスで発生する磁束を低減させて、正確な電圧安定化のための磁束信号を送受信することができる。

【0020】請求項11の発明は、請求項9の発明において、電力送電用1次コイルと電力受電用2次コイルとを、前記コイルの軸方向に垂直な方向に開口部を有する有底筒型の磁性体からなるコアに巻装し、前記コアを互いに前記コアの軸方向に対向配置させ、前記コアの非開口部の近傍に1次側信号受信コイルと2次側信号送信コイルとを配置したことを特徴とし、信号送受用トランスに鎖交する電流送授用トランスで発生する磁束を低減させて、正確な電圧安定化のための磁束信号を送受信することができる。

【0021】請求項12の発明は、請求項8乃至11いずれかの発明において、2次側信号送信コイルは、非接触プラグの内部の電気状態を表す情報を交流電圧に変換した信号を入力されて、電力送電用1次コイルが発生させる磁束とは逆位相の位相を有する磁束信号を発生することを特徴とし、正確な電圧安定化のための束信号を送受信することができる。

【0022】請求項13の発明は、請求項12記載の発明において、2次側信号送信コイルの一方の端子は、電力受電用2次コイルのどちらか一方の端子に接続していることを特徴とし、正確な電圧安定化のための磁束信号を送受信することができる。

【0023】請求項14の発明は、請求項3乃至7いずれかの発明において、非接触コンセントは、電力送電用1次コイルの近傍に電力送電用1次コイルと電力受電用2次コイルとの間に発生する磁束を検出する磁束検出用コイルを設け、前記磁束検出用コイルは、磁気信号として電力送電用1次コイルで発生する磁束を検出し、前記磁束検出用コイルから前記検出する磁束に応じて出力される電圧に基づいて前記制御手段は、インバータ回路を間引き制御することを特徴とし、正確な電圧安定化のための磁束信号を受信することができる。

【0024】請求項15の発明は、請求項14の発明において、電力送電用1次コイルと電力受電用2次コイルとを、前記コイルの軸方向に垂直な方向に開口部を有する有底筒型の磁性体からなるコアに設けて前記コアを互いに前記コアの軸方向に対向配置させ、前記電力送電用1次コイルのコアの開口部の近傍に前記磁束検出用コイルを配置したことを特徴とし、正確な電圧安定化のための磁束信号を受信することができる。

【0025】請求項16の発明は、請求項1乃至15いずれかの発明において、一つの非接触コンセントは、出力電圧の異なる複数の非接触プラグに適合し、各非接触プラグが対象としている負荷領域を含む全領域において前記各非接触プラグの出力電圧を所定の電圧範囲内に収める前記制御手段を有することを特徴とし、経済的である。

【0026】請求項17の発明は、請求項1乃至16いずれかの発明において、非接触プラグの出力端子に並列に抵抗を接続することを特徴とし、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができる。

【0027】請求項18の発明は、請求項1乃至17いずれかの発明において、非接触プラグが非接触コンセントの所定の位置に結合していない場合は、前記制御手段は、インバータ回路から電力送電用1次コイルへ供給する出力を制限することを特徴徴とし、高い安全性と信頼性とを備えることができる。

【0028】請求項19の発明は、請求項18の発明において、非接触コンセントはインバータ回路から電力送電用1次コイルへの高周波電圧の供給の制限を制御するスイッチ機能を備え、非接触プラグは前記スイッチ機能のオン オフ状態を制御する駆動体を備え、非接触プラグが非接触コンセントの所定の位置に結合すると前記スイッチ機能を動作させることで前記制御手段はインバータ回路から電力送電用1次コイルへの高周波電圧の供給を可能にすることを特徴とし、高い安全性と信頼性とを備えることができる。

【0029】請求項20の発明は、請求項19の発明において、非接触コンセントの前記スイッチ機能が機械接点からなり、非接触プラグが備える駆動体は磁石からなり、非接触プラグが非接触コンセントの所定の位置に結合すると前記磁石の磁力によって前記機械接点が動作して、前記制御手段はインバータ回路から電力送電用1次コイルへの高周波電圧の供給を可能にすることを特徴とし、高い安全性と信頼性とを備えることができる。

【0030】請求項21の発明は、請求項1乃至20いずれかの発明において、非接触プラグが非接触コンセントの所定の位置に結合すると、非接触プラグ及び非接触コンセントの少なくともどちらか一方に使用可能を報知する表示を行うことを特徴とし、システムや機器の使用

可否の判断をおこなうことができる。
【0031】請求項22の発明は、請求項1乃至21いずれかの発明において、非接触コンセント及び非接触プラグの少なくともどちらか一方は、非接触プラグの出力端子に接続された端末機器の負荷電力、及び非接触プラグの出力電圧の少なくともどちらか一方を表示する表示部を付加したことを特徴とし、システムや機器の使用可否の判断をおこなうことができる。
【0032】請求項23の発明は、請求項1乃至22いずれかの発明において、非接触プラグの出力端子に接続される端末機器は前記非接触プラグに対して、分離着脱自在なことを特徴とし、不特定の端末機器を使用することができる。
【0033】請求項24の発明は、請求項23の発明において、非接触プラグの出力端子から端末機器への電力の供給は、磁気結合によって供給されることを特徴とし、不特定の端末機器を使用することができる。
【0034】請求項25の発明は、請求項1乃至24いずれかの発明において、非接触プラグの出力端子間に、電圧クランプ素子を接続することを特徴とし、高い安全性と信頼性とを備えることができる。
【0035】
【発明の実施の形態】以下、本発明の実施の形態を図面に基づいて説明する。
【0036】図1は、磁気信号を用いて間引き制御を行う非接触電力伝達装置の回路構成を示す。非接触電力伝達装置5は、電力供給側となる1次側を構成する非接触コンセント1と負荷を持つ2次側を構成する非接触プラグ2とからなり、非接触コンセント1は、交流電源4からの交流入力を、直流電圧Eを出力する直流に変換する電源回路10と、半導体スイッチを有し、半導体スイッチをスイッチングさせることで電源回路10からの直流電圧Eを一定周波数の高周波電圧V1に変換するインバータ回路11と、インバータ回路11から前記高周波電圧V1を供給される電力送電用1次コイルL1と、非接触プラグ2からフィードバックされた磁気信号に応じてインバータ回路11の半導体スイッチのスイッチングを制御する制御信号を出力する制御部であるスイッチング制御回路12とから構成され、非接触プラグ2は、電力送電用1次コイルL1に印加された高周波電圧により発生した漏れ磁束F1と鎖交磁束F2との内、鎖交磁束F2と鎖交することで高周波電圧を誘起される電力受電用2次コイルL2と、電力受電用2次コイルL2から出力される高周波電圧を整流平滑する整流平滑回路20と、非接触プラグ2の出力電圧である出力端子電圧V3を検出し、検出結果に応じて非接触コンセント1のスイッチング制御回路12に磁気信号を出力する出力端子電圧検出回路21とから構成され、出力端子電圧V3は負荷である端末機器3に出力される。電力送電用1次コイルL1と電力受電用2次コイルL2とは、分離着脱できる電力送受用トランスT1を構成する。
【0037】本実施例では、出力端子電圧V3を検出した出力端子電圧検出回路21は、その検出結果に応じた磁気信号を発生させ、その磁気信号を受信したスイッチング制御回路12は磁気信号に基づいて、出力端子電圧V3が所定の電圧を上回った場合には、インバータ回路11から電力送電用1次コイルL1への一定周波数の高周波電圧V1の供給を一定時間間引き、一定時間間引きを行った後出力端子電圧V3が所定の電圧をまだ上回っていれば再び電力送電用1次コイルL1への高周波電圧V1の供給を一定時間間引くことを繰り返し、各一定時間間引きを行った後で出力端子電圧V3が所定の電圧を下回った場合には、出力端子電圧V3が所定の電圧を上回るまで電力送電用1次コイルL1への高周波電圧V1の供給を行う動作を継続させる間引き制御を行う制御信号をインバータ回路11に出力し、インバータ回路11の半導体スイッチは制御信号に応じて、スイッチング動作を行い、出力端子電圧V3を一定電圧に安定化させる。
【0038】図2は、本実施例の具体的な回路構成を示す。図2において、電源回路10は直流電圧Eを出力する直流電圧源10aで表し、出力端子電圧検出回路21及びスイッチング制御回路12は省略する。非接触コンセント1は、直流電圧源10aと、直流電圧源10aに並列に接続されたコンデンサC3、C4の直列回路及び半導体スイッチQ1、Q2の直列回路と、コンデンサC1とコンデンサC2との接続中点と半導体スイッチQ1と半導体スイッチQ2との接続中点との間に接続されたコンデンサC1とからなるインバータ回路11と、コンデンサC1に並列に接続された電力送電用1次コイルL1とから構成され、ハーフブリッジ型の部分共振インバータ回路となる。非接触プラグ2は、センタータップを備えた電力受電用2次コイルL2と、電力受電用2次コイルL2に並列に接続されたコンデンサC2、電力受電用2次コイルL2のセンタータップではない両出力端に直列且つ互いに逆方向に接続されたダイオードD3、D4、ダイオードD3、D4の接続中点に一端を接続されたチョークコイルL3、チョークコイルL3の他端と電力受電用2次コイルL2のセンタータップとの間に接続される平滑コンデンサC5からなる整流平滑回路20とから構成され、端末機器3は平滑コンデンサC5に並列に接続される。電力送電用1次コイルL1と電力受電用2次コイルL2とは、分離着脱できる電力送受用トランスT1を構成する。電力受電用2次コイルL2にはセンタータップを備えているものを使用し、2つのダイオードD3、D4で整流しているので装置の小型化を図ることができる。
【0039】次に図3に、図2における電力送電用1次コイルL1の両端電圧V1と、電力送電用1次コイルL1を流れる電流I1と、半導体スイッチQ1の両端電圧

Ｖ４ａと、半導体スイッチＱ１を流れる電流Ｉ４ａと、半導体スイッチＱ２の両端電圧Ｖ４ｂと、半導体スイッチＱ２を流れる電流Ｉ４ｂとの各波形を示す。半導体スイッチＱ１、Ｑ２は交互にオン オフを繰り返すが、この時一方の半導体スイッチがオンからオフした後、両方の半導体スイッチがオフになる一定期間を経てから他方の半導体スイッチがオンするように制御しているので、電力送電用１次コイルＬ１の両端電圧Ｖ１は、台形上の波形となる。部分共振区間１００は半導体スイッチＱ１、Ｑ２ともにオフしている区間であり、電力送電用１次コイルＬ１から２次側を見たインダクタンスと、コンデンサＣ１との共振動作による電圧振動が行われる期間である。半導体スイッチにＭＯＳＦＥＴを用いると、図２に示すように寄生ダイオードＤ１、Ｄ２が半導体スイッチＱ１、Ｑ２に並列に接続されるため、電力送電用１次コイルＬ１の両端電圧Ｖ１の振動電圧が大きくなり、電圧Ｅ／２または電圧Ｅ／２にでクランプされると、半導体スイッチＱ１の両端電圧Ｖ４ａと半導体スイッチＱ２の両端電圧Ｖ４ｂとは直流電源１０ａの電圧Ｅまたはグラウンドレベルにクランプされた台形波となる。また半導体スイッチＱ１、Ｑ２にＭＯＳＦＥＴを用いた場合は、ＭＯＳＦＥＴの寄生容量を利用しても部分共振動作ができる。この部分共振により半導体スイッチＱ１、Ｑ２はソフトスイッチングを行うことができ、ターンオン及びターンオフ時の損失が大幅に低減できる。

【００４０】図４は、負荷状態が無負荷、軽負荷近辺において従来技術の間引き制御を行った時の出力端子電圧Ｖ３と電力送電用１次コイルＬ１の両端電圧Ｖ１とを示す。従来技術の間引き制御は、出力端子電圧Ｖ３を検出し、その検出結果が目標電圧１０１を超えた時のみインバータ回路１１の固定周波数駆動を休止させて、一定周波数の高周波電圧Ｖ１の出力を停止させる。このような制御では、図４に示すように軽負荷、無負荷近辺において、目標電圧１０１の付近で駆動周波数の１周期にも満たない半導体スイッチＱ１、Ｑ２のオン オフが頻繁に行われ、共振型インバータのメリットである低損失のソフトスイッチングが行われず、ハードスイッチングになるとともに、強いノイズ源になることは前記従来の技術でも述べたとおりである。特に、非接触電力伝達では、漏れ磁束や磁束の広がりによる磁界の影響で、出力端子にノイズが乗りやすいためこの傾向は顕著に現れやすい。

【００４１】前記従来技術の間引き制御に対し、図５に、負荷状態が無負荷、軽負荷近辺において、出力端子電圧Ｖ３の目標電圧として２つの目標電圧１０２、１０３を設け、出力端子電圧Ｖ３が目標電圧１０２を超えるとインバータ回路１１の固定周波数駆動を停止させ、出力端子電圧Ｖ３が目標電圧１０３より下回るとインバータ回路１１の固定周波数駆動を行う制御を行った時の出力端子電圧Ｖ３と電力送電用１次コイルＬ１の両端電圧Ｖ１とを示す。２つの目標電圧１０２、１０３によってヒステリシスをつくることでインバータ回路１１の固定周波数駆動の動作と停止が図４に示す従来の方式に比べて良好に行われる。実用的にはこの方式で使用可能なものもあるが、ノイズが大きく重畳される場合にはヒステリシス幅を大きくしなければならず、出力端子電圧Ｖ３のリプル電圧増大の原因となる。

【００４２】そこで発明では図６に示すように、出力端子電圧Ｖ３が目標電圧１０８を上回った場合には、インバータ回路１１から電力送電用１次コイルＬ１への一定周波数の高周波電圧Ｖ１の供給を一定時間１０６間引き、一定時間１０６の間引きを行った後出力端子電圧Ｖ３が目標電圧１０８をまだ上回っていれば再び電力送電用１次コイルＬ１への高周波電圧Ｖ１の供給を一定時間１０６間引くことを繰り返し、各一定時間１０６の間引きを行った後で出力端子電圧Ｖ３が目標電圧１０８を下回った場合には、出力端子電圧Ｖ３が目標電圧１０８を上回るまで電力送電用１次コイルＬ１への高周波電圧Ｖ１の供給を行う動作を継続させる間引き制御を行い、この一連の動作を継続させて出力端子電圧Ｖ３を一定にする安定化を行う。この方式では、軽負荷から全負荷までの範囲において、一定時間１０６の休止期間の終了時には出力端子電圧Ｖ３は目標電圧１０８を確実にある程度下回り、インバータ回路１１の固定周波数駆動も連続１周期以上は確保できる。そして、完全な無負荷の場合にはインバータ回路１１の固定周波数駆動が１周期未満になることもありうるが、この場合にでもインバータ回路１１の固定周波数駆動動作の期間と停止の期間とは一定の周期で規則的に繰り返されるため、インバータ回路１１の固定周波数駆動の期間と停止の期間とが不規則に繰り返される図４の場合に比べて高調波ノイズは低減できる。また、本実施例のもう一つのメリットは、負荷状態が無負荷に近い時も全負荷に近い時も、出力端子電圧Ｖ３の最大電圧１０７をほぼ同程度にできるため、とくに浴室などの水まわりで使う低い電圧を安定化させる場合に、その電圧規格の上限値に対し少しのマージン分だけ低い電圧に目標電圧１０８を設定すれば、確実に電圧規格の上限値以内に出力端子電圧Ｖ３を制御できるため、安全安心に配慮した出力端子電圧Ｖ３の電圧安定化を行うことができる。

【００４３】次に図７に、電力送電用１次コイルＬ１の両端電圧Ｖ１と、コンデンサＣ２の両端電圧Ｖ２と、コンデンサＣ２を流れる電流Ｉ２と、端末機器３を流れる負荷電流Ｉ３との各波形を示す。コンデンサＣ２を電力受電用２次コイルＬ２に並列に接続して最適な負荷整合を行うことができる条件は、図７にタイミング１０９に示すように電力送電用１次コイルＬ１の両端電圧Ｖ１の極性反転時と、コンデンサＣ２の両端電圧Ｖ２の振動電圧が極大値に達する時とが一致すること及びタイミング１１０のように電力送電用１次コイルＬ１の両端電圧Ｖ

１の極性反転時と、コンデンサＣ２の両端電圧Ｖ２の振動電圧が極小値に達する時とが一致することと等価である。図７のように最適な負荷整合を行うためのコンデンサＣ２の静電容量値は、インバータ回路１１の駆動周波数や、電力送電用１次コイルＬ１と電力受電用２次コイルＬ２間の漏れインダクタンスＬ４以外に出力端子電圧Ｖ３や整流平滑回路２０の整流方式にも影響を受ける。

【００４４】図８、９は本実施例における負荷電流Ｉ３に対する出力端子電圧Ｖ３の特性１１７ｄ、１１７ｅを示す。最大負荷電力がとれる点Ｋ、即ち負荷整合が最適にとれている点Ｋより負荷電流Ｉ３が小さい領域１１１及び１１３では出力端子電圧Ｖ３は、点Ｋにおける出力端子電圧Ｖ３より高くなっているため、本実施例の間引き制御による電圧低減動作により出力端子電圧Ｖ３の安定化を行うことができる。一方負荷電流Ｉ３が点Ｋを超える領域１１２、１１４では、出力端子電圧Ｖ３は急激に電圧降下を起こし利用できない。このようにコンデンサＣ２により最適な負荷整合を行うことで、本発明の無接触電力伝達装置５を最も効率の高い状態で動作させることができる。また、適用負荷範囲を超えた場合、例えば端末機器３の故障により内部短絡が起こっても、点Ｋよりも負荷電流Ｉ３が大きくなると出力端子電圧Ｖ３の電圧降下が急激に起こり、出力端子電圧Ｖ３は低電圧になるとともに負荷電流Ｉ３は電流制限がかかり安全であり、安全安心に配慮したシステムとなっている。

【００４５】図１０乃至２３は本発明の実施形態の具体例を示し、基本的な構成は図１及び図２とほぼ同様であり、同一の構成要素には同一の符号を付して説明は省略する。図１０において、電力供給側となる１次側を構成する非接触コンセント１は、直流電源を入力されて一定周波数の高周波電圧を出力するインバータ回路１１と（図１０乃至１６では直流電源を出力する電源回路は省略）、インバータ回路１１から前記高周波電圧を供給される電力送電用１次コイルＬ１と、非接触プラグ２の２次側信号送信コイル２３からフィードバックされた磁気信号により電圧を誘起される１次側信号受信コイル１４と、前記誘起電圧に基づいた信号を出力する信号変換回路１３と、信号変換回路１３の出力信号に応じてインバータ回路１１の半導体スイッチのスイッチングを間引き制御する制御信号を出力するスイッチング制御回路１２とから構成され、負荷を持つ２次側を構成する非接触プラグ２は、電力送電用１次コイルＬ１に印加された高周波電圧により発生した磁束Ｆ３と鎖交することで高周波電圧を誘起される電力受電用２次コイルＬ２と、電力受電用２次コイルＬ２の高周波出力を整流平滑する整流平滑回路２０と、非接触プラグ２の出力端子電圧Ｖ３を検出し、検出信号を出力する出力端子電圧検出回路２１と、前記検出信号に応じた交流信号を出力する信号変換回路２２と、信号変換回路２２から出力される交流信号を入力されて、磁気信号としての磁束信号を発生する２次側信号送信コイル２３とから構成され、非接触プラグ２の出力は端末機器３に接続される。電力送電用１次コイルＬ１と電力受電用２次コイルＬ２とは、分離着脱できる電力送受用トランスＴ１を構成し、１次側信号受信コイル１４と２次側信号送信コイル２３とは、分離着脱できる信号授受用トランスＴ２を構成する。

【００４６】しかし、図１０に示す回路構成のように電力送受用トランスＴ１と信号授受用トランスＴ２とが互いに近傍に配置されると磁束Ｆ３の広がりによって、磁束Ｆ３の一部は１次側信号受信コイル１４と２次側信号送信コイル２３とに鎖交しており、信号授受用トランスＴ２にはノイズが入ることになり正確な非接触プラグ２の出力端子電圧Ｖ３の情報を非接触コンセント１にフィードバックできない。そこで、前述の問題を改善する実施例を図１１～図１４に示す。

【００４７】図１１は、非接触コンセント１、非接触プラグ２と、信号授受用トランスＴ２との間に磁気を通しやすい磁性体からなる隔壁Ａ１を設け、電力送電用１次コイルＬ１により発生する磁束Ｆ３を障壁Ａ１に集中させることで、磁束Ｆ３の内、信号授受用トランスＴ２に鎖交する磁束を低減させたものである。

【００４８】図１２は、電力送電用１次コイルＬ１と電力受電用２次コイルＬ２とを磁性体からなるコアＡ２に巻装し、電力送電用１次コイルＬ１と電力受電用２次コイルＬ２との軸方向に互いに対向配置させており、電力送電用１次コイルＬ１により発生する磁束Ｆ３をコアＡ２に集中させることで、磁束Ｆ３の広がり度合いを低減させて、磁束Ｆ３の内、信号授受用トランスＴ２に鎖交する磁束を低減させたものである。

【００４９】図１３は、電力送電用１次コイルＬ１と電力受電用２次コイルＬ２とを、磁性体からなり開口部を有する一般によく使われているトランス用のコアＡ３に巻装し、電力送電用１次コイルＬ１と電力受電用２次コイルＬ２との軸方向に互いに対向配置させており、電力送電用１次コイルＬ１により発生する磁束Ｆ３をコアＡ３に集中させることで、磁束Ｆ３の広がり度合いを低減させて、磁束Ｆ３の内、信号授受用トランスＴ２に鎖交する磁束を低減させたものである。また、図１３においてはコアＡ３の開口部１２２から磁束Ｆ３の一部が漏れるので、信号授受用トランスＴ２は、その磁束が鎖交しないようにコアＡ３の非開口部１２３側に設置しておく。

【００５０】図１４に示す実施例においては、出力端子電圧Ｖ３を信号変換回路２４に入力して、信号変換回路２４は出力端子電圧Ｖ３に応じた信号を出力し、２次側信号送信コイル２３の一端は前記信号が出力される信号変換回路２４の出力に接続され、他端は電力受電用２次コイルの一端に接続されている。また、電力送電用１次コイルＬ１で発生し電力受電用２次コイルＬ２と鎖交する磁束Ｆ３ａ及び電力送電用１次コイルＬ１で発生し１

次側信号受信コイル１４と鎖交する磁束Ｆ３ｂとの方向と、２次側信号送信コイル２３で発生する磁束信号Ｆ４の方向とが互いに反対方向になるように、電力送電用１次コイルＬ１と１次側信号受信コイル１４との巻線の方向と、電力受電用２次コイルＬ２と２次側信号送信コイル２３との巻線の方向とを互いに反対方向にすることで、２次側信号送信コイル２３で発生する磁束信号Ｆ４の位相は、電力送電用１次コイルＬ１で発生する磁束Ｆ３ａ、Ｆ３ｂの位相とは逆位相となり、信号授受用トランスＴ２は電力送電用１次コイルＬ１で発生する磁束Ｆ３ａ、Ｆ３ｂの影響を受けにくくなる。

【００５１】また、前記図３３の負荷電流Ｉ３に対する出力端子電圧Ｖ３の特性１１７ｂに示すように、無負荷状態に近くなると出力端子電圧Ｖ３は高くなる傾向があり、負荷が軽くなるほど出力端子電圧Ｖ３の安定化は難しくなる。間引き制御によって全負荷領域をカバーするようにフィードバック制御系を設計できるが、制御信号の分解能向上、応答速度向上、対ノイズ性強化などで制御回路の部品も増えコスト、サイズで不利となる。しかし、図１４に示すように非接触プラグ２の出力端子間に抵抗Ｒ１を並列に接続することで、図２４の負荷電流Ｉ３に対する出力端子電圧Ｖ３の特性１１７ｆに示すように、抵抗Ｒ１に電流１１５を常に流しておき、領域１１１において出力端子電圧Ｖ３の安定化を行うことができる。さらに、負荷の急変時には過渡的な出力端子電圧Ｖ３の上昇もありうるため、図１４に示すように非接触プラグ２の出力端子間に定電圧ダイオードＺＤ１を並列に接続することで、出力端子電圧Ｖ３を常に安定化させることができる。前述のような負荷急変時の出力端子電圧Ｖ３の上昇頻度は少なく、また上昇電圧も小さいため定電圧ダイオードＺＤ１の損失は小さい。本実施例では定電圧ダイオードを使っているが電圧クランプ素子であればよい。

【００５２】次に図１５は、間引き制御に必要な非接触プラグ２の電気情報を電力送電用１次コイルＬ１で発生する磁束Ｆ３の変化から得るもので、電力送電用１次コイルＬ１で発生する磁束Ｆ３の変化を磁束検出コイル１４ａで検出して、その検出結果に基づいてインバータ回路１１を間引き制御するものである。非接触伝送においては、伝送する電力が増加すれば、電力送電用１次コイルＬ１で発生する磁束Ｆ３も電力に比例して増加し、出力端子電圧は電力に反比例して低下する。前述の特性は、一つのシステムにおいては同一な特性であるので、電力送電用１次コイルＬ１で発生する磁束Ｆ３の変化を磁束検出コイル１４ａで検出すれば、間接的に非接触プラグ２の出力端子電圧の情報を得ることができ、インバータ回路１１を間引き制御することができる。図１５に示す回路は、電力送電用１次コイルＬ１と電力受電用２次コイルＬ２とを空芯とし、磁束Ｆ３の広がりや漏れを大きくして磁束Ｆ３を磁束検出コイル１４ａに鎖交させるものである。

【００５３】図１６に示す回路は、前記図１５に示した回路の電力送電用１次コイルＬ１と電力受電用２次コイルＬ２とを、磁性体からなり開口部１２２を有する一般によく使われているトランス用のコアＡ３に設けて互いに対向配置させており、開口部１２２近傍に磁束検出コイル１４ａを配置することで、磁束Ｆ３の内、開口部１２２から漏れる磁束を磁束検出コイル１４ａに鎖交させるものである。

【００５４】以上に示したように、本発明は広い負荷領域に対して、必要な電圧への安定化を行うことができる。

【００５５】図１７に、浴室内で使う本発明の非接触電力伝達システム例の外観を示す。壁２００に埋設された非接触コンセント１は、壁２００の表面と接する外周部にシール１５を設けて防水性を高めている。非接触コンセント１の内部には、前記の電源回路１０、インバータ回路１１、スイッチング制御回路１２及び信号変換回路１３が内蔵され、交流電源４と接続された回路ブロックＸ１と、凹部１９に対して配置された電力送電用１次コイルＬ１と、同様に凹部１９に対して配置された１次側信号受信コイル１４とが設けられ、非接触プラグ２側の面には非接触コンセント１が使用可能状態である時点灯するコンセント通電表示ＬＥＤ１６が設けられている。非接触プラグ２は、通電時は、非接触コンセント１の凹部１９に嵌合させて、内部には、嵌合時に電力送電用１次コイルＬ１に対向配置するように設けられた電力受電用２次コイルＬ２と、１次側信号受信コイル１４に対向配置するように設けられた２次側信号送信コイル２３と、前記整流平滑回路２０、出力端子電圧検出回路２１及び信号変換回路２２が内蔵された回路ブロックＸ２と、機器３に電力を伝達するケーブルコード２６とから構成され、端末機器３は、ケーブルコード２６を接続されて電力を伝達され、表面に非接触プラグ２が使用可能状態である時点灯するプラグ通電表示ＬＥＤ２５が設けられている。

【００５６】図１８は、図１７を非接触プラグ２側から見た図を示す。非接触コンセント１及び非接触プラグ２が使用可能かどうかを表示することはユーザにとって必要であり、非接触コンセント１の非接触プラグ２側表面には、非接触コンセント１が使用可能状態である時点灯するコンセント通電表示ＬＥＤ１６を設け、非接触プラグ２表面には非接触プラグ２が使用可能状態である時点灯するコンセント通電表示ＬＥＤ１６を設けている。また、広い負荷領域を対象としているため、現在使っている端末機器３がどの程度の負荷なのか、使用限界を超えていないのかなどの情報は重要である。この情報は間引き制御の間引き率より得ることができる。即ち間引き率が大きいと負荷は小さく、間引き率が小さいほど負荷は大きいことに相当する。さらに予め最低間引き率を設定

しておき、間引き率が最低間引き率を下回り、対象負荷領域を越えると出力端子電圧Ｖ３は急激に低下するので、出力端子電圧Ｖ３が所定の電圧値以下になったことで過負荷状態を判定できる。この使用負荷量を表示するのが非接触コンセント１の非接触プラグ２側表面に設けられた負荷量表示インジケータ１７である。

【００５７】図１９は、１２Ｖ用端末機器３ａに接続された１２Ｖ機器用非接触プラグ２ａと、２４Ｖ用端末機器３ｂに接続された２４Ｖ機器用非接触プラグ２ｂとを、１台の非接触コンセント１で電力伝達可能なことを示している。前記のように本発明の非接触電力伝達システムの間引き制御は、負荷領域が広くても制御可能なので、非接触コンセント１の電力送電用１次コイルＬ１の巻数が一定でも、１２Ｖ機器用非接触プラグ２ａと２４Ｖ機器用非接触プラグ２ｂとの電力受電用２次コイルＬ２ａと電力受電用２次コイルＬ２ｂとの巻数を変えることで各々の出力端子電圧Ｖ３を安定化させることができ、また任意の電圧に安定化させることもできる。

【００５８】また、非接触電力伝達システムでは、電力送電用１次コイルＬ１と電力受電用２次コイルＬ２との距離が長くなるほど伝達できる電力は減少するため、非接触コンセント１と非接触プラグ２との相対的位置関係を所定の位置関係に保つ必要がある。図２０は、非接触プラグ２を非接触コンセント１の凹部１９に完全に嵌合させていない状態を示しており、このような場合には非接触コンセント１から非接触プラグ２への電力伝達を停止させる必要がある。そこで、非接触コンセント１は凹部１９に対して配置された機械接点１８を設け、機械接点１８がオンした時のみ、、非接触コンセント１の回路ブロックＸ１に内蔵されたインバータ回路１１が動作し、非接触コンセント１から非接触プラグ２への電力伝達を行い、非接触プラグ２は嵌合時に機械接点１８に対向配置するように永久磁石３０を設ける。機械接点１８は、永久磁石３０の磁力によって動作するスイッチで、図２０においては非接触プラグ２は非接触コンセント１の凹部１９に完全に嵌合していないので、永久磁石３０と機械接点１８とは離れすぎており、永久磁石３０の磁力は機械接点１８を動作させることはできない。図２１は非接触プラグ２を非接触コンセント１の凹部１９に完全に嵌合させている状態を示しており、永久磁石３０の磁力は機械接点１８を動作させることができ、非接触コンセント１の回路ブロックＸ１に内蔵されたインバータ回路１１が動作し、非接触コンセント１から非接触プラグ２への電力伝達を行うことができる。なお、永久磁石３０は永久磁石なので、１次側信号受信コイル１４、２次側信号送信コイル２３、磁束検出用コイル１４ａの磁束信号に悪影響を与えない。また、コンセント通電表示ＬＥＤ１６は、機械接点１８がオンすることで点灯させることができ、プラグ通電表示ＬＥＤ２５は出力端子電圧Ｖ３を監視することで点灯させることができる。

【００５９】次に、非接触プラグ２と端末機器３との接続は、水まわりで使用するときは一体型とするほうが望ましいが、水まわりで使用しないとき、及び水まわりで使用するときでも水中につけるような使い方をしないときであれば簡易防水でもよいため、非接触プラグ２と端末機器３との接続を脱着可能な構造にしてもよい。このようにすれば、非接触コンセント１と非接触プラグ２とは各１つずつあれば、端末機器３のみ用途に応じて揃えればよいため経済的である。図２２において、端末機器３ｃ、３ｄはケーブルコード２６ｃ、２６ｄを備え、ケーブルコード２６ｃ、２６ｄの端末には各々コネクタ２７ｃ、２７ｄが接続されており、非接触プラグ２の表面に設けられ非接触プラグ２の出力端と接続しているソケット２８ｃ、２８ｄと分離着脱可能になっており、１つの非接触プラグ２に複数の端末機器３ｃ、３ｄを接続できるようになっている。図２３においては、端末機器３ｅはケーブルコード２６ｅを備え、ケーブルコード２６ｅの端末には電力受電コイルＬ５が接続され、非接触プラグ２の表面近傍には非接触プラグ２の出力端と接続している電力送電コイルＬ４を備え、電力受電コイルＬ５は非接触プラグ２表面の凹部２９と嵌合して電力送信コイルＬ４から電磁誘導により電力伝達される。図２３においては、電力送信コイルＬ４に印可される回路ブロックＸ２の出力電圧は高周波電圧である。

【００６０】また、浴室内のように水まわりで使用し、感電対策のために低電圧出力が必要な場合には、非接触コンセント２の故障時においても非接触プラグ２及び端末機器３での電圧上昇をできる限り抑えなければならない。本発明においては、分離着脱できる電力伝送用トランスＴ１を使って電力伝達を行うため、非接触コンセント１の１次側電力送電コイルＬ１に印可される高周波電圧Ｖ１の振幅に比例した電圧が、非接触プラグ２の２次側電力受電コイルＬ２に誘起される。そのため非接触コンセント１側のインバータ回路や、制御回路の故障で１次側電力送電コイルＬ１に高い電圧が印加された場合には２次側電力受電コイルＬ２に誘起される電圧Ｖ２も上昇し、制御可能な領域を越えて非接触プラグ２の出力端子電圧Ｖ３に高い電圧がかかる可能性がある。そこで本発明では、図２に示すようにインバータ回路１１はハーフブリッジ回路を用いているので、１次側電力送電コイルＬ１の両端電圧Ｖ１は、直流電源１０ａの電圧Ｅに対して電圧−Ｅ／２と電圧Ｅ／２とで確実にクランプされ、２次側電力受電コイルＬ２に誘起される電圧Ｖ２の上昇は一定電圧以上上昇せず、安全なシステムとなっている。

【００６１】なお図２のコンデンサＣ２は、図２５に示すように電力受電用２次コイルＬ２のセンタータップと他の端子間にコンデンサＣ２１、Ｃ２２を接続してもよいし、図２６に示すようにダイオードＤ３、Ｄ４に並列にコンデンサＣ２１、Ｃ２２を各々接続しても同様の効

果を得ることができる。これは、コンデンサＣ２は高周波交流に作用するコンデンサであり、図２、図２５及び図２６の交流的な等価回路は同等になるためであり、いずれも図７に示す電力受電用２次コイルＬ２の両端電圧Ｖ２の波形条件を得ることができる。このように本発明の各波形条件を満たしておればそれらは本発明に含まれることはもちろん、このことは電力受電用２次コイルＬ２がセンタータップを備えていない場合も同様である。

【００６２】

【発明の効果】請求項１の発明は、直流電圧を出力する電源回路と前記直流電圧を一定周波数の高周波電圧に変換するインバータ回路と前記インバータ回路から前記高周波電圧を供給される電力送電用１次コイルとから構成される非接触コンセントと、前記電力送電用１次コイルと分離着脱自在なトランス構造を構成して高周波電圧を誘起される電力受電用２次コイルと前記電力受電用２次コイルに誘起される高周波電圧を整流平滑する整流平滑回路とから構成される非接触プラグと、前記非接触プラグの出力端子に接続され負荷となる端末機器とから構成される非接触電力伝達装置において、前記非接触コンセントは、対象としている負荷領域に対する前記非接触プラグの出力端子電圧を、前記インバータ回路より前記電力送電用１次コイルに供給される高周波電圧を間引いて安定化させる間引き制御を行う制御手段を備えることを特徴とし、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができるという効果がある。

【００６３】請求項２の発明は、請求項１の発明において、前記制御手段は、非接触プラグの出力端子電圧が所定の電圧を上回った場合には、インバータ回路から電力送電用１次コイルへの高周波電圧の供給を一定時間間引き、前記一定時間間引きを行った後非接触プラグの出力端子電圧が前記所定の電圧を上回っていれば再び電力送電用１次コイルへの前記高周波電圧の供給を一定時間間引くことを繰り返し、前記各一定時間間引きを行った後で非接触プラグの出力端子電圧が所定の電圧を下回った場合には、非接触プラグの出力端子電圧が所定の電圧を上回るまで電力送電用１次コイルへの前記高周波電圧の供給を連続的に行う動作を継続させることを特徴とし、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができるという効果がある。

【００６４】請求項３の発明は、請求項１または２の発明において、非接触プラグは、非接触プラグ内部の電気状態を表す情報を磁気信号に変換して非接触コンセントに伝送し、前記制御手段は、前記磁気信号に基づいて間引き制御のための制御信号を形成し、前記制御信号によりインバータ回路を間引き制御することを特徴とし、電圧安定化のためのフィードバック信号に磁気信号を使うため、まわりの明るさや汚れの影響を受けずに、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができるという効果がある。

【００６５】請求項４の発明は、請求項１乃至３いずれかの発明において、インバータ回路は、ハーフブリッジ型の部分共振インバータであることを特徴とし、故障時の出力電圧の上昇を抑えることができるという効果がある。

【００６６】請求項５の発明は、請求項４の発明において、電力受電用２次コイルはセンタータップを備え、整流平滑回路は、電力受電用２次コイルのセンタータップではない両出力端に直列に且つ互いに逆方向に接続する整流素子の電力受電用２次コイルに接続していない各他端同士を接続した全波整流部を有し、前記整流素子の接続中点にチョークコイルを接続することを特徴とし、整流部を小型化することができるという効果がある。

【００６７】請求項６の発明は、請求項１乃至５いずれかの発明において、電力受電用２次コイルに並列にコンデンサを接続することを特徴とし、負荷整合をとることで１次側から２次側へ伝達できる有効電力を増加させることができるという効果がある。

【００６８】請求項７の発明は、請求項６の発明において、前記コンデンサの静電容量値は、対象とする負荷領域の最大負荷時において、電力送電用１次コイルに供給される高周波電圧の極性反転時期と、前記コンデンサの両端に発生する振動電圧が極大値または極小値となる時期とが一致する静電容量値であることを特徴とし、最適な負荷整合を行って回路効率を向上させることができるという効果がある。

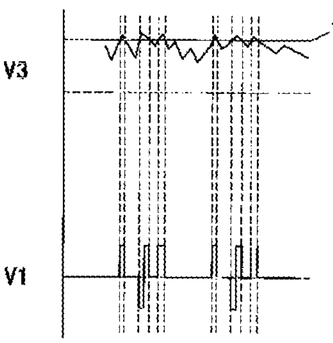
【００６９】請求項８の発明は、請求項３乃至７いずれかの発明において、非接触コンセントに１次側信号受信コイルを設け、非接触プラグには前記１次側信号受信コイルに対向配置され前記１次側信号受信コイルと分離着脱自在なトランス構造を構成する２次側信号送信コイルを設け、前記２次側信号送信コイルは非接触プラグの内部の電気状態を表す情報を交流電圧に変換した信号を入力され、磁気信号として磁束信号を発生し、前記１次側信号受信コイルは前記磁束信号により電圧を誘起され、前記制御手段はインバータ回路を前記誘起された電圧に基づいた制御信号により前記間引き制御することを特徴とし、電圧安定化のためのフィードバック信号に磁束信号を使うため、まわりの明るさや汚れの影響を受けずに、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができるという効果がある。

【００７０】請求項９の発明は、請求項８の発明において、電力送電用１次コイルと１次側信号受信コイルとの間、及び電力受電用２次コイルと２次側信号送信コイルとの間の少なくとも一方の間に磁性体からなる磁気シールド用隔壁を設けたことを特徴とし、信号送受用トランスに鎖交する電流送授用トランスで発生する磁束を低減

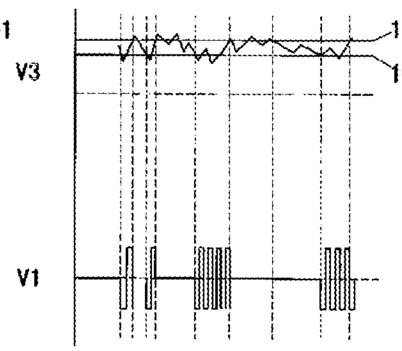
させて、正確な電圧安定化のための磁束信号を送受信することができるという効果がある。
【0071】請求項10の発明は、請求項9の発明において、電力送電用1次コイルと電力受電用2次コイルとを、磁性体からなるコアに巻装し、前記コアを互いに前記コアの軸方向に対向配置させたことを特徴とし、信号送受用トランスに鎖交する電流送授用トランスで発生する磁束を低減させて、正確な電圧安定化のための磁束信号を送受信することができるという効果がある。
【0072】請求項11の発明は、請求項9の発明において、電力送電用1次コイルと電力受電用2次コイルとを、前記コイルの軸方向に垂直な方向に開口部を有する有底筒型の磁性体からなるコアに巻装し、前記コアを互いに前記コアの軸方向に対向配置させ、前記コアの非開口部の近傍に1次側信号受信コイルと2次側信号送信コイルとを配置したことを特徴とし、信号送受用トランスに鎖交する電流送授用トランスで発生する磁束を低減させて、正確な電圧安定化のための磁束信号を送受信することができるという効果がある。
【0073】請求項12の発明は、請求項8乃至11いずれかの発明において、2次側信号送信コイルは、非接触プラグの内部の電気状態を表す情報を交流電圧に変換した信号を入力されて、電力送電用1次コイルが発生させる磁束とは逆位相の位相を有する磁束信号を発生することを特徴とし、正確な電圧安定化のための束信号を送受信することができるという効果がある。
【0074】請求項13の発明は、請求項12記載の発明において、2次側信号送信コイルの一方の端子は、電力受電用2次コイルのどちらか一方の端子に接続していることを特徴とし、正確な電圧安定化のための磁束信号を送受信することができるという効果がある。
【0075】請求項14の発明は、請求項3乃至7いずれかの発明において、非接触コンセントは、電力送電用1次コイルの近傍に電力送電用1次コイルと電力受電用2次コイルとの間に発生する磁束を検出する磁束検出用コイルを設け、前記磁束検出用コイルは、磁気信号として電力送電用1次コイルで発生する磁束を検出し、前記磁束検出用コイルから前記検出する磁束に応じて出力される電圧に基づいて前記制御手段は、インバータ回路を間引き制御することを特徴とし、正確な電圧安定化のための磁束信号を受信することができるという効果がある。
【0076】請求項15の発明は、請求項14の発明において、電力送電用1次コイルと電力受電用2次コイルとを、前記コイルの軸方向に垂直な方向に開口部を有する有底筒型の磁性体からなるコアに設けて前記コアを互いに前記コアの軸方向に対向配置させ、前記電力送電用1次コイルのコアの開口部の近傍に前記磁束検出用コイルを配置したことを特徴とし、正確な電圧安定化のための磁束信号を受信することができるという効果がある。
【0077】請求項16の発明は、請求項1乃至15いずれかの発明において、一つの非接触コンセントは、出力電圧の異なる複数の非接触プラグに適合し、各非接触プラグが対象としている負荷領域を含む全領域において前記各非接触プラグの出力電圧を所定の電圧範囲内に収める前記制御手段を有することを特徴とし、経済的であるという効果がある。
【0078】請求項17の発明は、請求項1乃至16いずれかの発明において、非接触プラグの出力端子に並列に抵抗を接続することを特徴とし、広い負荷範囲で出力端子電圧を一定値に安定化できる非接触電力伝達装置を提供することができるという効果がある。
【0079】請求項18の発明は、請求項1乃至17いずれかの発明において、非接触プラグが非接触コンセントの所定の位置に結合していない場合は、前記制御手段は、インバータ回路から電力送電用1次コイルへ供給する出力を制限することを特徴徴とし、高い安全性と信頼性とを備えることができるという効果がある。
【0080】請求項19の発明は、請求項18の発明において、非接触コンセントはインバータ回路から電力送電用1次コイルへの高周波電圧の供給の制限を制御するスイッチ機能を備え、非接触プラグは前記スイッチ機能のオン/オフ状態を制御する駆動体を備え、非接触プラグが非接触コンセントの所定の位置に結合すると前記スイッチ機能を動作させることで前記制御手段はインバータ回路から電力送電用1次コイルへの高周波電圧の供給を可能にすることを特徴とし、高い安全性と信頼性とを備えることができるという効果がある。
【0081】請求項20の発明は、請求項19の発明において、非接触コンセントの前記スイッチ機能が機械接点からなり、非接触プラグが備える駆動体は磁石からなり、非接触プラグが非接触コンセントの所定の位置に結合すると前記磁石の磁力によって前記機械接点が動作して、前記制御手段はインバータ回路から電力送電用1次コイルへの高周波電圧の供給を可能にすることを特徴とし、高い安全性と信頼性とを備えることができるという効果がある。
【0082】請求項21の発明は、請求項1乃至20いずれかの発明において、非接触プラグが非接触コンセントの所定の位置に結合すると、非接触プラグ及び非接触コンセントの少なくともどちらか一方に使用可能を報知する表示を行うことを特徴とし、システムや機器の使用可否の判断をおこなうことができるという効果がある。
【0083】請求項22の発明は、請求項1乃至21いずれかの発明において、非接触コンセント及び非接触プラグの少なくともどちらか一方は、非接触プラグの出力端子に接続された端末機器の負荷電力、及び非接触プラグの出力電圧の少なくともどちらか一方を表示する表示部を付加したことを特徴とし、システムや機器の使用可否の判断をおこなうことができるという効果がある。

【0084】請求項23の発明は、請求項1乃至22いずれかの発明において、非接触プラグの出力端子に接続される端末機器は前記非接触プラグに対して、分離着脱自在なことを特徴とし、不特定の端末機器を使用することができるという効果がある。
【0085】請求項24の発明は、請求項23の発明において、非接触プラグの出力端子から端末機器への電力の供給は、磁気結合によって供給されることを特徴とし、不特定の端末機器を使用することができるという効果がある。
【0086】請求項25の発明は、請求項1乃至24いずれかの発明において、非接触プラグの出力端子間に、電圧クランプ素子を接続することを特徴とし、高い安全性と信頼性とを備えることができるという効果がある。
【0087】このように本発明で構成される非接触電力伝達システムは、安全や安心と、高い信頼性を背景に、浴室などの水まわり環境を電化し、様々な電気機器により多様なユーザニーズに応えることができるものである。
【図面の簡単な説明】
【図1】本発明の実施例を示す回路構成図である。
【図2】本発明の実施例を示す具体的な回路構成図である。
【図3】本発明の実施例の特性を示す図である。
【図4】本発明の実施例の特性を示す図である。
【図5】本発明の実施例の特性を示す図である。
【図6】本発明の実施例の特性を示す図である。
【図7】本発明の実施例の特性を示す図である。
【図8】本発明の実施例の特性を示す図である。
【図9】本発明の実施例の特性を示す図である。
【図10】本発明の実施例を示す回路構成図である。
【図11】本発明の実施例を示す回路構成図である。
【図12】本発明の実施例を示す回路構成図である。
【図13】本発明の実施例を示す回路構成図である。
【図14】本発明の実施例を示す回路構成図である。
【図15】本発明の実施例を示す回路構成図である。
【図16】本発明の実施例を示す回路構成図である。
【図17】本発明の実施例を示す外観図である。
【図18】本発明の実施例を示す外観図である。
【図19】本発明の実施例を示す外観図である。
【図20】本発明の実施例を示す外観図である。
【図21】本発明の実施例を示す外観図である。
【図22】本発明の実施例を示す外観図である。
【図23】本発明の実施例を示す外観図である。
【図24】本発明の実施例の特性を示す図である。
【図25】本発明の実施例を示す回路構成図である。
【図26】本発明の実施例を示す回路構成図である。
【図27】本発明の従来例を示す回路構成図である。
【図28】本発明の従来例の電力授受用トランスを示す構成図である。
【図29】本発明の従来例を示す回路構成図である。
【図30】本発明の従来例の特性を示す図である。
【図31】本発明の従来例を示す回路構成図である。
【図32】本発明の従来例を示す回路構成図である。
【図33】本発明の従来例の特性を示す図である。
【図34】本発明の従来例の特性を示す図である。
【符号の説明】
1　非接触コンセント
2　非接触プラグ
3　端末機器
10　電源回路
11　インバータ回路
20　整流平滑回路
E　直流電圧
V1　高周波電圧
V2　高周波電圧
L1　電力送電用1次コイル
L2　電力受電用2次コイル

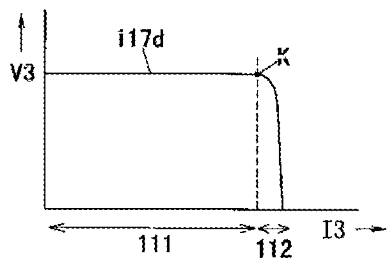
【図4】



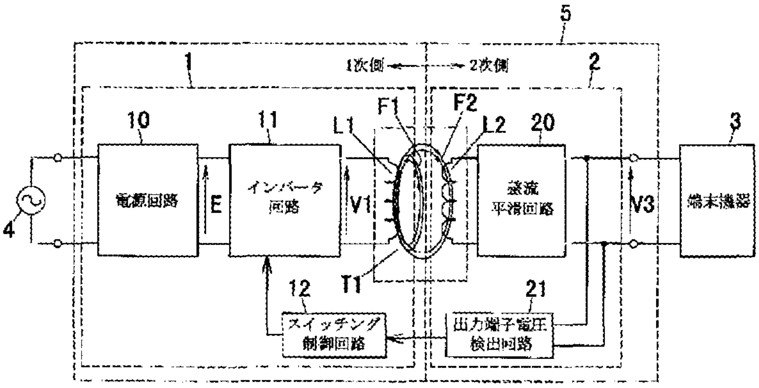
【図5】



【図8】



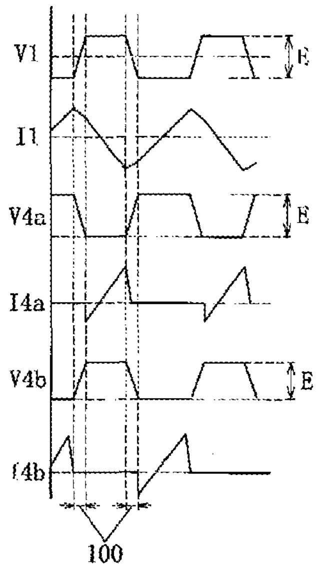
【図1】



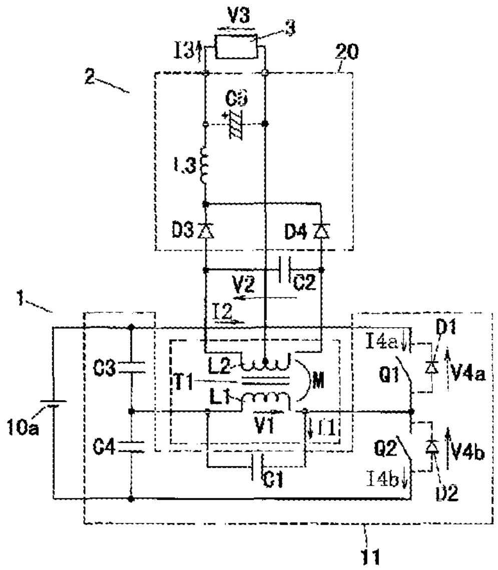
1 非接触コンセント
2 非接触プラグ
3 端末機器
10 電源回路
11 インバータ回路
20 整流平滑回路

E 直流電圧
V1 高周波電圧
V2 高周波電圧
L1 電力送電用1次コイル
L2 電力受電用2次コイル

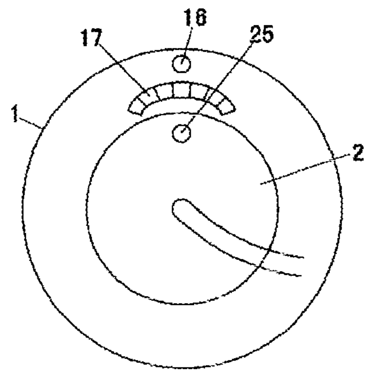
【図3】



【図2】



【図18】



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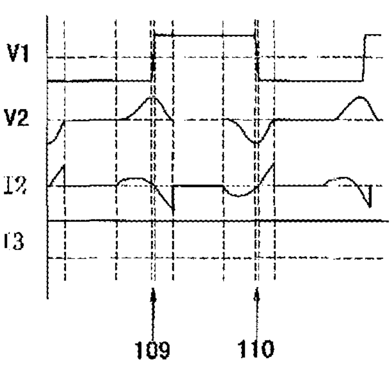

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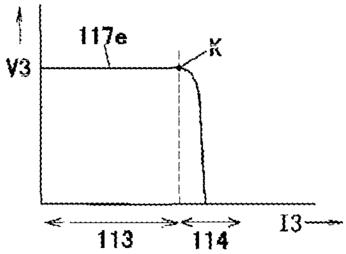

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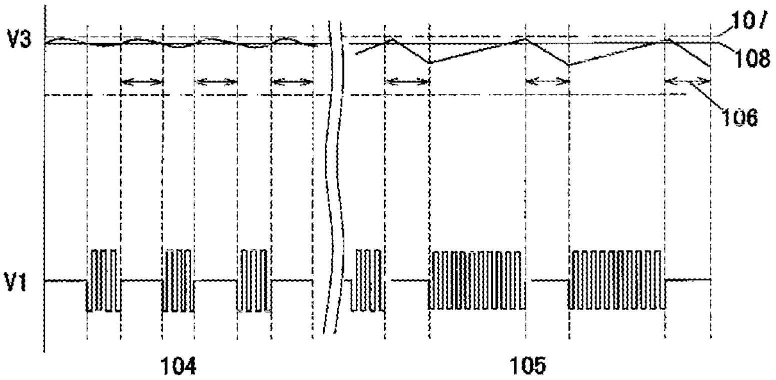

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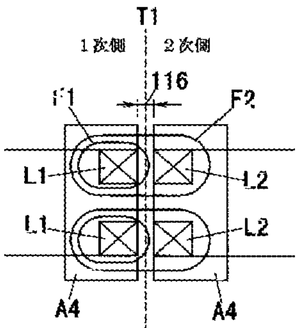

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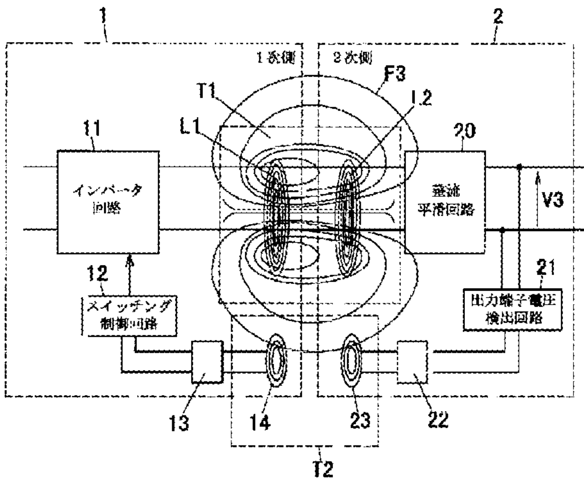
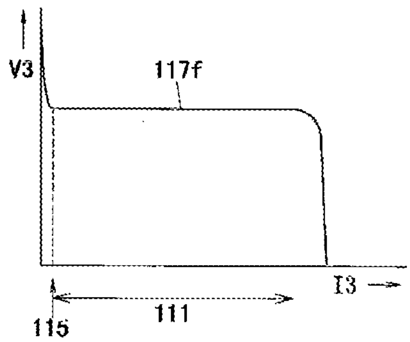


【図24】



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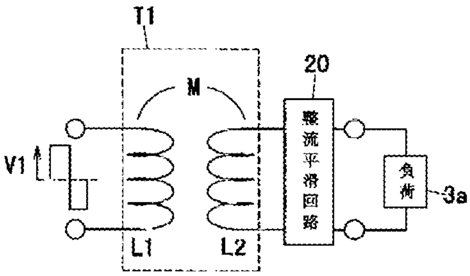

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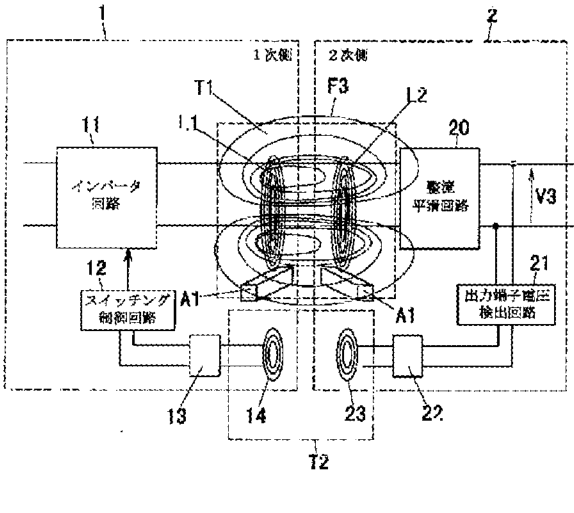
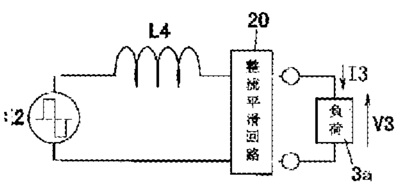
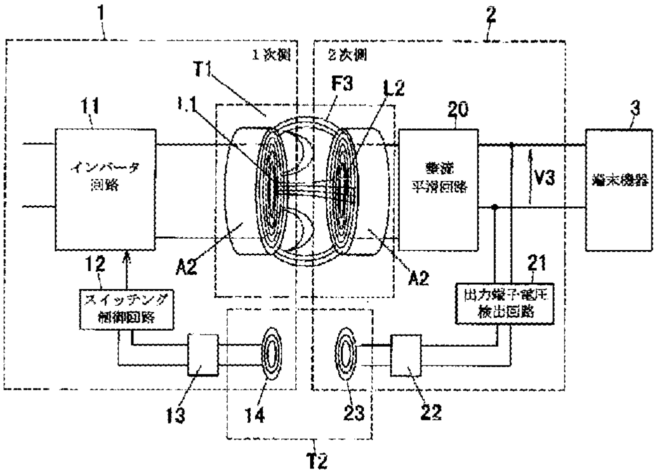


【図29】



【図12】



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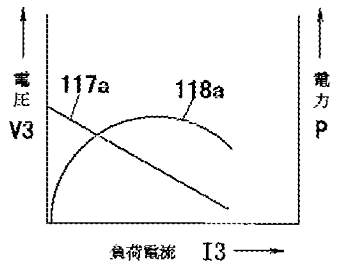
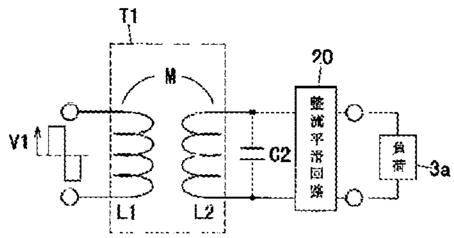
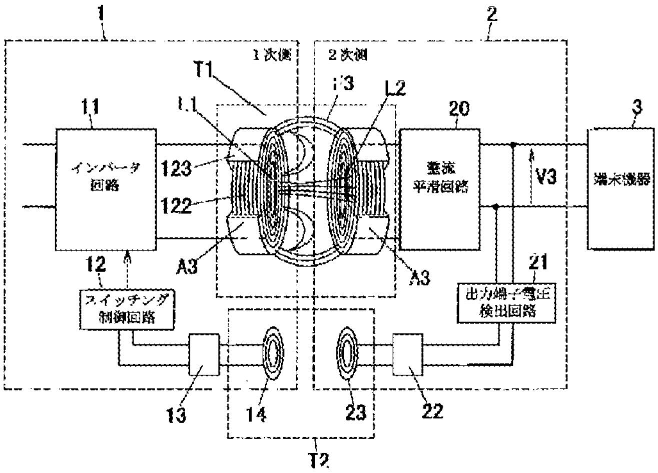


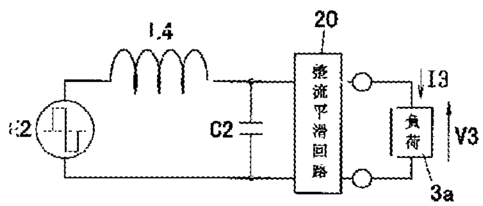
【図31】



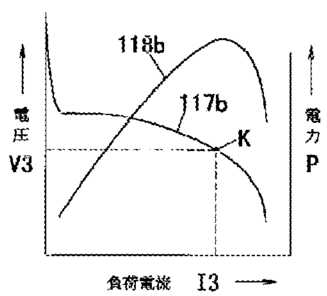
【図13】



【図32】



【図33】



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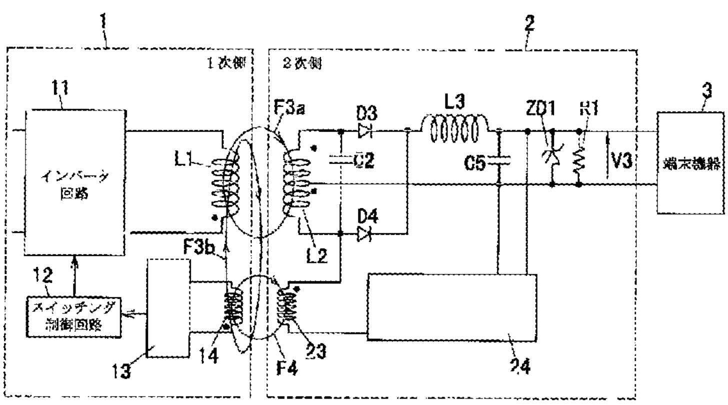
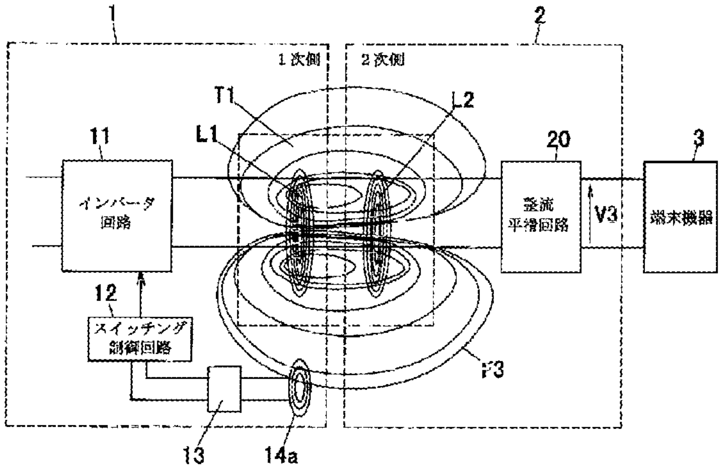
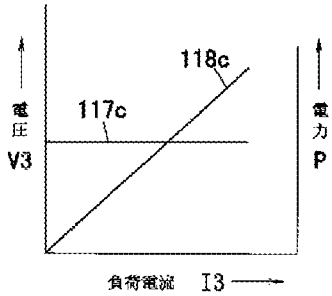


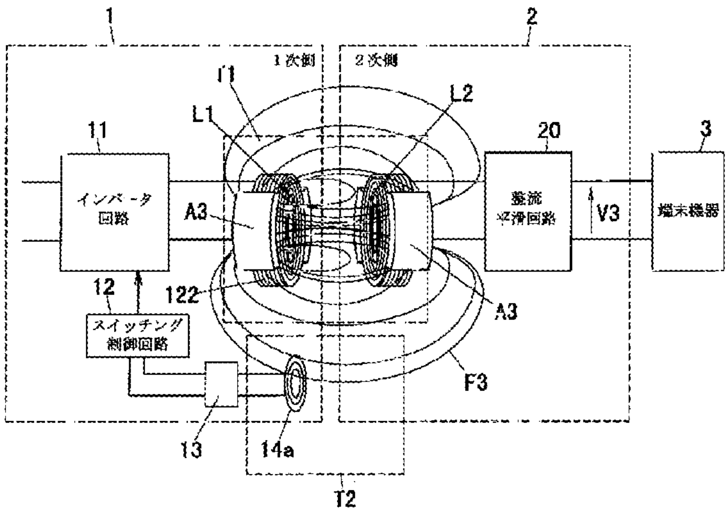
【図15】



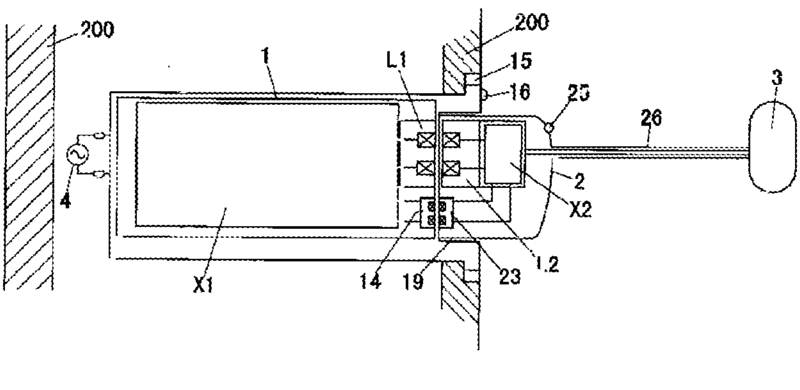
【図34】



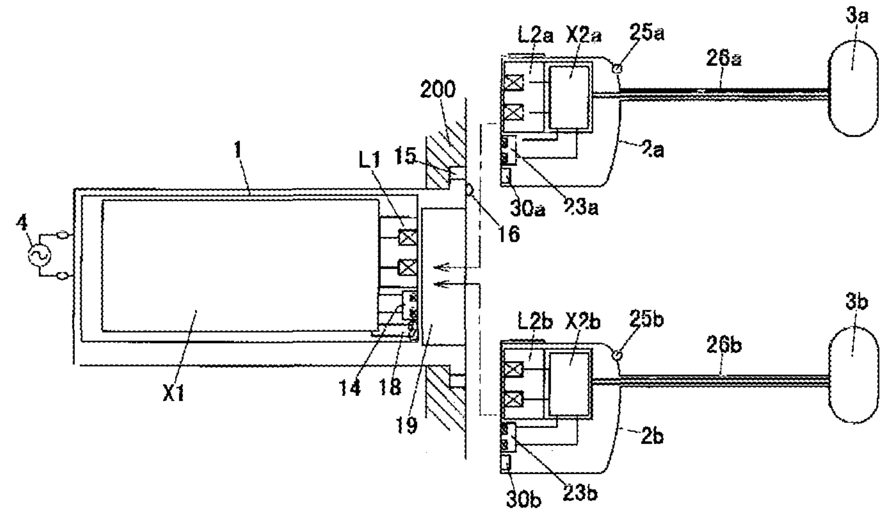
【図16】



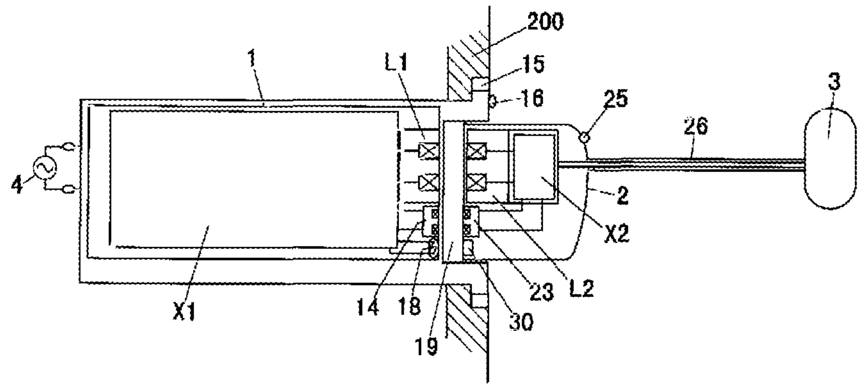
【図17】



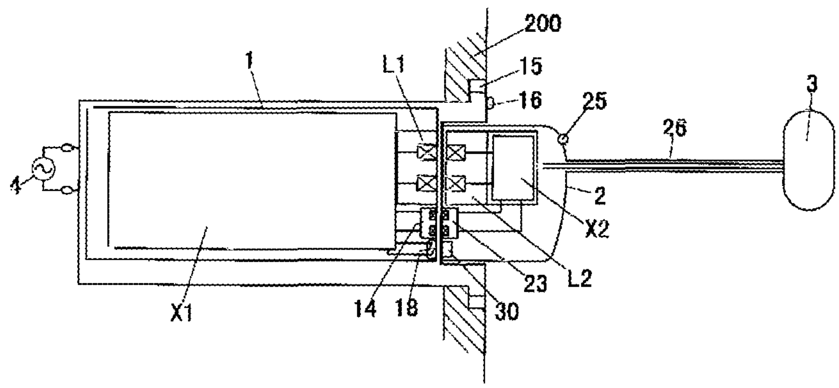
【図19】


L2a
X2a
25a
3a
26a
200
2a
1
L1
15
30a
23a
16
4
L2b
X2b
25b
3b
26b
X1
14
18
19
2b
30b
23b

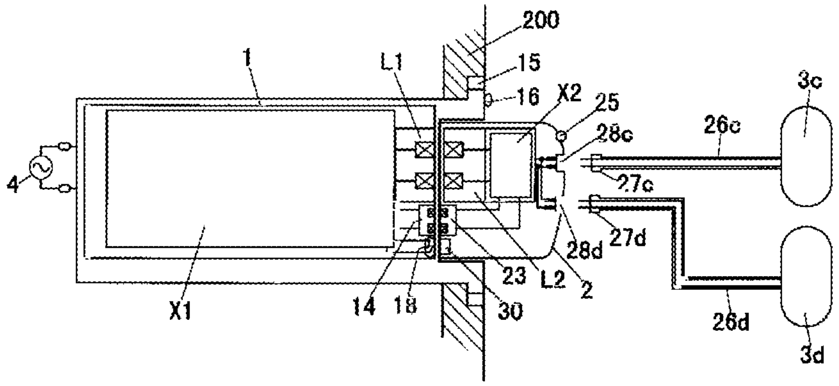
【図20】


200
1
L1
15
16
25
3
26
4
2
X2
X1
14
18
23
L2
30
19

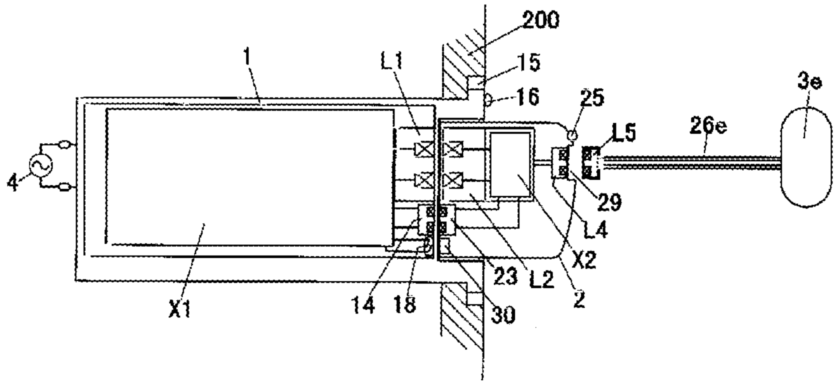
【図21】


200
1
L1
15
16
25
3
26
4
2
X2
23
L2
X1
14
18
30

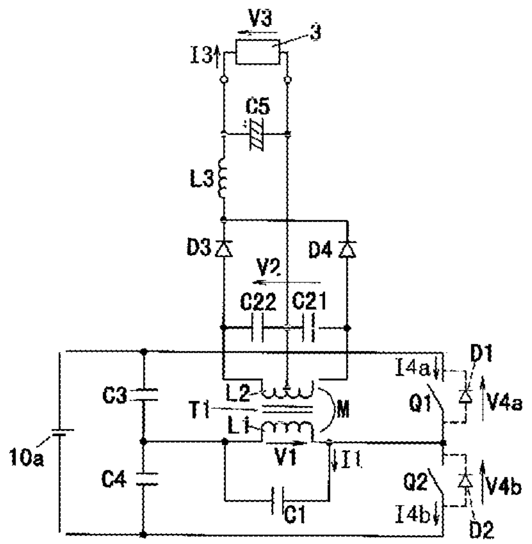
【図22】



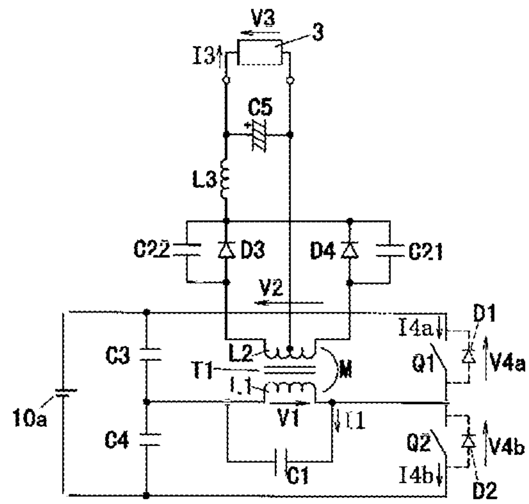
【図23】



【図25】



【図26】



フロントページの続き

(51)Int.Cl.⁷	識別記号	F I		(参考)
H02M 3/335		H01F 23/00	B	

(72)発明者 武藤 元治
大阪府門真市大字門真1048番地松下電工株式会社内

Fターム(参考) 5G065 AA00 DA06 DA07 EA06 HA04 JA01 LA01 MA01 MA02 MA03 MA09 MA10 NA01 NA02 NA03 NA09
5H730 AA17 AS01 BB25 BB26 BB57 BB75 CC01 EE03 EE08 EE59 FD01 FF18 FG07

Title: **System for wireless power and data transmission**

German patent DE20016655 **Kind Code:** U1

Publication Date: 02/14/2002

Export Citation: Click for automatic bibliography generation

International Class: *G08C17/02* ; *H02J7/02* ; G08C17/00 ; H02J7/02 (IPC1-7): H02J17/00; G05F1/46; G08C17/02; H04B7/005

Claims:

First System for wireless power and data transmission with a first transceiver (10) having a controllable power supply means (16) for providing a supply of energy for a second transceiver (20) and transmitting means (12) for the wireless and data energy transmission, wherein the second transceiver (20) comprising: receiving means (30, 32, 34) for receiving from the first transceiver device (10) wirelessly transmitted energy supply, one of the receiving means (30, 32 , 34) associated with the rectifier (22), an energy storage device (24) which for at least partly storing the wirelessly transmitted and rectified supply power, a detection means (40) for detecting a border a predetermined amount of energy amount of energy, a control device (50) of a function output signal of the detection device (40), a manipulated variable for controlling the power supply means (16) generates the first transceiver (10) anda transmitting means (60) for wireless transmission of the control variable for the first transceiver (10). 2nd System for wireless power and data transmission according to claim 1, characterized in that the detection device (40) comprises a series circuit composed of a voltage stabilizing means (42) and an ammeter (44) and the current flowing through the voltage-stabilizing means (42) can flow with a predetermined current value. third System for wireless power and data transmission according to claim 1, characterized in that the detection means comprises a load associated voltmeter and compare the voltage drop across the load voltage to a predetermined voltage value. 4th System for wireless power and data transmission according to one of claims 1 to 3, characterized in that the energy transfer takes place inductively and the receiving means of the second transmitting / receiving device (30) a resonant circuit (32, 34) with a fixed resonant frequency. 5 . System for wireless power and data transmission according to claim 4, characterized in that the carrier frequency of the respective transmission means (12, 60). And the resonant frequency of the resonant circuit (32, 34) is about 130 kHz 6th System for wireless power and data transmission according to one of claims 1 to 5, characterized in that the second transceiver device (20) comprises a temperature sensor (80), wherein said control means ((50), a manipulated variable as a function of the output signal of the detection device 40) and the temperature sensor 80) (produced. 7th System for wireless power and data transmission according to one of claims 1 to 6, characterized in that the first transceiver (10) an interrogation device and the second transceiver (20), an implantable transponder. 8th Transceiver, in particular an implantable transponder for use in a system for wireless power and data transmission according to one of claims 1 to 7, comprising a receiving device (30) for receiving from a remote transceiver (10) wirelessly transmitted supply energy one of said receiving means (30) associated with the rectifier (22), an energy storage device (24) for at least partly storing the wirelessly transmitted and rectified supply power, a detection means (40) for detecting a border a predetermined amount of energy amount of energy, a control means (50) provided in depending on the output signal of the detection device (40), a manipulated variable for controlling a power supply device (16) generates the remote transceiver (10) anda transmitting means (60) for wirelessly transmitting the control value to the remote transceiver. 9th Transceiver according to claim 8 characterized in that the detection device (40) comprises a series circuit comprising a voltage stabilizing means (42) and an ammeter (44) and the predetermined by the voltage stabilizing means (42) with a current flowing can compare current value. 10th Transceiver according to claim 8, characterized in that the detection means comprises a load associated voltmeter and to compare the voltage drop across the load voltage to a predetermined voltage value. 11th Transceiver according to claim 8 or 9, characterized in that the energy transfer takes place inductively and the receiving device (30) of the second transceiver (20) is a resonant circuit (32, 34) with a fixed resonant frequency. 12th Sende-/und receiving device according to any one of claims 8 to 11, characterized in that the second transceiver (20) a temperature sensor (80), wherein the control means (50), a manipulated variable as a function of the output signal of the detection device (40) and the temperature sensor (80) is generated.

Description: The description text was not not electronically recorded, the description text was not recorded electronically The description text was not recorded electronically The description text was not recorded electronically The description text was not recorded electronically The description text was not recorded electronically, the descriptive text has been entered electronically.

<- Previous Patent (parking meter as Slec ...) | Next Patent (Two-stage Auswerfe ...) ->

DERWENT-ACC-NO: 2003-560319

DERWENT-WEEK: 200353

TITLE: System for wireless energy and data transmission has detector of received energy level, regulator producing control signal for seeding transmitter/receiver depending on detector signal

PATENT-ASSIGNEE: IC HAUS GMBH[ICHAN]

PRIORITY-DATA: 2000DE-2016655 (September 25, 2000)

PATENT-FAMILY:

PUB-NO	PUB-DATE	LANGUAGE
DE 20016655 U1	February 14, 2002	DE

INT-CL-CURRENT:

TYPE	IPC DATE
CIPS	G08C17/02 20060101
CIPS	H02J7/02 20060101

ABSTRACTED-PUB-NO: DE 20016655 U1

BASIC-ABSTRACT:

NOVELTY - The system has a first transmitter/receiver with a regulated supply for supplying a second transmitter/receiver and a wireless data and energy transmitter with a transmitted energy receiver, a rectifier, a device for storing transmitted energy, an energy level detector, a regulator producing a control signal for the first transmitter/receiver and a transmitter for sending the signal to the first transmitter/receiver

DESCRIPTION - The system has a first transmitter/receiver (10) with a regulated supply device for supplying a second transmitter/receiver (20) and a transmitter for wireless data and energy transmission. The second transmitter/receiver has a receiver (30) for the transmitted energy, a rectifier (22), a device (24) for at least partly storing the transmitted energy, a detector (40) of the energy level, a regulator (50) for producing a control signal for the first transmitter/receiver and a transmitter (60) for sending the signal to the first transmitter/receiver. AN INDEPENDENT

CLAIM is also included for the following: a transmitter/receiver, especially an implantable transponder for use in an inventive system.

USE - For wireless energy and data transmission.

ADVANTAGE - Enables a transmitter/receiver with no batteries to be supplied with energy in a certain manner, preferably regulated as required for operation of the transmitter/receiver.

DESCRIPTION OF DRAWING(S) - The drawing shows a schematic representation of an inventive system

first transmitter/receiver (10)

second transmitter/receiver (20)

receiver (30)

rectifier (22)

device (24)

detector (40)

regulator (50)

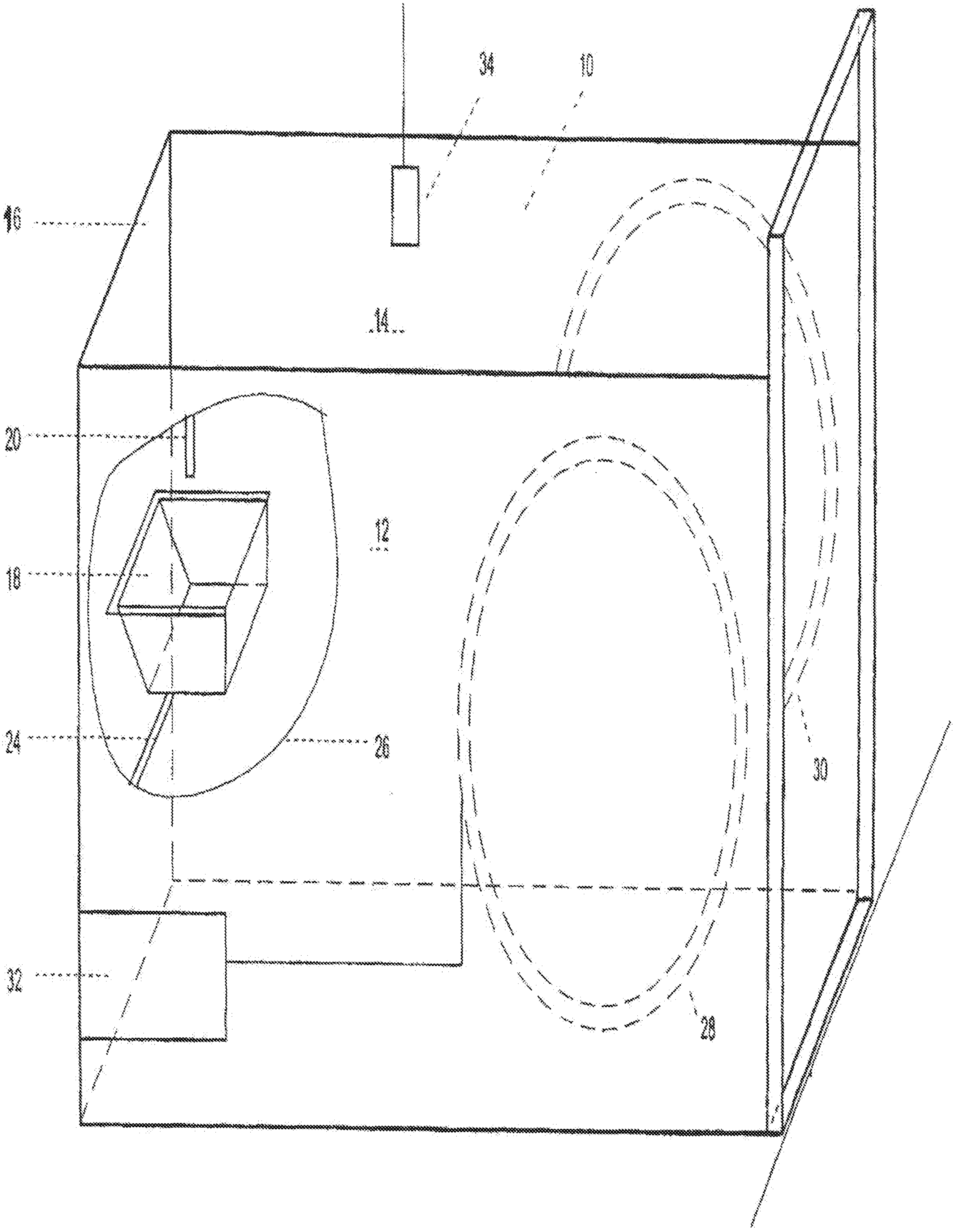
transmitter (60)

CHOSEN-DRAWING: Dwg.1/1

TITLE-TERMS: SYSTEM WIRELESS ENERGY DATA TRANSMISSION DETECT RECEIVE LEVEL REGULATE PRODUCE CONTROL SIGNAL SEND TRANSMIT DEPEND

DERWENT-CLASS: U24 W02 W05

EPI-CODES: U24-E02; W02-G05A; W05-D06A1A; W05-D07G;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Description DE20016655

< Desc/Clms Page number 1>
EMI 1.1

EMI 1.2
Energy and data transmission, and a transmitting / receiving device for use in such a system.

Numerous transponder systems are known that consist essentially of an interrogator and an implantable, for example in a human or animal body transponder.
Known transponder can consist of multiple actuators and sensors, run the commands and identify specific data.
The collected data are then transmitted from the transponder to the interrogator and evaluated there.
Such a transponder system is described for example in DE 195 382 13th

The power supply of a transponder can be performed using a separate battery, or in case of a battery-free transponder via an externally coupled supply energy.
Such a battery-free transponder for example disclosed in EP 0 442 390th

It describes batteryless transponder has a resonant circuit which is tuned to the frequency of the transmission signal of the interrogator.
Furthermore, an energy storage is provided which is charged by the light coming from the interrogator transmitter signal rectified.
The energy storage device provides in the charged state, the supply voltage for the transponder.
Further comprising a voltage-limiting means for limiting the voltage across the energy storage device is provided at a predetermined value.
With the known device and the query batteryless transponders it is not possible to
EMI 1.3

<Desc/Clms Page number 2>

to regulate from the interrogator provided for the transponder as a function of energy supply in the transponder determined and evaluated data.

The invention is therefore based on the object, a system for wireless power and data transmission as well as
EMI 2.1
to provide a supply of energy, which is regulated to a certain value, preferably for the operation of the battery-less transceiver required energy.

The gist of the invention is the fact that in the self-powered transceiver a manipulated variable is determined, which is used to a controllable
EMI 2.2
Receiving means to settle such that the wireless transceiver to the battery-less energy transferred substantially to the information required by the battery-free transmission / reception device energy quantity.

The above-mentioned technical problem is solved by the invention for one of the features of claim 1

For this purpose a system for wireless power and data transmission is provided, which preferably has a first and a second transceiver.
The first transceiver has a variable power supply means for providing a
EMI 2.3
and power transmission means for transmitting via a wireless data and.
The second, advantageously powered wireless transceiver comprises a receiving means for receiving from the first transmitting / receiving means wirelessly transmitted energy supply.
For rectifying the transmitted via an RF carrier signal energy of the receiving device is a rectifier, preferably associated with a bridge rectifier.
An energy storage device is used to the wirelessly transmitted and rectified supply energy

<Desc/Clms Page number 3>

EMI3.1
Amount of energy provided border energy quantity.
A regulating device is used to generate, in response to the output signal of the detection means a control signal for controlling the power supply means of the first transmitting / receiving device, wherein the control signal via a transmitting means is wireless to the first transmitting / receiving means transferable.

Advantageous developments are the subject of the dependent claims.

The detection device has, according to a first alternative embodiment of a series circuit comprising a voltage stabilizing means, and a current meter.
The detection means and the control means are able to compare the current flowing through the voltage-stabilizing device current with a predetermined current value.
The predetermined current value is preferably from the first transceiver to operate the required supply energy.

That is, the excess energy is preferably kept small.

According to a further embodiment, the detecting means to one of a load associated voltmeter.
The falling of the load voltage in turn can be compared by means of the detection device or the control device with a predetermined voltage value, which in turn reflects the time required by the second transmitting / receiving device energy.

By the special design of the detection device according to the above-described alternatives, it is possible to regulate the power supply device of the first transmitter / receiver device such that the transmitted output power substantially corresponds to the energy that is required by the second battery-free transceiver.
In this way it is possible to
EMI3.2

< Desc/Clms Page number 4>

Heat keeping in the second transceiver to a minimum.
In addition, during battery operation of the first transceiver can therefore its battery life can be extended, also, the transmission field strength can be reduced to the necessary degree.

Advantageously, the energy transfer takes place inductively, in which case the receiving means of the second transceiver for receiving said energy comprises a resonant circuit with a fixed resonant frequency.

The two transceivers used in the near field, a carrier frequency for the respective transmission means and a resonant frequency for the resonant circuit can be selected, which lie at around 130 kHz.

The second batteryless transceiver used for example as in a body implantable transponders, it is useful to measure with an implantable temperature sensor measures the temperature in the vicinity of the transponder, in order to avoid a critical heating of the environment.
For this purpose the control device is designed such that it can generate a control signal in dependence of the output signal of the detection device and the temperature sensor.
In this way it is possible, the transmit power to reduce by means of the variable power supply means in the first transmitting / receiving device, even when although the transmitted energy is not required by the second transmitting / receiving device of energy is exceeded, but the temperature in the vicinity of transponder reaches a critical value.

As mentioned, it may, at the second transmitting / receiving device, be an implantable transponder, and then the first transceiver advantageously acts as interrogator.

At this point it should be mentioned that the second transmitting / receiving device according to the various application

< Desc/Clms Page number 5>

May have actuators and sensors, with the exception of the integration of the temperature sensor are not the subject of the invention.

The above object is also achieved by a transmitting / receiving device, which can for example be designed as an implantable, batteryless transponder.
The essential features of the batteryless
EMI5.1
that the characteristics are not repeated at this point.

The invention will now be described by way of example in more detail in conjunction with FIG.

In the present example as the first transmitting / receiving means comprises a retrieval means 10 is used, which communicates for example with a battery-less transponder 20 via a known inductive coupling.
Wherein said implantable batteryless transponder 20 may be a transponder to be used in medical inkorporalen nerve stimulation.

The interrogation device comprises in addition to a known transmission means 12, and receiving device 14 includes a variable power supply means 16, which provides the supply energy for the transponder 20.
The wireless power and data transmission between the interrogator 10 and the transponder 20 via a carrier signal having a frequency of 130kHz for example.
The data can be transmitted, for example as a frequency-modulated signals via the transmitting means 12 for transponder 20.
For this purpose, the transponder 20 corresponding decoding and demodulation, which are not shown.

The transmitted RF signals are coupled via a resonant frequency circuit 30, which is constructed by a parallel circuit of a coil 32 and a capacitor 34.
The resonant frequency of the resonant circuit 30 is
EMI5.2

< Desc/Clms Page number 6>

EMI6.1
this example, 130 kHz. The injected HFSpannungen be rectified by a bridge rectifier 22, and then at least partially loading a charging capacitor 24.
The charging capacitor 24 is used as an energy storage in the power supply of the transponder 20th
A voltage-stabilizing or voltage limiting element 42, the voltage drop across the charging capacitor 24 voltage is stabilized and limited.
The voltage stabilizing element 42 may be realized for example as a Zener diode 42.
The Zener diode 42 in the present example is part of a detection device 40, further comprising a capacitor connected in series with the Zener diode 42 current blade 44.
The ammeter 44 of the detection device has the task to measure the effluent through the Zener diode 42 current.
The measured current is a measure of whether the transponder 20 is placed too much or too little power supply energy from the interrogation device 10 are available.
In a control device 50 of the measured current with a predetermined current value is compared to the required mapping of the transponder 20 supply energy.
In the control means 50 or alternatively, in the detection device 40 of the measured current from the current sensor 44 with the predetermined current value is compared.

From the comparison value, the control device 50 determines a control signal which is transmitted via a transmission device 60 to the interrogation device 10.
Increases as a function of the actuating signal, or lowers the controllable power supply device, the transmission power of the interrogation device 10
In other words, the transmission power of the interrogator 10 is increased, when the current flowing through the Zener diode 42 current falls below the predetermined current value, while the transmission power is lowered when the measured current exceeds the predetermined current value.

Alternatively, the detection means comprise a voltage meter and a load, wherein the voltage drop is measured at the load from the voltage meter.
The measured voltage value is then compared with a predetermined voltage value, which in turn corresponds to the required by the transponder 20 supply energy.

This embodiment is not shown in the figure.

For example, the body temperature in the vicinity of the receiving means 30 and the transmitting means 60 of the transponder 20 can measure a temperature sensor 80 is provided.
To avoid that the skin is heated in a critical way, the measured temperature value is also supplied to the control means 50 which produces now both the measured temperature as well as from the current flowing through the Zener diode 42 power a control signal, which power supply means, the controllable 16 of the interrogator prompted to change the transmit power is such that on the one hand, the environment can not be heated in a critical manner and also ensure sufficient energy supply for the transponder.
The signal generated by the control means 50 in the extreme case the control signal can turn the interrogator in order to avoid damage to the body in the vicinity of the transponder.

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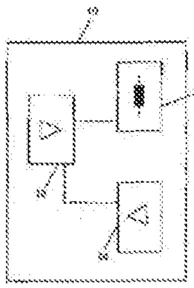
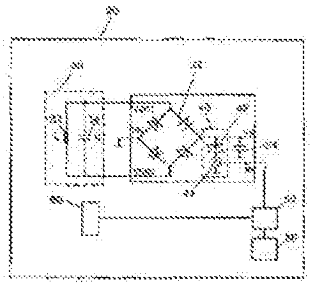
(54) System zur drahtlosen Energie- und Datenübertragung

(57) System zur drahtlosen Energie- und Datenübertragung mit einer ersten Sende-/Empfangseinrichtung (10), die eine regelbare Energieversorgungseinrichtung (16) zur Bereitstellung einer Versorgungsenergie für eine zweite Sende-/Empfangseinrichtung (20) und eine Sendeeinrichtung (12) zur drahtlosen Daten- und Energieübertragung aufweist, wobei die zweite Sende-/Empfangseinrichtung (20) folgende Merkmale aufweist:
eine Empfangseinrichtung (30, 32, 34) zum Empfangen der von der ersten Sende-/Empfangseinrichtung (10) drahtlos übertragenen Versorgungsenergie,
einen der Empfangseinrichtung (30, 32, 34) zugeordneten Gleichrichter (22), einen Energiespeicher (24) zum wenigstens teilweisen Speichern der drahtlos übertragenen und gleichgerichteten Versorgungsenergie,
eine Detektionseinrichtung (40) zum Erfassen einer eine vorbestimmte Energiemenge überschreitende Energiemenge,
eine Regeleinrichtung (50), die in Abhängigkeit von dem Ausgangssignal der Detektionseinrichtung (40) eine Stellgröße zur Regelung der Energieversorgungseinrichtung (16) der ersten Sende-/Empfangseinrichtung (10) erzeugt und
eine Sendeeinrichtung (60) zum drahtlosen Übertragen der Stellgröße zur ersten Sende-/Empfangseinrichtung (10).





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iC-Haus GmbH

System zur drahtlosen Energie- und Datenübertragung

Die Erfindung betrifft ein System zur drahtlosen Energie- und Datenübertragung sowie eine Sende-/ Empfangseinrichtung zum Einsatz in einem solchen System.

Zahlreiche Transpondersysteme sind bekannt, die im Wesentlichen aus einer Abfrageeinrichtung und einem beispielsweise in einen menschlichen oder tierischen Körper implantierbaren Transponder bestehen. Bekannte Transponder können aus mehreren Aktoren und Sensoren bestehen, die Befehle ausführen bzw. bestimmte Daten ermitteln. Die ermittelten Daten werden dann vom Transponder zur Abfrageeinrichtung übertragen und dort ausgewertet. Ein solches Transpondersystem ist beispielsweise in der DE 195 382 13 beschrieben.

Die Energieversorgung eines Transponders kann mittels einer eigenen Batterie oder im Falle eines batterielosen Transponders über eine extern eingekoppelte Versorgungsenergie erfolgen. Ein solcher batterieloser Transponder ist beispielsweise Gegenstand der EP 0442 390. Der darin beschriebene batterielose Transponder weist einen Resonanzschwingkreis auf, der auf die Frequenz des Sendesignals der Abfrageeinrichtung abgestimmt ist. Ferner ist ein Energiespeicher vorgesehen, der durch das von der Abfrageeinrichtung kommende gleichgerichtete Sendesignal aufgeladen wird. Der Energiespeicher liefert im geladenen Zustand die Versorgungsspannung für den Transponder. Ferner ist eine Spannungs-begrenzende Einrichtung zum Begrenzen der Spannung an dem Energiespeicher auf einen vorbestimmten Wert vorgesehen. Mit der bekannten Abfrageeinrichtung und dem batterielosen Transponder ist es jedoch nicht möglich, die von der Abfrageeinrichtung für den Transponder bereitgestellte Versorgungsenergie in Abhängigkeit von im Transponder ermittelten und ausgewerteten Daten zu regeln.

Der Erfindung liegt daher die Aufgabe zugrunde, ein System zur drahtlosen Energie- und Datenübertragung sowie eine Sende-/Empfangseinrichtung zu schaffen, mit denen es möglich ist, eine batterielose Sende-/Empfangseinrichtung mit einer Versorgungsenergie zu versorgen, die auf einen bestimmten Wert, vorzugsweise auf die zum Betrieb der batterielosen Sende-/Empfangseinrichtung benötigte Energie geregelt wird.

Der Kerngedanke der Erfindung ist darin zu sehen, dass in der batterielosen Sende-/Empfangseinrichtung eine Stellgröße ermittelt wird, die dazu dient, eine regelbare Versorgungsenergie in der externen Sende-/ Empfangseinrichtung derart zu regeln, dass die drahtlos zur batterielosen Sende-/Empfangseinrichtung übertragene Energie im Wesentlichen der von der batterielosen Sende-/ Empfangseinrichtung benötigten Energiemenge entspricht.

Das oben genannte technische Problem löst die Erfindung zum einen mit den Merkmalen des Anspruchs 1.

Hierzu ist ein System zur drahtlosen Energie- und Datenübertragung vorgesehen, welches vorzugsweise eine erste und eine zweite Sende-/Empfangseinrichtung aufweist. Die erste Sende-/Empfangseinrichtung verfügt über eine regelbare Energieversorgungseinrichtung zur Bereitstellung einer Versorgungsenergie für die zweite Sende-/Empfangseinrichtung und über eine Sendeeinrichtung zur drahtlosen Daten- und Energieübertragung. Die zweite, zweckmäßigerweise batterielose Sende-/Empfangseinrichtung weist eine Empfangseinrichtung zum Empfangen der von der ersten Sende-/ Empfangseinrichtung drahtlos übertragenen Versorgungsenergie auf. Zur Gleichrichtung der über ein HF-Trägersignal übertragenen Energie ist der Empfangseinrichtung ein Gleichrichter, vorzugsweise ein Brückengleichrichter zugeordnet. Ein Energiespeicher dient dazu, die drahtlos übertragene und gleichgerichtete Versorgungsenergie wenigstens teilweise zu speichern. Ferner ist eine Detektionseinrichtung zum Erfassen einer eine vorbestimmte Energiemenge überschreitende Energiemenge vorgesehen. Eine Regeleinrichtung dient dazu, in Abhängigkeit von dem Ausgangssignal der Detektionseinrichtung ein Stellsignal zur Regelung der Energieversorgungseinrichtung der ersten Sende-/Empfangseinrichtung zu erzeugen, wobei das Stellsignal über eine Sendeeinrichtung drahtlos zur ersten Sende-/ Empfangseinrichtung übertragbar ist.

Vorteilhafte Weiterbildungen sind Gegenstand der Unteransprüche.

Die Detektionseinrichtung weist gemäß einer ersten alternativen Ausführungsform eine Serienschaltung aus einer Spannungs-stabilisierenden Einrichtung und einem Strommessgerät auf. Die Detektionseinrichtung oder die Regeleinrichtung sind in der Lage, den durch die Spannung-stabilisierende Einrichtung fließenden Strom mit einem vorbestimmten Stromwert zu vergleichen. Der vorbestimmte Stromwert bildet vorzugsweise die zum Betrieb der ersten Sende-/ Empfangseinrichtung benötigte Versorgungsenergie ab. Das heißt, die überschüssige Energie wird vorzugsweise klein gehalten.

Gemäß einer weiteren Ausführungsform weist die Detektionseinrichtung einen einer Last zugeordneten Spannungsmesser auf. Die an der Last abfallende Spannung kann wiederum mittels der Detektionseinrichtung oder der Regeleinrichtung mit einem vorbestimmten Spannungswert verglichen werden, der wiederum die von der zweiten Sende-/ Empfangseinrichtung benötigte Energie abbildet.

Durch die spezielle Ausgestaltung der Detektionseinrichtung gemäß den oben beschriebenen Alternativen ist es möglich, die Energieversorgungseinrichtung der ersten Sende-/Empfangseinrichtung derart zu regeln, dass die übermittelte Sendeleistung im Wesentlichen der Energie entspricht, die von der zweiten, batterielosen Sende-/ Empfangseinrichtung benötigt wird. Auf diese Weise ist es möglich, die

Wärmeentwicklung in der zweiten Sende-/ Empfangseinrichtung möglichst klein zu halten. Darüber hinaus kann bei Batteriebetrieb der ersten Sende-/ Empfangseinrichtung demzufolge deren Batterielebensdauer verlängert werden. Ferner kann die Sendefeldstärke auf das notwendige Maß reduziert werden.

Zweckmäßigerweise erfolgt die Energieübertragung induktiv, wobei dann die Empfangseinrichtung der zweiten Sende-/Empfangseinrichtung zum Empfang der Energie einen Schwingkreis mit einer fest vorgegebenen Resonanzfrequenz aufweist.

Werden die beiden Sende-/Empfangseinrichtungen im Nahfeld benutzt, kann eine Trägerfrequenz für die jeweiligen Sendeeinrichtungen und eine Resonanzfrequenz für den Schwingkreis gewählt werden, die etwa bei 130 kHz liegen. Wird die zweite batterielose Sende-/Empfangseinrichtung beispielsweise als in einem Körper implantierbarer Transponder verwendet, ist es sinnvoll, mit einem implantierbaren Temperatursensor die Temperatur in der Umgebung des Transponders zu messen, um eine kritische Erwärmung der Umgebung zu vermeiden. Hierzu ist die Regeleinrichtung derart ausgebildet, dass sie ein Stellsignal in Abhängigkeit des Ausgangssignals der Detektionseinrichtung und des Temperatursensors erzeugen kann. Auf diese Weise ist es möglich, die Sendeleistung mittels der regelbaren Energieversorgungseinrichtung in der ersten Sende-/ Empfangseinrichtung auch dann zu reduzieren, wenn zwar die übertragene Energie die von der zweiten Sende-/ Empfangseinrichtung benötigte Energie nicht überschritten, aber die Temperatur in der Umgebung des Transponders einen kritischen Wert erreicht hat.

Wie erwähnt, kann es sich bei der zweiten Sende-/ Empfangseinrichtung um einen implantierbaren Transponder handeln, wobei dann die erste Sende-/Empfangseinrichtung zweckmäßigerweise als Abfrageeinrichtung fungiert.

An dieser Stelle sei erwähnt, dass die zweite Sende-/ Empfangseinrichtung je nach Anwendungsfall verschiedene

Aktoren und Sensoren aufweisen kann, die mit Ausnahme der Einbindung des Temperatursensors nicht Gegenstand der Erfindung sind.

Die oben genannte Aufgabe wird ferner durch eine Sende-/Empfangseinrichtung gelöst, die beispielsweise als implantierbarer, batterieloser Transponder ausgebildet sein kann. Die wesentlichen Merkmale der batterielosen Sende-/Empfangseinrichtung wurden obenstehend in Bezug auf die zweite Sende-/Empfangseinrichtung näher ausgeführt, so dass die Merkmale an dieser Stelle nicht mehr wiederholt werden.

Die Erfindung wird nachstehend anhand eines Ausführungsbeispiels in Verbindung mit einer Figur näher erläutert.

In dem vorliegenden Beispiel wird als erste Sende-/Empfangseinrichtung eine Abfrageeinrichtung 10 verwendet, die beispielsweise mit einem batterielosen Transponder 20 über eine an sich bekannte induktive Kopplung kommuniziert. Bei dem implantierbaren batterielosen Transponder 20 kann es sich um einen in der Medizintechnik einsetzbaren Transponder zur inkorporalen Nervenstimulation handeln.

Die Abfrageeinrichtung weist neben einer an sich bekannten Sendeeinrichtung 12 und Empfangseinrichtung 14 eine regelbare Energieversorgungseinrichtung 16 auf, die die Versorgungsenergie für den Transponder 20 liefert. Die drahtlose Energie- und Datenübertragung zwischen der Abfrageeinrichtung 10 und dem Transponder 20 erfolgt über ein Trägersignal, welches beispielsweise eine Frequenz von 130kHz aufweist. Die Daten können beispielsweise als frequenzmodulierte Signale über die Sendeeinrichtung 12 zum Transponder 20 übertragen werden. Hierzu weist der Transponder 20 entsprechende Decodier- und Demodulationseinrichtungen auf, die nicht dargestellt sind. Die übertragenen HF-Signale werden über einen Resonanzfrequenzkreis 30 eingekoppelt, der durch eine Parallelschaltung aus einer Spule 32 und einem Kondensator 34 aufgebaut ist. Die Resonanzfrequenz des Schwingkreises 30 ist auf die Trägerfrequenz des Sendesignals der Abfrageeinrichtung abgestimmt und beträgt daher in dem vorliegenden Beispiel 130 kHz. Die eingekoppelten HF-Spannungen werden über einen Brückengleichrichter 22 gleichgerichtet und laden anschließend zumindest teilweise einen Ladekondensator 24 auf. Der Ladekondensator 24 dient als Energiespeicher bei der Energieversorgung des Transponders 20. Über ein Spannungs-stabilisierendes oder Spannungs-begrenzendes Element 42 wird die über den Ladekondensator 24 abfallende Spannung stabilisiert und begrenzt. Das Spannungs-stabilisierende Element 42 kann beispielsweise als Zener-Diode 42 realisiert werden. Die Zener-Diode 42 ist im vorliegenden Beispiel Bestandteil einer Detektionseinrichtung 40, die ferner einen in Reihe zur Zener-Diode 42 geschalteten Strommesser 44 aufweist. Der Strommesser 44 der Detektionseinrichtung hat die Aufgabe, den über die Zener-Diode 42 abfließenden Strom zu messen. Der gemessene Strom ist ein Maß dafür, ob dem Transponder 20 zu viel oder zu wenig Versorgungsenergie von der Abfrageeinrichtung 10 zur Verfügung gestellt wird. In einer Regeleinrichtung 50 wird der gemessene Strom mit einem vorbestimmten Stromwert verglichen, der die von dem Transponder 20 benötigte Versorgungsenergie abbildet. In der Regeleinrichtung 50 oder alternativ auch in der Detektionseinrichtung 40 wird der vom Strommesser 44 gemessene Strom mit dem vorbestimmten Stromwert verglichen. Aus dem Vergleichswert ermittelt die Regeleinrichtung 50 ein Stellsignal, welches über eine Sendeeinrichtung 60 zur Abfrageeinrichtung 10 übertragen wird. In Abhängigkeit des Stellsignals erhöht oder erniedrigt die regelbare Energieversorgungseinrichtung die Sendeleistung der Abfrageeinrichtung 10. Mit anderen Worten wird die Sendeleistung der Abfrageeinrichtung 10 erhöht, wenn der durch die Zener-Diode 42 fließende Strom den vorbestimmten Stromwert unterschreitet, während die Sendeleistung erniedrigt wird, wenn der gemessene Strom den vorbestimmten Stromwert überschreitet.

Alternativ kann die Detektionseinrichtung einen Spannungsmesser und eine Last aufweisen, wobei der Spannungsabfall an der Last vom Spannungsmesser gemessen wird. Der gemessene Spannungswert wird dann mit einem vorbestimmten Spannungswert verglichen, der wiederum der von dem Transponder 20 benötigten Versorgungsenergie entspricht. Dieses Ausführungsbeispiel ist jedoch nicht in der Figur dargestellt.

Um beispielsweise die Körpertemperatur in der Nähe der Empfangseinrichtung 30 und der Sendeeinrichtung 60 des Transponders 20 messen zu können, ist ein Temperatursensor 80 vorgesehen. Um zu vermeiden, dass die Haut sich in kritischer Weise erwärmt, wird der gemessene Temperaturwert ebenfalls der Regeleinrichtung 50 zugeführt, die nunmehr sowohl aus der gemessenen Temperatur als auch aus dem durch die Zener-Diode 42 fließenden Strom ein Stellsignal erzeugt, welches die regelbare Energieversorgungseinrichtung 16 der Abfrageeinrichtung veranlasst, die Sendeleistung derart zu ändern, dass zum einen die Umgebung sich nicht in kritischer Weise erwärmt und andererseits eine ausreichende Energieversorgung für den Transponder gewährleistet ist. Das von der Regeleinrichtung 50 erzeugte Stellsignal kann im Extremfall die Abfrageeinrichtung deaktivieren, um Schädigungen des Körpers in der Nähe des Transponders zu vermeiden.

Schutzansprüche

1. System zur drahtlosen Energie- und Datenübertragung mit einer ersten Sende-/Empfangseinrichtung (10), die eine regelbare Energieversorgungseinrichtung (16) zur Bereitstellung einer Versorgungsenergie für eine zweite Sende-/Empfangseinrichtung (20) und eine Sendeeinrichtung (12) zur drahtlosen Daten- und Energieübertragung aufweist, wobei
die zweite Sende-/Empfangseinrichtung (20) folgende Merkmale aufweist:
eine Empfangseinrichtung (30, 32, 34) zum Empfangen der von der ersten Sende-/Empfangseinrichtung (10) drahtlos übertragenen Versorgungsenergie,
einen der Empfangseinrichtung (30, 32, 34) zugeordneten Gleichrichter (22), einen Energiespeicher (24) zum wenigstens teilweisen Speichern der drahtlos übertragenen und gleichgerichteten Versorgungsenergie,
eine Detektionseinrichtung (40) zum Erfassen einer eine vorbestimmte Energiemenge überschreitende Energiemenge,
eine Regeleinrichtung (50), die in Abhängigkeit von dem Ausgangssignal der Detektionseinrichtung (40) eine Stellgröße zur Regelung der Energieversorgungseinrichtung (16) der ersten Sende-/Empfangseinrichtung (10) erzeugt und
eine Sendeeinrichtung (60) zum drahtlosen Übertragen der Stellgröße zur ersten Sende-/Empfangseinrichtung (10).

2. System zur drahtlosen Energie- und Datenübertragung nach Anspruch 1,
dadurch gekennzeichnet, dass
die Detektionseinrichtung (40) eine Serienschaltung aus

einer Spannungs-stabilisierenden Einrichtung (42) und einem Strommessgerät (44) umfasst und den durch die Spannungs-stabilisierende Einrichtung (42) fließenden Strom mit einem vorbestimmten Stromwert vergleichen kann.

3. System zur drahtlosen Energie- und Datenübertragung nach Anspruch 1,
dadurch gekennzeichnet, dass
die Detektionseinrichtung einen einer Last zugeordneten Spannungsmesser aufweist und die an der Last abfallende Spannung mit einem vorbestimmten Spannungswert vergleichen kann.

4. System zur drahtlosen Energie- und Datenübertragung nach einem der Ansprüche 1 bis 3,
dadurch gekennzeichnet, dass
die Energieübertragung induktiv erfolgt und die Empfangseinrichtung der zweiten Sende-/Empfangseinrichtung (30) ein Schwingkreis (32, 34) mit einer fest vorgegebenen Resonanzfrequenz ist.

5. System zur drahtlosen Energie- und Datenübertragung nach Anspruch 4,
dadurch gekennzeichnet, dass
die Trägerfrequenz der jeweiligen Sendeeinrichtungen (12; 60) und die Resonanzfrequenz des Schwingkreises (32, 34) bei etwa 130 kHz liegt.

6. System zur drahtlosen Energie- und Datenübertragung nach einem der Ansprüche 1 bis 5,
dadurch gekennzeichnet, dass
die zweite Sende-/Empfangseinrichtung (20) einen Temperatursensor (80) aufweist, wobei die

Regeleinrichtung (50) eine Stellgröße in Abhängigkeit des Ausgangssignals der Detektionseinrichtung (40) und des Temperatursensor (80) erzeugt.

7 System zur drahtlosen Energie- und Datenübertragung nach einem der Ansprüche 1 bis 6, dadurch gekennzeichnet, dass die erste Sende-/Empfangseinrichtung (10) eine Abfrageeinrichtung und die zweite Sende-/Empfangseinrichtung (20) ein implantierbarer Transponder ist.

8. Sende-/Empfangseinrichtung, insbesondere ein implantierbarer Transponder zum Einsatz in einem System zur drahtlosen Energie- und Datenübertragung nach einem der Ansprüche 1 bis 7, umfassend
eine Empfangseinrichtung (30) zum Empfangen der von einer entfernten Sende-/Empfangseinrichtung (10) drahtlos übertragenen Versorgungsenergie,
einen der Empfangseinrichtung (30) zugeordneten Gleichrichter (22), einen Energiespeicher (24) zum wenigstens teilweise Speichern der drahtlos übertragenen und gleichgerichteten Versorgungsenergie,
eine Detektionseinrichtung (40) zum Erfassen einer eine vorbestimmte Energiemenge überschreitende Energiemenge,
eine Regeleinrichtung (50), die in Abhängigkeit von dem Ausgangssignal der Detektionseinrichtung (40) eine Stellgröße zur Regelung einer Energieversorgungseinrichtung (16) der entfernten Sende-/Empfangseinrichtung (10) erzeugt und
eine Sendeeinrichtung (60) zum drahtlosen Übertragen der Stellgröße zur entfernten Sende-/Empfangseinrichtung.

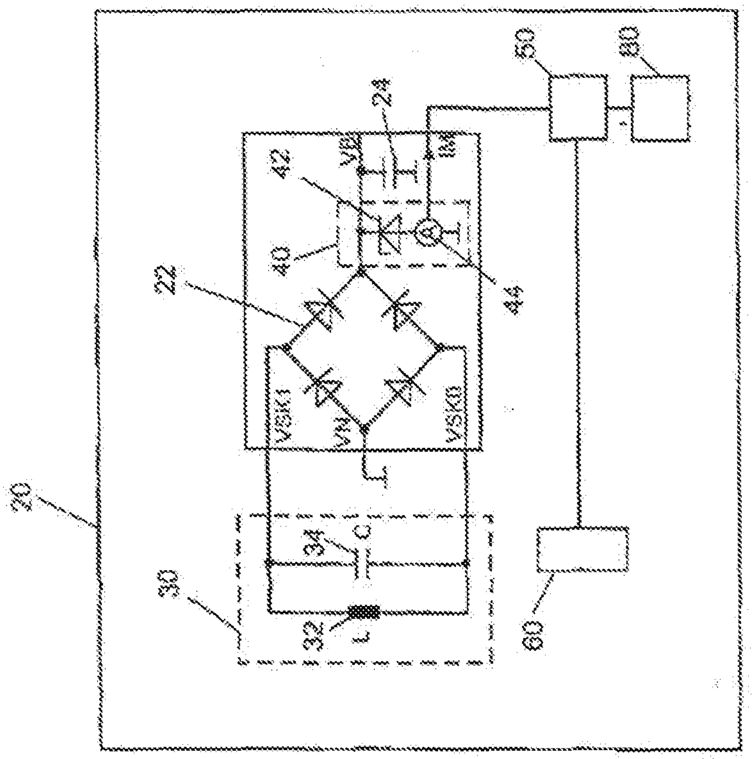
9. Sende-/Empfangseinrichtung nach Anspruch 8 dadurch gekennzeichnet, dass die Detektionseinrichtung (40) eine Serienschaltung aus einer Spannungs-stabilisierenden Einrichtung (42) und einem Strommessgerät (44) umfasst und den durch die Spannungs-stabilisierende Einrichtung (42) fließenden Strom mit einem vorbestimmten Stromwert vergleichen kann.

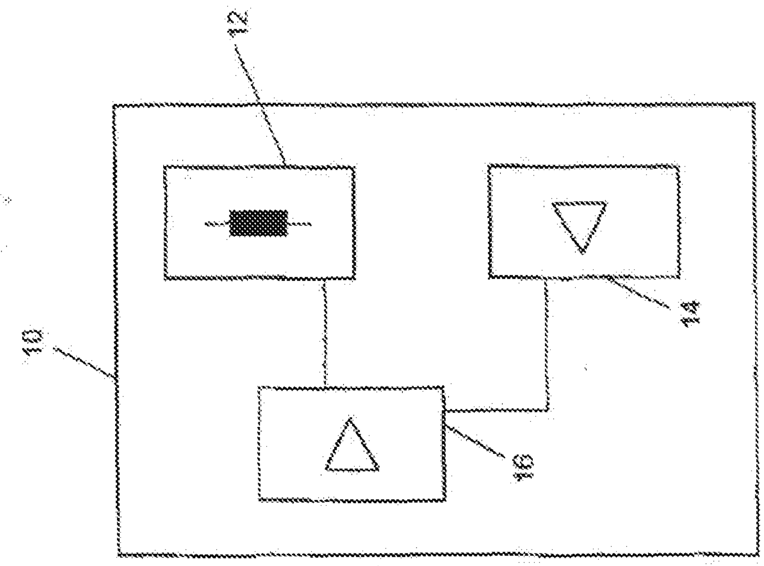
10. Sende-/Empfangseinrichtung nach Anspruch 8, dadurch gekennzeichnet, dass die Detektionseinrichtung einen einer Last zugeordneten Spannungsmesser aufweist und die an der Last abfallende Spannung mit einem vorbestimmten Spannungswert vergleichen kann.

11. Sende-/Empfangseinrichtung nach Anspruch 8 oder 9, dadurch gekennzeichnet, dass die Energieübertragung induktiv erfolgt und die Empfangseinrichtung (30) der zweiten Sende-/Empfangseinrichtung (20) ein Schwingkreis (32, 34) mit einer fest vorgegebenen Resonanzfrequenz ist.

12. Sende-/und Empfangseinrichtung nach einem der Ansprüche 8 bis 11, dadurch gekennzeichnet, dass die zweite Sende-/Empfangseinrichtung (20) einen Temperatursensor (80) aufweist, wobei die Regeleinrichtung (50) eine Stellgröße in Abhängigkeit des Ausgangssignals der Detektionseinrichtung (40) und des Temperatursensor (80) erzeugt.

26.09.00





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(54) Inductively powered lighting

(57) An inductively powered lamp unit (500) that uses an inductive power pick up comprising a resonant circuit including an inductance (401) and capacitance (402), the induced current circulating in the resonant circuit is limited to a maximum value by a shorting switch (503) that closes a connection across the inductance (401) shorting the resonant circuit. The shorting switch (503) is controlled by a comparator (506) that compares the sensed current with a reference value (510). Voltage control maybe similarly implemented. Power is supplied to LED's (405), control data may also be conveyed through the inductive link. Applications include roadway markers, fire escape indicators, underwater or explosive environmental lighting.

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Description

TECHNICAL FIELD OF THE INVENTION

[0001] This invention relates to the field of electrically driven lighting, to means for driving one or more lamps using inductive power transfer, and more particularly but not exclusively to the provision of emergency lights, indicating lights, and roadway signal lighting powered from adjacent concealed cables.

BACKGROUND

[0002] Transmission of electrical power to articles which consume power over significant gaps by means of inductive power transfer has become increasingly feasible with developments in resonant primary and resonant secondary conductors, means to control and limit the resonant secondaries, and suitable energising power supplies.

[0003] There are a number of applications where even a fixed source of light is advantageously driven by an inductively powered source, rather than by simple direct connections using conductive materials.

[0004] In most ofthe situations below, some of which are particularly adverse for conventional lighting, a particularly reliable lighting source is an advantage and in most ofthese situations the nature of inductive powering of lights will inherently enhance the reliability of a system over that using alternative power supplies such as direct connections, internal batteries, or solar cells with rechargeable batteries. Some situations include: where electrical isolation is necessary, as in lights used in or near water such as in swimming pools or areas where people work in contact with water, where corrosive or conductive fluids are likely to occur, where sparks may cause explosions, as in coal mines and in operating theatres or in certain other industrial sites where flammable powders, gases, or the like are found, where the added robustness of buried cables assists in maintaining power transfer during exceptional circumstances, where a surface on which lights are laid is prone to be replaced, such as on a roadway with a tar sealed surface.

[0005] In our US patent 5,293,328 we describe an inductive power transfer system having particular application to a multiplicity of vehicles.

OBJECT

[0006] It is an object ofthe present invention to provide an improved system for the inductive transfer of electrical energy to a source of light or one which will at least provide the public with a useful choice.

STATEMENT OF THE INVENTION

[0007] In one aspect the invention provides an inductively powered lamp unit; the lamp unit including one or more lamps capable of radiating light and comprising means to collect inductively transferred power from an external alternating primary magnetic field; said collection means comprising a resonant circuit having a resonant period and including at least one inductance and at least one capacitance; wherein the at least one inductance has a winding adapted to be intersected by a portion ofthe alternating magnetic field and thereby collect power as a secondary current, means capable of limiting the maximum amount of secondary current circulating in the resonant circuit, means to transfer power at an output from the resonant circuit to the lamp or lamps, and means to control the power provided to the lamp or lamps.

[0008] Preferably the means capable of limiting the amount of secondary current circulating in the resonant circuit comprises a shorting switch capable of closing a connection across the inductance; the shorting switch being controlled by a controller provided with means capable of sensing the magnitude ofthe output so that when the output exceeds a first, higher, predetermined threshold the shorting switch is closed for a period exceeding the resonant period ofthe circuit, or when the output falls below a second, lower, predetermined threshold the shorting switch is opened; thereby limiting the secondary current flowing in the resonant circuit so that any magnetic flux generated by the secondary current does not have a significant counteracting effect on the primary field and so that the output of the resonant circuit is not able to exceed a predetermined maximum.

[0009] Preferably the means capable of sensing the magnitude ofthe output is configured so as to sense an output current.

[0010] Alternatively the means capable of sensing the magnitude ofthe output is configured so as to sense a relative or absolute output light intensity.

[0011] Preferably the resonant inductance comprises one or more coils, each coil being u rapped around an elongated member composed of a ferromagnetic material having a midpoint, whichmember is orientated when the lamp unit is placed in position so as to lie with its midpoint substantially adjacent to a primary conductor (capable when energised of radiating a primary field), and substantially at right angles to the direction of the primary conductor.

[0012] Preferably the lamp unit has a low profile and at least one window capable of transmitting light; the unit being capable of being attached to the surface of a roadway; and wherein the lamp or lamps comprise one or more light-emitting diodes.

[0013] It is also preferable that the lamp unit is packaged in a strong housing having a low profile and at least one window capable of transmitting light; the unit being capable ofbeing attached onto the surface of a roadway, capable ofwithstanding loads applied by a road vehicle driving over it, and not capable of adversely affecting the integrity of the road vehicle nor deflecting the road vehicle from its course.

[0014] Preferably the lamp unit also includes at least one retroreflector unit for passively reflecting the light of vehicle beams.

[0015] In another aspect the invention provides a lighting installation comprising one or more inductively powered lamp units as described above, each affixed to a surface of a substrate, each lamp unit being capable of emitting light on being energised by inductive transfer of power across a space from a primary conductor located beneath the surface ofthe substrate; the primary conductor carrying, when in use, an alternating current.

[0016] Preferably the primary conductor radiates an external alternating magnetic field, at a frequency which is substantially the same as the resonant circuit in at least one ofthe lamp units; the frequency lying in the range of between 200 Hz and 2 MHz.

Preferably the primary conductor is laid down within a substrate in the topology of a loop, connected at a first open end to a power supply and having a second, closed end, the loop comprising a pair of closely spaced conductors, though spread apart in an axis substantially perpendicular to the surface of the substrate at each site where a lamp unit is to be placed.

[0017] Preferably the one or more inductively powered lamp units are placed upon the substrate so as to guide a moving person (whether on foot or steering a vehicle) to pass along a particular route.

[0018] Preferably one or more lamp units may be selectively addressed using the primary conductor as a medium, so that the light radiated therefrom may be changed from time to time.

[0019] Preferably selective addressing is accomplished by superimposing a message over the primary current, in the form of momentary variations of the amplitude of the primary current.

[0020] Preferably selective addressing is accomplished by superimposing a message over the primary current, in the form of momentary variations of the phase of the primary current.

[0021] Preferably selective addressing is accomplished by superimposing a message over the primary current, in the form of information carried within a carrier frequency, separate from the frequency of the power for inductive transfer.

[0022] Preferably selective addressing is accomplished by setting the frequency of the primary current so as to match the resonant frequency of the resonant circuit of the addressed one or more lamp units which, for this purpose, may each be provided with one of a variety of resonant frequencies.

[0023] In another aspect the invention provides an installation for laying out marking lights on a road, comprising a set of inductively powered roadway markers, a primary energising loop cable, and a power supply.

[0024] Preferably the power supply is capable of energising the primary energising loop in response to an external triggering event.

[0025] Preferably the power supply is capable of remotely controlling one or more lamp units by means of the primary energising loop.

[0026] Preferably the power supply is capable of remotely controlling one or more lamp units by means of the primary energising loop in response to an external triggering event.

[0027] In another aspect the invention provides an installation for laying out marking lights along a fire escape route or egress route in relation to a building, comprising a set of inductively powered lamp units, a primary energising loop cable capable ofbeing buried within a substrate ofthe building, and a power supply having a battery backup; the installation being capable of being activated during an emergency.

[0028] Preferably the primary alternating current is a sine wave.

[0029] Preferably it has a frequency in the range of from 500 Hz to 1 MHz, although more preferably it has a frequency in the range of from about 10 KHz to about 50 KHz.

[0030] Preferably the alternating current is generated within a resonant power converter.

[0031] Preferably the concealed primary cable is electrically insulated and mechanically protected by being embedded within the substrate. Optionally it maybe sealed into a slit cut into the substrate with a circular saw or the like.

[0032] Preferably the concealed cable comprises a pair of conductors orientated substantially perpendicular to the surface ofthe substrate, although optionally a pair of conductors may lie side by side within parallel slits. Preferably the cable is composed of a litz wire or other wire having a high surface-to-volume ratio such as a strip.

[0033] In another aspect the invention provides a lamp unit within a strong housing, comprising a resonant secondary or pickup coil and capacitor, one or more light-emitting lamps, and optionally power conditioning means.

[0034] Optionally the lamp unit has a low profile and may be applied to a road surface.

[0035] Optionally the lamp unit also contains one or more retro-reflector modules.

[0036] Preferably the power conditioning means comprises a current limit and optionally this maybe built into light-emitting diodes or be an intrinsic property of metallic filament lamps.

[0037] In the case of light-emitting diodes, a pair of lamps or of banks of lamps may be connected in inverse parallel in order to utilise both half-cycles of an AC waveform.

[0038] In a further aspect the invention may provide a road-markings set of lamps comprising a series of lamp units, an embedded cable, and a power supply.

[0039] Optionally this invention may be used to highlight dangerous portions of a highway.

[0040] Optionally it may be energised by the proximity of a vehicle.

[0041] In a related aspect the invention provides a pedestrian crossing, comprising means to detect the presence of a waiting pedestrian, sets of road markings, and a sequencer to energise the road markings lamps for a period oftime before signalling to the pedestrian that a warning has been given.

[0042] In a yet further aspect the invention may provide a fire escape indication set of lamps.

[0043] Preferably the power supply for the invention is driven from a set of storage batteries so that it can operate in the at least temporary absence of a mains supply.

DRAWINGS

[0044] The following is a description of a preferred form of the invention, given by way of example only, with reference to the accompanying diagrams.

[0045] Fig 1: is an illustration of a section through a light housing above a pair of primary conductors embedded in a substrate.

[0046] is 2: is a perspective view of a row of lights energised inductively by alternating current in a concealed cable.

[0047] Fig 3: illustrates energisation using a cable carried within a single vertical slit.

[0048] Fig 4: shows a typical circuit for use in a light housing of the present invention.

[0049] Fig 5: shows a preferred circuit including control of the resonant pickup circuit.

[0050] Fig 6: shows a preferred circuit like Fig 5, also including means for detecting and responding to control impulses.

[0051] Fig 7: shows the interior of a roadway marker incorporating a pair of ferrite strips as pickup devices to collect inductive power.

[0052] Fig 8: shows the disposition of the primary inductive loop in an installation.

[0053] Fig 9: shows the flux about the primary conductors, entering the ferrite mainly at its ends.

[0054] Fig 10: shows options for controlling the output of individual lamp units by way of currents within the primary conductor.

PREFERRED EMBODIMENTS

[0055] One application ofthis invention is for 'self-illuminated "cats-eye style" roadway reflectors'. This specification describes an installation for laying out a series of marking or warning lights (which may also include retro-reflectors) along a generally linear course, and particular applications for these lights include roadway lighting. Here they maybe substituted for the well-known "cats-eye" retro-reflectors which are placed upon the road and being of low profile, may be driven over. Many applications beyond the known range of uses for "cats-eye" reflectors become available for a system of self-powered units.

[0056] In relation to another application; fire egress lighting, the type of energisation used in this invention offers advantages over conventional lighting in that the invention is more resistant to fire damage than other types of emergency guidance and therefore will persist for a longer time.

[0057] We shall describe a basic type of light unit and cabling, (Example 1) and a more advanced type of light unit (Example 2) as reduced to practice, but it should be realised that these examples are in no way limiting and that further examples, exploiting the characteristic features ofthe invention, may become obvious to the skilled reader.

[0058] In principle, we feed alternating current at preferably about 3 6-40 KHz and at a sufficient current (typically 10-12A) into a cable buried within the substrate ofthe road or building or the like, and provide radiated magnetic flux from the cable at discrete sites for use in energising lamp units adapted for using inductive power transfer.

[0059] Although it is convenient and effective to use resonating current and aresonant power supply to power the primary inductive loop (the cable) power of similar characteristics could be generated in other ways.

[0060] Principles of resonant pickup of inductive power do apply for effective operation of the lamp units and the Examples illustrate this.

EXAMPLE 1

[0061] Our most basic system comprises: (a) A power supply 200, generating a sine-wave output of a desired power level at usually around 40 KHz into a (mainly inductive) resonating cable 201, and in the applications described herein here at a power level ofperhaps up to 100-200 watts although much higher levels can be generated.

(b) A cable 201 of up to 800-1000 m length having closed-loop topology which is placed alongside the intended position of a or each lamp unit 203, 204. We prefer to use litz wire in installations where efficiency and long-term reliability at high loading levels is important, although for cheapness ordinary insulated copper (or aluminium) cables can be used.

(c) One or more lamp units 203, 204, 100, laid out in a series like a chain, each of which units comprises a pickup coil preferably resonant at the power supply frequency, one or more lamps, and preferably power conditioning means. We generally prefer light-emitting diodes as they are reliable.

[0062] The cable can be laid out as a single U-shaped loop or can be run out along several branches, though preferably as a single length without joins. A particular application may require tuning, as only one length has the correct resonant frequency and for this purpose the installer can either vary the resonating capacitors within the power supply or add toroids (including air gaps) over the cable to artificially increase its inductance and thereby simulate a longer cable than is actually present.

We prefer to run the cable at a low power and at a low voltage, for safety's sake.

[0063] As there are no exposed metallic conductors in an inductively powered lighting system, it may be used for long periods in a corrosive atmosphere or one where seawater is present. The relative absence of risk of sparks allows its use in inflammable or explosive situations.

[0064] Fig 1 illustrates the road warning lamp 100 of Example 3 in place on a road surface 102. In this drawing we have shown the energising cables 109 in a parallel pair of slits 108, although roading engineers prefer a single slit as 302 in Fig 3. The lamp 100 comprises a tough housing 101, having a clear or translucent window in front of an array of lights or preferably light-emitting diodes 103.

These diodes derive their power from a secondary pick-up coil 104 which is made resonant at about the preferred operating frequency by a capacitor 106, and the lamps are driven through a rectifier module 107. The slits 108 in the roadway 102 are preferably filled with matrix. Fig 3 illustrates the vertical wiring alternative, in which the secondary coil 304 is placed above the slit 302 containing the pair of wires 305. Preferably the slit is cut deeper at about the intended position of each lamp unit 306, so that one of the cables 308 may be brought deeper and so increase the inductive field available at that point. Between lamp units, the cable 305 has a reduced inductance

where its conducting members are closer together and so an increased length of cable can be driven with a limited voltage. A further way to enhance the magnetic flux at a lamp site is to use a ferrite rod or peg as at 205 in Fig 2. This may limit the freedom of placement of lamp units. Ferrite may be incorporated within lamp units, as suggested by the core of the inductor 401. At least one conductor may, instead of being litz wire, be a flat strip of metal, as this will raise the amount of surface available for carrying skin-effect currents.

[0065] Fig 4 shows one preferred circuit, in which 401 and 402 comprise a resonant circuit, 403 is a rectifier to make a DC voltage, and 405 is a set of LED lamps in series. 404 may be a shunt regulator acting as a current limiter, or a flasher module. Preferably, 404 is a repetitively acting shorting switch (see 503 with 501, 502 in Fig 5). If a current limiter is not used, the operating current in the lamps may be set to the usual preferred value of around 20 mA by choosing from a range of lamp units or placing a lamp unit so as to give a predetermined brightness.

EXAMPLE 2

[0066] This portion of the specification describes a preferred inductively powered lamp unit.

[0067] There are two versions, shown as Fig 5 (no ability for external control) and Fig 6 having internal means for detecting and responding to control impulses. Certain parts ofthese two circuits have been discussed in relation to Fig 4.

[0068] The non-controlled circuit is shown as 500 in Fig 5. The resonant pickup coil 401 may actually comprise two coils 704 (as in Fig 7) wound around each ferrite strip 703, and if several coils are used they are placed in series. The capacitor(s) ofthe resonant circuit are shown at 402; here 247 nF and including provision (pads) on the circuit board for adding a small "tuning" capacitor. The resonant frequency is at about 40 KHz. The bridge rectifier 403 is made up offour diodes (type BAT83), the output ofwhich is passed through an inductor 501(7.5 mH) and through a steering diode 502 (BAT83) to charge a capacitor 505 (33 µF, 25V). Power FET transistor 503 (type IFRDI10) is used as a shorting switch to short out the resonant circuit from time to time, each time lasting for a number of cycles. Means to control the shorting switch comprise the operational amplifier/comparator 506 (type MC33171) which has at its inverting input a zener diode 510 (type TC9491) as a voltage reference. The comparator compares the zener voltage with a proportion ofthe current passed through the output lamps at resistor 610 (30 ohms) (via a 1K resistor 509) and uses a diode 507 (type BAT83) in series with a 68K resistor 508 as a non-inverting feedback loop, for hysteresis. This control circuit provides a controlled current centered on a design value and fluctuating to a small extent about that value when the resonant circuit is alternately shorted, then allowed to charge the capacitor 505. Typically, there are about 500 shorting events per second.

[0069] Providing current regulation of this type allows the lamp unit to emit substantially a controlled amount of light regardless of its position, within limits. Exact placement is not critical. It is not uncommon for a marker on a hot, tar-sealed road to be displaced laterally by tyres of heavy vehicles and this regulation provides some tolerance to displacement after positioning.

[0070] In our preferred circuit two chains (405) of high-intensity (orange) light-emitting diodes (type HLMT-CL00) are used to radiate light to one side ofthe lamp unit. Of course, other colours could be used.

[0071] Variations to Fig 5 include (for example) monitoring the ambient light with a light-dependent resistor, so that the brightness ofthe marker is proportional to daylight, or regulating current in terms of actual light output rather than lamp current.

[0072] Fig 6 illustrates one means 600 for rendering the circuit capable ofbeing externally controlled. As suggested in Fig 10, it is possible to superimpose control signals over the resonant power circulating in the primary loop. This circuit is well-adapted for control by means of low-frequency tones or dual tones. Fig 6, which is a development of Fig 5 and includes the components of

Fig 5, also includes means to short-circuit the pickup coil 401 from time to time (typically once per millisecond) and during that time read the current circulating in the primary loop. This circuit is tentative because it appears that an application-specific integrated circuit will be an appropriate implementation.

[0073] Box 602 represents a clock generator producing a pulse of 50 μsec every 1 msec.

[0074] (There is no requirement to synchronise all clocks in all markers in an installation to pulse synchronously). Its output is passed to (a) an AND gate 606 shared by the comparator and supplying the gate ofthe power FET, 503. Its output also goes to the control input of a sample and hold circuit 603, which reads the current across a current sense resistor 601 inserted in the source lead of 503. At times when the switch 503 is closed, the resistor will, after a cycle or two at 40 KHz, or about 50 used, have a voltage on it representing the current in the primary inductive loop at that time. This voltage is taken to the signal input ofthe sample and hold circuit, and the output is passed to a circuit 604 which comprises a tone detector.

[0075] In this simple example we have provided a resistor 605 between the tone detector output and an input ofthe comparator, so that activation ofthe tone detector has an effect on the setting ofthe comparator 506 and the mean brightness of the lamps is altered as a result of detecting a specific tone carried within the primary inductive loop.

[0076] "Stealing time" from the action of the comparator as for Fig 5 is of little moment because the inherent regulation can compensate. Repetitive sampling at a rate of about 1 KHz will satisfy the Nyquist criterion for control signals which are single or multiple tones of up to about 250 Hz.

[0077] Clearly there are many possible options; such as whether or not the tone detector outputs switch from one state to another state on each tone detection, or change state only during a tone, and there may be more than one tone and hence more than one action, or the detector output maybe treated as a code signal passed to a microprocessor which will execute one of a series of actions on the light output from the lamps 405.

[0078] There may be a red series and a yellow (or orange, green or blue or even infra-red) series of lamps which can be driven separately, or separately controllable lamps may face in various directions.

HIGHWAY MARKERS

[0079] In Fig 7, we show a highway marker 700 from above. The casing 701 encloses a pair of ferrite cores 703 (only one core and coil is labelled) which are on each side of a printed-circuit board 702 bearing the circuit of Fig 6 and along one edge a row of light-emitting diodes 705. We have not also illustrated retro-reflectors in this diagram, but they maybe interspersed with the diodes 705.

[0080] Fig 8 shows part of a roadway installation in side view. A power supply 801 puts power into a loop of cable forming a primary inductive loop. In the portions where the two conductors are close together (802) the flux tends to cancel out and the cable radiated little flux. Hence it may be elongated. At positions (803) where a lamp unit (804) maybe placed, the cable is spread apart, preferably using a spreader (805) to maintain spacing during and after installation. The end ofthe loop remote from the cable is shown at 806.

[0081] If the power supply is a resonant power supply, and this type of energisation is economical and, by energising the cable with a sine wave, minimises problems of radiation of radio or electromagnetic energy, it is preferable to use litz wire for the cables. We prefer 4 mm^2 litz wire. Our typical resonant power supplies are run at 24 volts, which allows for battery backup and safe running and at 24 volts it can power about a 25 metre long primary inductive pathway, and about 10-14 amperes at a 40 kHz frequency circulates in the cable when in operation. Using a higher voltage allows longer primary inductive loops to be used. If an unusually short cable is used, its inductance maybe boosted with a lumped inductance, trimmed to make the installation resonate at 40 kHz.

EXAMPLE 3

[0082] Our basic system maybe embellished by providing for control ofthe output ofthe lamp units, either as a group or individually. Preferably this control is more than simply turning the entire set on or off. One approach is to provide each lamp unit in an installation with control electronics that can detect signals of some sort radiated from the primary conductor cable, because this cable is already functionally connected with all operational lamps.

[0083] It is possible to superimpose a message over the primary current, in the form of momentary variations ofthe amplitude of the primary current, which can be sensed within the or each lamp unit as changes in the operational settings ofthe regulating mechanism. Coding ofthe amplitude could follow any convenient code, such as the letters ofthe ASCII coding system, or Morse code, or some other system such as those used in serial bus digital control, such as the I^2C bus. This requires a small amount of complexity in each lamp unit that is capable ofbeing addressed. Each "bit:" ofthe code would have to be sufficiently long in time to "catch" any lamp unit that at the time has shorted its inductive pickup coil, unless a separate data sensing arrangement was used.

[0084] Information may be carried within a carrier frequency, separate from the frequency ofthe power for inductive transfer.

[0085] Variations of the phase of the primary current are another way to transmit data.

[0086] A cheap way ofaddressing lamp units is to make a variety of units each having a different resonant frequency. Then only those lamp unit that resonate at the frequency of the transmitted power can operate. If a resonant power supply is used, it might be provided with subsidiary switchable resonating capacitors. By this means it is possible to create a traveling wave of- flashing lights, for decorative or directional purposes.

FIRE EGRESS INDICATION LAMPS

[0087] This is - as a preferred example - a fire-exit indicating network, which when energised provides a chain of illuminated beacons 203,204 along the floor of a building. The beacons are intended to direct people to the nearest fire exit. In addition to the basic system above, we would usually include means to supply the power from batteries as in an emergency the mains power is likely to fail, and means to cause the power supply to start up when an emergency condition, such as a blackout at night, and/or a fire alarm is in effect. The energising cable 201 is preferably embedded into a concrete or similar floor, and may be embedded at a depth of several inches as our inductive power transfer system is a loosely coupled one that tolerates spacings ofthat order. The energising cable is placed along the floors of passageways that lead to fire exits, preferably along the centre lines ofthe passageways. The drive voltage may be as low as 12 volts, depending on the power required.

[0088] The lamp units are preferably light-emitting diodes or the like, embedded in wear-resistant transparent or translucent housings so that they remain capable of emitting visible light even after years in position. Preferably the lit lamps display a clearly understood and preferably standardised direction so that people in panic are not confused. Optionally the lamps or the power supply may be operated in an attention-getting flashing mode and optionally the lamp units may also generate audible signals. In fact, they may also generate vibrations so that blind people can locate and use the indicators. Our preferred lamp units may have bases about 10 cm square containing the resonant pickup coil - with a height of perhaps 5 mm, and have a top made of a wear-resistant material such as polycarbonate or even glass. They may include other electronic devices such as a voltage sensor and a switch to short-circuit the coil when the voltage rises above a threshold. (This means of regulation limits the tendency of a resonant secondary to develop a large circulating current which tends to block the primary current from reaching past this secondary coil to reach others. On the other hand, as this application of inductive power transfer has substantially constant operating parameters, and it maybe preferable to select a lamp unit for a particular position from a range of units having various brightnesses - actually flux collection and conversion capabilities.

[0089] These illuminated display devices may be glued onto a carpet, or let into holes cut in a carpet, or glued onto a hard surface, and need no electrical connections. Thus replacement of damaged or displaced units is not a skilled job. Typicalbuildings where the devices maybeused include hotels, schools, hospitals, auditoriums, and other public buildings.

[0090] Advantages ofthis device include that the system is located on or in floors where it is unlikely to be damaged until after surrounding structures have been destroyed, and the floor location is compatible with people who are keeping low or even forced to crawl in order to avoid smoke and fumes. (Conventional practices of placing often illuminated EXIT signs high up above doorways can lead to obscuration by smoke).

[0091] The device has inherently a high reliability because the destruction of any lamp unit by flames or the like does not compromise the remainder - rendering its pickup coil an open circuit or a short circuit does not substantially affect the primary current and so the remainder of the lamp units may remain lit.

[0092] Furthermore the lamp units themselves are electrically isolated, and the energising power supply is preferably provided with fault detection means so that it provides no electrical hazards in itself.

[0093] A variant of this device can be used in theatres, hotels, houses and the like, and would be energised steadily or on pressure on a sensing pressure pad, to better indicate the positions of stairs in the dark.

ROADWAY-DETAILS

[0094] A similar arrangement can be used on roadways to better indicate lanes routes hazards and other events to motorists. A particular application is in providing warnings at pedestrian crossings. In the pedestrian crossing application, the power supply is connected to a reliable source of AC power and is arranged to be energised when (for example) a person steps onto a contact pad at the kerbside, or when a conventional button is pushed. The energising cables are placed along selected patterns and maybe embedded within slits cut with a diamond saw. As our inductive power transfer system uses only loose coupling, the cables maybe several centimetres deep and even the later addition of further road surfaces will not affect coupling of power from the cables. The cables are preferably sealed in place, using a suitable adhesive or the like so that the installation is substantially permanent.

[0095] The preferred slit dimensions for slits cut into roadways is 5 mm wide by 10 mm deep, rather than the more idealised parallel pair of slits shown in Fig 2. (Roads tend to crack and chip between parallel, close slits). Therefore we have also made a modified arrangement in which one of the pair of wires forming the cable is above the other, as shown in Fig 3, and optionally in order to enhance the flux at the position of a lamp we make the slit deeper at that site and push one conductor further away from the road surface at that point.

[0096] Preferably the cables are energised from a power supply operating at 12 or 24 volts, compatible with storage batteries fed from a wind generator or solar cells, although a highervoltage may be needed to inject resonant power into a longer run of cable, particularly ifthe more efficient litz wire is not available.

[0097] The lamp units may be built into the existing "cats-eye" housings widely used on roadways to demarcate lanes by means of retro-reflective inserts. Glues or other means to mount these devices are well known and the dimensions of existing housings are adequate for housing the power pickup coils, control electronics, and lamps. In order to catch drivers' attention we expect that high-intensity beams from light-emitting diode lamps will be used, aimed towards oncoming traffic. These lamps may be pulsed in a synchronised, attention-gathering manner by for example pulsing the power supply on and off. As the preferred resonant frequency is high, the decay time for power is small.

[0098] Forty cycles of 40 KHz power = 1 millisecond. Alternatively the internal regulator within each housing may be arranged to operate in a cyclic manner, although this may not give as clear a signal of danger to an approaching driver. In the pedestrian crossing application, a vandal-proof warning device would preferably comprise (a) a sensing pad for detecting a waiting pedestrian, a sequencer to first energise the array of warning lamps for a suitable time, and then means to energise a "Cross now" or "Walk" signal of some type which may be (a) conventional illuminated signs, (b) audible, and/or (c) made of further lamps on the roadway, this time over the crossing itself and orientated so that they are visible to the pedestrian.

[0099] In cases where the currents in the buried cables are likely to affect inductive sensors used for controlling automatic traffic lights, the operating frequency can be selected to be separated from that used by the traffic light, and the relatively low harmonic content of the resonant power means that a simple trap tuned to the fundamental frequency should reject any interference to the traffic light sensor.

[0100] In case further buried cables are used to provide power to moving vehicles according to our inductive power transfer principles, a separation in frequency should minimise any cross-interference between cables or affecting the pickup coils. It may well be preferable to adopt a different frequency of perhaps 40 KHz for these low-power lighting devices and run the vehicle power cables at 10 KHz, whereupon the tuned resonant circuits ofthe lighting devices should not develop any significant power when exposed to magnetic flux at a 10 KHz cycle rate.

VARIATIONS

[0101] In order to arrange for switching of lanes on a roadway, for example at a bridge where diurnal reversals in the flow of traffic promote the use of more lanes in one direction than another at one time, lane switching may be accomplished by linear arrays of illuminated housings which are laid on the road along predetermined lines or courses, and illuminated as required in order to steer cars into lanes.

[0102] These types of lights can also be used to demarcate sharp corners and the like and enhance areas of poor visibility. Here they have the advantage over conventional reflectors that by generating their own light they are effective outside (and particularly to either side of) the region illuminated by the headlights of a car. Preferably warning lights intended for motorists are intermittently energised by the approach of a motor vehicle, using a pressure pad or a proximity sensing device so that they can be maintained from a rechargeable storage battery with a solar cell as a source of power.

[0103] When in operation, the bands of light emitted from the arrays of lamp units may extend far beyond the range of the driver's headlights.

UNDERWATER VARIATIONS

[0104] As inductive power transfer is inherently unaffected by non-magnetic materials that may appear or disappear in the gap, it may be used under water. Accordingly a series of housings containing lamps may be placed on the bottom (and sides, and edges) of a swimming pool to indicate lanes, and energised as required by buried cables concealed in the substance of the pool floor. These lamp units may be fixed in place, and various combinations energised by selecting particular runs of cable for various combinations of lamp unit spacing. Alternatively they may be clipped into retaining clips as and when required. Magnets, particularly magnets formed from ferrites, may be used to temporarily locate lamp units. Adjacent, magnetically soft ferrites may be included to act as flux concentrators.

OPTIONS

[0105] A light housing could be provided with more than one pickup coil and ancillary light sources, so that by changing the frequency of the power in the primary cable, different colours of light (for example) could be produced. Power modulation may also be arranged to select different lamps. Light emitting diodes are at present available in red, orange, yellow, green and blue, although the latter two are not particularly bright. Laser diodes of various visible colours may soon become cheap enough for use in this application, where their enhanced beam-forming ability will aid in the detection of these lights at a distance. Light-emitting diodes have an advantage in that their ON-voltage can be used to provide a degree of intrinsic regulation as shown in Figures 3 and 4 where even the rectifier can be deleted if a second string of LEDs with the opposite polarity is placed across the first string.

[0106] As the light housings will generally be fixed it is possible to extend the cable length by bringing the wires close together unless, at the site of a lamp, they are spread apart so that the magnetic field increases. To further enhance the field, a loop can be constructed in the primary cable, or a magnetically permeable coupler such as a ferrite can be used.

[0107] In situations where lateral variations in lighting may extend beyond the "tram-track" layout of primary coils, one wire may be placed above the other, providing a more diffuse field. If this field is weaker, a ferrite flux concentrator maybe provided to increase the power available within the secondary device.

[0108] Movable lights may be mounted on a light track or on a surface such as awall, ceiling, or table in such a way that they can be held in position without requiring direct electrical contact with the power source. In one example wall mountable lights can be mounted in one or more plastic channel members attached to the wall and maybe allowed to slide along a channel member to a desired position whilst picking up inductive power from a primary circuit embedded in the wall or in the base of the channel member. As the attachment ofthe light to the surface does not require any direct electrical contacts whether sliding or stationary it is possible to adopt any number of different attachment means for the location or placement ofthe lights. The lights may take any desired shape or design.

[0109] In the case of a photographic studio the lights may have a base containing the resonant pick-up and an arm or stem extending therefrom which a suitable reflector or light housing is mounted and containing the light source. In such a case it is preferable to position the primary resonant circuit (or circuits) in a sinuous pattern in the wall or ceiling so that the lamp bases can be placed anywhere on the surface and still receive enough resonant power to activate its light source. An advantage of placing the primary cables in a "slit configuration" as previously described is that the primary cables generate an external alternating magnetic field which is predominately parallel to the surface of the substrate, allowing the lamp base to be moved from side to side ofthe "slit" containing the pair of cables and still receive enough power for its light source.

ADVANTAGES

[0110] Inductively powered lamp units in accordance with this invention have a variety of uses where direct contact between the power cables and the lamp units is undesirable.

[0111] Examples of such uses include lights used in or near water such as in swimming pools or areas where people work in contact with water, lights used in corrosive environments or where conductive fluids are likely to occur, lights used in mines and in operating theatres or in certain other industrial sites where flammable powders, gases, or the like are found, and lights used in roadways, or where the lights need to be moved relative to the power supply (eg in display areas or in photographic studios).

[0112] Finally, it will be appreciated that various alterations and modifications may be made to the foregoing without departing from the scope of this invention as set forth.

Claims

1. An inductively powered lamp unit comprising:
one or more lamps (103) for radiating light;
collection means (104) to collect loosely coupled inductively transferred power from an external alternating primary magnetic field radiated from an inductive power distribution cable (201) operating at at least one selected frequency;
wherein:
said collection means comprises a resonant circuit (104, 106) having a'resonant period corresponding to a selected frequency and including at least one inductance (104) and at least one capacitance (106);
and the at least one inductance (104) has a winding adapted to be intersected by a portion of the alternating magnetic field and thereby collecting power as a secondary current;
and the lamp unit further comprises:
means (403) to transfer power at an output from the resonant circuit (104) to the lamp or lamps (103);
and control means to control the power provided to the lamp or lamps (103), said controlmeans including means (404) for limiting the maximum amount of secondary current circulating in the resonant circuit thereby to regulate current to said lamp or lamps to cause said lamp or lamps to emit a controlled amount of light substantially independantly of the relative spacing between said lamp unit and said power distribution cable (201) when the coupling efficiency between said cable (201) and said collection means (104, 106) is above a set level.

2. A roadway marking system comprising:
a power supply (200) for producing an alternating current at at least one selected frequency;
an inductive power distribution cable (201) connected to the power supply and placed along or beneath an area of a roadway (102) to be marked, the inductive power distribution cable being a loop with both conductors positioned one above the other in a substantially vertical slit in the roadway;
and at least one road warning lamp unit (204) located above or close to said power distribution cable;
wherein the or each lamp unit comprises:
one or more lamps (103) for radiating light;
collection means (104) to collect loosely coupled inductively transferred power from an external alternating primary magnetic field from the inductive power distribution cable (201) operating at the at least one selected frequency;

wherein:
said collection means comprises a resonant circuit (104, 106) having a resonant period corresponding to a selected frequency and including at least one inductance (104) and at least one capacitance (106);
and the at least one inductance (104) has a winding adapted to be intersected by a portion ofthe alternating magnetic field and thereby collecting power as a secondary current;
and each lamp unit further comprises:
means (403) to transfer power at an output from the resonant circuit (104) to the lamp or lamps (103);
and control means to control the power provided to the lamp or lamps (103), said controlmeans including means (404) for limiting the maximum amount of secondary current circulating in the resonant circuit thereby to regulate current to said lamp or lamps to cause said lamp or lamps to emit a controlled amount of light substantially independently of the relative spacing between said lamp unit and said power distribution cable (201) when the coupling efficiency between said cable (201) and said collection means (104, 106)is above a set level.

3. A roadway marking system as claimed in claim 2, wherein the cable (201) is spread apart at selected locations where lamp units (204) are to be located.

4. A roadway marking system as claimed in claim 3, wherein the power supply (200) is capable of being controlled by control signals superimposed from time to time on the alternating magnetic field radiated by the inductive power distribution cable (201), and the at least one road warning lamp unit (204) is capable of detecting said control signals and varying its light output in response thereto.

5. A roadway marking system as claimed in any of claims 2 to 4 wherein the or each said lamp is a light emitting diode (103).

6. A method of supplying electricity to a discrete lamp unit, comprising the steps of:
forming a hole (108) in stationary material (105);
positioning in the hole wiring (109) capable of generating an alternating inductive magnetic field outside the hole when an alternating electrical current is passed through the wiring;
covering the wiring in the hole; and
positioning remote from the wiring (109) the discrete lamp unit which is adapted to provide illumination when energized inductively with an induced alternating electrical current generated by the inductive magnetic field.

7. A method as claimed in claim 6, including the steps offorming the hole (108) as an elongate groove, and positioning the wiring (109) inside the groove so that, in use, the alternating inductive magnetic field is elongate and extends outside the groove.

8. A method as claimed in claim 7, including the steps of positioning outside the groove a row of said discrete lamp units.

9. A method as claimed in claim 7 or 8, including the step of forming the groove along a track selected from the group consisting of a road, a pathway, an aircraft runway, a quay, a corridor, a pedestrian crossing, a swimming pool wall and a swimming pool floor.

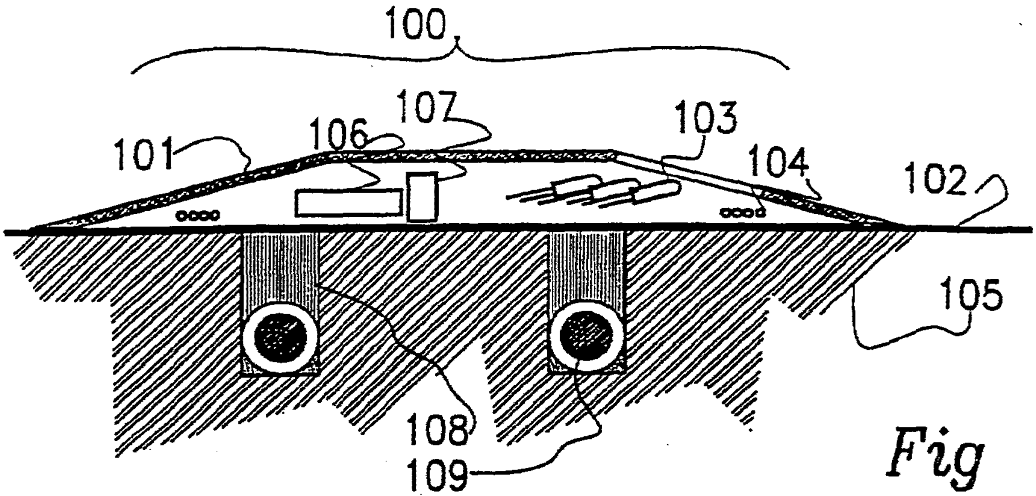

Fig 1

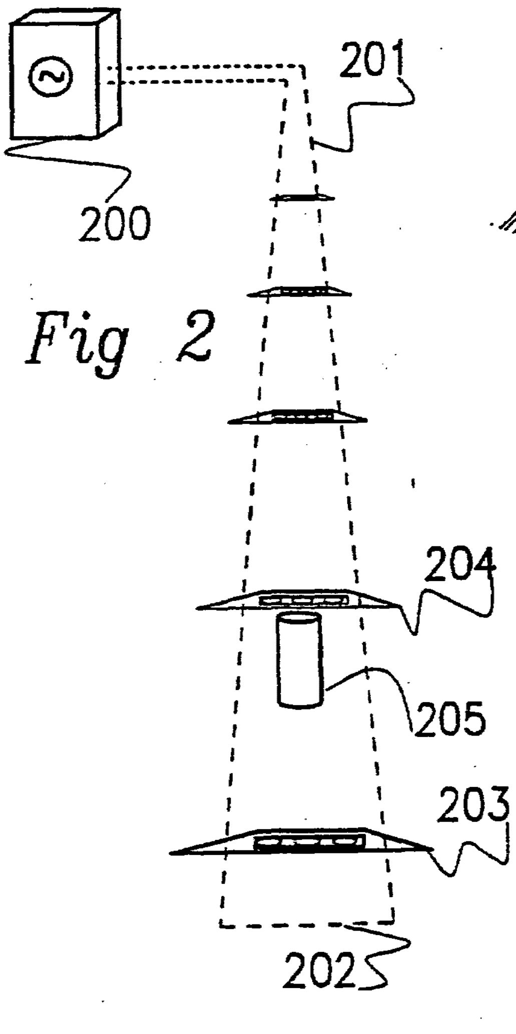

Fig 2

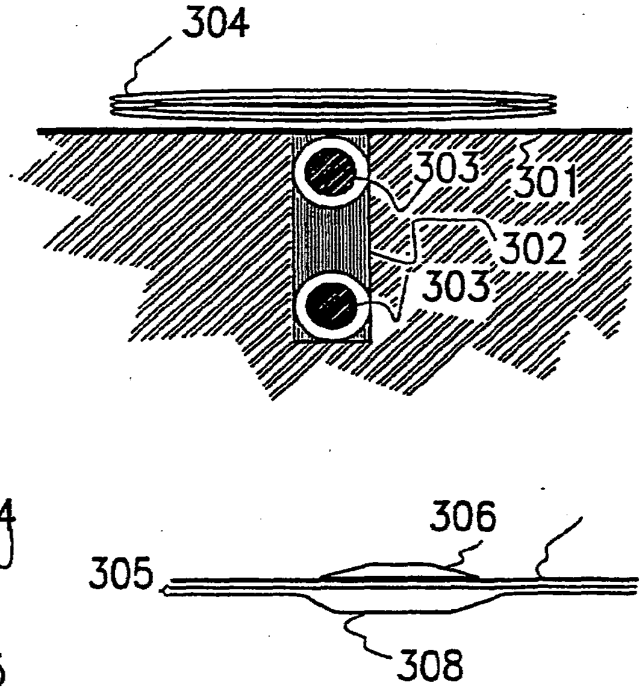

Fig 3

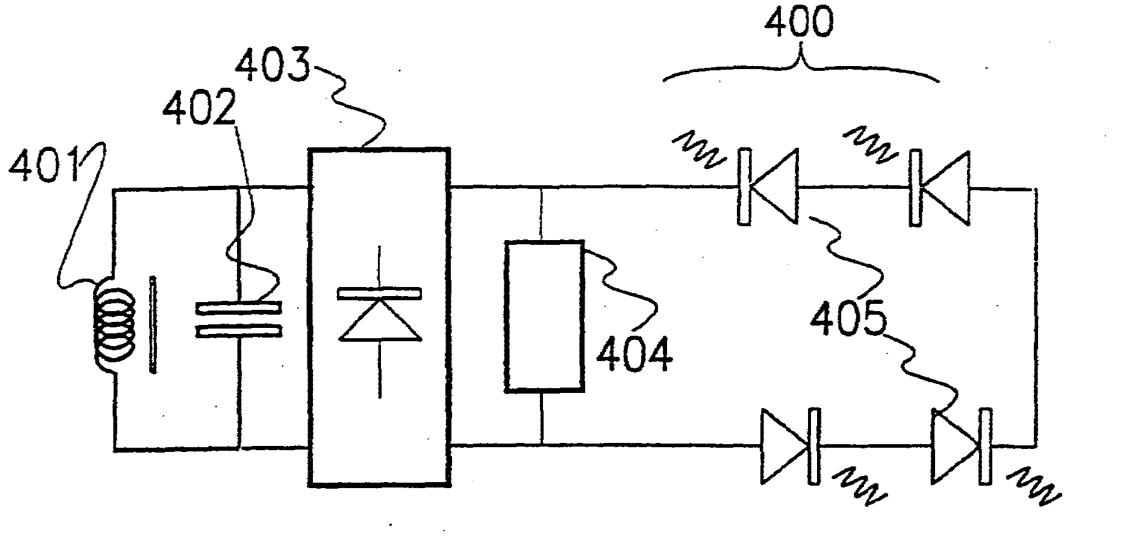
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Fig 4

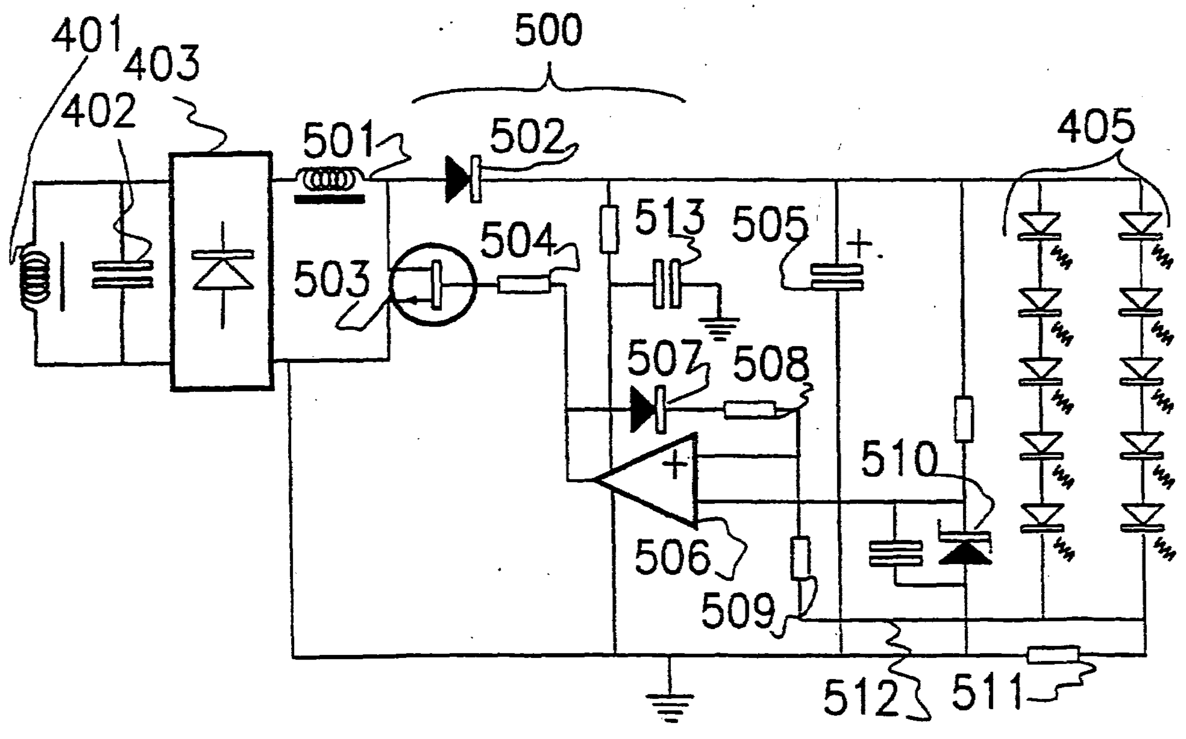
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Fig 5

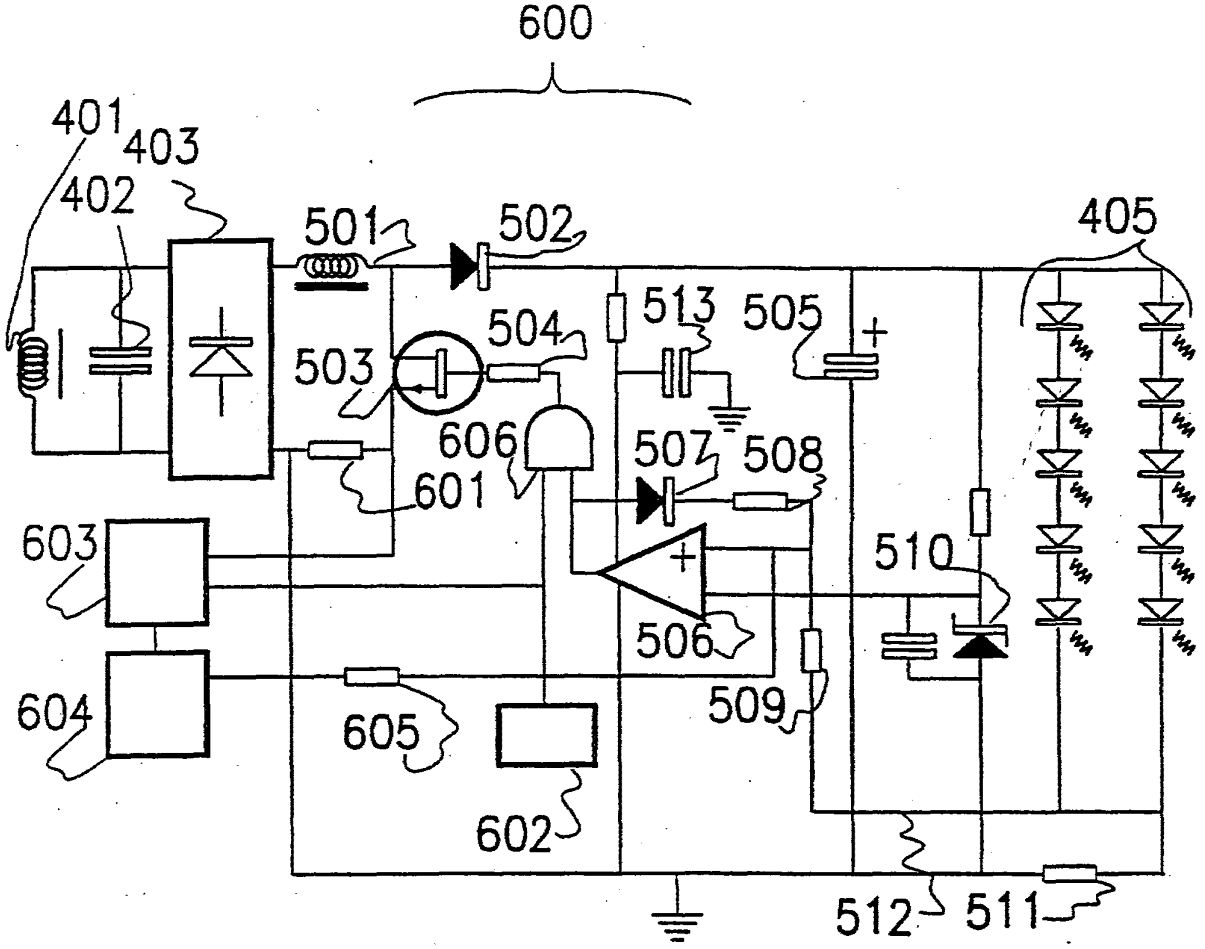
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Fig 6

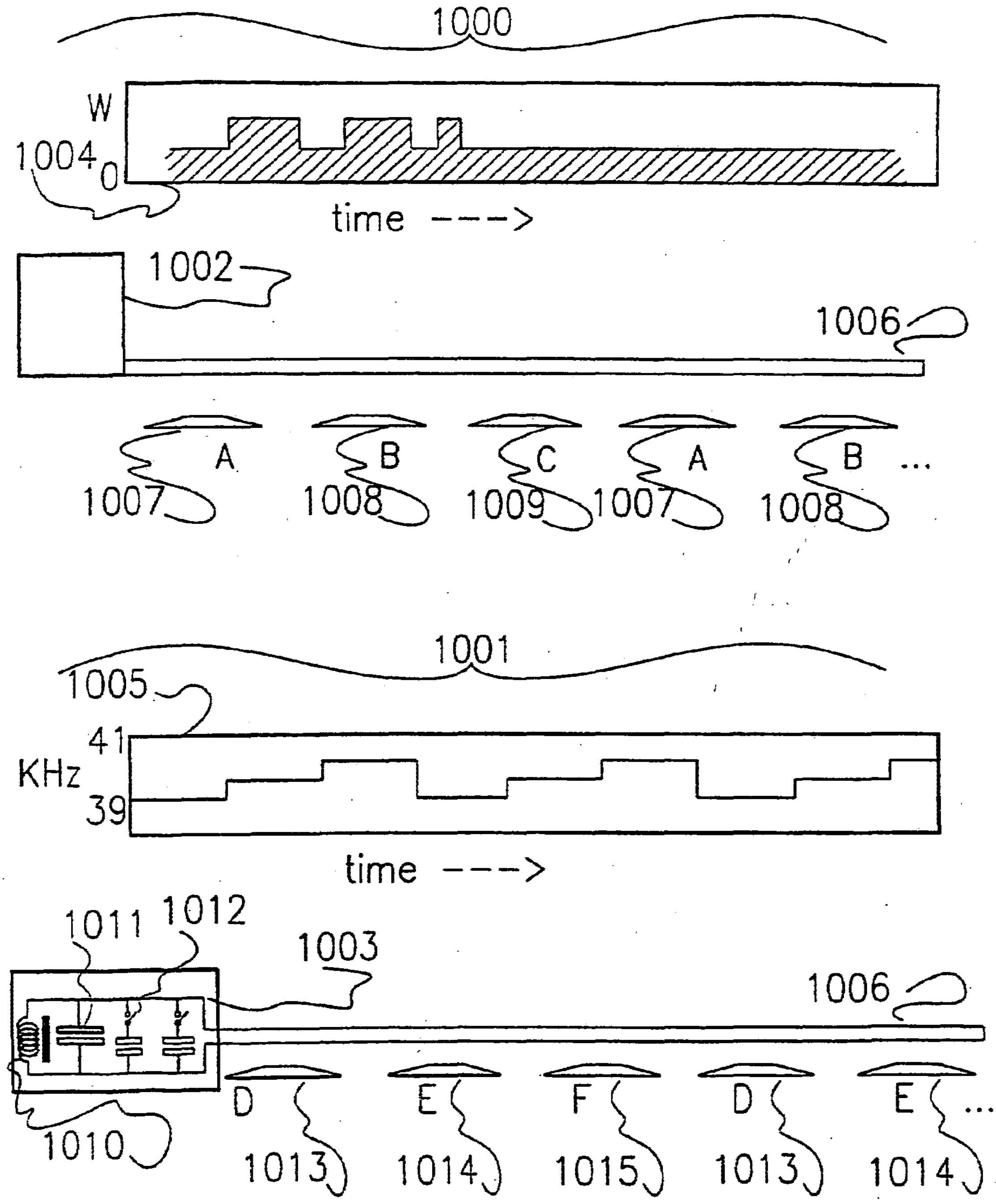
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Fig 10