Novel Wireless Power Supply System for Wireless Communication Devices in Industrial Automation Systems

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Abstract – **In recent years we have seen considerable advances in low power, integration and micro-systems technologies, enabling wireless communication for very small, affordable, lightweight and high performance devices. These technologies are still mainly used for consumer and office applications, but significant advantages can be obtained by applying the technologies to new areas. One area of particular interest industrial automation and control systems, such as robotics and factory automation.**

In this paper we discuss the main challenges involved with realizing a reliable, wireless, and energy autonomous communication system suited for industrial automation. Special emphasis is placed on providing an overview of suitable power supply possibilities and describing a novel magnetic medium frequency power supply concept enabling true wireless energy supply within cell-volumes of more than 100m³ with sufficiently small infrastructure.

The novel resonant power supply concept uses medium frequencies (~120kHz) in a "coreless transformer", enabling the supply of devices within a certain volume, for example a production cell, surrounded by coils. By using omni-directional or rotating magnetic fields, together with three orthogonal receiver coils, it enables a shielding tolerant supply system with unique properties. Compared to primary battery technologies, the new approach offers approximately 50 times higher energy densities over the application lifetime.

I. INTRODUCTION

In recent years there has been quite a revolution within the area of electronics and micro-systems suited for smart industrial, process and energy distribution systems:

- Electronics have become very cheap, small, intelligent and communicative (e.g. wireless)
- Sensors have become significantly smaller and cheaper and often can be integrated
- Control and automation systems (e.g. PLC) including advanced communication are also much smaller, more "low power", cheaper and offer new flexibility and advanced engineering assistance.

In each of these areas the costs have fallen dramatically and advanced technologies have been developed. New communication technologies have been introduced (e.g. WLAN and Bluetooth), offering new mechanisms for wireless connectivity and networking within a control system [1].

A further revolution in the sensor and small actuator area is going to take place with micro- electro- mechanical- systems (MEMS), which integrate mechanical structures, multifunctional materials and microcircuits on one and the same chip. The vision is to create chips that sense, think, act and communicate[2].

All these developments create a strong technology push for new wireless devices in industrial applications such as process control, discrete manufacturing, power distribution and in building automation and instrumentation.

These performance improvements, at very low overall cost, may allow not only the replacement of existing devices but enable new technical and automation system options, providing increased system performance at reduced cost. For example the purchase cost of a typical industrial sensor may currently be less than 20 USD, but the overall cost including the engineering, installation, wiring, and maintenance in an application may typically cost more than 200 USD. These figures are significantly higher in difficult environments (e.g. MV applications, off-shore installation etc.).

Therefore wireless devices can allow for:

- Significantly reduced installation , service cost or
- more devices (e.g. sensors) to be installed allowing superior application/process knowledge and control

Wireless devices offer the benefits, such as mobility/flexibility, reduced maintenance cost (due to wear and tear of cables), reduced weight, easy re-configuration and more. In many applications wired solutions (and energy transfer) are often not possible or suitable, especially in robot type applications or other mobile systems, but also in medium or high voltage applications with large isolation requirements. In several applications wires and related costs dominate the installation and service efforts.

In section II we discuss the applications and requirements for a reliable, wireless and energy autonomous system suited for industrial automation Section III presents an overview of a wireless communication system develop to simultaneously address the low power requirements of an autonomous system and the real-time requirements of an industrial automation system. As a suitable "wireless" power supply should be similarly small, reliable and low cost to enable the creation of

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fully wireless and energy autonomous devices. Therefore in section IV we provide an overview of suitable power supply possibilities for general use in industrial applications.
The chosen wireless power system is described in more detail in section V and a novel magnetic power supply concept using medium frequencies in a coreless transformer is sketched in more detail. The novel resonant power supply concept provides a shielding tolerant supply system with unique properties by using rotating magnetic fields. Section VI provides practical results verifying the calculations and assumptions of the concept description in section V.

II. Application Description and Requirements

Although wireless communication has become increasingly reliable and cheap, the convenient supply of the necessary electrical auxiliary energy remains a major problem.
However, in parallel with the introduction of new wireless technologies, the power consumption of electronics has been reduced significantly. Therefore, new possibilities for the supply of power will be realistic for some applications. There are two main categories of energy supply where autonomous power sources are needed:

- **Autonomous systems**: For example the supply of remote actuators and sensors in large chemical plants, industrial automation and control, or for temporary measurements like oil exploration, geo- or environmental measurements. The main problem in this case is **to have a supply of energy** (at favorable costs)
- **Accessibility-limited systems**: For example systems with a very high voltage potential or with moving parts as in robotics, electronics control or measurement equipment in generators, wellheads, turbines, etc. The main problem here can sometimes be reduced **to transfer energy!**

For the latter, all of the supply possibilities for autonomous systems can be used, but often additional possibilities exist (e.g. contactless systems such as rotating or high frequency isolation transformers, transfer via optical fibers etc.).

The industrial use of autonomous systems would be advantageous for a variety of possible applications, for example in the following technical areas:

- **Accessibility limited** areas:
  - High temperatures (turbines, down holes),
  - Aggressive atmospheres
  - High voltages (MV or HV equipment)
- Extended systems
  - Widely spread plants (e.g. chemical)
- Systems with a large number of sensors
  - Robots,
  - Fully automated production machines
- Systems with changing system configuration
  - Long term tests (fatigue tests),
  - Measurements (data collection)
- Moving objects, units
  - mobile terminals
  - Robot parts,
  - Product flow devices/carriers.

In these examples fully wireless, energy autonomous devices would be extremely beneficial from a user point of view for example for:

- New applications (not possible with wires)
- Cheaper applications (reduced engineering/wiring costs)
- Retrofit applications (additional functionality needed for older systems due to new requirements)

Specifications and requirements:
Cost, reliability and long lifetime are the key device selection factors in such systems. For industrial real time discrete automation (production machines, robotics) the following main requirements exist for most applications, e.g. sensors, actuators and their communication devices:

- Maximum cycle time or latency: < 10ms
- Minimum repetition rate ≥ 5 events pr second
- Typ. lifetime: ≥10 years
- Truly wireless, maintenance free (no power cable/battery)
- Low cost (to maintain competitive advantage)
- Small size (retrofit without redesign of machine/mechanics)
- High availability and reliability (comparable to, or better than wired)
- High density of nodes 1000's per factory floor
- Globally available frequency bands

III. Proposed Communication System for Real-Time Applications

This section outlines design considerations and a proposed format for a wireless communication system applicable to real-time applications. The major principles for a system that has been realised is prestented. The detailed characteristics of the system fall beyond the scope of this paper.

The design requirements for a wireless communication system for industrial automation differ significantly from those for existing commercial applications such as mobile telephony, wireless LAN (eg. IEEE 802.11b), and wireless PAN (eg. Bluetooth). The communication needs for automation are characterized by:

- Short messages
- Short telegram latency
- Extremely high reliability
- Large density of devices
- Ultra-low power consumption
- Low cost.

In contrast existing systems are typically designed for:
(a) connection-oriented communication (e.g. voice, streaming multi-media) and
(b) transfer of large blocks of data without specific real-time requirements. There are also systems available for wireless data aqcuisition, but the current offerings provide slow update rates suitable only to slow processes.
A number of technologies for wireless communications are available. This paper discusses wireless communication by radio. Other options exist such as optical communication (infra-red). Wireless communication by radio is by far the best option for systems in wireless automation due to the

possibility for high data rates and the need for communication without line-of-sight.

Frequency Band

An important consideration when choosing radio technology for wireless automation is the choice of frequency band. For un-licensed systems requiring global deployment without the need for configuration to fit local regulations, a number of open ISM (Industrial, Scientific, Medical) bands exist. The most commonly preferred ISM bands today are the 433MHz, the 860MHz and the 2.4 GHz bands. The 433MHz/860MHz bands are popular with remote monitoring and control applications. The advantages with using these frequencies are the availability of low-power RF technology and the relatively low propagation losses (i.e. large range). However, the bandwidth is a severe restriction when applying these technologies to distributed systems that require real-time data and a high density of devices.

The 2.4GHz ISM band is suitable for wireless automation due to its global availability and relatively high bandwidth (83,5MHz). In recent years there have been significant advancements in highly integrated, relatively low power and low-cost RF transceivers for this band. This is driven by standard technologies such as Bluetooth and IEEE 802.11b. There is also a suitable frequency band at 5.5GHz, but the RF technology at this frequency is not yet mature.

Network topology

With the requirement for real-time communication combined with a high number and density of devices, the efficient use of the available bandwidth is important. This calls for a cellular network topology, with re-use of frequencies. A number of base stations can be distributed in the plant, with short-range communication with local sensors/actuators. As for cellular telephony networks in larger geographical areas, , the same bandwidth can be re-used in cells that are separated by a sufficiently large distance.

The base stations are directly wired to the control network and communicate with the local wireless devices. In typical applications the devices need only limited mobility, so there is not a need for roaming. This means that there may be a one-to-one connection between a wireless device and a base station. This simplifies the communication protocol, which does not require the network layer. This paper proposes a simple point-to-multipoint topology.

Communication Environment

The main threats to a reliable communication are:

(a) interference from other wireless communication systems

(b) frequency selective fading.

It is necessary to design the system such that it can co-exist with systems such as Bluetooth and IEEE802.11b, which also operate in the 2.4GHz band. Systems must also cope with the frequency-selective fading caused by multipath propagation of the radiowaves and resulting destructive combination.

Two diversity techniques are commonly applied in wireless communication systems in order to combat frequency selective fading. These are antenna diversity techniques and spread spectrum technology (frequency diversity). Antenna diversity techniques are generally more expensive due to equipment cost and installation of multiple antennas. Additionally, antenna diversity techniques do not offer protection in terms of interfering systems.

It is therefore necessary to apply a suitable spread spectrum technology, which may be combined with antenna diversity to further improved system performance.

Physical layer and Medium Access Control (MAC)

In a system that needs to achieve the delivery of messages with a very high probability of success and high number of devices, the sharing of the communication medium is important. The techniques widely applied are Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA).

The technique most suitable for low-cost and low-power communication is TDMA. In combination with Frequency Hopping (FH) this can provide reliable communication with the possibility for low-cost and low-power implementation.

Communication system description

A wireless system has been design to meet the special needs of wireless in control and automation, as described above.

The system uses TDM on the downlink, i.e the basestation to device link. The downlink is used to continuously transmit synchronisation information, acknowledgements and control data to the devices. Each frame is 2048 us.

The devices are granted one slot each for uplink communication per frame in a TDMA scheme.The frames on the uplink are synchronised to the downlink frames, but the channels are separated by a fixed frequency offset (Frequency Division Duplexing.)

A simple transmission control protocol is applied.Telegrams received by the basestation are acknowledged. In case of a missing acknowledge, the device will re-transmit the telegram. The short frames allows for several re-transmissions within the permissible delay window, and a sufficiently high reliability can be obtained

A special requirement for an energy-autonomous system is the extremely low-power requirement for communication. This is a challenge when combined with the real-time requirement. The use of the radio needs to be minimized. It is necessary to exploit the possibility of a more complex base station design. The system has a continuous downlink, offering synchronization information to sensors. When a sensor wakes up, it can immediately find synchronization, meaning less use of the receiver.

A novel Frequency Hopping scheme has been developed, with unique properties that ensure a maximum likelihood of proper transfer within a given window of a few frames. The novel Frequency Hopping scheme guarantees that the frequencies used in successive frames are widely spread, providing robust communication in the presence of wideband interference or faded channels.

IV. Evaluation of Power Supply Possibilities

The resulting **requirements** for energy/power supply can vary quite a lot from application to application. Furthermore, to be usable in general, the device should be usable in any mounting position/orientation and while in motion, which must be taken into account when looking at radiated quantities such as PV (photovoltaic) and high frequency (HF) supplies (=shadowing/shielding). A main focus in developing autonomous applications is on power supply possibilities, as they often define the allowable power/energy for the sensor and the communication actions. Batteries are used as comparison here; unfortunately developments in this area have not shown progress in the last ten years, especially regarding energy densities of primary batteries [4,5].

General Design Aspects of Autonomous Systems

For the reliable supply of autonomous systems at reasonable costs, there are two most important basic design rules:

I. Reduce the energy consumption as far as possible!

This can be achieved for most applications of interest here with energy minimized consumption, pulsed operation, and a kind of energy management. The use of existing conventional systems or parts thereof will normally lead to excessive energy consumption compared to newly developed systems with a focus on **energy consumption minimization**.

II. Use hierarchical pulsed operation modes only

Most applications normally allow the intense use of **pulsed operation modes** as data collection, actuation, processing, and communication are to be done at discrete times only. Speed must be reduced to the necessary minimum (e.g. in dependence of transients in the measurement signal). If the time behavior of the alternative energy is purely stochastic, 100% reliability of the power supply cannot be guaranteed (e.g. photovoltaic) or can be guaranteed only at a very large oversizing.

Power Distribution

Power distribution in industrial systems is currently "conducted" with wires (exotic applications are also known with optical fibers, air ducts or a combination with conducting parts). Generally the necessary auxiliary energy for fully wireless devices can be either:

- **Included** in the system: Batteries incl. fuel cell, RTG ; with manual/time discrete (re/)placement
- **Transmitted** to the system: Optical, RF, acoustic, ...
- Taken out of the **system environment** light, heat, acceleration/vibration, sensor effect, user activation

Most industrial applications will need significantly higher reliability than consumer devices; Batteries are generally not acceptable, especially in factories with thousands of devices.

With communication via wires, the power supply has never been a serious problem and also power consumption has been not a major concern when developing devices. This changes dramatically if wireless data transmission is considered: Power supply is now a, or the, major problem [3].

Alternative Power Sources

In **Table 1** energy/power supply estimates for a typical autonomous application in an industrial environment are shown. Assumptions were that 1/3rd of a typical application housing is usable ($6cm^2$ surface, $2,4cm^3$ of volume). The application should be operable for a reasonable time, e.g. five years have been assumed in the comparison.

Other sources like flow, acceleration and vibration and those related to the sensed quantities have not been investigated, as these are only present in some sensor applications with a significant quantity and therefore will not be generally usable in a wide range of applications. Nuclear generators (e.g. RTG as used in pacemakers) are not considered due to likely objections.

The comparison states the power levels achievable together with the determining size (area/volume) and calculates the deliverable energy (density) for 5 years. From that an average power can be calculated which, together with a risk and cost estimation, allows the calculation of a figure of merit (=energy/cost/risk) for the supply possibilities. The risks are described in the last column of the table. A high energy density with low risk and cost gives the highest figure of merit! Best suited for the analysed automation application is according to **Table 1** a HF-supply using magnetic fields around 100kHz ($\lambda >>$ dimensions of target system).

General System Description

The type of wireless system of interest here is suited for cell structures, as commonly used in industrial production processes for highly automated production machines or robotic manufacturing cells. The designed system consists of a communication subsystem as described in section III. The power supply system should be able to cover systems sizes matching typical manufacturing cell sizes, e.g. $6x3x3m^3$. The system is modular, so cells can be modularly connected to cover larger areas with several cells.

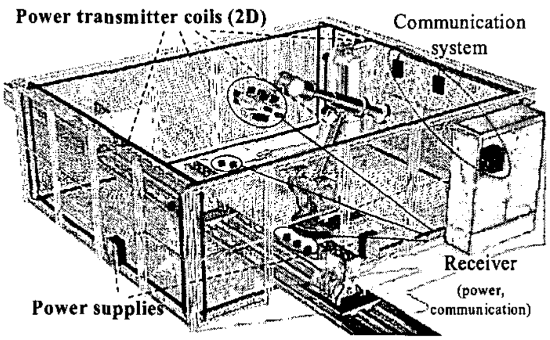

Fig. 1: Wireless power and communication system for automated production cell (e.g. with robot)

V. MAGNETIC POWER SUPPLY CONCEPT

A.) Magnetic Supply Principle:

The basic principle of a wireless supply via magnetic fields can be completely described by the well-known transformer model with parasitic elements. The primary winding is a large coil around the volume to be supplied, the secondary(s) are small receiver coils, with a ferrite core to increase the flux through the coil.

The main difference is that there is practically no core, and that medium frequencies (MF) are used. The parasitic elements therefore dominate the characteristics and lead to a very low coupling value of 0,01-0,1%, with which the primary power supply has to cope [4], in order to transfer energy. The main coupling quantity is the field strength at the receiver position. If the primary coils are setup in a Helmholtz-like arrangement, this quantity is fairly constant over a large volume.

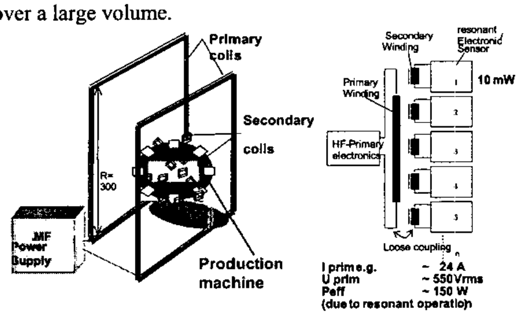

Fig. 2: Principle of medium frequency (MF) power supply via magnetic fields and block diagram

The losses are mainly determined by the conduction losses of the coil(s) due to the skin and proximity effect. System tests have been done at 13,56 MHz and 120kHz. At 13,56MHz, which is an ISM frequency [5] dedicated to such applications, EMC problems are more likely, due to the proposed cell sizes and the small wavelength, so that also radiation already starts. Therefore a frequency has been chosen which is well below the regulations limits, starting above 148,5kHz in the ISM standards. The reliability of the system is also determined by the choice of the frequency and the allowed field strength values regarding operator safety values.

Keeping the field strength as low as possible and within all known regulations was a main design criteria.

The dominating biological effect is considered to be heating of tissue and the regulations and recommendations state levels that allow the realization of the concept [6]. E.g. the German "Berufsgenossenschaft" allows up to 42 A/m @120kHz for occupational exposure [7], IEEE C 95 allows even 163A/m [8]. We have used 42A/m as a worst-case design criterion. This would allow a worker to continuously touch the coil wire with his head (an unrealistic case) for a full shift, every day without exceeding occupational limits. Applying the ICNIRP recommendations, a distance of roughly 30cm to the coils for continuous working positions should be observed. Public values are 5A/m (@120kHz)!

A bit less clear, but not differing from other more powerful high frequency applications (e.g. induction heating), is the regulation situation regarding EMC of pacemakers. EN 50061 states acceptable disturbance voltage levels U_{ss} for pace makers of e.g. 1V @120kHz, nevertheless they are not referred to in the pacemaker industry. Applying the significantly stricter VDE 0848 [9] leads to U_{SS} values of 130mV @120kHz. This translates to observable distances for pacemaker carriers of e.g. 0,5m for a small setup, and 1,5m for the largest setup with 3m of typical coil quantity (=max. distance of two perpendicular conductors and $24A_{rms}$ each.

B.) Resonant Medium Frequency Power Supply

Such a transformer can only be operated conveniently in a resonant mode, where the large (leakage) inductance is compensated. Then an operation with low voltage or current quantities is possible.

As such a supply should also be able to cope with:

1.) smaller changes in the environment, e.g. large and moving metallic obstacles (e.g. robots) and
2.) large "load" variations such as different sized primary coils (=inductance values) and different amount of losses created for example by eddy currents in adjacent metallic obstacles

the primary supply needs an automatic and highly accurate control to always quickly achieve a perfect tuning for the resonant system to the fixed power frequency of 120kHz. Such a supply must also be suited for synchronized operation of multiple coil structures [4].

C.) Omni-directional Receiver Structure

To achieve significant power at the receiver side, these coils must also be operated in a resonant mode. To also achieve constant power output regardless of orientation in relation to the primary field vector, an orthogonal setup of three coils must be used. This orthogonality provides the opportunity to achieve a fairly simple tunable resonant system, still suited for industrial mass production.

D.) Rotating Field:

Obviously all types of metal will be present in the target application (production machines, robots,etc.) therefore a unidirectional field vector of the magnetic field is not sufficient. Ideally an omnidirectional type of field would be needed to achieve maximum field strength in heavily shielded environments. This means at least two coils or coil-systems (creating a rotating field), but ideally 3 orthogonal coils (or coil-systems) for an omnidirectional field are needed.

VI. RESULTS

Considering worst-case minimal field strength under shielding conditions, achievable power levels on the secondary coils mainly depend on the size of the coil and core size/shape used. A typical specific value achieved in the first prototypes is $1mW/cm^3$ @6A/m, 120kHz also under worst-case conditions. A typical value of up to $3mW/cm^3$ has been practically achieved. This is sufficient to operate optimized wireless communication and sensing electronics using programmable logic and advanced bluetooth components to achieve the specifications set in section II.

The energy density achievable under worst case shielding conditions over 10 years is still 50 times higher when

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