Inductive Powering of Sensor Modules

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***Abstract*-An inductively powered system, aimed at providing wireless power to sensor modules, has been built and tested. The goal of the work is to determine the limits in terms of distances, and power transferable, using a 13.56 MHz system. Powering distances of up to 10 cm were obtained for power levels up to 1 mW. This distance reduced to 7 cm for 10 mW. Transfer of power levels of 30 mW was only possible for distances of 3 cm.**

I. INTRODUCTION

There is an increasing interest in the use of wireless sensor nodes for the remote collection of environmental data in applications such as in buildings, industrial equipment, automotive, healthcare, etc. .One of the major issues for such sensor nodes is the provision of power, and in particular the fact that the sensor node lifetime is limited by the battery. In order to increase battery lifetime minimization of the power consumption is critical. In addition to power minimization, techniques such as energy harvesting are also being investigated to extend the sensor node lifetime. This paper presents an investigation into the provision of power to sensor modules by means of inductive coupling, via a magnetic field. Such an approach would allow the use of wireless, battery-less sensor modules, with zero maintenance requirements, making them ideally suitable for use in inaccessible areas.

Inductive powering is used extensively in the area of Radio Frequency Identification, RFID, to remotely power tags containing a stored ID and then transmit the data. However in such applications the power levels required to power and transmit the ID are generally very low, being of the order of microwatts [1]. In order to be useful for sensor modules enough power must be transmitted so as to power a sensor, perform a reading, process the data, and transmit it back to a reader. A review of the sensors available today show that the majority require power levels of several milliwatts

Inductive powering has also been extensively used in the biomedical area, for the powering of systems implanted in the body. Applications include, recharging of an implanted battery as in the case of the artificial heart [2] or an alternative to implanted batteries in the case of long term monitoring, in for example hip prosthesis [3]. There are also, some commercially available, inductively powered sensor modules designed for industrial applications [4].

The two main frequency ranges used for inductively coupled applications are 125kHz and 13.56MHz. The lower range is particularly used in applications where a high energy transfer is required and implementation is required in harsh medical and industrial environments where for example the remote module is surrounded with metal. The 13.56 MHz range generally allows the use of higher data transfer rates, which is essential if fast sensor reading is required or if reading of multiple sensor modules is required. For this reason this work focuses on the 13.56 MHz frequency.

It is not clear what the limits are for the inductive powering technology, particularly at 13.56 MHz, from previously published work. This work presents an investigation into the distances and power levels which can be achieved using inductive powering at 13.56 MHz. Section II reviews the basic principle of inductive power transfer. In section III the field limits which restrict the allowable magnetic fields are discussed. Section IV describes the design of an inductively powered sensor system which consists of a reader and an inductively powered sensor module. In section V test results for the power transferable using such a system are presented.

II. INDUCTIVE POWERING

In an inductively coupled system power is transferred from a transmitter power supply which we will refer to as the reader, to a remotely located transponder. Power is transferred by means of the magnetic field, which is created by the current through the reader antenna or coil. A series resonant LC circuit is used in the reader to maximize the current through the coil. If a transponder antenna or coil, is brought within this field, then it will have a voltage induced, according to Faraday's law. If this antenna is connected to a load than a current will flow and power is transferred to the load. The magnitude of the voltage induced on the transponder coil will depend on the size, shape and relative positioning of the coils, on the magnitude of the field emitted by the reader, and on the frequency of this field. The size and shape of the coils can be optimized based on the application. The magnitude of the field emitted by the reader is determined by the current through the reader coil. The power which can be transferred depends on this current and frequency. The frequencies which can be used are determined by regulation and the fields which can be emitted must be restricted in order to a) prevent interference with other wireless transmission, b) ensure that there are no adverse health effects from the fields emitted. These field limits are discussed in more detail in the following section.

III. FIELD LIMITS

The magnetic fields which can be emitted by the reader coil must be restricted to prevent electromagnetic interference and also to limit human exposure to electromagnetic fields. The limits imposed in terms of preventing interference are specified by standards such as EN300330 [5] and by FCC regulations

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[6]. These are usually specified in terms of fields at 10 or 30 m distant. The more restrictive limits, for the short range inductive coupling devices being investigated here, are the limits imposed in order to prevent human exposure to electromagnetic fields. These limits are based on the guidelines specified by the International Commission on non-ionizing radiation protection (ICNIRP) in Europe [7] and by the FCC [8][9] in the USA. The basic restrictions are placed on quantities such as current density, and specific absorption rate (SAR) for the human body and power density (in the air) outside the body. Reference levels for allowable electric and magnetic field strengths are then derived from these basic restrictions. The graph in Figure 1 shows the reference level for magnetic field strength vs. frequency as specified by both the ICNIRP and the FCC for general public exposure to magnetic fields.

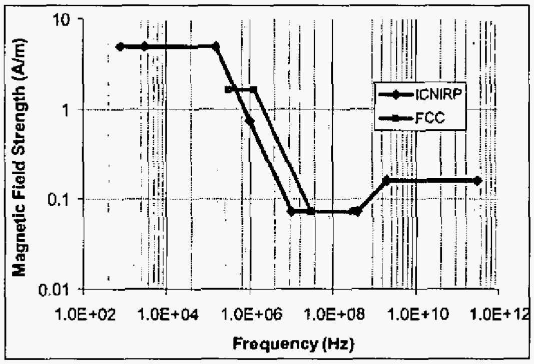

Figure 1 : Reference levels for allowable magnetic field strength as specified by the ICNIRP and FCC. The levels shown in the graph are those which apply to the general public.

At 13.56 MHz the ICNIRP guidelines place a limit of 0.073 A/m and the FCC place a limit of 0.16 A/m on the magnetic field which can be emitted. However it is worth noting that these limits are based on time averaging over a period of 6 minutes, i.e. the time averaged magnetic field may not exceed these limits. It is therefore possible to operate the inductively coupled system in a "burst mode" manner, where the magnetic fields emitted are high for a short duration of time and zero for the remainder of the time so that the average magnetic field over 6 mins does not exceed the limit. However even in this mode of operation the ICNIRP guidelines restrict the maximum field to 32 times the time averaged value. In the system used in this work, which is described in the next section, the reader is designed so as to work in a burst mode, whereby relatively high magnetic field strengths are emitted for a short time duration.

IV. SYSTEM DESIGN

The system consists of a reader and a transponder. The reader consists of an antenna driver circuit, the function of which is to provide the 13.56 MHz current to the reader antenna coil which will in turn produce the magnetic field resulting in inductive coupling action and power transfer between the reader and transponder.

A. Reader Design

Several factors are of importance to the antenna driver circuit design. The circuit has to be flexible for use with multiple transmitter antennae sizes, so that the circuit has to be capable of producing a broad range of output current levels. *Figure 2* below shows a diagram of the antenna driver circuit. The oscillator circuit generates the 13.56 MHz system operating signal. The gate drive takes this signal and provides the drive capability required to switch the gate of a power MOSFET. The power stage consists of an RF power amplifier which provides the current to the transmitter antenna and series resonant circuit. The burst mode control block manages the enable signal of the gate drive network to facilitate a means of pulsed power operation whereby a relatively strong magnetic field can be pulsed for a pre-determined duty cycle.

The gate drive is accomplished by using a high speed comparator which has the dual purpose of buffering the clock signal and producing a 0V-5V square wave with a frequency of 13.56 MHz. Octal-buffer IC's, which are usually intended for use as drivers for bus lines are then used as the MOSFET gate drive. A parallel combination of the of these high speed BiCMOS buffers is used to provide the required amount of current drive to charge the gate capacitance and switch the MOSFET on quickly. The square wave output from the comparator is inputted to 16 BiCMOS buffers connected in parallel which in turn provide a square wave to the gate of the MOSFET. The burst mode control circuitry consists of a CMOS 555 timer and a bank of DIP switches connected to various resistors and capacitors. The duty cycle of the burst signal is set by the R-C combination selected using the switches. The timer outputs a square wave signal which is connected to the enable pin the gate driver octal buffer IC's.

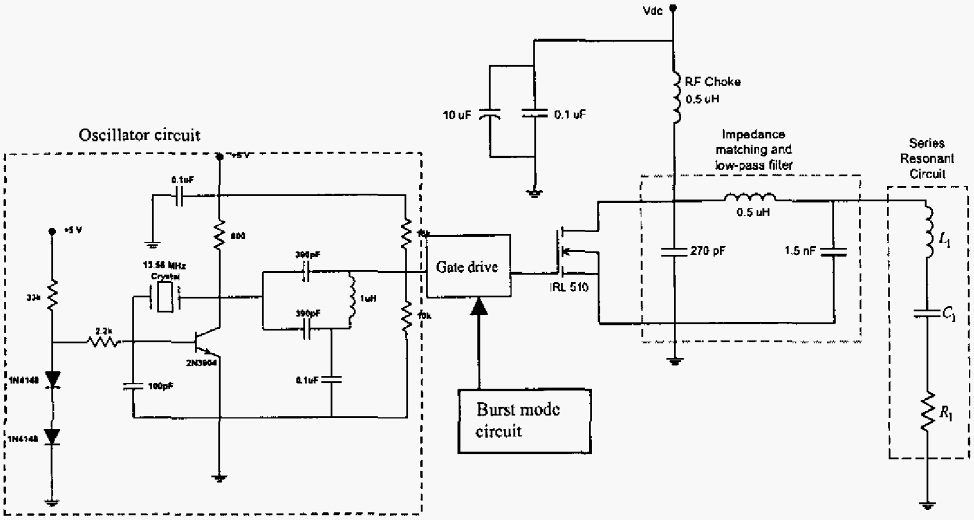

Figure 2: Schematic of reader powering circuit.

B. Transponder design

The schematic of the transponder is shown in *Figure 3*. It consists of a parallel tuned LC circuit, a voltage clamp, a rectifier using schottky diodes, and a 3 V low drop out regulator. The voltage clamp ensures that the voltage presented to the input of the regulator does not exceed the rating when the transponder is placed close to the reader coil. The regulator supplies a 3 V output. This regulated 3V output supplies the transponder load which consists of the digital section of the transponder, which is a low power micro-controller, and the sensor.

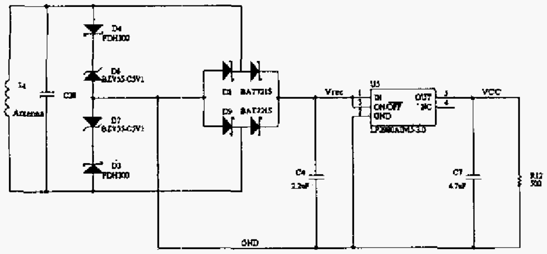

Figure 3 : Schematic of the transponder circuit.

The operating voltage of 3 V was decided on following a review of "off the shelf" sensors. The voltage and power range of some commercially available sensors are summarized in Table 1. As can be seen from the table, most sensors require an operating voltage in the 3 – 5V range and power levels of tens of milli-watts.

TABLE 1: TYPICAL ELECTRICAL CHARACTERISTICS OF COMMERCIAL SENSORS.

Sensor	Voltage range	Power range
Pressure	3-to-5V	1-to-20mW
Acceleration	3-to-5V	7.5-to-35mW
Displacement	3-to-6V	10-to-25mW
Temperature	1.8-to-5.5V	300-to-600µW
Humidity	4-to-5.8V	1-to-3mW
Gas	2.3-to-5V	25-to-800mW

Many low power micro-controllers can operate of voltages lower than 3 V, e.g. 1.8 V is typical, and consume hundreds of micro-watts. The power demands of the transponder are therefore dominated by the sensor. The transponder system has therefore been designed around the goal of providing 3 V and 5 mA. A set of planar coils, etched in printed circuit board, were used as the antennae for the system. It is important that these antenna be optimized for the system so as to maximize the range. The design of the antennae is described in the next section.

C. Antenna Design

In order to maximize the range of the system (maximize the distance at which the transponder can be powered) the reader antenna should be designed so as to maximize the magnetic field at a distance and the transponder antenna should be designed so as to maximize the voltage induced.

The magnetic field at a distance, d, along the center axis of a circular current loop of radius R, with N turns, carrying a current I, is given by;

$$H = \frac{NIR^2}{2\left(R^2 + d^2\right)^{\frac{3}{2}}} \qquad (1)$$

At distance, d = 0, the magnetic field is a maximum and this field must remain with the specified limits. For any given coil radius the NI product can therefore be chosen so that the maximum allowable field is not exceeded at zero distance. The graph in Figure 4 plots the magnetic field strength vs. distance for coils of different radius, where in each case the NI product for the coil is chosen so that the field is 0.073 A/m at distance zero. As can be seen from the graph, coils of larger radius give higher magnetic fields at a greater distance. In order to maximize the range therefore the reader coil radius should be large.

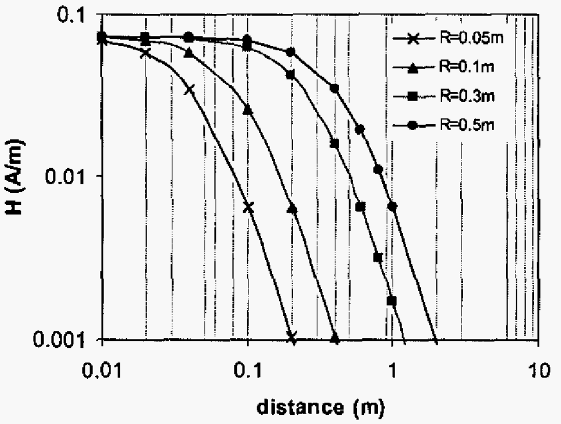

Figure 4: Magnetic field strength vs. distance for different coil of various radii. In each case the NI product for the coil is chosen so that the field at zero distance does not exceed 0.073 A/m.

The maximum size of the reader coil is however limited by the fact that in order to avoid transmission line effects the total length of the reader coil should be significantly less that the wavelength at 13.56 MHz. which is approximately 22 m. The reader coil used here was chosen to have an outer diameter of 15 cm and consist of a single turn. The total length of the coil is therefore significantly less than the wavelength and transmission line effects do not have to be considered.

The transponder antenna should be designed so as to maximize the voltage available at the load. As a first approximation the transponder can be modeled as a simple parallel RLC circuit as shown in Figure 5. The voltage induced on the transponder depends on the magnetic field linking the antenna, and the geometry and position of the antenna relative to the reader. Using phasor notation, this voltage can be written as[1]

$$v_t = \frac{j\omega k\sqrt{L_t L_r}\, i_r}{1 + (j\omega L_t + R_t)(1/R_L + j\omega C_t)} \qquad (2)$$

where k is the coupling factor between the reader and transponder coil. The reader current, i_r, depends on the voltage across the reader antenna and the impedance seen by the reader. The impedance seen by the reader includes its own impedance and also the coupled impedance of the transponder and can be written as[1]

$$Z_r = R_r + \frac{\omega^2 k^2 L_r L_t}{Z_t + R_t + j\omega L_t} \qquad (3)$$

$$i_r = v_{supply}/Z_r \qquad (4)$$

where ω=2πf, and Z_t is the impedance of the parallel combination of the load resistance and the transponder resonant capacitance. Given the RLC parameters of the reader and transponder, and the reader voltage, the voltage at the transponder load can be obtained from (2) with (3) and (4) being used to determine the reader current. The coupling factor, k, between the two coils, will depend on the geometry and relative positioning of the coils and k can be readily determined using finite element analysis.

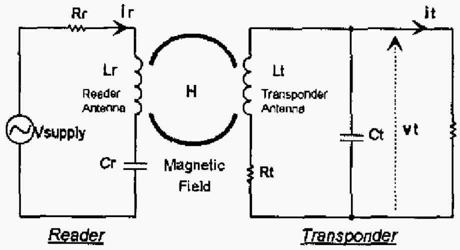

Figure 5: RLC circuit model of the transponder.

The equations given in (2) (3) and (4) can be used to optimize the geometry of the transponder coil so as to maximize the voltage available to the transponder load. If the transponder coil is implemented as a planar spiral coil, then the parameters available for optimization are the coil outer diameter, the number of turns and the track width and spacing.

The graph in Figure 6 shows how the calculated voltage on the transponder coil varies with distance from the transponder for different numbers of turns on the coil. This data is obtained using a single turn, 15 cm outer diameter reader coil, with a 500 mA peak current. The transponder coil outer diameter is 60 mm and the transponder coil track width is 5mm.The load resistance is 600 Ω. The load voltage at a distance of 10 cm increases with fewer turns on the transponder coil. However the load voltage at a distance of less than 5 cm decreases with fewer turns on the coil. A good compromise between the voltage at close proximity and further away is to choose a 2 turn transponder coil. Figure 7 shows how the transponder load voltage varies for a two turn coil for different coil track widths. Higher track widths are favored due to the lower resistance.

The antennae have been optimized around the goal of providing 15 mW (5 mA at 3 V) output power to the transponder. Based on an analysis similar to that presented in the above graphs the geometric and electrical characteristics of the antenna used are presented in Table 1

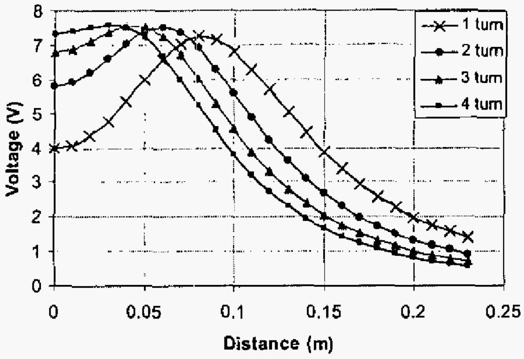

Figure 6 : Variation of the calculated voltage on the transponder load vs. distance from the transponder for different numbers of turns on the transponder coil.

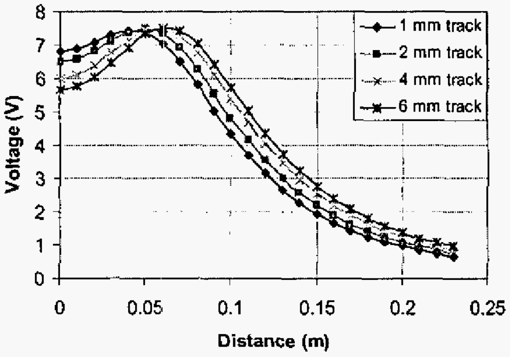

Figure 7 Variation of the calculated voltage on the transponder load vs. distance from the transponder for different track widths of the transponder coil:

TABLE 1: GEOMETRIC AND ELECTRIC CHARACTERISTICS OF THE ANTENNAS.

	Reader	Transponder
Outer Diameter	159 mm	60 mm
Track width	2 mm	6.1 mm
Track spacing	N/a	1 mm
# of turns	1	2
Ls @ 13.56 MHz	530 nH	167 nH
Rs @ 13.56 MHz	0.528 Ω	0.116 Ω

V. TEST RESULTS

As a first step the basic relationship between transponder voltage and distance from the reader has been measured. Both reader and transponder coils were tuned separately to 13.56 MHz and the voltage induced on the transponder coil was measured, using an oscilloscope, as the coil was moved away from the reader. The reader current was set at 0.5 A peak without the transponder in the field. The transponder consisted of the coil, the rectifier, and a load resistance. No rectifier was present The graph in Figure 8 shows the measured voltage across the coil vs. distance from the reader coil for a load resistance of 600 Ω and for no load. For these measurement the reader and transponder coils were aligned parallel to each other with their center axes aligned. The voltage calculated using equation (2) is also shown for comparison.

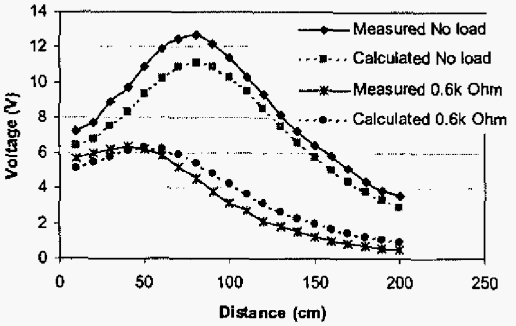

Figure 8 : Measured and calculated voltage vs. distance curves for the reader and transponder.

The shape of the voltage vs. distance curve is similar to that predicted by the equations. However there is some difference in the values of the voltage. For example the measured no-load voltage is approximately 1 V greater at 10 cm than the calculated voltage. Some of this difference is certainly due to the fact that the calculation takes no account of the rectifier, which can have the effect of changing the resonant frequency of the transponder. This can de-tune the reader and transponder with respect to one another. Further investigation of the measurement set-up is required to further resolve the difference.

Next the limits of the distances and power transferable using the inductive system at 13.56 MHz. was investigated In order to do this the transponder shown in Figure 3 , which includes the 3 V regulator, was used with the load replaced by a variable resistor. Since the power available to the transponder depends on the current through the reader coil, the power transferred using different reader currents is investigated. The maximum powering distance is considered to be the maximum reader and transponder coil separation for which 3 V can be obtained across the transponder load. The graph in figure 9 shows the results for the maximum powering distance achievable, vs. the transponder load current for various reader currents. This data was measured by fixing the reader current, to the value indicated without the transponder in the field. The transponder load was then varied, and for each load current the transponder was moved so as to obtain the maximum distance for which 3V was achievable at the output of the transponder regulator.

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