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Long range inductive power transfer system

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Abstract. We report upon a recently developed long range inductive power transfer system (IPT) designed to power remote sensors with mW level power consumption at distances up to 7 m. In this paper an inductive link is established between a large planar (1 x 1 m) transmit coil (Tx) and a small planer (170 x 170 mm) receiver coil (Rx), demonstrating the viability of highly asymmetrical coil configurations that real-world applications such as sensor networks impose. High Q factor Tx and Rx coils required for viable power transfer efficiencies over such distances are measured using a resonant method. The applicability of the Class-E amplifier in very low magnetic coupling scenarios and at the high frequencies of operation required for high Q operation is demonstrated by its usage as the Tx coil driver.

1. Introduction

Attempts to transmit power using electromagnetic fields beyond 1 m have tended to use the far field, rather than near field region [1, 2]. However such operation involves radiating energy and is intrinsically inefficient, unless the receiver intercepts a significant portion of the radiated energy. This limits such systems to the use of antennas with narrow beam pattens. The technology presented here uses loop antennas which have very broad magnetic field distributions allowing power transfer to receivers over a wide area [3]. Coils are kept electrically small, to keep radiation losses to a minimum, avoiding significant radio emission [4]. Ambient RF systems are capable of tens of μW with cm scale antennas [5] and although they are able to operate in many urban environments without an explicit power source many applications are not achievable at this power level. Hubregt J. Visser has developed a directional radiative system, capable of delivering hundreds of μW to the load at a distance of 1 m [2]. However, inductive coupling has been recently demonstrated with watt level received power at distances over 0.6 m [6]. Another IPT system has been demonstrated transmitting power with 15% efficiency over 2 m [7], using a 1 x 1 m Tx and 1 x 1 m Rx coil at a frequency of 513 kHz.

When optimising the coils in an inductive power transfer system within a given dimensional constraint, the most important parameter is Q factor. The link efficiency η_{link} is given by [8]:

$$\eta_{link} = \frac{k^2 Q_{Tx} Q_{Rx}}{\left(1 + \sqrt{1 + k^2 Q_{Tx} Q_{Rx}}\right)^2} \tag{1}$$

where the coupling factor k is given by:

$$k = \frac{M_{TxRx}}{\sqrt{L_{Tx} L_{Rx}}} \tag{2}$$

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Coil's self inductance, L, is proportional to the number of turns squared, while the mutual inductance between the Tx and Rx coils, M_{TxRx}, is proportional to the turns product of the two coils. Therefore k is effectively set by the coil diameter and varies little with changes in the number of turns. As such, maximising Q factor by selection of appropriate operating frequency and minimising the coil's loss resistance are key to obtaining high link efficiency [6].

2. Design

2.1. Miniaturised receiver coils

Direct measurement of coil parameters via the reflection coefficient using a traditional network analyser is not generally possible for Qs greater than 30 [9]. Therefore measurement of coil parameters was performed using a transmission-type resonant measurement [10] with 2 pF coupling capacitors to minimally load the resonators. An estimate of resonator loading was obtained using the peak transmission coefficient [11].

$$Q_L(f_0) = \frac{f_0}{f_2 - f_1} \tag{3}$$

$$Q_0(f_0) = \frac{Q_L(f_0)}{1 - |S_{21}(f_0)|} \tag{4}$$

Where Q_L is the loaded Q factor obtained from the resonator bandwidth, $|S_{21}(f_0)|$ the magnitude of the resonant peak, f_2 is the upper $-3dB$ point and f_1 the lower $-3dB$ point. Inductance of the coils varies little with frequency and therefore was found by measurement of the resonant frequency with a large resonant capacitor to minimise the effects of the coil self capacitance. The capacitors used to resonate the coils (American Technical Ceramics) have Qs in excess of 10,000 at the frequencies of interest and were therefore assumed to be lossless. A series of 20 mm outside diameter Rx coils were constructed, aiming to maximise the Q factor at 3 MHz, which is the target frequency of operation of the IPT system. This frequency of operation was primarily dictated by the need to avoid spurious radio emission from the Tx coil, caused by the transmission wavelength approaching its electrical length. Coil parameters (turns, turn spacing) were optimised in an EM simulator (CST Microwave Studio) before construction and via empirical models [12, 13, 14]. The number of turns and conductor diameter for the Rx coil was constrained by manufacturing capability. It was found that PCB coils, due to the small conductor cross-sectional areas, had poor Q compared to copper wire coils. The wire coils were constructed by threading enameled wire through a former, composed of thin 100 (μm) flexible PCB material, with holes drilled at each wire corner; a thin ferrite, TDK IRJ04 ($\mu = 40$, depth = 0.5mm) was then stuck to the reverse side of the coil to reduce the effect of metallic planes behind the coil. The ferrite had little measurable effect on the coils Q factor.

The results shown in figure 1 compare favourably with published research, achieving almost 2x the Q factor of optimised PCB coils at 3 MHz of 40 mm diameter [12]. Litz wire was found to offer a small advantage in Q factor over equivalent diameter solid wire; the lack of dramatic improvement is likely due to the reduced conductor area available in such finely stranded insulated wire. However these miniaturised 20 mm coils only harvest 1 mW within a meter of the transmitting coil and are of limited use for a long range system. A 170 mm diameter Rx coil was therefore developed for the long range wireless power transfer system using a 3D printed ABS former loaded with 3 overlayed parallel connected litz wires shown in figure 2. Due to its greater Q factor (280 at 3 MHz) and 72x greater area than the miniaturised coils, it was found to be able to harvest greater than a mW up to 7 m from the Tx coil. To obtain an estimate of the power transferred, not taking into account the environment the coil is placed in, the mutual inductance has been estimated via the loop areas of the antennas using [14]:

$$M_{TxRx} = \frac{\mu_0 A_{Tx} A_{Rx}}{2r^3} \tag{5}$$

Where A_{TX}, A_{RX} are the sum of the areas of the turns for the Tx and Rx coils respectively and r is the on axis displacement of the coils.

Table 1. Miniaturised 20 mm diameter receiver coils

Coil	Spacing (mm)	Conductor	Turns	Inductance (μH)	Q(3 MHz)
Litz wire	0.5	Litz wire 0.025 mm x 160	11	1.11	97
Solid wire	0.5	0.321 mm diameter copper wire	11	1.25	68
PCB	0.25	0.4 x 0.035 mm Cu track with HASL	15	2.07	30

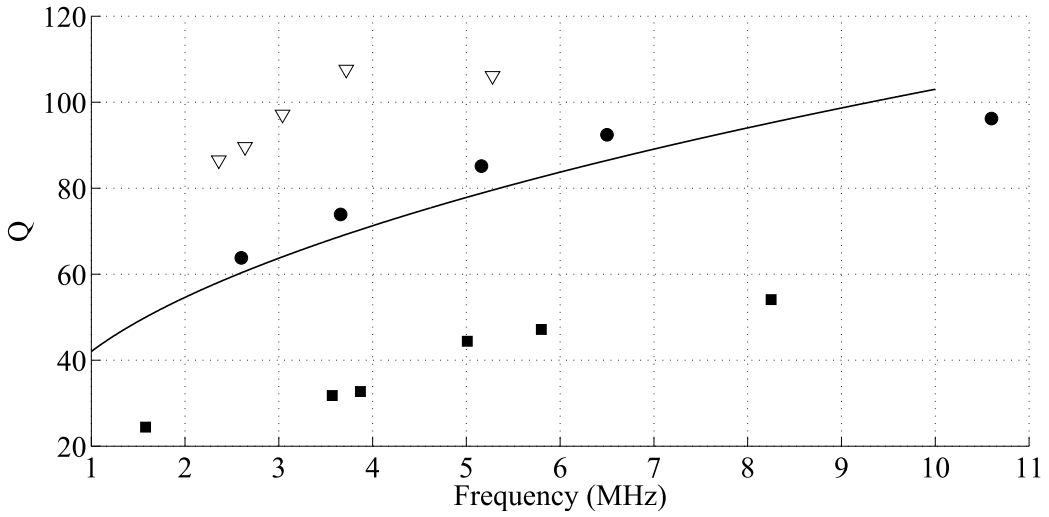


Figure 1. Q factor measurements and simulation results for 2cm coils. Simulation of solid wire coil ——, Litz wire coil ▽, Solid wire ● , PCB coil ■.

Table 2. Long range IPT system coils. [1]Simulation result.

Coil	Diameter (m)	Spacing (mm)	Conductor	Turns	Inductance (μH)	Q(3 MHz)
Rx	0.17	1.5	3 strands of 1.3 mm litz	6	9.70	280
Tx	1	30	28 mm Cu pipe	2	7.63	2890[1]



Figure 2. 170 mm and 20 mm Rx coils



Figure 3. 1 m Tx coil and class-E amplifier

2.2. Long range IPT approximations

In a conventional IPT system, where efficiency is $> 50\%$, the Rx coil reflected impedance makes up the majority of the primary tank impedance formed between the Tx coil and its tuning capacitor [6]. As this varies with position and Rx load, the Class-E amplfier must be retuned for optimal efficiancy. However, with a long-range system, the Rx coil is so weakly coupled that it has negligable effect on the Tx coil impedance, simplifying both design and operation. Furthermore, the impedance match for the Rx coil can be simplified to the conjugate match of the Rx tank at the operating frequency:

$$Z_{tank} = \frac{1}{\frac{1}{R_{Rx}+j\omega L_{Rx}} + j\omega C} \tag{6}$$

where R_{Rx} is the series loss resistance of the Rx coil, L_{Rx} the inductance of the Rx coil and C the turning capacitance used to resonate the LC tank at the systems operating frequency. As this model makes use of the coil's loss resistance, the Q factor measurements of the coils can be verified by checking that the calculated impedance match is optimal. The match should be resistive at resonance, since the tank presents a real impedance. M_{TxRx} can be found using the measured magnetic field generated by the circulating current from a free wheeling primary I_{Tx} and the area A of flux that the Rx coil encloses (i.e. sum of areas of all turns). The free wheeling coil current can be found using the coil voltage and the impedance of the Tx coil (from inductance and Q factor measurements) or by approximating the coil as line segments of current and measuring the magnetic field at a known close location to the Tx coil (e.g. 1 m away on axis).

$$M_{TxRx} = \frac{A_{rx}B}{I_{Tx}} \tag{7}$$

This methodology allows for prediction of system efficiency in real-world environments where the magnetic field strength is modified by conductive objects.

3. Results

The 1 x 1 m Tx coil and 170 x 170 mm Rx coil were displaced from 2 to 10 m, on axis, in a large laboratory with the coils located far away from any boundary and with no objects placed between the coils. The laboratory contained a number of non-removable conductive objects, such as the flooring (steel backed) and the bench supports (steel bar). This is reflected in the magnetic

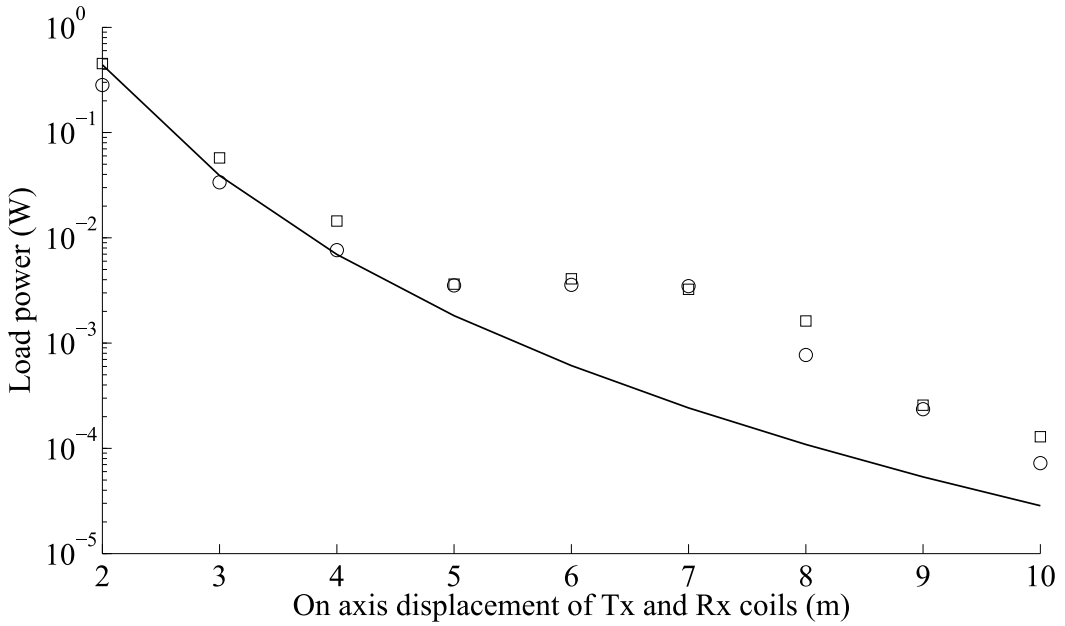


Figure 4. Load power transferred to 170 x 170mm Rx coil from 1 x1 m Tx coil with 98W DC power input to Tx amplifier. Simulation using round loops approximation ——, Prediction using local magnetic field strength □, Measured power at Rx coil ○ .

field strength readings in table 3 which are greater than would be expected at 6 m and beyond. This shows that in real-world environments, range may be greater than expected for long-range systems. Magnetic field readings were taken using a 50 mm Aaronia PBS1 magnetic field probe and Agilent FieldFox Handheld spectrum analyser, orientated such that the component of the field in the direction of displacement was measured. To measure the received power for the system, the Rx coil was first was tuned to the excitation frequency of the Tx coil and then impedance matched with a 51 kΩ 1206 surface mount resistor. The Rx coil was then positioned at the locations the magnetic field probe readings had previously been taken with the system operated at the same 98 W DC power input to the Class-E amplifier. The voltage at the load was then measured to determine the power transferred to the load from the Tx coil, using a Fluke 190 Scopemeter connected to the tuning capacitors, via a short stub of coaxial cable to avoid adding additional loop area to the Rx coil. To test the maximum power input to the system, a 246 W DC power input test was run where 10.9 mW was transferred to the receiver coil located 6 m away on axis; the limiting factor was found to be the 1,000 V rating of the MOSFET used in the Class-E amplifier, due to the high impedance of the free-wheeling Tx coil. The litz wire 20 x 20 mm coil was found to be able to harvest 832 μW at 1 m for 98 W of DC power input to the Tx amplifier.

4. Conclusion

A practical long-range IPT system has been demonstrated. While showing low efficiency, useful amounts of power (> 10 mW) at distances up to 6 m from the Tx coil to compact 170 x 170 mm receivers was recovered. This system makes use of recent advances in IPT technology, using a quasi-resonant Tx coil with a Class-E driver, MHz transmission frequency, quasi-resonant primary and resonant secondary coils [6]. Novel coil constructions, with the aim of maximising Q factor, have been developed for the link. We have demonstrated the systems performance

Table 3. long-range IPT system results

Distance (m)	Pin (W)	Pout (mW)	Tx voltage (kVpp)	B field (μT)	Clock (MHz)
1	97.9	NA	4.06	2.91	2.87126
2	97.9	282	4.06	0.331	2.87126
3	97.9	33.6	4.06	0.117	2.87126
4	97.9	7.53	4.06	0.0588	2.87126
5	97.9	3.52	4.06	0.0294	2.87126
6	97.9(246)	3.57(10.9)	4.06(8.19)	0.0322(NA)	2.87126(2.87721)
7	97.9	3.47	4.06	0.0278	2.87126
8	97.9	0.771	4.06	0.0197	2.87126
9	97.9	0.235	4.06	0.0078	2.87126
10	97.9	0.072	4.06	0.0056	2.87126

in a real-world environment, showing the validity of using magnetic field measurements for performance prediction. In addition we have demonstrated with a 246 W power input test that greater Tx coil power levels are possible, given the main constraint of the maximum drain-source voltage the MOSFET can withstand in the Class-E amplifier. Although efficiency is very low, many sensors can be powered at the same time from the same transmitter and distributed around a room, increasing overall system efficiency and providing an alternative solution to energy harvesters for power supplies in remote applications.

Acknowledgments

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