MAXIMISING THE LINK EFFICIENCY OF RESONANT INDUCTIVE COUPLING FOR WIRELESS POWER TRANSFER

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This paper presents an efficient and low cost wireless energy transfer system for applications where some degree of misalignment between the transmitting and receiving coils is unavoidable in the application. A possible application for this system is for water sensor networks where power is transmitted from an unmanned surface vehicle to remote sensors. A high frequency and medium power wireless link is analysed to achieve an air-gap of tens of centimetres without the use of field shaping ferromagnetic materials. An extensive model of resonant inductive link theory tailored to this application was developed, which shows that transfer efficiencies above 90% could be accomplished with an air-gap between the sending and receiving coils of more than 50 cm of separation. To verify the equations and assumptions presented, fast and precise Q factor measurement techniques and an adjustable test fixture were designed to characterize coil setups and wireless energy transfer in an aquatic environment. Q factors over 1,000 were measured, proving that a cost effective high Q coil assembly to optimize the wireless power transfer is achievable. The results presented in this paper, together with analytical and numerical models, provide a design framework for resonant inductive coupling systems for applications where the transmitting and receiving coils have different dimensions. A good match between experimental and simulation results was achieved.

Keywords: wireless power transfer, resonant inductive coupling, Q factor measurements, water sensor network

INTRODUCTION

Wireless power transfer without a magnetic core is not a new topic: Nikola Tesla proposed various schemes for supplying wireless mains power over long distances around 100 years ago [1], low-power, closely coupled wireless charging methods have been used to power medical implants for decades [2], while the wireless powering of portable devices through charging mats is today a commercial product [3]. Nonetheless, there has been a recent resurgence in research interest in wireless transfer for medium range (10s of cm) applications such as electric vehicle charging through resonant inductive coupling [4-6].

Another application for wireless charging can be found in certain configurations of wireless sensor networks (WSN), where remote sensors could receive energy from time to time if a suitably equipped energy source passes by. An example of this type of WSN is in a recently prototyped water quality monitoring network [7], comprising fixed sensors spread across a body of water and unmanned surface vehicle (USV) capable of navigating across the water. In this scenario the sensors could periodically receive energy wirelessly from the autonomous craft.

In order for these medium range wireless links to operate efficiently, the sending coil must either be driven at very high frequency, which reduces the efficiency of the power electronics, or lower frequencies can be used if magnetic field shaping is employed using ferromagnetic materials [8]. These materials are heavy, the required fabrication techniques are expensive and the field shaping means that the transmitting and receiving coils must be aligned to achieve high efficiency. These disadvantages mean that the field shaping approach is not particularly suitable for the water quality WSN example. The challenge here, therefore, is to realise a high frequency, cost effective and efficient solution for mid-range inductive power transfer (IPT) for water applications in the absence of field shaping techniques.

This paper provides an overview of IPT theory, simulations and measurements to achieve efficiencies above 90%, for gaps of at least half a metre. Furthermore, fabrication and measurement techniques to achieve coil Q factors above 1,000 are detailed.

HIGH Q INDUCTIVE COUPLING THEORY

Figure 1 shows a basic IPT system, where a driver provides high frequency power to a primary coil with a quality factor Q_1, which couples with a coupling factor of k to a secondary coil having a coupling factor Q_2. Finally the AC voltage on the primary side is rectified and conditioned to provide power to the load.

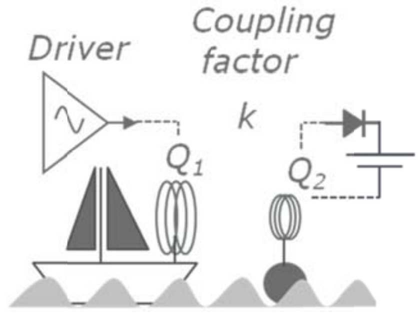

Figure 1 Basic configuration of an IPT system for water monitoring sensor network

It is well known that by using secondary resonance and optimising the load impedance, the link efficiency is maximized and is then given by [9]:

$$\eta = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)^2} \qquad (1)$$

As can be seen from Figure 1 and (1) the key to achieving high efficiency is to maximise $k^2Q_1Q_2$.

The coil Q factor can be maximized by choosing the correct operating frequency [10]. The analysis on the interactions of these key variables using both closed-form mathematical expressions and more detailed numerical modelling in Matlab has yielded the following underlying principles for optimisation.

- The loop radii should be the maximum possible to maximize the coupling factor *k*.
- For a given constraint on loop dimensions there is an optimal frequency, which is approximately the point at which the radiation resistance begins to dominate over the skin-effect resistance.
- The wire radius and the number of turns of the coils should be as large as possible (bearing in mind that the coils should remain electrically small to limit the electric field and hence the radiation).
- In the case when the loops are not of equal size the optimal frequency will be mainly determined by the larger of the two coils.

A. Q factor

The coupling factor, k, is typically around 0.01 for medium range air-gaps (10s of cm), therefore, the Q factor of the coils has to be above 1,000 to achieve high transfer efficiencies above 90%. Achieving these values can be difficult and commercially available coils can only achieve Q factors on the order of a few hundred. The coil Q factor is:

$$Q = \frac{\omega L}{R_{Rad} + R_{Skin}} \qquad (2)$$

where ω is the angular frequency, L is the self inductance of the coil, R_{rad} is the radiation resistance and R_{skin} is the skin-effect resistance. The dominance of the different resistances depends on the size of the antenna and the frequency of operation. Substituting the corresponding equations for L and R_{skin} into (2), gives the expression for Q factor when the ohmic losses dominate, as:

$$Q = \sqrt{2\sigma\omega\mu} \cdot Na\left[\ln\left(\frac{8r}{a}\right) - 2\right] \qquad (3)$$

where N is the number of turns, a is the wire radius and r is the loop radius. When the frequency is high enough for the antenna to start radiating then R_{rad} dominates and the Q factor is as follows, where η_0 is the impedance of free space.

$$Q = \frac{6\mu c^4\left[\ln\left(\frac{8r}{a}\right) - 2\right]}{\eta_0 r^3 \omega^3 \pi} \qquad (4)$$

For this application, it is very likely that the primary and secondary coils are limited to different sizes (the USV coil could be larger than that on the sensor node), and the optimal frequency will be therefore determined by the larger coil. Beyond the frequency at which the radiation resistance begins to dominate the losses of the larger coil, the Q factor of the latter will decrease with ω^3 whilst the Q factor of the smaller coil will increase only with ω.

The Q of the resonant circuit also depends on the Q factor of the capacitor that will be used to tune the coil to the selected operating frequency. The total Q of the resonant circuit:

$$Q_T = \frac{Q_L Q_C}{Q_L + Q_C} \qquad (5)$$

where Q_L and Q_C are the Q factors for the inductor and capacitor respectively.

B. Optimal Load Selection

To optimize the power transfer efficiency, an optimal load impedance has to be selected. To achieve this, analytical expressions were introduced in [2], where the optimal load will vary depending on the selected configuration, of which there are six. The primary can be non-resonant, series resonant or parallel resonant and the secondary can be either series resonant or parallel resonant. A series resonance can only be used if the self-capacitance or parasitic capacitance of the inductor is assumed to be negligible. In contrast, this assumption is not needed in the parallel case, since the resonant capacitor will parallel with the self-capacitance of the coil. Furthermore, the secondary is always assumed to be operating at resonance, since in that mode the equivalent impedance on the primary due to the secondary will be purely resistive, affecting only the damping of the primary. The factor, $\alpha = \omega_0 C_2 R_L$ for a parallel resonant secondary for which Equation (1) is optimal is:

$$\alpha_{opt} = \frac{Q_2}{\sqrt{1+k^2 Q_1 Q_2}} \qquad (6)$$

Using α_{opt} to calculate the optimal load gives:

$$R_L = L_2 \omega_0 \left(\frac{\alpha_{opt}^2 + 1}{\alpha_{opt}}\right) \qquad (7)$$

where L_2 is the self inductance of the secondary.

To further calculate the effect of the load on the damping of the system, the resistance, R_{eq} referred to the primary from the secondary is given in [2], as:

$$R_{eq} = R_P \frac{k^2 Q_1 Q_2}{1+\sqrt{1+k^2 Q_1 Q_2}} \qquad (8)$$

where R_P is the skin-effect and radiation resistance of the primary. This expression is valid for all link configurations

C. Simulation Results

Based on the previous equations Matlab simulations were undertaken to provide a clear understanding of the efficiency that could be reached for the present design. To achieve a higher precision during simulations, a numerical model for skin depth was used. This model was originally explained by

Butterworth in [11] and further described in [12]. Figure 2 shows the efficiency versus frequency for different loop diameters for identical transmit and receive circular cross-section copper coils. The existence of an optimal frequency and the dependence of the efficiency on coil dimensions can be clearly seen.

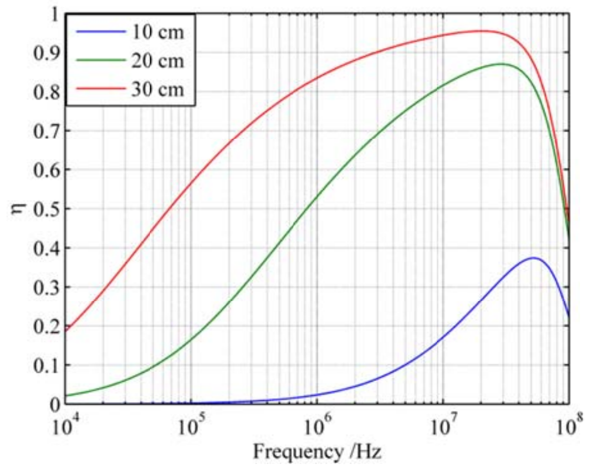

Figure 2 Wireless transfer efficiency versus frequency for coils of 2 turns, with different loop diameters, at a distance of 50 cm and a wire diameter of 1 cm.

Graphs of efficiency vs. distance were plotted to investigate how the efficiency would vary with different air-gaps. Figure 3 illustrates that the efficiency drops rapidly with distance and provides a clear indication of the air-gap over which this technology can be effectively employed for coil diameters in the low 10s of cm. This data prompts the use of a maximum air-gap between 40 and 60 cm for efficiencies over 90% for coils < 30 cm diameter.

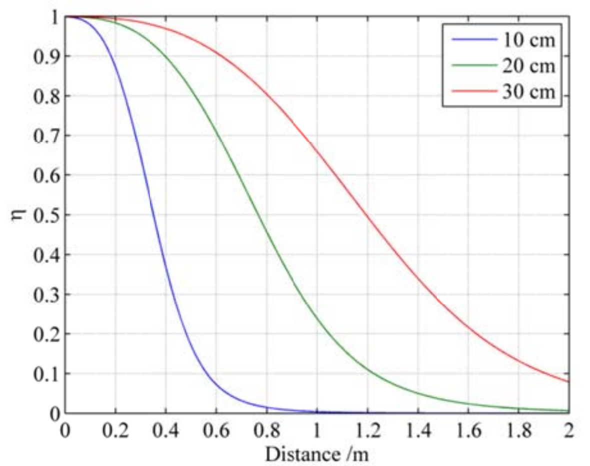

Figure 3 Wireless transfer efficiency versus distance at a frequency of 10 MHz for coils of 2 turns, with different loop diameters, and a wire diameter of 1 cm.

Once the operating distance was defined, a set of simulations had to be performed to account for the intrinsic size limitations of the USV and the sensor node. Several coil size combinations were simulated and are presented in Figure *4*. This figure shows how the optimal frequency is determined mainly by the electrical size needed to maximise the Q of the largest coil. When the secondary coil size is constrained, this figure shows that the link efficiency can still be improved by increasing the primary coil diameter and tuning the operating frequency.

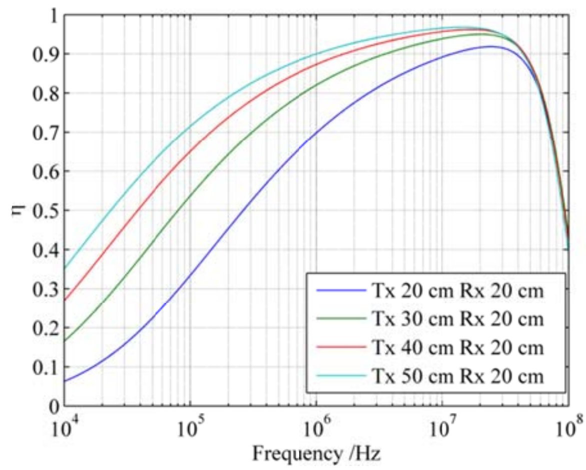

Figure 4 Wireless transfer efficiency versus frequency for different transmitter (Tx) coils sizes with a fixed receiver size (Rx). The transmit coils had 3 turns and the receive coils had 5 turns, with different loop diameters, at a distance of 50 cm and a wire diameter of 1 cm.

Given the size constraints, the selected sizes for our water monitoring application are 30 cm and 20 cm for transmit and receive coils 30 and 20 cm respectively. With these sizes, efficiencies above 90% can be achieved above ~3 MHz.

The primary driver needs a switch that can handle high frequency and high current to be able to transmit enough power to achieve a 100 W on the secondary side. Commercial off- the-shelf MOSFETs with these characteristics can be found with a maximum switching frequency of approximately 10 MHz.

MEASUREMENT SETUP AND RESULTS

A. Test Fixture

To prove that Q factors above 1,000 could be achieved and that simulations results reflect reality, Q measurements were undertaken for the resonating primary and secondary. Furthermore, a proof-of-concept in terms of the coil design was needed to see if a cost effective solution of building coils from copper piping could yield good results, alleviating the need for expensive Litz wire fabrication.

To measure the Q-factor through transmission coefficient measurements, two loosely inductive coupled coils were used as the measuring probes. To avoid carrying the insertion loss error, as described by Kajfez *et al.* [13], two conditions had to be met. First, the return loss of both measuring probes had to be the same, ensuring that the coupling coefficient from the probes to the coil was the same. To achieve this, careful considerations of the test setup had to be taken into account, ensuring that the mechanical tolerances of the test setup were the same for both probes. Second, the coupling between the probes and the coil had to be very small, *i.e.* the coupling had to be small enough so that the insertion loss at the resonant frequency was well below unity, meaning that the coil was absorbing negligible energy.

The complete test fixture was fabricated using Perspex, to avoid the generation of eddy currents that would provide inaccurate measurements. Coil spacers between turns were used to maintain a distance of 2 cm between the centres of the pipe. This helped to reduce the proximity effect between turns.

Figure 5 shows the test fixture for measuring the coil's Q factor and, furthermore, the transmission of wireless energy at different distances and alignment angles, in order to emulate real life situations on water prior to the deployment of the setup.

Figure 5 Misaligned 3 turn (left) and 2 turn (right) 30 cm diameter coils.

B. Measurement Results

Q factor measurements were conducted for several coils with copper piping having a 1 cm cross-sectional area and a 1 mm wall thickness. An array of high Q capacitors was used in parallel with the coil, to tune the operating frequency and conduct measurements at different frequencies. Figure 6 shows measurement results for a 3 turn 30 cm diameter coil.

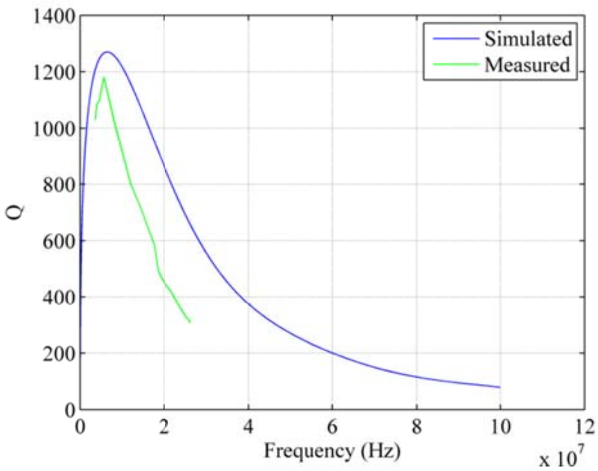

Figure 6 Simulation and measurement results of Q vs. f for a 3 turn 30 cm diameter coil.

A reasonably good agreement between measurements and results was realized for different coil configurations, having taken great care in setting up the experiment considerations for the test. The mismatch between measurements and simulated results is mainly due to the fact that the Q of the tuneable air capacitors was only available for the highest rated values. While the capacitor value was changed, the Q was also modified. In addition, even though rigorous procedures were taken, to ensure that both probe coupling factors remained as equal as possible, it is likely that the mechanical characteristics of the cables, *e.g.* the sagging of the cables between the output ports of the series network analyser and the probes, may be enough to increase the precision error, as described in [13].

CONCLUSIONS

Resonant tank Q factors above 1,000 have been simulated and measured for a medium range wireless power transfer system. The results and the measurement techniques shown in this paper provide a design framework to achieve efficient inductive links with an air-gap of more than 50 cm. Furthermore, coil and test fixture fabrication procedures were conducted to achieve low cost and reproducible designs that will help to potentially commercialize this technology for aquatic wireless sensor networks.

ACKNOWLEDGMENTS

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