Design of an Inductive Power Transfer System with Flexible Coils for Body-worn Applications

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Abstract. This paper describes an IPT (Inductive Power Transfer) system for body worn electronics, and investigates the challenges for an IPT system that arise specifically in this scenario. Principally, these are: highly variable coil coupling through time-varying miss-alignment and coil separation; a requirement that one or both of the coils must be wearable and thus flexible; and proximity to the human body introducing limits on the maximum EM field. The highly variable coupling results in a system that must operate effectively with a large range of received powers, whilst the constraints on the realisation of the coils typically reduce the Q-factor; the human exposure considerations limit both the maximum field strengths that the wearer of a receiver coil might experience, and also the field strengths that a 3rd party might be exposed to, for instance when approaching the transmit coil.

1. Introduction

Wireless power transfer is commonly implemented using inductive coupling to transfer power between transmit and receive coils, this is commonly known as inductive power transfer (IPT) [1], or ‘near-field transfer’. Near-field IPT systems operate at frequencies determined by the desire to make both transmit and receive coils electrically resonant, and with power levels and transmission ranges typically of the order of watts over 10’s cm range. In this paper IPT for body-worn sensors is considered, and hence the maximum power and maximum coil separation distance is limited by regulations governing the maximum magnetic field strength to which a person might be exposed. In an illustrative scenario the transmit coil is integrated within a chair arm (fig. 1a), and the receive coil is worn on the body, for instance as part of a wrist mounted health sensor (fig. 1b).

The power transfer between the coils of an IPT system is highly dependent on the magnetic coupling between them, which in turn is sensitive to distance and relative orientation of the coils and hence the dynamic body-worn scenario is challenging: if the system is designed for the peak coupling it may ‘brown-out’ for long periods; if it is designed for the lowest coupling then there will be periods when significant excess power must be dissipated. Additionally when one or both of the coils are flexible, a further degree of freedom is introduced as they can deform, affecting coupling and inductance – key parameters in determining the operation of resonant coils. Flexible coils present their own challenges, particularly as it is more difficult to obtain both flexibility and the low coil resistance required for a high quality factor, which is important in maximising power transfer in a resonant system.
2. System operation

2.1. IPT fundamentals

The doubly-tuned transformer, which forms the basis of most IPT systems, is shown in fig. 2, and is well-described in the literature, e.g. [3,4]. The circuit comprises primary and secondary coils with inductance \( L_p, L_s \) and parasitic resistance \( R_{cp}, R_{cs} \) coupled by their mutual inductance \( M \). Both coils are tuned to resonate at the desired frequency by their respective tuning capacitors: forming the coils into resonant circuits helps to mitigate the effects of reduced magnetic coupling due to higher separations and the absence of a high permeability flux path, compared to iron cored transformers [5].

Assuming both primary and secondary are tuned to resonate at the drive frequency, \( \omega \), and using standard circuit theory it can be shown that:

\[
P_{RL} = \frac{(\omega L_p M Q_s)^2}{R_L} \tag{1}
\]

Where \( Q_s \) is the secondary circuit quality factor and \( M \) is the mutual inductance, which at critical coupling (peak power) is given by:
\[ M = \frac{\sqrt{\frac{R_C (R_L' + R_C)}}{\omega}} \] (2), and the primary current by: \[ I_p = \frac{V_p}{R_C + \frac{(\omega M)^2}{R_C + R_L}} \] (3)

Where: \[ R_L' = \frac{1}{(\omega C_3)^2 R_L} \] (4)

2.2. Coupling between coils

The coupling between primary and secondary coils can be described by a coupling factor, \( k \), a dimensionless number between 0 and 1, defined by equ. 5. Coupling factor is equal to 1 if the secondary coil couples with all of the flux generated by the primary coil.

\[ k = \frac{M}{\sqrt{L_p L_s}} = \frac{V_{SEC}}{V_{PRI}} \sqrt{\frac{L_p}{L_s}} \] (5), where \( V_{PRI} \) & \( V_{SEC} \) are primary and secondary coil voltages.

The coupling between coils is highly sensitive to separation and alignment, however modelling the variation is not trivial, and mathematical derivations do not yield simple analytical expressions. The majority of authors thus rely on empirical or numerical results and an understanding of qualitative effects. The variation in coupling factor between two pairs of coils, experimentally measured, is shown in fig. 3a, coupling between the two flexible TX coils and a TX/RX pair is shown for contrast; the larger flexible pair give better coupling but would not physically fit in the application.

![Coupling factor and load voltage frequency response](image)

Figure 3. Coupling factor \( k \) and load voltage frequency response against coil separation.

A second important effect of a varying coupling factor is seen in the frequency response function of the coupled-tuned system. This effect is illustrated in fig. 3b, and is significant for IPT systems that have variable coupling (as we consider in this paper) since this forms an additional factor modulating the transmitted power with coil separation. This is further illustrated in fig. 4, which shows the locus of the peak in frequency response as the coil separation (hence coupling factor) changes. The bifurcation represents the critical coupling condition, described in section 2.1.

3. System Design

3.1. Choosing parameters

Choosing the coil geometry, and electrical parameters for an IPT system is somewhat of an iterative process, constrained by the particular application. Because the coil often must be resonant with a high Q, coils geometry feeds into the choice of operating frequency, but EM emission and human exposure...
regulations, and topology of drive also strongly influence these design decisions. Often the Q of coils will rise with frequency, indicating efficient operation in the MHz or above region, however higher frequencies require a move from hard-switching drive electronics to resonant approaches.

To ensure human EM exposure limits are not exceeded, the TX coil current in this paper is set such that the resultant magnetic field complies with a Specific Absorption Rate (SAR) of 2W/kg for the set head/trunk by the International Commission on Non Ionizing Radiation Protection (ICNIRP) [6], which, to the authors’ knowledge, are the most stringent. At the thermal limit of the flexible coil (2 Amps) the SAR limit is reached at approximately 1MHz.

3.2. Coils

The prototype coil illustrated in fig. 1a, is formed from flexible wire embroidered onto a light canvas backing: 10 turns of 7 x 0.07 mm PTFE-insulated wire, with a diameter of 90mm, produce an inductance of approximately 9.8 µH and a d.c. resistance of 1.2 Ω. The quality factor of the coil i.e. \( \omega L/R \), where \( R \) is the coil resistance at that frequency, and a.c. resistance is shown in fig. 5.

The 12µH rectangular receive coil, fig. 1b, is formed from 10 turns of 36 x 0.04 mm wire, the overall size of 25x47mm is determined by the enclosure for the wrist electronics. The coil is wound to maximize the turn-area product and thereby the induced voltage. The quality factor and resistance of the coil is also shown in fig. 5.
3.3. Drive and load electronics

Two drive topologies are described in this paper: the first is a fixed frequency Class D half-bridge of MOSFET circuit; the second is a self oscillating drive which tracks the peak in frequency response as the coil separation changes. The circuits were tested with several frequencies in the range 0.5-1MHz, the upper limit being determined by human exposure limit at the peak coil current.

The goal of the self oscillating drive is to maximise the range of coil separations over which the IPT system can usefully operate, but it does so at the expense of being frequency-wild. In both cases the receiver side circuit is a peak rectifier circuit formed from a full bridge of 1N5818 diodes.

4. Experimental results

Fig 7 shows two of the most illustrative test results. In both tests the TX coil drive voltage was set to produce the maximum (2 A) current when the RX coil was at a significant distance; fig. 7a shows the variation in load power as the coils are brought together; fig. 7b shows the primary current variation. Critical coupling (set by load resistance, see equ. 2) occurred a separation distance of 45mm – a compromise to achieve best power transfer over the widest range of separations in the fixed frequency case. The self-oscillating circuit was able to improve upon this performance at close separation.

5. Conclusions

IPT system-design trades off many design parameters, especially when performance must be persevered against dynamic changes in separation. The adaptive frequency self-oscillating drive shows potential in this respect.

References

[1] Hubregt J. Visser. Aspects of Far-Field RF Energy Transport. Proceedings of the 42nd European Microwave Conference.
[2] S. Y. R. Hui, Wenxing Zhong, and C. K. Lee. A Critical Review of Recent Progress in Mid-Range Wireless Power Transfer, IEEE Transactions on Power Electronics, Vol. 29, No. 9, September 2014
[3] Terman F. E. Electronic and Radio Engineering. McGraw-Hill Book Company Inc. 1955. pp 63-70.
[4] Albert A.L. Radio Fundamentals. McGraw Hill Book Company Inc. 1948. pp 101-108.
[5] General Analysis on the Use of Tesla’s Resonators in Domino Forms for Wireless Power Transfer. Wenxing Zhong, Chi Kwan Lee, S. Y. Ron Hui. IEEE Transactions on Industrial Electronics, Vol. 60, No. 1, January 2013
[6] ICNIRP guidelines for limiting exposure to time-varying electric and magnetic fields, Health Physics, vol. 74, no. 4, pp. 494–522, April 1998.