

Design of loosely coupled inductive power transfer systems

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Abstract: A design methodology for loosely coupled inductive power transfer systems is proposed. Such systems are used for non-contact power transfer, often over large airgaps to moving loads. Due to the large leakage inductances that result, compensation is usually necessary to achieve the required power transfer capability. The level of compensation, as well as possible compensation topologies, are discussed in the paper. Special attention is paid to the tradeoffs involved during the design process.

Keywords: Electromagnetic induction, electromagnetic coupling, inductive power transfer, inductive transmission, design.

I. INTRODUCTION

Inductive power transfer (IPT) systems are defined as systems where energy is transferred from a primary winding to a secondary winding using an alternating magnetic field. Such systems can be divided into two categories, namely closely coupled IPT systems and loosely coupled IPT systems.

Closely coupled IPT systems are systems where the magnetic coupling between the primary and the secondary is very good. These would be systems where the leakage inductances are small relative to the magnetising inductance in the system. Such systems are very common in the power systems arena where transformers of all shapes and sizes are used to transform power from one form to another.

Loosely coupled systems, on the other hand, are systems where the magnetic coupling between the primary and the secondary is poor. In these systems the leakage inductances are usually much larger than the magnetising inductance. Such systems usually result due to mechanical constraints of the application, in many cases there would be a requirement that the secondary must be able to move relative to the primary with no physical contact between the two. Examples of such systems are non-contact vehicle battery charging [1-3], roadway powered electric vehicles [4,5], sliding transformers [6], robotic applications [7-8], contactless energy transfer in wet or hazardous environments [9], and underwater power transfer [10]. Few such systems exist in practice due to the difficulty in transmitting power effectively, but with the recent improvements in power electronic technologies this is about to change.

Designing closely coupled systems is a well-known procedure. Designing loosely coupled IPT systems, however, can be a daunting task. Many design examples have been described in the literature [4,9], but no generalised design procedure explaining how to go about designing a complete system has been found. In this paper a design methodology is proposed to deal with the additional complexities of loosely coupled systems. The main objective is to optimise a system

with a controllable power transfer capability over a specified operating range.

The paper is by no means comprehensive and assumes that some major design parameters are known. One such parameter is the operating frequency, which has a major effect on the power transfer capability of any inductively coupled system.

II. STRUCTURE OF IPT SYSTEMS

Fig. 1 shows a generalised structure of an IPT system. The blocks in solid lines are common to both closely coupled and loosely coupled systems, while the blocks in dotted lines are found only in loosely coupled systems. Because of the large leakage inductances of the primary and secondary windings in loosely coupled systems, compensation of the windings is usually necessary for efficient power transfer. As a result, loosely coupled IPT systems tend to be more complex than closely coupled systems.

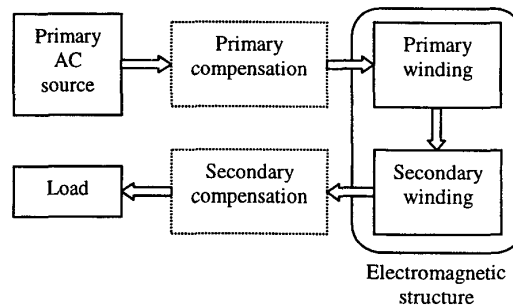


Fig. 1. Block diagram showing components of inductive power transfer systems.

With closely coupled systems such as transformers, the voltage across the primary winding determines the flux in the magnetic core. To utilise the core fully, the primary is usually operated at rated voltage corresponding to rated flux density, with the current is a function of the load.

With loosely coupled systems, the primary often does not use a magnetic core in order to minimise cost. Since there is no closed magnetic core, a major portion of the magnetomotive force will be situated across a substantial airgap. In such cases it is advantageous to fully utilise the primary by operating at the rated current of the coil, and letting the voltage vary as a function of the load. The primary power source thus needs to supply a controlled current to the primary coil or track.

Fig. 2 shows the main parameters of a loosely coupled IPT system.

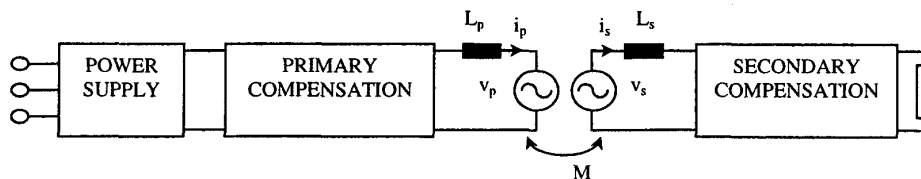


Fig. 2: Main parameters in a loosely coupled IPT system.

To differentiate between primary side and secondary side parameters, subscripts p and s are used respectively. A power supply energises the primary coil or track with a sinusoidal current with frequency ω and amplitude i_p .

The fundamental equations governing power transfer are given by

$$v_s = j\omega M i_p \quad (1)$$

and

$$v_p = j\omega M i_s \quad (2)$$

with v_s the induced voltage in the secondary due to the primary current i_p , v_p the feedback voltage due to the current in the secondary i_s , ω the frequency of operation, and M the mutual inductance between the primary and the secondary.

The primary leakage inductance is shown as L_p , while the secondary winding has a leakage inductance L_s associated with it. These leakage inductances are large, and tend to dominate the power transfer capability.

III. COMPENSATION

The concept of leakage inductance compensation is not new and is regularly used in power systems applications. Common examples include the use of power factor correction capacitors or series compensation of long transmission lines. In power systems, however, the reactive power is generally less than the active power transferred, while in loosely coupled systems the compensation level can be up to 50 times the transmitted power.

When compensating for the leakage inductances, two choices need to be made. Firstly the compensation topology has to be decided on, and secondly the level of compensation needs to be determined.

A. Compensation topology

There are two basic compensation topologies, namely series compensation and parallel (shunt) compensation. With series compensation, a compensation capacitor is placed in series with the primary or secondary leakage inductance, whereas with parallel compensation the compensation capacitor is placed in parallel with the primary or the secondary. Adding the uncompensated case, there are thus three basic topologies for both the primary and the secondary, and a total of nine basic topologies thus exist for the complete system. These nine topologies are shown in Fig. 3.

Secondary compensation has been discussed in detail [3]. Series compensation results in a secondary that has voltage source characteristics, and is well suited for systems that have an intermediate DC bus [11]. Parallel compensated secondaries have current source characteristics and are well suited for applications such as battery charging [1, 3].

Primary compensation depends very much on the application. With long track applications, the track voltage becomes very high. Series compensation becomes very attractive as the power supply voltage can then be reduced to manageable levels [6]. Applications with a concentrated

Primary \ Secondary	Uncompensated	Series compensated	Parallel compensated
Uncompensated			
Series compensated			
Parallel compensated			

Fig. 3. Compensation topologies.

primary coil often require large primary currents, making parallel compensation more attractive [12].

B. Compensation level

The level of compensation can be easily quantified by the quality factor of the resulting resonant circuit. The quality factor can be visualised as the ratio between the reactive power in the circuit and the active power transferred. If both the primary and the secondary are compensated, there will be two quality factors, Q_p being the primary quality factor and Q_s the secondary quality factor. These can be calculated as

$$Q_p = \frac{\text{VAR}_p}{P}, \quad (3)$$

and

$$Q_s = \frac{\text{VAR}_s}{P}. \quad (4)$$

with VAR_p and VAR_s the reactive powers of the primary and secondary respectively.

For the secondary, a larger Q_s results in an increased power transfer capability at the expense of a higher secondary VA rating. The choice of Q_s is an important design parameter and will be discussed in more detail in section VI. Typical values of Q_s in practical circuits range from about 2 to about 10.

The primary quality factor depends on the geometry of the primary and the required primary current. Q_p can vary considerably with different design approaches, and typical values lie between 2 and 50.

The ratio of Q_p to Q_s is very important, and may be grouped into one of three categories namely $Q_p \gg Q_s$, $Q_p \sim Q_s$, and $Q_p \ll Q_s$. From a stability point of view, it is preferable that $Q_p \gg Q_s$, but this does not always result in the most cost-effective design. The trade-offs involved are elaborated in section V.

IV. PERFORMANCE OF THE ELECTROMAGNETIC STRUCTURE

One of the difficulties in designing loosely coupled systems has been the lack of simple, easy to use parameters that combine the performance of the electromagnetic design with that of the electrical design. In loosely coupled systems there is always a trade-off between the electromagnetic and the electrical design, the poorer the electromagnetic design, the more difficult the electrical design becomes and vice-versa. To further complicate the issue, it is possible that the same electromagnetic geometry can have a nominal output power falling over a wide range depending on the electrical design of the system.

To solve this problem, a system is proposed for specifying the rating of a given secondary in terms of two parameters, namely the VA rating of the secondary (S_s), and the transfer impedance of the secondary (Z_{transfer}). These two parameters are discussed in more detail below.

A. Secondary VA rating

The VA rating of the secondary is the product of the secondary current and the secondary voltage ratings. The current rating is determined by the secondary winding losses,

and at rated current the winding temperature has to be within acceptable temperature limits. The secondary voltage rating is determined by core losses, and at rated voltage the core temperature has to be within acceptable temperature limits. In addition, total secondary losses at rated voltage and current may not result in unacceptably high temperatures.

The VA rating is purely a function of the geometry and material properties of the secondary, and is independent of the compensation topology or compensation level. It is, however, a function of frequency, with the VA rating of a given geometry typically increasing with frequency.

B. Transfer impedance

The transfer impedance (Z_{transfer}) gives a measure of the ability of the electromagnetic structure to transfer power, and is a function of the geometry and materials used. It is defined as

$$Z_{\text{transfer}} = \frac{V_{\text{oc}} * I_{\text{sc}}}{i_p^2} \quad (5)$$

where:

i_p is the primary current,

V_{oc} is the open circuit voltage at the primary current i_p , and

I_{sc} is the short circuit current at the primary current i_p .

The secondary open circuit voltage and short circuit current are two parameters that are easy to measure, but form an important part of the design process. It is not necessary to build a full-scale secondary to do the measurement, a simple test coil with the same number of turns as the secondary will suffice. The only prerequisite is that the resistive impedance of the test coil is low compared to the inductive impedance, as the measured short circuit current will otherwise be less than in the final design.

It is also possible to determine the $V_{\text{oc}} * I_{\text{sc}}$ product by using an electromagnetic simulation package. Since the operating frequency is generally in the tens of kHz region, electromagnetic analysis is still very difficult, requiring fine meshes to calculate induced eddy currents.

The transfer impedance is a direct measure of how effectively the electromagnetic structure can transfer power. It can be used to compare different electromagnetic designs, with a larger transfer impedance corresponding to a better design. Usually the transfer impedance will change if there is mechanical movement between the primary and the secondary, and in this case the transfer impedance needs to be specified as a function of position.

V. STABILITY CONSIDERATIONS

One of the most important design checks is to ensure that the system will be stable under all load conditions. Systems with primary and secondary compensation are inherently fourth order systems, and under certain conditions demonstrate the phenomenon of bifurcation. This phenomenon has been discussed [1,13] and the conditions under which it will occur have been presented. A simplistic rule is that if the primary quality factor (Q_p) is much larger than the secondary quality factor (Q_s), the system will generally exhibit stable

characteristics, whereas with $Q_s > Q_p$, a thorough system stability analysis will need to be undertaken.

The power supply characteristics play an important role in this analysis. For variable frequency power supplies, power transfer can be controlled by controlling the operating frequency. The controllers used in these supplies are usually very sensitive to the slope of the phase between the power supply voltage and current, and since this slope changes during bifurcation the power supply can become unstable.

With fixed frequency power supplies, the problem becomes one of actually being able to transfer the power. The power transfer characteristics of the secondary are a function of frequency, and for compensated secondaries with high quality factors, a frequency deviation of only a few percent off the resonant frequency will cause the power transfer capability to drop drastically. A complete analysis falls outside the scope of this paper, but a model has been developed to determine the extent of the interaction between the secondary and the primary [14].

VI. DESIGN METHODOLOGY

A. Assumptions

Due to the complexity involved in the design procedure of loosely coupled systems, it is necessary to make some assumptions. One important assumption is that the operating frequency is known. The choice of frequency involves a trade-off between the cost and complexity of the power supply, and the power transfer capability of the electromagnetic structure.

The power transfer capability of any IPT system is a strong function of operating frequency. In theory, the relationship is linear, but secondary effects such as skin and proximity effects, as well as increased core losses, result in a less than linear power increase with frequency. The cost and complexity of the power supply will, on the other hand, increase with increasing frequency. An iterative process is necessary to determine the most cost-effective frequency.

With the current state of power electronic technology, the most economic power transfer frequencies are in the order of 10kHz to 100kHz for multi-kilowatt systems [1-2,6], and even higher at lower powers [9]. These frequencies are bound to move up as the technology improves.

The design of both closely and loosely coupled systems will be discussed using flowcharts. One glance at the flowcharts gives a good indication of the complexity of the design of loosely coupled systems compared with closely coupled systems.

B. Design methodology for closely coupled IPT systems

The flowchart shown in Fig. 4 shows a simplified design methodology for a closely coupled IPT system such as an ordinary transformer. The main parameter in the design is the choice of the magnetic core, and an iterative process is followed that results in the optimum core size.

For a given core geometry, the winding parameters are calculated. If the winding does not fit on the core, a larger core must be chosen. If the window area is underutilised, a smaller core may be used.

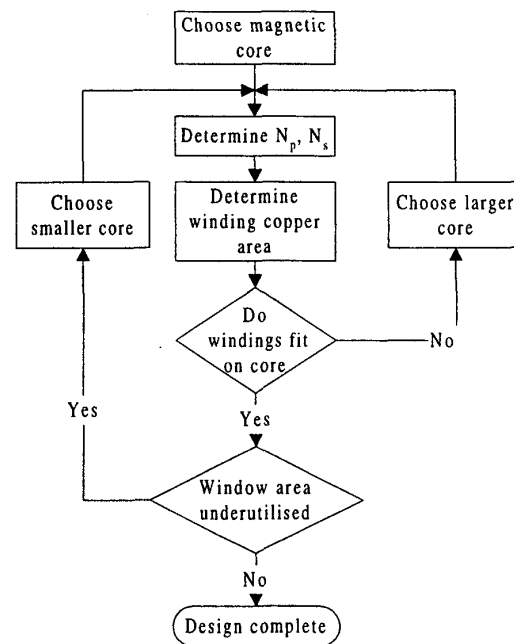


Fig. 4. Design of a closely coupled IPT system.

C. Design methodology for loosely coupled IPT systems

The flowchart shown in Fig. 5 shows the design methodology of a loosely coupled IPT system. A number of choices need to be made along the way, influenced mainly by the cost distribution of the various components in the system.

The design process starts off with the choice of an electromagnetic structure. Where the structure for a conventional transformer is limited to available magnetic cores, the possibilities for loosely coupled systems are virtually unlimited. Systems of all shapes and sizes have been built, and there is little substitute for experience in making a good first choice.

The next step is to choose a primary current. As explained earlier, loosely coupled systems are best driven by a current source, and the level to this current needs to be chosen. Since the cost of the primary is a strong function of this current, the first choice should be to choose a low current. If the system cannot transfer the required power, the current can progressively be increased.

It is now necessary to determine the $V_{oc} \cdot I_{sc}$ product of the electromagnetic structure using the chosen primary current. This can be done either by measurement or by an electromagnetic analysis as explained earlier in section IV.

Once the $V_{oc} \cdot I_{sc}$ product is known, the secondary compensation can be determined. It has been shown [3] that the maximum power transfer capability of an uncompensated secondary is equal to $(V_{oc} \cdot I_{sc})/2$. If the power to be transferred exceeds this amount, the secondary needs to be compensated. The quality factor of the compensation circuit can be calculated as

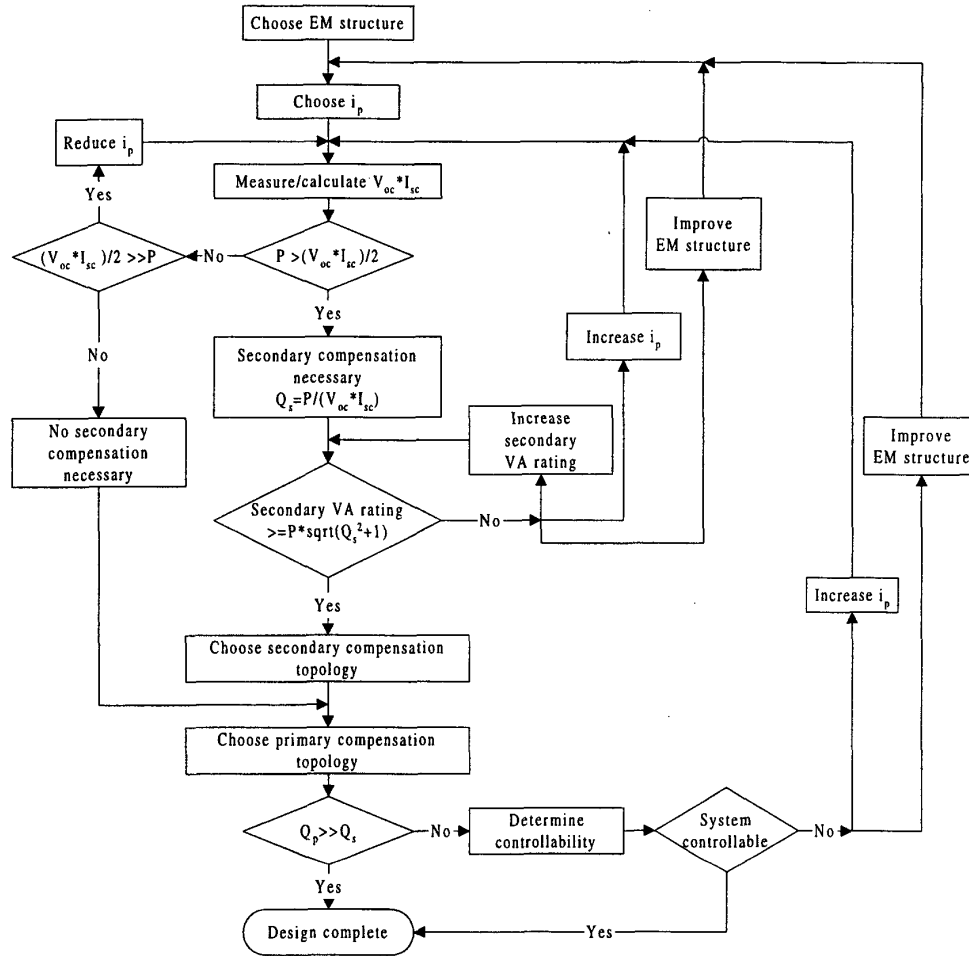


Fig. 5. Design of a loosely coupled IPT system.

$$Q_s = \frac{P}{V_{oc} * I_{sc}}, \quad (6)$$

with P the power to be transferred. Knowing the quality factor, the required VA rating of the secondary (VA_s) can also be determined [3] as

$$VA_s = P * \sqrt{Q_s^2 + 1}. \quad (7)$$

If the actual VA rating of the secondary is more than this value, the system will be able to transfer the required power. If not, the chosen configuration will not be able to transfer the required power, and the design has to be modified to increase the power transfer capability. There are three ways to do this, namely

- Increasing the VA rating of the secondary by adding more copper or magnetic material,
- Increasing the primary current, or
- Improving the coupling of the electromagnetic structure (increasing the transfer impedance).

The first option increases the cost of the secondary, the second option increases the cost of the primary, and the third

option increases the cost of the interconnecting structure. To optimise the system design, the option with the highest benefit to cost ratio needs to be chosen.

If the performance falls far short of the specification, it might be necessary to do a few iterations before the design results in the VA rating of the secondary being equal to or greater than $P * \sqrt{Q_s^2 + 1}$. Only when this point is reached will the system be able to transfer the required power.

The secondary compensation topology can now be chosen. The best choice of topology will be determined by the application. Parallel compensation, which results in a current source output, is well suited for applications such as battery charging. Series compensation, on the other hand, is well suited for systems that have an intermediate DC bus, such as most modern variable speed AC drives.

The design of the secondary is now complete, and it is time to move over to the primary. Since the geometry of the primary is known and the primary current has already been determined, the voltage across the primary can be calculated.

The primary VA rating can thus be determined, as well as the primary quality factor Q_p .

The choice of primary compensation topology again depends on the application. Series compensation is well suited for systems with long primary tracks, with compensation capacitors placed in series along the track. This allows track voltages to be managed within the maximum allowable limits. Parallel compensation is better suited for concentrated windings, as these are usually high current systems. A single capacitor at the terminals of the coil is used.

It is, however, not of much use being able to transfer the power if it cannot be controlled. Here the system stability needs to be investigated further. As discussed in section V, a stability analysis needs to be undertaken if Q_p is not much larger than Q_s . If $Q_p \sim Q_s$, increasing the primary current slightly will increase Q_p while at the same time reducing Q_s , and might be the cheapest means of ensuring system stability.

The design shown above assumes a known frequency. When starting a completely new design, the optimum frequency is usually unknown. In certain cases, regulatory limits would determine a logical choice of frequency, eg the requirement in Japan for systems to run below 10kHz in order to be exempt from radio licensing. In most other applications, an iterative process is necessary to determine the optimum operating frequency. This process would form an outer loop around the flowchart shown in Fig. 5. An increase in frequency would allow an increased power transfer capability for a given electromagnetic structure, but the cost to be paid would be in the form of a more expensive power supply.

VII. CONCLUSION

The design of loosely coupled inductive power transfer systems is really an exercise in trade-offs. The biggest trade-off is between the performance of the electromagnetic structure, and the level of complexity of the electrical design. Good electromagnetic performance, which means that the coupling should be as good as possible, is essential for a low cost system.

In many systems, mechanical considerations make good coupling impossible. In these cases, the trade-off becomes one of the cost of the primary versus the cost of the secondary. Economic considerations thus end up playing a major role in the system design.

It is important that system controllability is checked before the design is concluded. Systems with a secondary quality factor larger than the primary quality factor are very difficult to control, and in these systems the costs will be biased toward a cheaper secondary and a more expensive primary.

VIII. REFERENCES

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IX. BIOGRAPHIES

Oskar Stielau received his B.Eng, M.Eng and D.Eng degrees at the Rand Afrikaans University in Johannesburg, South Africa in 1986, 1988 and 1991 respectively. He then spent five years working as an engineer at ISCOR, Vanderbijlpark and two years as a consultant in the induction heating field. He currently leads the research group on inductive power transfer at the University of Auckland in New Zealand.

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