Design of New Contactless Power Supply System

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Abstract

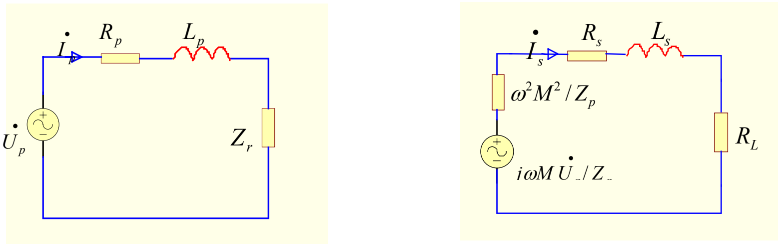
A design method for new contactless power supply systems is proposed. Such systems realize contactless power supply to electrical apparatus, which may keep still or moving relative to the power source. Optimized electric parameters are determined to maximize the power transfer capability. Secondary compensation may be taken to further improve the power transfer characteristics. The applicability for two basic compensation topologies is analyzed. Two possible magnetic structures are presented and compared in respect of coupling coefficient.

1 Introduction

New contactless power supply system realizes power transmission from the primary to the secondary with no physical connection between them by inductive coupling technique [1]. The secondary may keep still or moving relative to the primary. Such systems can be used for non-contact battery charging, robotic applications, contactless energy transfer in wet or hazardous environments, and so on [1]. Due to the loosely coupled characteristics the design of the new contactless power supply system is quite complicated. How to maximize the power transfer capability and fully utilize the system at given load conditions is a big problem. Many design examples or methods have been described in [7,8], but no generalized design method has been given on how to determine all the electrical parameters. The output power and transmission efficiency are two most important performance parameters. According to these two respects this paper presents a design method for this system. And related tradeoffs have been considered.

2 Performance of New Contactless Supply System

In this system the leakage inductance is comparable to the magnetizing inductance, and may be even much more than the magnetizing inductance. According to the conventional transformer model, the magnetizing and leakage inductance must be separated for circuit analysis with the leakage inductance not to be neglected. To simplify the analysis, the mutual inductance model is employed. The equivalent circuits of the primary and secondary are as shown in Fig.1. The primary is driven by high frequency sinusoidal voltage U_p. The frequency is ω. The resistance and inductance values of both sides are respectively R_p, L_p, R_s, L_s. M is the mutual inductance. R_L is the load resistance. Litz wires are assumed for both primary and secondary windings. Z_r is the reflected impedance and can be given as follows:



(a) Primary circuit (b) Secondary circuit

Fig. 1. Equivalent circuits of primary and secondary

$$Z_r = R_r + jX_r = -j\omega M \dot{I}_s / \dot{I}_p \tag{1}$$

The primary and secondary resistances are low compared to their respective reactance and are often omitted in the analysis. The output power for the load resistance is

$$P = \frac{k^2 U_p{}^2 R_L / L_p}{\omega^2 (1-k^2)^2 L_s{}^2 + R_L{}^2 / L_s} \tag{2}$$

The output power reaches its maximum when the secondary inductance meets the following equation:

$$L_s = \frac{R_L}{\omega(1-k^2)} \tag{3}$$

The maximum power is

$$P_m = \frac{k^2 U_p{}^2 / L_p}{2\omega(1-k^2)} \tag{4}$$

To increase the power transfer capability, the primary inductance should be minimized. For given magnetic structure, the optimal primary should have one turn.

3 Secondary Compensation

With secondary compensation, both the output power and transmission efficiency can be greatly improved. Secondary compensation topology can be selected according to specific application. There are two basic compensation topologies for secondary compensation, namely series compensation and parallel compensation. The change ratio of output power after compensation can be given as:

$$\Delta P = \frac{P_c - P}{P} \tag{5}$$

Among which, P_c is the output power after compensation.

For series resonant compensation $\Delta P = \frac{\omega^2 (L_s L_p - M^2)^2}{L_p{}^2 R_L{}^2}$ (6)

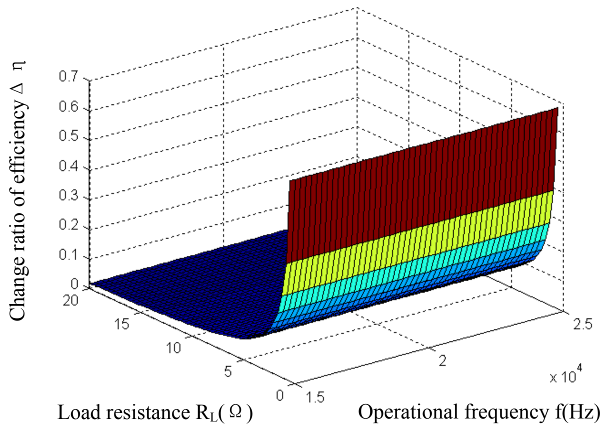
For parallel resonant compensation $\Delta P = \dfrac{L_p{}^2 R_L{}^2}{\omega^2 (L_p L_s - M^2)^2}$ (7)

From the two equations above, it can be seen that series compensation is more effective for small load resistance, while parallel compensation is more fit for large load resistance.

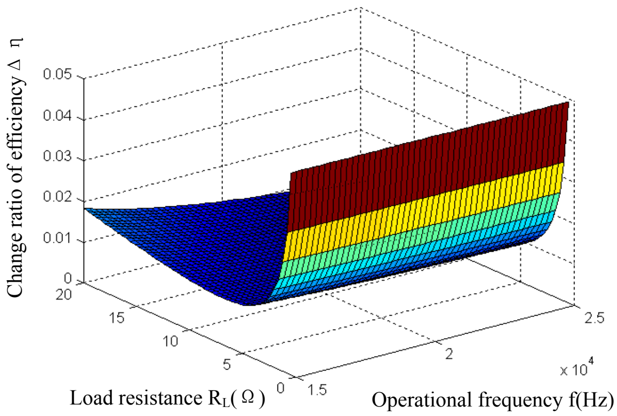
The change ratio of efficiency after compensation can be given as:

$$\Delta\eta = \frac{\eta_c - \eta}{\eta} \tag{8}$$

The expressions for series and parallel compensation are very complicated and will be different for air core transformer and iron core transformer. Fig.2 (a), (b) respectively shows the curve for series and parallel compensation with load resistance and operational frequency in variation. No core loss is assumed for both curves. For series compensation, efficiency can be improved more with smaller resistance. The efficiency is less improved for parallel compensation. The extent of improvement is influenced by the specific parameters.



(a) series compensation

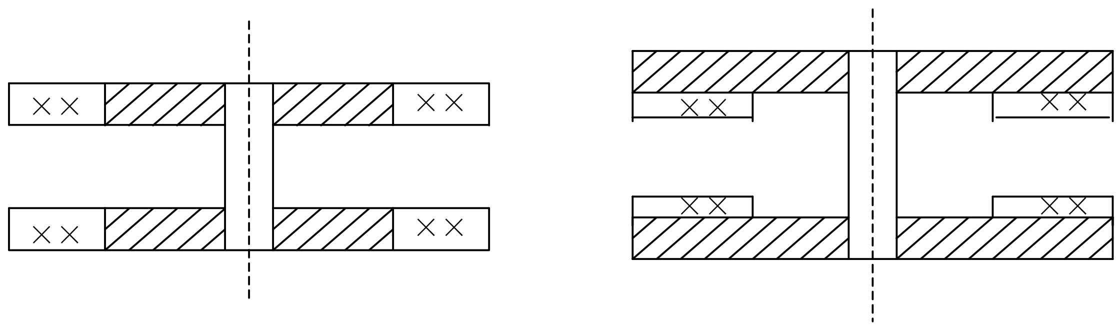


(b) parallel compensation

Fig.2 Change ratio of efficiency with load and frequency in variation

4 Selection of New Contactless Electromagnetic Structure

The selection of new contactless electromagnetic structure is considered mainly from two respects: namely the application and the coupling characteristics. The coupling coefficient is mainly influenced by geometrical parameters of the magnetic structure and the characteristics of the magnetic material. The most common used contactless electromagnetic structures are as follows: pot-core type structure [2], flat coils structures [5], sliding transformers [6] etc. Pot core type transformers are more appropriate for power supply for still and rotating apparatus, where the relative position between the primary and the secondary is fixed. Due to the poor heat dispersibility of the pot core transformer, two flat core structures are proposed in fig.3. The coupling coefficients with different coil thickness for both structures are compared and results are shown in fig.4. According to the figure structure (b) is more appropriate for thin coil structure application. For moving apparatus, the magnetic structure with little iron or no iron is more favorable. More accurately controlled equipments are needed for flat coil structures, while more iron is needed for sliding transformers for power supply for moving apparatus. Detailed analysis of the benefit to cost ratio needs to be made before the magnetic structure being determined.



(a) **(b)**

Fig.3 planar core structures

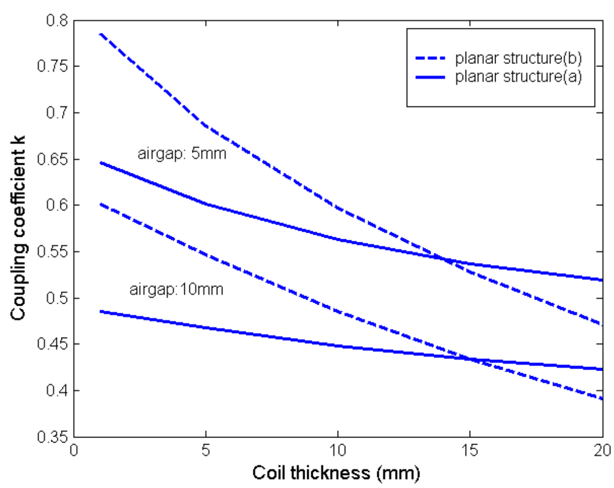


Fig.4 Coupling coefficient with different coil thickness for both structures

5 Design of New Contactless Power Delivery System

The flowchart shown in Fig.5 shows the design methodology of a new contactless power supply system. The design process starts from the selection of an electromagnetic structure. This has been talked about in above section. Once the electromagnetic structure has been fixed, the coupling coefficient is determined.

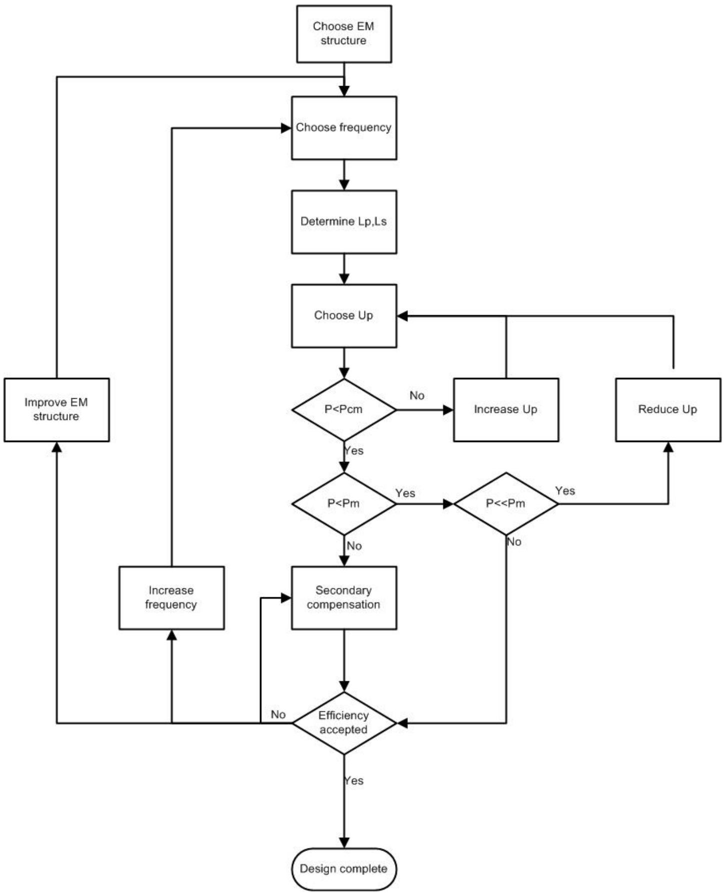


Fig.5 Design of new contactless power supply system

The next step is to choose operational 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 [3,6]. These frequencies are bound to move up as the technology improves. The cost and complexity of the power supply will increase with higher frequency. So low frequency should be selected at first.

According to (3), the optimal secondary inductance can be determined. The secondary turns can also be determined according to the single turn inductance of the magnetic structure. This can be calculated by finite element method. The optimal primary winding should have one turn. Due to the high operational frequency litz wires are required for both the primary and secondary windings.

Then it's necessary to determine the primary voltage. Since the cost of the primary is much related to the primary voltage, at first low voltage value should be selected. With all these parameters known, the maximum power transmitted with secondary compensation can be calculated. If the system can't transfer the required power, the voltage can be gradually increased.

The final step is to consider if the transmission efficiency can be accepted. If not, three means can be selected, namely

- Secondary compensation
- Increasing the operational frequency
- Improving the coupling of the contactless electromagnetic structure

The first option increases the cost of the secondary, the second option increases the cost of the power supply, and the third option increases the cost of the electromagnetic structure. It should be noticed that according to the analysis presented above, higher frequency will result in increased efficiency but reduced output power. A few iterations might be done before the design results meet the required power and efficiency. For each step of the whole design process, the temperature of the magnetic structure must be within acceptable temperature limits.

In addition, the benefit to cost ratio also needs to be considered to further optimize the system design.

6 Conclusion

The design of new contactless power supply system involves some tradeoffs, the biggest one of which is between the performance and the cost of the system. Well-coupled electromagnetic structure is necessary for low cost system. Structure (b) is more appropriate for thin coil structure application. In respect of maximizing the power transfer capability and fully utilizing the system optimal primary should have one turn, secondary inductance may be determined according to (3). From the improvement of the output power by secondary compensation series compensation is more favorable for small load resistance while parallel compensation is more fit for large load resistance.

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