FOM-r_d 평면을 이용한 자기유도형 무선전력전송에서의 비대칭 코일설계 방법론

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Novel Intuitive Design Scheme for Asymmetric Inductive Power Transfer Coils using FOM-r_d Plane Approach

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ABSTRACT

This paper proposes a coil design scheme for inductive power transfer (IPT) using FOM-r_d plane. By extending the conventional symmetrical coil design flow, the asymmetric coils are considered, which is common in IPT systems. Furthermore, the time constant factor of individual coil is used to make the coil geometric design simple and flexible. Starting from the given voltage gain and minimum power transfer efficiency specification, the geometric size of coil can be easily determined using the time constant factor. The proposed method is formulated with theoretical analysis and then is verified by simulation.

1. Introduction

Inductive power transfer is widely applied for many applications such as electric vehicles (EVs), biomedical implants, portable electronics due to the convenience and durability. However, these features can only be achieved when some difficulties are overcome. One of the most important challenges lies in coil design.

In coil design of IPT systems, two key performance indices are voltage gain and power transfer efficiency. In addition, the geometry of the coil is also very important to implement the inductive couplers in practical application. Those factors should be the design target in the IPT system. In the conventional works, such an approaches only dealt with the symmetric case. However, an asymmetric coil size of transmitter (Tx) and receiver (Rx) is common for reducing misalignment effect. It is also because the space allowed for the Rx coil is usually more tight than Tx coil in most applications. However, the asymmetric coil design research in term of voltage gain, efficiency, and coil geometry has not been investigated yet.

To fill that gap, based on our previous research in [1], the design method of the asymmetric circuit for IPT is proposed in this paper. Under the information of Tx coil, the receiver coil will be designed to meet the target voltage gain and power transfer efficiency. In addition, the coil can be flexibly by the time constant factor.

2. Proposed Design Method

In the IPT system, the series-series (SS) compensation is the most common topology due to the advantages such as simplicity, resonant frequency-independency from coupling coefficient, and low sensitivity to coil misalignment. Therefore, the SS topology is adopted for this study. The simplified circuit of the IPT system with an SS compensation network is shown in Fig. 1a. L_1 and L_2; C_1 and C_2; R_1 and R_2 are self-inductances, compensation capacitances, and equivalent series resistances of the Tx and Rx coils, respectively. M is the mutual inductance between L_1 and L_2. and R_L is the AC load resistance. The AC source, V_i, is usually generated from a full-bridge inverter.

Voltage gain and power transfer efficiency of the system can be formulated in terms of *FOM*-r_d plane in similar way of symmetric coil case as [1], but considering asymmetric case, they are reformulated by (1) and (2).

$$M_{V,AC} = \left|\frac{V_o}{V_i}\right| = \frac{FOM \cdot r_{d2}}{FOM^2+1+r_{d2}}\sqrt{\frac{R_L}{R_1 r_{d2}}} \tag{1}$$

$$\eta = \frac{FOM^2 \cdot r_{d2}}{(1+r_{d2})^2+FOM^2(1+r_{d2})}, \tag{2}$$

where figure-of-merit (*FOM*) and r_{d2} are defined as $FOM = kQ$, $r_{d2} = R_L/R_2$, k is the geometric mean of coupling coefficients k_1 and k_2 of Tx and Rx, and Q is the geometric mean of quality factors Q_1 and Q_2.

In this paper. the Tx circuit parameters, input voltage, coupling coefficient, k, and load resistance, R_L, are assumed to be given. At first, *FOM* and r_{d2} can be obtained from *FOM*-r_d plane. After that, the Rx circuit parameters can be calculated as follows:

$$Q_2 = FOM/(k^2Q_1),\ R_2 = R_L/r_{d2} \tag{3}$$

$$L_2 = Q_2R_2/\omega_o,\ C_2 = 1/(\omega_oQ_2R_2). \tag{4}$$

The quality factor of Rx, Q_2, can expressed as:

$$Q_2 = \omega_oL_2/R_2 = \omega_o\tau \tag{5}$$

where $\tau = L_2/R_2$ is defined as the time constant factor of Rx coil. Meanwhile, the inductance and winding resistance of a

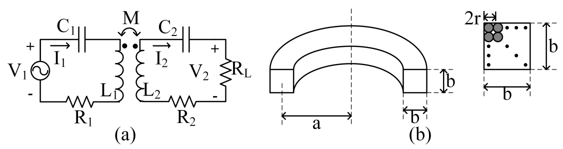


Fig 1. System configuration (a) Series-Series compensated IPT system (b) Circular coil with square cross section.

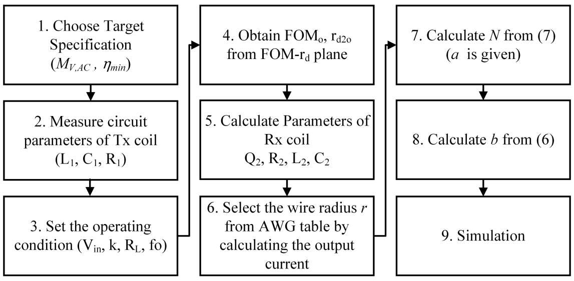


Fig 2. Design procedure of the proposed design method.

circular coil can be respectively calculated by (6) and (7)

$$L_2 = 2 \cdot 10^{-7}\pi^2 K(\zeta) a N^2 \zeta \qquad (6)$$

$$R_2 = \rho \cdot 2\pi a N/(\pi r^2) \qquad (7)$$

where a, b, and r are coil radius, coil length, and wire radius of coil as shown in Fig. 1b; $\zeta=2a/b$ is configuration index, ρ is resistivity, and $K=1/(1+0.528\zeta^{0.846})$ is Nagaoka coefficient[2],[3]. Before calculating coil geometric parameters, we have to calculate the output current to select the wire radius r from the AWG table. Then the coil radius a is determined, N can be obtain by solving (7). In addition, coil length b can be calculated from (6).

However, in practical cases, it is very difficult to implement coil to meet exact L_2 and R_2 at the same time. To mitigate the issue, the efficiency constraint can be loosen to be a form of inequality. Now, the coil inductance and winding resistance only need to meet the condition (8), and the coil design becomes more flexible. Here, FOM_o and r_{d2o} are the boundary values when η is equal to x%

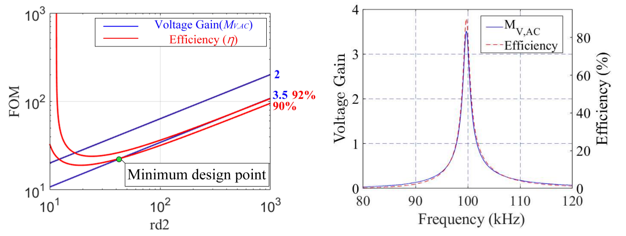
$$\begin{cases} \eta \ge x\% \\ M_{V,AC} = y \end{cases} \rightarrow \begin{cases} R_2 \le \dfrac{R_L}{r_{d2o}} \text{ and } \tau \ge \dfrac{FOM_o^2}{k^2 Q_1 \omega_o} \\ FOM = \dfrac{\sqrt{\dfrac{R_L}{R_1} r_{d2}} + \sqrt{\dfrac{R_L}{R_1} r_{d2} - 4M_{V,AC}^2 (1+r_{d2})}}{2M_{V,AC}} \end{cases} \qquad (8)$$

The overall design procedure of the proposed method is summarized in Fig. 2.

3. Design Example and Simulation Verification

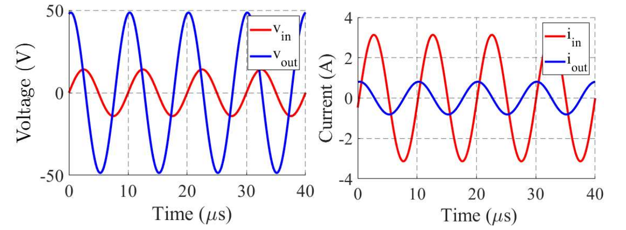
To verify the proposed method, a test Rx coil is designed according to the system target $M_{V,AC} = 3.5$, $\eta \ge 90\%$. Let us assume the Tx coil parameters are L_1 = 618μH, C_1 = 4.05nF, R_1 = 352mΩ, and the operation condition is V_{in} = 20V, k = 0.05, R_L = 60Ω, and f_o = 100kHz. To obtain Rx coil parameters values, the design procedure in Fig. 2 is applied. The boundary values, FOM_o and r_{d2o} are 22.94, 44.67 in the FOM-r_d plane, respectively. From these values, the circuit parameters of Rx coil can be obtained as follows: L_2 = 407.94μH, C_2 = 6.21nF, R_2 = 1.34Ω. The design results are verified by LTspice simulation. The results of simulation are shown in Fig. 3 and 4, which show $M_{V,AC} = 3.5$, $\eta = 90\%$. These values match the target specification.

To obtain the coil geometric parameters, the output current is calculated: V_{out} = $V_{in}M_{V,AC}$ = 20×3.5 = 70V, I_{out} = V_{out}/R_L = 70/60 = 1.167A. So, wire radius r is chosen as 0.2865mm from AWG table by the current rating. If we assume the coil radius a = 10cm, turn ratio N = 31.974 and coil length b = 2.28cm are obtained from (6) and (7), respectively.



(a) (b)

Fig 3. Design target (a) FOM-r_d plane (b) AC Voltage Gain and power transfer efficiency.



(a) (b)

Fig 4. Simulation results (a) input and output voltage (b) input and output current.

Whenever the time constant and the resistance meet the conditions in (9), the target voltage gain is still close to 3.5 and the efficiency is more than 90%, so it can give design flexibility.

$$\begin{cases} \eta \ge 90\% \\ M_{V,AC} = 3.5 \end{cases} \rightarrow \begin{cases} R_2 \le 1.34\Omega \text{ and } \tau \ge 304\mu s \\ FOM = \dfrac{\sqrt{\dfrac{R_L}{R_1} r_{d2}} + \sqrt{\dfrac{R_L}{R_1} r_{d2} - 49(1+r_{d2})}}{7} \end{cases} . \qquad (9)$$

4. Conclusion and Future Work

This paper proposes a novel asymmetric coil design flow using FOM-r_d plane. This proposed method can design a circuit parameters and geometry of Rx coil under the information of Tx coil to meet target specifications. Conversely, Tx coil can be designed from a Rx coil information in similar fashion. Besides, the design procedure employs time constant method to give flexibility in practical design. The proposed method is verified with example design by simulation, and the results match well with theoretical analysis. In the future, the hardware will be implemented to further verify the proposed design method.

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