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Simulation Study on Coil Design of Wireless Power Transfer System for Optimal Transmission Efficiency

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Abstract: As an emerging research field, Wireless Power Transfer (WPT) has attracted wide spread attention recently. In this study, the coil design of WPT system for optimal transmission efficiency is investigated. We deduce Tthe design criteria are deduced to meet various conditions of transmission distance and load. The results of simulation and experiment show the transmission efficiency from transmitting coil to receiving coil can keep high when the corresponding optimal condition is achieved. Thusen it can improve the overall transmission efficiency of the WPT system and it makes it suitable for the practical application of WPT system.

Keywords: Coil design, optimal transmission efficiency, wireless power transfer

INTRODUCTION

The traditional electricity transmission is mainly accomplished by the direct contact with the wire, there must have the direct physical connection between the power supply and the load. WPT is always humans' dream, for many years some scientists continually have being carryingied out the study (Boy and Green, 1995), but had little progress. Till 2007, a new breakthrough was made by MIT. With the "Witricity" technology (electromagnetic resonant principle), they successfully lighted a 60 W bulb outside 2 m with the transmission efficiency of 40% (Kurs *et al.*, 2007). Meanwhile, with the development of power electronics technology, resonant coupling WPT technology is becoming a hot pursuing topic for research institutions in recent years (Tan *et al.*, 2011) and has been made some breakthroughs in electric vehicle (Krishnan *et al.*, 2012), body implantable medical devices (Jung *et al.*, 2009), small robots (Yan *et al.*, 2007), portable mobile device charger. For the practical application of WPT system, the coil design is studied and some design criteria are presented for optimal transmission efficiency in this study.

OPTIMAL TRANSMISSION EFFICIENCY OF WPT SYSTEM

The typical magnetic resonance coupling WPT system is envisaged as shown in Fig. 1 (Qiang *et al.*, 2012). It is composed of two independent parts called primary circuit and secondary circuit, connecting power supply and load, respectively.

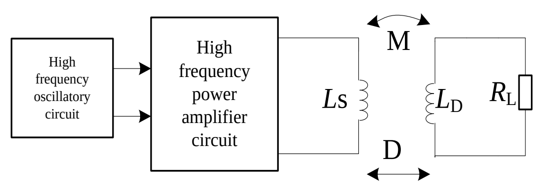

Fig. 1: Schematic of WPT system

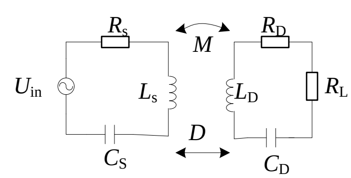

Fig. 2: Circuit model of WPT system

Except for two resonant coils, a complete WPT system still must have the transmitting power source and receiving power equipment. The high frequency oscillating circuit and power amplifying circuit are used to generate a high frequency electromagnetic field. L_S and L_D are the two air-core coils for transferring the, where the subscripts "S" and "D" represent the primary coil and the secondary coil, respectively. R_L is the load resistance. When the two coils reach resonance, the coil L_D can most effectively induct the energy from the coil L_S and supply the power to the load R_L, thus completing the entire wireless power transmission.

To simplify the analysis, in this research only two transceiver coils, L_S and L_D, are equivalently studied.

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Considering the system work in the High Frequency (HF) mode, the parasitic resistance and capacitance could not be ignored, so the WPT circuit model can be built as shown in Fig. 2.
where, the U_{in} is the voltage source; R_S, 、R_D, 、C_S and C_D are the equivalent parasitic parameters in HF; Suppose that the coils are ideal, C_S and C_D could be included in the external resonance capacitances; L_D and L_S are the self-inductances of the two coils; M and D are respectively the mutual inductance and distance between the two coils.

With the system operating angular frequency ω, it is easy to deduce the voltage KVL equations of the two circuits:

$$\begin{cases} Z_S I_S - j\omega M I_D = U_{\text{in}} \\ -j\omega M I_S + Z_D I_D = 0 \end{cases} \tag{1}$$

Then the input power Pin of primary circuit and the output power on the load Pout can be obtained, given as:

$$\begin{aligned} P_{\text{in}} &= \frac{U_{\text{in}}^2 Z_D}{Z_S Z_D + (\omega M)^2} \\ P_{\text{out}} &= \frac{U_{\text{in}}^2 (\omega M)^2 R_L}{[Z_S Z_D + (\omega M)^2]^2} \end{aligned} \tag{2}$$

When the primary and secondary coils are in their self-resonance state and the resonance frequencies are consistent, the system impedance achieves the minimum with zero reflected reactance. At this time, the transmission efficiency is optimal and can be expressed as:

$$\eta = \frac{(\omega M)^2 R_L}{(R_D + R_L)[R_S(R_D + R_L) + (\omega M)^2]} \times 100\% \tag{3}$$

By taking the derivative of (3), it is evident that the system transmission efficiency would achieve optimal when:

$$(\omega M)^2 = R_S (R_L^2 - R_D^2) / R_D \tag{4}$$

Take (4) into (3) and yield the expression of optimal transmission efficiency, given as:

$$\eta_{\max} = \frac{R_L - R_D}{R_L + R_D} \times 100\% \tag{5}$$

Clearly, in (5) the optimal efficiency is correlated with the load resistance R_L and the equivalent loss resistance of secondary coil R_D. And if $R_L >> R_D$, it can be nearly close to 100%.

In HF, R_D mainly includes the ohmic resistance (R_o) and the radiation resistance (R_r):

$$R_o = \sqrt{\frac{\mu_0 \omega}{2\sigma}} \frac{l}{2\pi a} = \sqrt{\frac{\mu_0 \omega}{2\sigma}} \frac{nr}{a} \tag{6}$$

$$R_r = \sqrt{\frac{\mu_0}{\varepsilon_0}} [\frac{\pi n^2}{12} (\frac{\omega r}{c})^4 + \frac{2}{3\pi^3} (\frac{\omega h}{c})^2] \tag{7}$$

where,

μ_0	:	The vacuum permeability
a and r	:	The radius of the wire and the coil respectively
n	:	The number of coil turns
σ	:	The electrical conductivity
l	:	The length of wire
ε_0	:	The air dielectric constant
h	:	The width of the coil
c	:	The ray velocity

For a mid-range WPT system with the operating frequency of 1~50MHz, the R_r can be neglected because $R_r << R_o$, so the R_S and R_D is mainly composed of the ohmic loss. Mutual inductance M could be calculated by the approximate formula:

$$M = \frac{\pi}{2} \mu_0 n_S n_D \frac{(r_S r_D)^2}{D^3} \tag{8}$$

COIL DESIGN FOR THE OPTIMAL EFFICIENCY

In the study, we mainly investigate the design of the receiving coil for the optimal efficiency with the other system parameters, shown in Table 1.

By the maximum efficiency condition (4), R_D^2 could be negligible if $R_L >> R_D$. Suppose that the materials of two coils are the same, i.e. the parameters a and σ are also the same, take the (6) and (8) into Eq. (4), then yield:

$$D^6 = \frac{\mu_0^2 \omega^2 \pi^2 r_S^3 n_S r_D^5 n_D^3}{4R_L^2} = K n_D^3 r_D^5 \tag{9}$$

Based on (9), the researches of receiving coil design for various conditions are carried out.

Same load and different distance: In this case, the design criterion could be deduced from (9), given as (10) and the simulation data are in Table 2:

$$\begin{aligned} D^6 &= \frac{\mu_0^2 \omega^2 \pi^2 r_S^3 n_S r_D^5 n_D^3}{4R_L^2} = K_R n_D^3 r_D^5 \\ K_R &= \frac{\mu_0^2 \omega^2 \pi^2 r_S^3 n_S}{4R_L^2} \end{aligned} \tag{10}$$

Table 1: Simulation parameters

Parameter	Value
f	3.45 MHz
r_S	0.45 m
n_S	5
D	0.3 m
R_L	50Ω
R_S	0.2707Ω

Table 2: Same load and different distance

$R_L = 50 : K_R = 0.3337$

D (m)	n_D	r_D (m)	η (%)	D (m)	n_D	r_D (m)	η (%)
0.2	2	0.119	0.999	0.4	2	0.274	0.997
	5	0.069	0.998		5	0.158	0.996
0.8	2	0.629	0.994	1.0	2	0.822	0.992
	5	0.363	0.991		5	0.474	0.989

Table 3: Different load and same distance

$D = 0.3\text{m} : K_D = 1.1443\text{e}6$

R_L (Ω)	n_D	r_D (m)	η (%)	R_L (Ω)	n_D	r_D (m)	η (%)
20	2	0.134	0.997	50	2	0.194	0.998
	5	0.078	0.995		5	0.112	0.997
100	2	0.256	0.999	150	2	0.300	0.999
	5	0.148	0.998		5	0.174	0.999

Table 4: Same load and distance

$D = 0.3$; $R_L = 50$; $K_{RD} = 834.19$

n_D	r_D (m)	η (%)	n_D	r_D (m)	η (%)
2	0.1938	0.9981	5	0.1118	0.9973
3	0.1519	0.9978	6	0.1002	0.9971
4	0.1278	0.9975	8	0.0842	0.9968

Different load and same distance: In this case the design criterion could be deduced and the simulation data are in Table 3:

$$R_L^2 = \frac{\mu_0^2 \omega^2 \pi^2 r_S^3 n_S r_D^5 n_D^3}{4D^6} = K_D n_D^3 r_D^5$$
$$K_D = \frac{\mu_0^2 \omega^2 \pi^2 r_S^3 n_S}{4D^6} \tag{11}$$

Same load and distance: In this case the design criterion could be deduced and the simulation data are in Table 4:

$$R_L^2 D^6 = \frac{\mu_0^2 \omega^2 \pi^2 r_S^3 n_S r_D^5 n_D^3}{4} = K_{RD} n_D^3 r_D^5$$
$$K_{RD} = \frac{\mu_0^2 \omega^2 \pi^2 r_S^3 n_S}{4} \tag{12}$$

From Table 2, 3 and 4, it is known that with the transmission distance increasing, the optimal transfer efficiency becomes more smaller. Moreover, the greater the radius, the higher the efficiency is. higher. Generally, the three power of n_D is inversely proportional to the five power of r_D. But this conclusions are obtained under the condition of $R_L >> R_D$, calling resistance matching. Then we could design the receiving coil could be designed to make the optimal transfer efficiency close to 100%, in accordance with (10), (11) and (12) in various cases.

CONCLUSION

In this study, the receiving coil design is studied. When the resistances are matched, the design criterions are deduced in various cases to make little power loss from the transmitting coil to receiving coil. It is very important to design the practical applications of WPT systems.

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