Optimal Range of Coupling Coefficient of Loosely Coupled Transformer Considering System Resistance

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***Abstract*—Accurate system resistance may lead to an obvious error between the simulated and the real efficiency of the system. This paper proposes an optimal range of coupling coefficient for ensuring the efficiency and the sufficient output power of the WPT (wireless power transfer) system. A 3-kW prototype WPT system is manufactured and the effectiveness of the optimal range of coupling coefficient is validated.**

***Index Terms*—Wireless power transfer system (WPTS), system resistance, system efficiency.**

I. Introduction

Several studies focused on improving the performance of WPTS. For efficiency improvement, the square coils were considered to be more suitable [1]. Moreover, the wide variety of output voltage and coupling coefficient were also optimized [2], and a compensation topology named as LC/S was also proposed [3]. For reducing the iron losses of LCT, the multi-coil LCT, which uses wires and air as the carrier and medium for the transmission of energy, were proposed [4], and a misalignment-tolerant series-hybrid wireless EV charging system was also proposed [5]. During the design of the above LCT, the researchers followed the steps which are firstly to simulate and then perform the experimental verification after the. However, these LCTs neglected the system resistance at the design stage considering the operating duty, which may lead to an error between the simulated and the real efficiency of WPT system [6].

In this paper, an optimal range of coupling coefficient is proposed to reduce the error between the simulated and the real system efficiency, as well as, to ensure the sufficient system output power. The optimal range of the coupling coefficient at 85 kHz is also identified. Finally, a 3-kW WPT prototype is manufactured and related experimental validations are also carried out.

II. Efficiency Error Between the Simulated and the Real System

A. Model of WPTS

The equivalent circuit of the resonant WPT system with the series-series (SS) topology is given in Fig. 1, where, U_t is the high-frequency supply, L_t and L_r are the self-inductances of the transmitting and the receiving coils, respectively; R_t and R_r are the resistances of the transmitting and the receiving system, respectively; C_t and C_r are the compensate capacitors of the transmitting and the receiving system, respectively; R_{eq} is the equivalent load resistance and M_{tr} is the mutual inductance between the transmitting and the receiving coils.

Since the WPT operates under resonance condition, the output power and efficiency of WPT system can be derived as in (1) and (2).

$$P_{out} = \frac{U_t^2 \omega^2 M_{tr}^2 R_{eq}}{\left[R_t\left(R_r+R_{eq}\right)+\omega^2 M_{tr}^2\right]^2}, \tag{1}$$

$$\eta = \frac{\omega^2 M_{tr}^2 R_{eq}}{\left[R_t\left(R_r+R_{eq}\right)+\omega^2 M_{tr}^2\right]\left(R_r+R_{eq}\right)}. \tag{2}$$

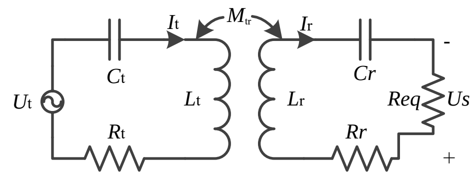

Fig. 1. Equivalent circuit of WPT system.

B. Effects of Neglecting Resistance on System Efficiency

With a 3-kW WPTS, the parameters are shown in Table I, where, k_{tr} is the coupling coefficient between the transmitting and the receiving coils. The variation of system efficiency with the R_t and R_r is obtained in Fig. 2. To illustrate clearly, it is assumed that when the system resistance is neglected and the real system resistance is a random value, from 0 to 1 Ω. It can be seen that the system efficiency can drop to 90% when the R_t and R_r are up to 1 Ω, the maximum error can reach 10% between the simulated and the real efficiency.

Table I. Parameters of a resonant WPTS

Parameters	Value
Transmitting voltage U_t (V)	318
Equivalent load resistance R_{eq} (Ω)	28.65
Operating frequency f (kHz)	85
Self-inductance of transmitting coil L_t (μH)	272.07
Self-inductance of receiving coil L_r (μH)	205.6
Resonant capacitor of transmitting coil C_t (nF)	12.89
Resonant capacitor of receiving coil C_r (nF)	17.05
Coupling coefficient k_{tr}	0.16

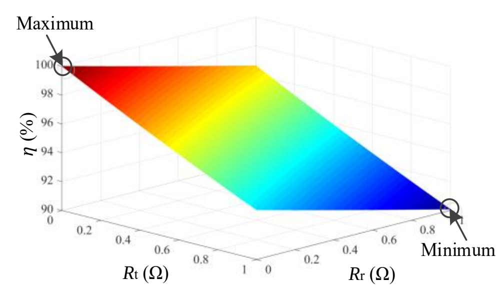

Fig. 2. Variation of efficiency with R_t and R_r.

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III. Optimal Range of Coupling Coefficient

The variations of system output power and efficiency with the k_{tr} under the different R_s are given in Fig. 3, where, the k_{tr} is the coupling coefficient of WPT system, the R_s is the system resistance, $R_s=R_t+R_r$, the R_{s2} is the real system resistance, the R_{s1} and R_{s3} are the assumed system resistance, $R_{s2}=1.36R_{s1}$, $R_{s3}=1.265R_{s2}$. It can be seen that, with the increases of k_{tr}, the system efficiency gradually approaches 100%, and the output power of system firstly increases and then gradually decreases to around 0 kW. For avoiding the insufficient output power of WPT system, the k_{tr} should not be too large, and the optimal range of coupling coefficient can be introduced. With (1) and (2) as the objective functions and (3) and (4) as the constraints, the optimal range of coupling coefficient of the case at 85 kHz can be obtained, which is 0.15 to 0.23, as shown in the green area of Fig. 3. Within this range, the error between the simulated and the real system efficiency is reduced by not more than 5%, and the system output power is always not less than 3.3 kW.

$$\frac{\eta_{R_{p1}} - \eta_{R_{p3}}}{\eta_{R_{p1}}} \times 100\% \le 5\%, \tag{3}$$

$$P_{out} \ge 3.3. \tag{4}$$

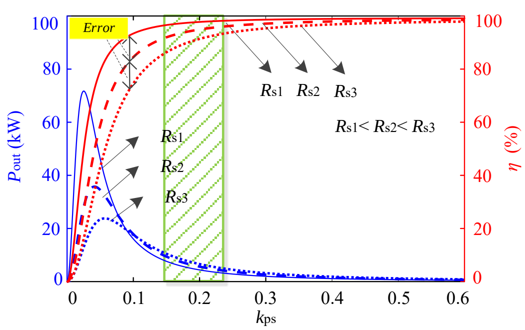

Fig. 3. Variations of output power and efficiency with coupling coefficient.

IV. Experimental Validations

A 3-kW prototype WPT system is manufactured, as shown in Fig. 4. The efficiencies and output power of 3-kW WPT system was measured for different k_{tr} when the R_s changes from 1.3Ω to 1.6Ω. The results are in Fig. 5. It can be seen that:

1) When R_s = 1.3Ω, with the increases of k_{tr}, the system efficiency increases gradually, but the output power of prototype decreases gradually. When the R_s are 1.6Ω and 1.7Ω, the variations of the system efficiency and output power with the increases of k_{tr} are same as that when the R_s is 1.3Ω.

2) When the k_{tr} is equal to 0.118 (less than the lower limit of the optimal coupling coefficient range), the decline of the system efficiency is 19.065%, when the k_{tr} rises to 0.165, the decline of the system efficiency can sharply reduce to 5.264%; when the k_{tr} is equal to 0.232 (more than the upper limit of the optimal coupling coefficient range), the decline of the system efficiency can be further suppressed by 3.968%.

3) As for the output power, when the k_{tr} is equal to 0.118, the output power of the prototype is gradually decreased with the increases of R_s. However, when the k_{tr} is 0.165 and 0.232, respectively, with the increases of R_s, the output power of the prototype is gradually increased.

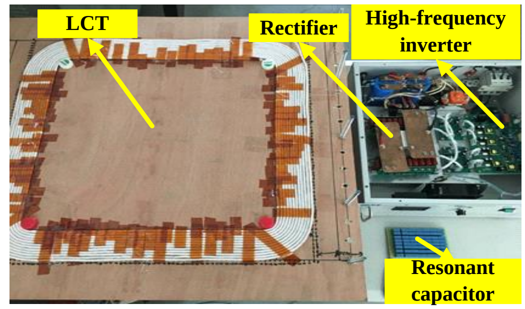

Fig. 4. 3-kW WPT Prototype.

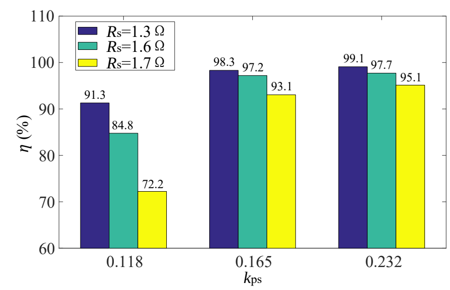

Fig. 5. Experimental results of system efficiency witht k_{tr} and different R_s.

V. Conclusion

This paper focuses on the influence of the inaccurate estimation of system resistance on efficiency of WPTS. An optimal range of coupling coefficient is proposed, by which the error between the simulated and the real system efficiency can be reduced to not more than 5%, and the system output power can be sufficient. A 3-kW prototype WPT is manufactured, and the effectiveness of optimal range of coupling coefficient is validated.

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