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Short communication

Design of a novel receiving structure for wireless power transfer with the enhancement of magnetic coupling

Yanyan Shi [a], Yiming Zhang [a], Minghui Shen [b], Yue Fan [a], Can Wang [a], Meng Wang [a,*]

[a] School of Electronic and Electrical Engineering, Henan Normal University, Xinxiang 453007, China
[b] Xinxiang Power Supply Company, State Grid Corporation of China, Xinxiang 453000, China

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ABSTRACT

In a wireless power transfer (WPT) system, the transfer performance is related to the mutual inductance between coils. However, the mutual inductance decreases with the increase of transfer distance. In this work, the relationship between the output voltage and the mutual inductance for WPT systems with air core and with ferrite core are analyzed. In order to improve the mutual inductance, a novel configuration of receiving resonator with a strong magnetic coupling is proposed. The mutual inductance and magnetic field distribution for coils with a cylindrical core and with the novel configuration are compared. Experiments are carried out for validation. The results indicate that the proposed WPT system is superior to the system with the cylindrical ferrite core in increasing the output voltage and power transfer efficiency.

1. Introduction

Due to the advantages of high reliability and convenience, wireless power transfer (WPT) technology has received considerable attention over the past few years [1–3]. Magnetic resonant coupling wireless power transfer (MRC-WPT) is considered to be the most attractive and effective approach for wireless power delivery and has shown great potential in wide applications, such as biomedical implants, electric vehicles, and consumer electronics [4–7].

It is well known that there exists a certain coupling distance between the transmitting and receiving coils where the output power of the MRC-WPT system is maximum [8]. However, once the transfer distance is larger than the threshold value, the output power drops sharply because of weak magnetic coupling. To enhance the magnetic coupling in the longer distance, a great deal of effort has been performed [9–12]. Generally, the MRC-WPT systems with multiple coils such as three coils, four coils and intermediate coils have commonly been used, which increases the power transfer ability [13,14]. However, there are strict requirements for the additional coils and the flexibility of such system is largely reduced. Increasing the number of the receiving coils is another alternative to improve the overall efficiency of the power transfer [15]. Nevertheless, the transmission efficiency to each individual receiver coil is relatively low and the overall efficiency tends to be saturated even when the number of receiver coils is increased. An alternative approach is to utilize the tunable impedance matching network [16]. Although the transfer performance is improved, the additional control circuits complicate the system structure. In addition, material with high permeability such as ferrites can be used in MRC-WPT for enhancement of magnetic coupling [17]. In this paper, a novel configuration of ferrite core is designed and positioned in the receiving coil to improve the performance of the MRC-WPT system.

The rest of this paper is organized as follows. In Section 2, the equivalent circuit models of WPT system with air core and with ferrite core are explored and the voltage across the load is calculated respectively. In Section 3, a novel receiving resonator structure is presented. Simulation and experiment have been performed to compare the MRC-WPT systems with different configurations of receiving resonator in Section 4. Finally, some conclusions are drawn in Section 5.

2. Equivalent circuit model of WPT system

The equivalent circuit model of a MRC-WPT system with air core and with ferrite core is shown in Fig. 1(a) and (b), respectively. $\boldsymbol{U}_S$ and R_S are the voltage and internal resistance of the power source. L_t and L_r are the self-inductance of the transmitting coil and receiving coil. C_t, C_r and C_r' are the capacitance connected in series with transmitting coil and receiving coil. R_t and R_r are the

* Corresponding author.
E-mail address: wangmeng@htu.cn (M. Wang).

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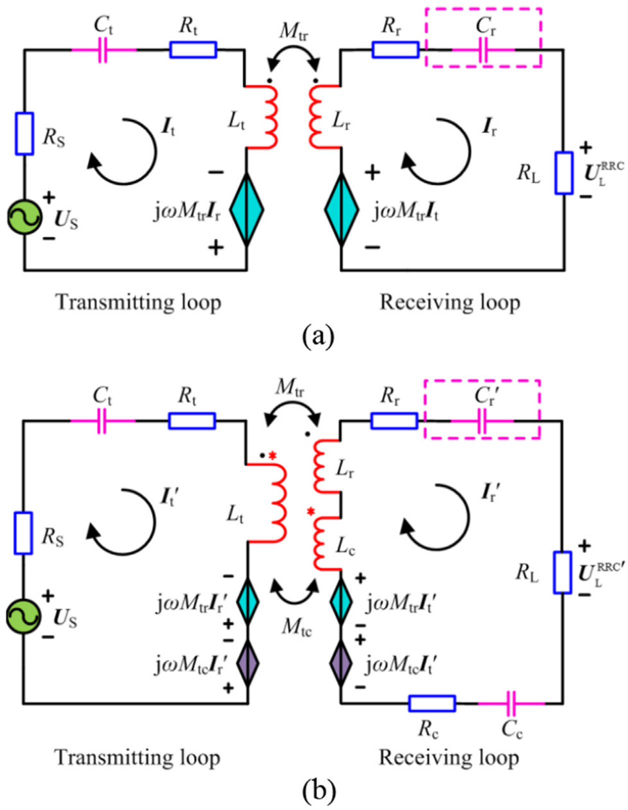

Fig. 1. Equivalent circuit models of MRC-WPT. (a) Coils with air core. (b) Coils with ferrite core.

resistance of the coils. R_L indicates the load. M_{tr} is the mutual inductance between L_t and L_r. The variation of the output power can be expressed by the output voltage. $\boldsymbol{U}_L^{RRC}$ is the load voltage in Fig. 1(a). The only difference between the two systems is the introduction of the additional ferrite core, which is placed in the receiving coil, as shown in Fig. 1(b). The ferrite core can be denoted by C_c, L_c and R_c connected in series. C_c and R_c can be ignored compared with the series capacitance of the resonant coils and the load, so the ferrite core can be represented as L_c. It should be noted that the magnetic coupling also exists between L_t and L_c which is denoted as M_{tc}, and $\boldsymbol{U}_L^{RRC'}$ is the load voltage in Fig. 1(b). In the MRC-WPT system, the coil loss is negligible because R_t and R_r are much smaller than R_S and R_L. Besides, it can be seen that the mutual inductance between the coils with ferrite core is not only related to the configuration of the coils and the transfer distance but also dependent on the magnetization of the ferrite materials and the geometry of the ferrite core.

For the WPT system with air core shown in Fig. 1(a), the circuit equations of the system at the frequency ω can be expressed as

$$\begin{cases} \boldsymbol{U}_S = Z_t\boldsymbol{I}_t - j\omega M_{tr}\boldsymbol{I}_r \\ Z_r\boldsymbol{I}_r - j\omega M_{tr}\boldsymbol{I}_t = 0 \end{cases} \tag{1}$$

where $Z_t = R_S + j(\omega L_t - 1/\omega C_t)$, $Z_r = R_L + j(\omega L_r - 1/\omega C_r)$, and $\boldsymbol{I}_t$ and $\boldsymbol{I}_r$ are the current flowing in the transmitting loop and receiving loop respectively.

In order to deliver power from transmitting loop to receiving loop efficiently, the transmitting coil is tuned at resonant state. According to the Eq. (1), the induced voltage across the load for the non-resonant WPT system U_L^{NRRC} can be calculated by

$$U_L^{NRRC} = \mathbf{Re}\left(\frac{j\omega M_{tr}\boldsymbol{U}_S R_L}{R_L R_S + (\omega M_{tr})^2 + \left(j\omega L_r + \frac{1}{j\omega C_r}\right)R_S}\right) \tag{2}$$

For WPT system operating at the resonant state where $\omega = \omega_0 = 1/(L_tC_t)^{0.5} = 1/(L_rC_r)^{0.5}$, the third item in the denominator is simplified to zero. Thus, the voltage across the load U_L^{RRC} can be expressed as

$$U_L^{RRC} = \mathbf{Re}\left(\frac{j\omega_0 M_{tr}\boldsymbol{U}_S R_L}{R_S R_L + (\omega_0 M_{tr})^2}\right) \tag{3}$$

Similar to the WPT system with air core, the circuit equations of the system with ferrite core shown in Fig. 1(b) can be expressed as

$$\begin{cases} \boldsymbol{U}_S = Z_t\boldsymbol{I}_t' - j\omega M_{tr}\boldsymbol{I}_r' - j\omega M_{tc}\boldsymbol{I}_r' \\ Z_r'\boldsymbol{I}_r' - j\omega M_{tr}\boldsymbol{I}_t' - j\omega M_{tc}\boldsymbol{I}_t' = 0 \end{cases} \tag{4}$$

where $Z_r' = R_L + j(\omega L_r + \omega L_c - 1/\omega C_r')$, and $\boldsymbol{I}_t'$ and $\boldsymbol{I}_r'$ are the current flowing in the transmitting loop and receiving loop respectively.

According to the Eq. (4), the induced voltage across the load for the non-resonant system with ferrite core $U_L^{NRRC'}$ can be calculated by

$$U_L^{NRRC'} = \mathbf{Re}\left(\frac{j\omega M_{tr}\boldsymbol{U}_S R_L + j\omega M_{tc}\boldsymbol{U}_S R_L}{R_L R_S + [\omega(M_{tr} + M_{tc})]^2 + \left(j\omega L_r + j\omega L_c + \frac{1}{j\omega C_r'}\right)R_S}\right) \tag{5}$$

When the WPT system with ferrite core is at the resonant state, the third item in the denominator can be simplified to zero. Therefore, the voltage across the load $U_L^{RRC'}$ can be expressed as

$$U_L^{RRC'} = \mathbf{Re}\left(\frac{j\omega_0 M_{tr}\boldsymbol{U}_S R_L + j\omega_0 M_{tc}\boldsymbol{U}_S R_L}{R_L R_S + [\omega_0(M_{tr} + M_{tc})]^2}\right) \tag{6}$$

where $\omega_0 = 1/[C_r'(L_r + L_c)]^{0.5}$.

Comparing Eq. (3) with Eq. (2), it can be seen that the voltage across the load in the resonant system with air core is higher than that in the non-resonant system with air core due to its smaller denominator at the resonant frequency. Similarly, the voltage in the resonant system using ferrite core shown in Eq. (6) is increased when compared with the induced voltage in the corresponding non-resonant system shown in Eq. (5). Based on the above analysis, a higher output voltage can be obtained by tuning the receiving coil at the resonant state. However, it is difficult to determine whether the performance of the system with ferrite core is better or not by comparing Eq. (5) with Eqs. (2) and (3).

3. Configuration of the novel ferrite core

In order to further analyze the impact of the ferrite core, the WPT systems with the air core and with the ferrite core are investigated respectively. In the study, the transmitting and receiving coils are identical. Coils with a cylindrical ferrite core which is positioned in the receiving coil are used for comparison, as shown in Fig. 2. The receiving coil is evenly wound on the ferrite core and the magnetic core is designed to have the same cross-sectional area as that of the transmitting coil. The results are shown in Fig. 3 in which RRC and NRRC indicate the resonant receiving coil and non-resonant receiving coil respectively.

As shown in Fig. 3, the performance of the resonant system outperforms the corresponding non-resonant system. The voltage in the resonant system with air core is about 104% higher than that in the corresponding non-resonant system, and the value is 25% in the system with ferrite core when the transfer distance is 10 mm. Additionally, the induced voltage of the non-resonant system with the ferrite core placed in the receiving coil is largely increased and the maximum improvement can reach 196% and 45% compared with the non-resonant system using air core and the resonant system using air core respectively due to the strong magnetic coupling caused by the ferrite core. Therefore, it can be