High-Efficiency Wireless Power Transfer by Controlling Free Resonant Frequencies

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***Abstract* – In the previous works, we proposed the method to maximize output power even in the over-coupled state by controlling free resonant frequencies. In this paper, we propose the mutual coupling approach to derive the optimum free resonant frequencies, and show the measured power transfer efficiency (PTE) using the transmission efficiency instead of the system energy efficiency. The results of the proposed approach exactly coincide with those of the previous work, and the fabricated prototype achieves the PTE of about 80% in the over-coupled state.**

***Index Terms* — Power transfer efficiency, system energy efficiency, transmission efficiency, wireless power transfer.**

1. Introduction

Figure 1 shows an equivalent circuit model of a two-coil wireless power transfer (WPT) system, where the changeable elements are voltage source, source and load impedance, primary and secondary coils, and capacitances of primary and secondary resonators. Depending on the changeable elements, various methods have been introduced to improve the power transfer efficiency (PTE) of the WPT system [1]-[7]. The most popular method is to use matching networks, which transform source and load impedances into optimum values. In [1]-[2], our group revealed that the WPT system using lumped reactive matching networks was considered as a two-coil WPT system, and the WPT system using air-core transformers as matching network was considered as a four-coil WPT system. Additionally, we showed how the source (or load) impedance was matched to the optimum value in the four-coil as well as two-coil WPT system. In [3], new switchable capacitor array circuit was proposed, and then a variety of matching cases of a L-section matching network could be implement using a confined number of capacitors.

Beside the method using matching networks, selection of optimum primary and secondary coils among the coil arrays depending on a variation of environments is suggested in [4].

A method of changing the voltage source transfers the operating frequency into split frequencies in over-coupled state, and thus it achieves a high PTE [5]. Similarly, our group recently proposed that free resonant frequencies of resonators were tuned to split frequencies in order to achieve a high PTE in over-coupled state [6]. The desired tuned free resonant frequencies were derived from a condition having a current ratio between the primary and secondary resonators identical to that in critical coupled state. In addition, the system energy efficiency was used to express the PTE instead of the familiar transmission efficiency.

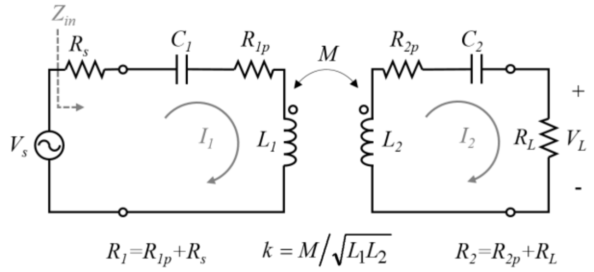

Fig. 1. Equivalent circuit model of a two-coil resonant WPT system.

In this paper, unlike [6], the effect of mutual inductance on a reflected inductance is used to derive the condition of the optimum free resonant frequencies for a high PTE. Moreover, we show that the tuned free resonant frequencies results in a high PTE using the transmission efficiency instead of the system energy efficiency.

2. Formulation

The circuit model of Fig. 1 can be described using the reflected impedance Z_r as shown in Fig. 2, and Z_r is expressed as

$$Z_r = \frac{\omega^2 M^2}{R_2 + j\omega L_2 + \dfrac{1}{j\omega C_2}}. \quad (1)$$

The imaginary part of the reflected impedance is derived as follows:

$$\mathrm{Im}\{Z_r\} = \omega L_1 \cdot \frac{\left(\dfrac{\omega_2^2}{\omega^2} - 1\right)}{\dfrac{1}{Q_2^2} + \left(\dfrac{\omega_2^2}{\omega^2} - 1\right)^2}. \quad (2)$$

where $Q_2=L_2/R_2$ is the loaded Q-factor and ω_2 is the free resonant frequency of the secondary resonator.

In the circuit model of the Fig. 1, a resonance frequency is called the free resonant frequency when there is not mutual coupling. The free resonance frequencies of the primary and secondary resonators are given, respectively,

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}}, \omega_2 = \frac{1}{\sqrt{L_2 C_2}}. \quad (3)$$

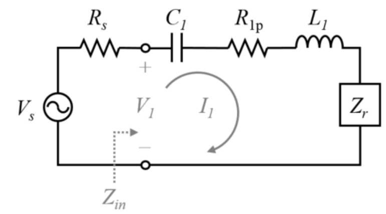

Fig. 2. Equivalent circuit model of a two-coil resonant WPT system using reflected impedance

On the other hand, let the right-hand side of (2) be the product of ωL_1 and a variable A. Then the free resonant frequency condition of the WPT system to be operated at the operating frequency ω_0 is

$$\omega_0 = \frac{1}{\sqrt{L_1(1+A)\cdot C_1}} = \frac{\omega_1}{\sqrt{1+A}}. \qquad (4)$$

Similarly, in order to operate the secondary resonator at the operating frequency ω_0, the free resonant frequency of the secondary resonator should also be

$$\omega_0 = \frac{1}{\sqrt{L_2(1+B)\cdot C_2}} = \frac{\omega_2}{\sqrt{1+B}}. \qquad (5)$$

Since variables A and B are functions of ω_2 and ω_1, respectively, thus (5) and (6) are the simultaneous equations.

3. Simulation and Experiment Results

It is cumbersome to solve directly the simultaneous equations of (5) and (6). We can find the optimal free resonant frequencies using an iteration process for a WPT system with parameter values identical to those of [6]. Figure 3 shows the estimated free resonant frequencies with respect to the iteration number for over-coupled states, $k = 0.129$ and 0.190. The estimated free resonant frequencies are the same as those of [6].

Figure 4 shows the measured load power and transmission efficiency. The system energy efficiency is about 45% as illustrated in [6], while the transmission efficiency is about 81%. As already revealed in [8], this difference between the system energy efficiency and transmission efficiency arises from whether the power loss is included in the input power from the power source or not. Because the input power of the transmission efficiency is defined as the available power from the output of the power source, the input power keep

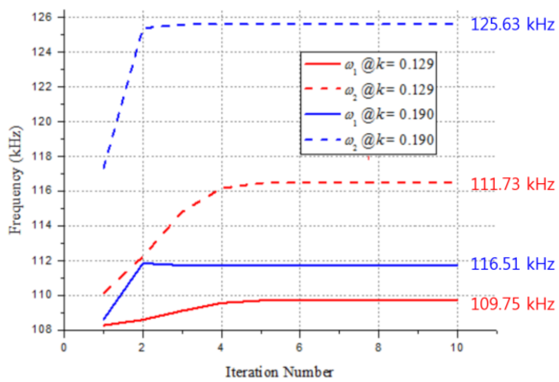

Fig. 3. Free resonant frequencies with respect to iteration number for $k = 0.129$ and 0.190.

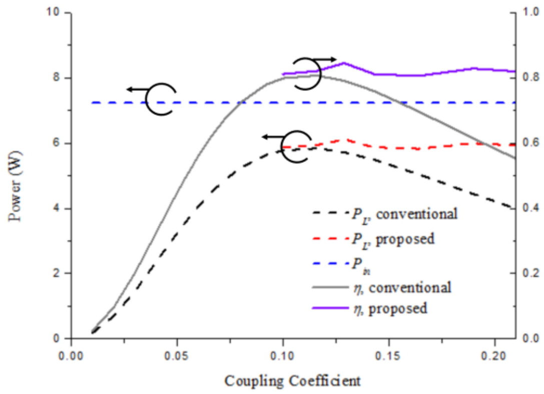

Fig. 4. Measured load power and PTE using transmission efficiency.

the constant power unchanged depending on coupling coefficient. Obviously, the tuned free resonant frequencies improve the PTE effectively in the over-coupled state.

4. Conclusion

In this paper, we propose new approach to derive the optimum free resonant frequencies in the over-coupled WPT system. The optimum values can be sufficiently obtained with several iterations, and are the same with results of previous works. Additionally, when the tuned free resonant frequencies are adopted in the over-coupled WPT system, the system achieves the transmission efficiency of about 80%.

Acknowledgment

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