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Comparative Study on the Power Transfer Efficiency of Magnetic Resonance and Radio Frequency Wireless Power Transmission

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Abstract

In this paper, the power transfer efficiencies (PTEs) of magnetic resonance (MR) wireless power transmission (WPT) and radio frequency (RF) WPT are compared as a function of the distances between resonators (or antennas). The PTE of the C-loaded loop resonators during MR WPT was theoretically calculated and simulated at 6.78MHz, showing good agreement. The PTE of the patch antennas, whose area is the same as the C-loaded loop resonator during MR WPT, was theoretically calculated using the Friis equation and the equation by N. Shinohara and simulated at 5.8 GHz. The three results from the Friis equation, the equation by N. Shinohara, and from a full wave simulation are in strong agreement. The PTEs, when using the same size resonators and antennas are compared by considering the distance between the receiver and transmitter. The compared results show that the MR WPT PTE is higher than that of the RF WPT PTE when the distance (r) between the resonators (or antennas) is shorter. However, the RF WPT PTE is much higher than that of the MR WPT PTE when the distance (r) between the resonators (or antennas) is longer since the RF WPT PTE is proportional to r^{-2} while the MR WPT PTE is proportional to r^{-6}.

Key Words: Magnetic Resonance Wireless Power Transmission, Radio Frequency Wireless Power Transmission.

I. Introduction

Wireless power transmission (WPT) the transmission of energy across free space without the use of wires has received considerable attention because this technology could be applied for the next IT products such as wearable displays and internet of things (IoT) devices. Magnetic resonance (MR) WPT makes use of the strong magnetic coupling in the near-field region. It consists of two resonators, one for the transmitter and the other for the receiver, which operate at the same resonant frequency.

MR WPT systems can transfer energy over a longer distance than magnetic induction (MI) WPT systems.

However, the power transfer efficiency (PTE) of MR WPT dramatically decrease with increasing distance. Thus, it still has limitations when in longer distance power transfer is required.

Radio-frequency (RF) WPT has become an alternative solution for longer distance power transfer. Thus, the RF WPT is actively being developed [1–3]. Even though RF WPT is capable of transmitting power over longer distances, there has been no quantitative comparison between the PTEs of MR WPT and RF WPT to date. In this paper, the PTEs of MR WPT and RF WPT are compared as a function of the distances be-

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tween the resonators (or antennas) when the areas of the antennas and the resonators are the same. It is expected that this comparative study will provide guidelines on selecting a more efficient WPT method depending on the applications.

II. THEORY OF MR AND RF WPT PTE

As shown in Fig. 1, the MR WPT model is considered as an equivalent circuit comprising of a 2-resonators systems, which means that the primary loop is a transmitter and the secondary loop is a receiver.

The MR WPT PTE (η) at a specific resonant frequency is given by [4]:

$$\eta = \frac{P_L}{P_{in}} = \frac{R_L\omega^2 M^2}{(R_2+R_L)(R_1(R_2+R_L)+\omega^2 M^2)}\ , \tag{1}$$

where P_{in} is the accepted power, P_L is the load power, ω is the angular frequency, R_1 and R_2 are the resistances of the transmitting and receiving resonators, respectively. M is the mutual inductance between the resonators and R_L is the load resistance that is determined in terms of maximum efficiency as follows:

$$R_L = R_2\sqrt{\frac{\omega^2 M^2}{R_1 R_2}+1}. \tag{2}$$

The maximum PTE can be achieved by substituting Eq. (2) with Eq. (1). Then, the PTE is a function of R_1, R_2, M, and ω, as $\eta = f(R_1, R_2, M, \omega)$. The resistance of the resonators is given by [5]:

$$R = \frac{L}{\sigma}\left(\frac{1}{wt}+\frac{1}{2\delta(t+w)}\right), \tag{3}$$

where σ is the conductivity of the resonator, δ is the skin depth, w, t, and L are the width, height, and the total length of the wire, respectively. The mutual inductance of the circle loop resonator is given by [6]:

$$M = \frac{\mu\pi a^2 b^2}{2(b^2+r^2)^{3/2}}, \tag{4}$$

where σ is the permeability, a is the radius of the transmittting resonator, b is the radius of the receiving resonator, and r is the distance between the resonators. The mutual inductance is proportional to r^{-3}. Thus, the PTE is reduced proportionally to r^{-6} when $R_1(R_2+R_L)$ is much larger than ω^2M^2 in Eq. (1) is at a longer distance.

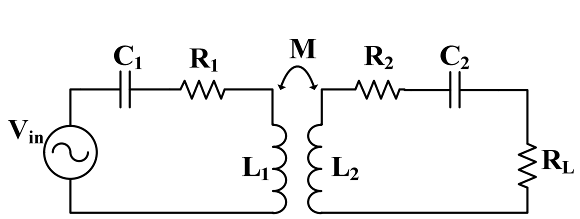

Fig. 1. Equivalent 2-resonator circuit for magnetic resonance wireless power transmission.

On the other hand, the RF WPT PTE can be obtained by the Friis equation, as follows [7]:

$$\eta = \frac{P_{RX}}{P_{TX}} = G_{TX}G_{RX}\left(\frac{\lambda}{4\pi r}\right)^2, \tag{5}$$

where P_{TX} and P_{RX} are the power of the transmitting and the receiving antennas, respectively. G_{TX} and G_{RX} are the gain of the transmitting and the receiving antenna, respectively. λ is the wavelength and r is the distance between the antennas. Note that the PTE is proportional to r^{-2}. However, the Friis equation is valid in the far-field region because the equation is derived base on the assumption of plane waves. Thus, it cannot be applied in the near-field region. In [8], the modified equation for the PTE (η) in the near-field was introduced as follows:

$$\tau^2 = \left(\frac{\lambda}{4\pi r}\right)^2 G_{TX}G_{RX}, \tag{6}$$

$$\eta = \frac{P_{RX}}{P_{TX}} = 1 - e^{-\tau^2}. \tag{7}$$

Eq. (7) can thus be used to estimate the PTE in the near-field region of RF WPT.

III. COMPARISON BETWEEN MR AND RF WPT PTE

To compare the MR WPT and RF WPT PTEs, the PTEs for the same size of antennas and resonators of 38 mm × 36 mm × 1.6 mm are shown in Fig. 2 since the PTE is strongly dependent on the size of the antenna (or resonator). Fig. 2(a) shows the configuration of the resonators for MR WPT. The resonator consists of a loop and a capacitor (11.3 μF) in series. Fig. 2(b) shows the configuration of the patch antennas for RF WPT.

Fig. 3 compares the calculated and simulated PTEs for both MR WPT and RF WPT as a function of distance and at frequencies of 6.78 MHz and 5.8 GHz, respectively. The calculated MR WPT PTE result is given by Eqs. (1)–(4) when the diameter of the circle loop ($2a$ and $2b$ in Eq. (4)) is 37 mm and when both the width and the height of the wire (t and w in Eq. (3)) are the same in the simulation structure. The calculated RF WPT PTE results are given by Eqs. (5)–(7). The gain (G_{TX} and G_{RX} in Eqs. (5) and (6)) is 6.3678 dBi and is determined based on the theory whereby it is dependent on the antenna size [9] and is calculated as $4\pi ab/\lambda^2$, where a and b are the width and length of the antenna, respectively, which are the same in the simulation structure. The Friis equation (Eq. (5)) is used in the far-field region and the equation of [8] (Eq. (7)) is used in the near-field region. The far-field and near-field boundary is 10.6 cm, which is given by $2D^2/\lambda$, where D is the diameter of the antenna.

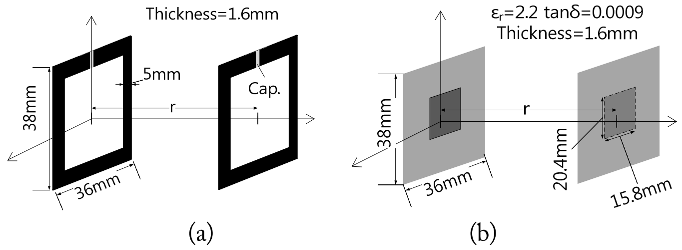

Fig. 2. Configuration of (a) resonators for magnetic resonance wireless power transmission (WPT) and (b) patch antennas for RF WPT.

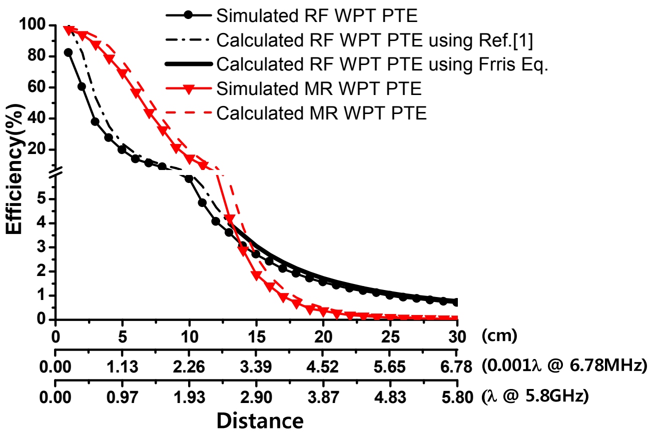

Fig. 3. Comparison between magnetic resonance and RF wireless power transmission (WPT) the power transfer efficiencies (PTEs) as a function of distance.

As shown in the calculated and simulated results in Fig. 3, the MR WPT method is better than the RF WPT method for a short distance of 14–15 cm. However, the RF WPT method has better PTE over longer distances, since the MR WPT PTE is proportional to r^{-6} and the RF WPT PTE is to r^{-2} in the far-field condition. The theoretical PTE calculation is verified by a full wave simulation (HFSS). Both the calculated and simulated PTEs show good agreement.

IV. Conclusion

This paper presents comparisons of MR and RF WPT PTEs as a function of distance. The PTEs were estimated both through theory and simulation. The theory predicts that the RF WPT PTE is proportional to r^{-2} while the MR WPT PTE is proportional to r^{-6}. Therefore, the MR WPT PTE is higher than that of the RF WPT PTE when the distance (r) between the resonators (or antennas) is shorter. However, the RF WPT PTE is much higher than the MR WPT PTE when the distance (r) between the resonators (or antennas) is longer. Thus, RF WPT has the advantage over longer distances. This comparison was verified via the simulated results for the MR WPT PTE and RF WPT PTE when the same sized resonators and antennas were used. Thus RF WPT would appear to be more useful for longer distance WPT such as in IoT applications.

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