Electromagnetic Radiated Emissions from a Wireless Power Transfer System using a Resonant Magnetic Field Coupling

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Abstract—Wireless power transfer technologies have been extensively researched for several decades and successfully deployed on a commercial scale. As studies on wireless power transfer technologies have progressed and its feasibility has been tested, electromagnetic radiated emissions have become more important subject than before. In this paper, we report the measurement and analysis of the electromagnetic radiated emissions from a wireless power transfer system using a resonant magnetic field. In this research, a relationship between the coil resonance and the transferred power are analyzed with respect to the impedance profile obtained from analytical expressions, simulations and measurements. As a result, it was demonstrated that the electromagnetic radiated emissions are enhanced at the series resonance peaks of the impedance profile in a wireless power transfer system using a resonant magnetic field coupling in the case of a constant-voltage AC source.

Keywords—electromagnetic radiated emission; resonance; transferred power; wireless power transfer

I. INTRODUCTION

Recently, many productive publications on wireless power transfer technologies have produced a dramatic increase in the attention given to wireless power transfer systems [1]. This resurgence has led to commercialization of many wireless power products including mobile electronic chargers [2]. However, as many studies on the wireless power transfer have progressed and people have begun to test the feasibility of this technology, electromagnetic radiated emissions, which have not been yet researched, have become much more important subject than before [3]. It could be the greatest obstacle to the commercialization with wireless power transfer technologies.

In the power transfer systems, through previous studies, the resonance was majorly used in order to maximize power transfer efficiency [4]. However, in cases, such as a tight magnetic coupling, a resonance peak is divided into several different peaks [5]. As a result, the transferred power changes, and these changes induce changes of the electromagnetic radiated emissions. In particular, when the harmonics of the voltage and current in the power electronics system coincide with a coil resonance, they can generate the electromagnetic radiated emissions of a significant magnitude. If the frequencies of the electromagnetic radiated emissions matches the operating frequency of other electronic devices or internal chips in the system, the emissions can cause numerous electromagnetic interference problems [6]. In spite of this problematic issues, most studies on the wireless power transfer technology have still mainly concentrated on maximizing the power charging distance while trying to maintain good transfer efficiency. In addition, there are a small number of limited studies on reducing the effects on the human body. However the electromagnetic radiated emissions that affect other electronic devices or internal chips in systems have been overlooked and their potential influence have not been sufficiently estimated.

In this paper, we report the measurement and analysis of the electromagnetic radiated emissions from a wireless power transfer system using a resonant magnetic field coupling. A relationship between the resonances and the electromagnetic radiated emission of the wireless power transfer system using the resonant magnetic field coupling is successfully investigated. In this research, the resonance peaks and the transferred power of the system are analyzed with respect to the impedance profile for analytical expression derivations, simulations and measurements. We measure the electromagnetic radiated emissions using a loop antenna in combination with a vector network analyzer. We have successfully found the relationship between the resonances and the electromagnetic radiated emission of the resonant wireless power transfer system.

II. RESONANCE AND TRANSFERRED POWER OF THE RESONANT WIRELESS POWER TRANSFER SYSTEM

Wireless power transfer, by its definition, is the transmission of an electrical energy from a power source to an electrical load without intentional interconnecting wires or conductors. Using the magnetic field in a wireless power transfer system has an advantage of high power transfer efficiency with a tight coupling. To minimize the magnitude of the reactance of the coupled coil system, and to maximize the transferred power between the magnetically coupled coils, the
magnetic field resonance is employed with tuning capacitors in a resonant wireless power transfer system.

The resonance peaks have high relationships not only with the transferred power and efficiency, but with the electromagnetic radiated emission in a resonant wireless power transfer system using a magnetic field coupling. Accordingly, we need to investigate the relationship between the resonances, the transferred power and the electromagnetic radiated emission. We analyze the resonance peaks of the input impedance of the coupled coil system and the transferred power in the resonant wireless power transfer system using analytical expressions, simulations and measurements.

A. Analytical Expressions

To derive analytical expressions for the input impedance and the transferred power, a simplified equivalent circuit model of the resonant wireless power transfer system is presented, as shown in Fig. 1. The system consists of the transmitting coil and the receiving coil, which are coupled through mutually coupled magnetic field. When an AC source excites a transmitting coil $L_S$, a magnetic coupling ($k$ is the magnetic coupling coefficient, $0<k<1$) is formed between the transmitting coil $L_S$ and the receiving coil $L_R$. $M$ is the mutual inductance. The tuning capacitors $C_S$ and $C_R$ are connected in series to the coils $L_S$ and $L_R$, respectively, to produce the magnetic field resonance. $R_S$ includes the internal resistance of the source and coil, and $R_L$ includes the coil and load resistance.

![Simplified equivalent circuit model of the resonant wireless power transfer system.](image_url)

The equation of the input impedance is derived based on the simplified equivalent circuit model. The analytical expression for the input impedance $Z_{II}$ can be described by

$$Z_{II} = \left( \frac{j\omega C_S R_L + 1 - \omega^2 L_S C_S}{j\omega C_S} \right) \left( \frac{j\omega C_R R_S + 1 - \omega^2 L_R C_R}{j\omega C_R} \right) \omega^2 M^2 C_S C_R (1)$$

Then, the resonance frequencies of the input impedance in the system can be derived from (1). $R_S$ and $R_L$ are neglected to simplify the calculations of the resonance frequencies. The input impedance should be assumed to be infinity for a parallel resonance $f_s$, and the input impedance should be considered negligible for the series resonances. Therefore, the low and high frequencies of the series resonances $f_{SL,\text{resonance}}$, $f_{SR,\text{resonance}}$ at the input impedance can be expressed as follows:

$$f_{SL,\text{resonance}}(\text{when } Z_{II} = 0) = f_s = \sqrt{\frac{L_S C_S + L_S C_R + 2(1 - 2k^2)L_S C_S C_R}{2\pi(1 - k^2)L_S C_S C_R}} (2)$$

$$f_{SR,\text{resonance}}(\text{when } Z_{II} = 0) = f_s = \sqrt{\frac{L_S C_S + L_S C_R + 2(1 - 2k^2)L_S C_S C_R}{2\pi(1 - k^2)L_S C_S C_R}} (3)$$

The load current $I_L$, which determines the transferred power $(P_L = I_L^2 V_S)$, is derived based on a simplified equivalent circuit model with a constant-voltage AC source. The load current $I_L$ is described as

$$I_L = \frac{-j\omega^2 M^2 C_S C_R}{(j\omega C_S) R_L + 1 - \omega^2 L_S C_S (j\omega C_S) R_S + 1 - \omega^2 L_R C_R - \omega^2 M^2 C_S C_R V_S} (4)$$

The transferred power is becoming maximum when the load current $I_L$ is maximized. $R_S$ and $R_L$ are neglected to simplify the calculations of the frequencies that maximize the load current. The parameters of $f_{SL,\text{power}}, f_{SR,\text{power}}$ mean the low and high frequencies of the maximized transferred power for a constant-voltage AC source in the system. These frequencies can be calculated from (4), and they are expressed as follows:

$$f_{SL,\text{power}}(\text{when } I_L = \infty) = f_s = \sqrt{\frac{L_S C_S + L_S C_R + 2(1 - 2k^2)L_S C_S C_R}{2\pi(1 - k^2)L_S C_S C_R}} (5)$$

$$f_{SR,\text{power}}(\text{when } I_L = \infty) = f_s = \sqrt{\frac{L_S C_S + L_S C_R + 2(1 - 2k^2)L_S C_S C_R}{2\pi(1 - k^2)L_S C_S C_R}} (6)$$

These expressions show that the frequencies of the maximum transferred power given in (5), (6) coincide with the series resonance frequencies of the input impedance equation in (2), (3). It means that the transferred power is maximized at the series resonance peaks of the input impedance for a constant-voltage AC source in the resonant wireless power transfer system.

B. Experimental Verification

To verify the relationship between the resonances and the transferred power, we have investigated the analytical expressions in (2), (3), (5) and (6). Test vehicles of coupled rectangular coils were fabricated on multi-layer printed circuit boards, which have advantages of high reproducibility and reliability for the manufactured products. The test vehicles designed, which consist of transmitting and receiving coils, as
shown in Fig. 2. It has an outer size of 3 cm by 3 cm, a line width of 0.5 mm, a line space of 0.2 mm and a line thickness of 0.018 mm. The coil has a total of 40 turn, which consist of 10 turn at each layer. All of the coils were designed to pursue target applications in mobile devices.

Transmitting/Receiving Coil

![Coil Diagram](image)

Table I: Frequency Parameter Values of the Resonant Wireless Power Transfer System with a Ferrite Plate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantity</th>
<th>Analytical Expression</th>
<th>Model Simulation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{LS}$</td>
<td>$f_{LS}$</td>
<td>315 kHz</td>
<td>310 kHz</td>
<td>318 kHz</td>
</tr>
<tr>
<td>$f_{SH}$</td>
<td>$f_{SH}$</td>
<td>424 kHz</td>
<td>433 kHz</td>
<td>450 kHz</td>
</tr>
<tr>
<td>$f_{ML}$</td>
<td>$f_{ML}$</td>
<td>315 kHz</td>
<td>312 kHz</td>
<td>320 kHz</td>
</tr>
<tr>
<td>$f_{SL}$</td>
<td>$f_{SL}$</td>
<td>424 kHz</td>
<td>429 kHz</td>
<td>446 kHz</td>
</tr>
</tbody>
</table>

The frequency parameter values of the resonant wireless power transfer system obtained from the analytical expressions, circuit model simulations and measurements are presented in Table I. The series resonance peaks of the input impedance predicted from the analytical expressions have a good correspondence with the circuit model simulation and the measurement results. The differences among the analytical expressions, the simulation and the measurement results caused by the ±10% tolerance in the capacitance of the tuning capacitors connected to the test vehicles and the difference in the series parasitic resistance of the coils.

Table I shows that the frequency of the maximized transferred power predicted from the analytical expressions in (5), (6) also has a good correspondence with them. And it shows the relationship between the resonances and the transferred power in the resonant wireless power transfer system. The SPICE simulation results based on the simulated and measured Z-parameters verify that the series resonance frequencies $f_s$, $f_s$ of the input impedance coincide with the frequencies $f_s$, $f_s$ at which the transferred power is maximized in the constant-voltage AC source in the resonant wireless power transfer system.

In the case of the constant-voltage AC source, the transmitting power is increased as the input impedance decreases. Although the power transfer increases at the parallel resonance frequency, the transferred power is not increased at that frequency because the transmitting power is too small compared with that at the series resonance frequencies. Thus, the transferred power is increased at the series resonance frequencies because the input impedance is minimized at those frequencies in the constant-voltage AC source.
ELECTROMAGNETIC RADIATED EMISSIONS FROM THE RESONANT WIRELESS POWER TRANSFER SYSTEM

\( S_{21} \) is analyzed using a 2-port VNA to examine at which frequency the most electromagnetic radiated emissions are generated from the resonant wireless power transfer system. The network system for \( S \)-parameter analysis is generally excited by voltage sources, and consequently \( S_{21} \) with VNA can represent the electromagnetic radiated emissions in the case of a voltage source. The measurement for the electromagnetic radiated emission using a loop antenna is shown in Fig. 3. \( Z_{11} \) should be re-measured because the input impedance changes slightly due to the loop antenna that is used for the measurement of the electromagnetic radiated emissions. Then, we analyze the electromagnetic radiated emissions with respect to the resonances in the system.

The configuration of the coupled coils and the loop antenna is described as in Fig. 3 to measure the electromagnetic radiated emissions in the frequency domain from the system. The transmitting coil is placed 1 cm apart from the receiving coil along the z-axis, and a perpendicularly positioned loop antenna is placed at 0.3 cm away from the transmitting coil. To study electromagnetic radiated emissions, the S-parameters are measured from 30 kHz to 2 MHz using a 2-port VNA while the transmitting coil and loop antenna are connected to port 1 and port 2 of the VNA, respectively. The same coils as shown in Fig. 2 are used for the transmitting and receiving coils with a ferrite plate, and the receiving coil is a closed loop with a load resistance of \( R_L = 5 \, \Omega \).

Fig. 4 shows the relationship between the resonance of the input impedance (dashed line) and the electromagnetic radiated emissions (solid line) from the system. The relationship between the series resonance frequencies \( f_2, f_3 \) and the electromagnetic radiated emissions from the resonant wireless power transfer system is demonstrated in Fig. 4. Below 100 kHz, the electromagnetic radiated emissions are not reliable due to the lack of the low antenna gain. Although the input impedance of the system changes because of the presence of the loop antenna, this change is negligible. It is proved that the series resonance frequencies of the input impedance coincide with the frequencies at which the electromagnetic radiated emissions from the system have maximum peaks in the constant-voltage AC source.

This result has a mechanism similar to the result obtained from the relationship between the resonances and the transferred power in (2), (3), (5) and (6). Basically, in the case of a constant-voltage or current AC source, the input power of source is determined by the input impedance of the mutual-coupled coils. The magnitude of the electromagnetic radiated emissions also behaves as the transferred power when the transmitting power is increased. The electromagnetic radiated emissions from the receiving coil are increased by this increased transferred power. It leads to the increased total magnitude of the electromagnetic radiated emissions. That is to say that the magnitude of the electromagnetic radiated emissions is increased when the input impedance is decreased in the case of a constant-voltage AC source at \( f_2, f_3 \). In the case of a constant-current AC source, which is not considered in this paper, the magnitude of the electromagnetic radiated emissions is increased when the input impedance is increased near the bandwidth of the resonance peak at \( f_1 \).

In this paper, we measured and analyzed the electromagnetic radiated emissions from the wireless power transfer system using a resonant magnetic field coupling. As a result, we have successfully demonstrated the relationship between the resonance peaks at the input impedance curve measured from the coupled coil input port and the electromagnetic radiated emission measurement obtained from the resonant wireless power transfer system. This research experimentally verified that the series resonance frequencies at the impedance profile coincide with the frequencies at which the transferred power and the electromagnetic radiated emissions are becoming maximized when using constant-voltage AC source in the resonant wireless power transfer system. This result can be further applied to the reduction of the problems associated with the electromagnetic radiated emissions when designing the wireless power transfer system.

REFERENCES