Minimizing Method of Leakage Magnetic Field in Wireless Power Transfer Systems for Electric Vehicles

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ABSTRACT: In this paper, a method for minimizing the leakage magnetic field is proposed from wireless power transfer (WPT) systems that employs the series-series (SS) compensation networks through finding the optimal resonant frequency of RX. Conventional shielding methods need additional materials, power source or shielding coil, but this method can suppress the leakage magnetic field without any additional materials. So, the proposed method is suitable for weight-limited or size-limited WPT systems. Lastly, the proposed method is verified through simulation.

KEY WORDS: wireless power transfer, leakage magnetic field, electric vehicle

1. INTRODUCTION

Due to the development of electrical energy, the quality of human life has improved. Using the electrical energy, we can use many applications from low-power to high-power products. The conventional charging method for these applications use wires, it can be uncomfortable or dangerous particularly when water is near the wires. Also, when use the wires, the aesthetics may be deteriorated. To overcome these limitations, the wireless power transfer (WPT) technology has been developed[(1)-(3)].

The WPT system can charge applications without wires, it uses the magnetic field to transfer power from transmitter (TX) to receiver (RX). During the procedure for transferring power, there are coupled magnetic field and leakage magnetic field as shown in Fig. 1. The leakage magnetic field has the possibility that affects human body. Furthermore, it may cause loss of function or malfunction for electronic devices. In the field of WPT, usually, the first term is called electromagnetic field (EMF) problem, and second term is called EMI. For commercialization of WPT technology, it is necessary to solve the EMF/EMI problems.

There are many researches to reduce the EMF/EMI as shown in Fig. 2[(4)-(7)]. First, the metallic shielding method, it uses a metallic material. When the magnetic field induces in the metallic material in the process of transferring power from TX coil to RX coil, the eddy current is generated, and magnetic field can be cancelled by the magnetic field generated by eddy current. This method has limitations in that it causes the heat and reduction in power transfer efficiency (PTE). Also, it increases cost and weight of the WPT systems. Second, the magnetic shielding method, it uses a magnetic material. The magnetic material has lower reluctance

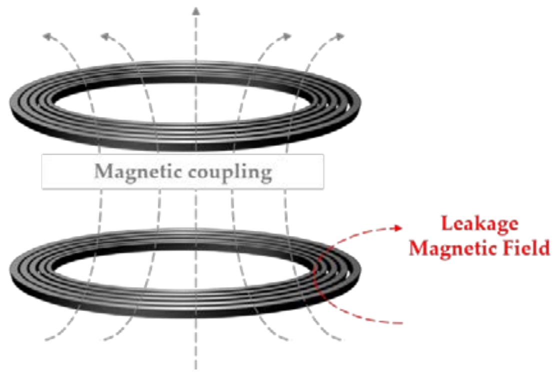


Fig. 1 Procedure of transferring power wirelessly.

than air, so the magnetic field can be guided into magnetic material. This method has limitations in that it increases the cost and weight of the WPT systems. Also, as the amount of power of WPT system increases, the magnetic material may be saturated. Third, the active shielding method uses a additional coil and power source. Using the power source such as inverter, it provides power to the shielding coil with opposite current phase of the WPT coils, it can reduce the EMF. This method has limitations in that additional power source and coil are needed, and the complexity of system can increase. Finally, the reactive shielding method uses a additional coil. When the voltage is induced at the shielding coil by the leakage magnetic field of WPT coils, then by controlling the impedance of shielding coil so that generate the opposite magnetic field, the cancellation of the leakage magnetic field can be possible. However, all the previous shielding methods need the additional materials such as the metallic, magnetic material, power source or shielding coil. As a result, the size, weight and cost of

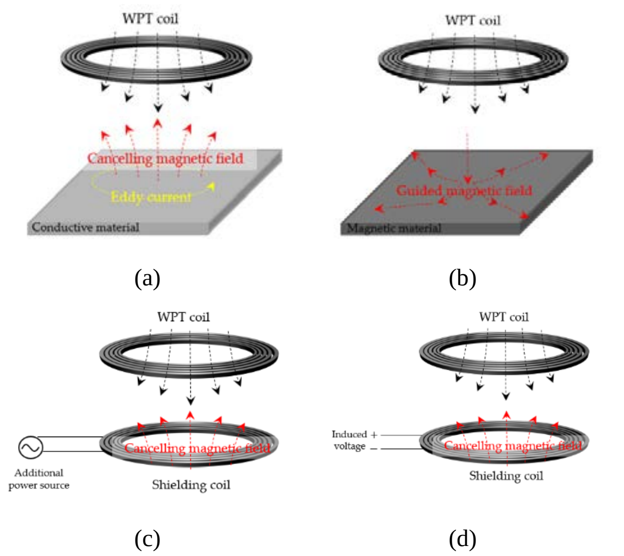


Fig. 2 Various shielding methods for reducing the EMF: (a) conductive shielding. (b) magnetic shielding. (c) active shielding. (d) reactive shielding methods.

the WPT system can be increased. To solve these problems, the method for minimizing the leakage magnetic field not using additional materials is needed.

In this research, we will propose a method for minimizing the leakage magnetic field using phase difference control between TX coil current and RX coil current without any additional materials.

This paper is arranged as follows. In Section 2, we explain the concept and method for minimizing the leakage magnetic field, and in Section 3, the proposed method is verified through simulation and experiment. Finally, in Section 4, we conclude our research.

2. METHOD FOR MINIMIZING THE LEAKAGE MAGNETIC FIELD

In Section 2, the proposed method for minimizing the leakage magnetic field will be explained more detail. Fig. 3 shows the equivalent circuit of the series-series (SS) compensation network in the WPT system. When applying KVL in the RX side, the $\mathbf{I_{RX}}$ can be expressed as in Equation (1).

$$\mathbf{I_{RX}}= \frac{-j\omega_o M_{TX-RX}}{R_{RX}+R_L+jX_{RX}}\mathbf{I_{TX}} \cong \frac{-j\omega_o M_{TX-RX}}{R_L+jX_{RX}}\mathbf{I_{TX}}= \frac{\omega_o M_{TX-RX}}{\sqrt{{R_L}^2+{X_{RX}}^2}} I_{TX}\angle\left(-\frac{\pi}{2}-\tan^{-1}\frac{X_{RX}}{R_L}\right) \tag{1}$$

Where the ω_o is the operating frequency of the WPT system and the X_{RX} is the reactance component in the RX side which value is $\frac{{\omega_o}^2 L_{RX}C_{RX}-1}{\omega_o C_{RX}}$. When X_{RX} is equal to zero, the phase difference between $\mathbf{I_{TX}}$ and $\mathbf{I_{RX}}$ is 90°.And, when X_{RX} has the negative value, the phase difference between $\mathbf{I_{TX}}$ and $\mathbf{I_{RX}}$ is 0°~90°, and when X_{RX} has the positive value, the phase difference between $\mathbf{I_{TX}}$ and $\mathbf{I_{RX}}$ is

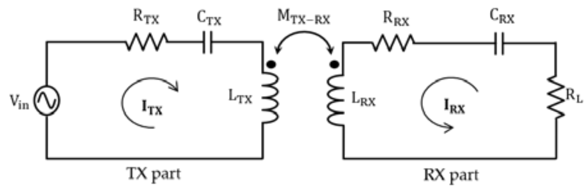
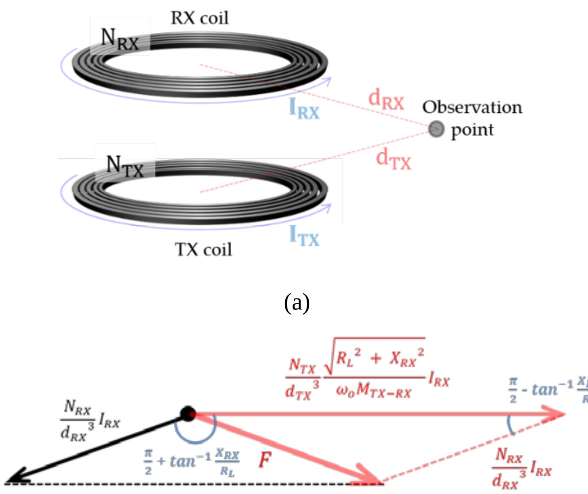


Fig. 3 The series-series compensation network in the WPT system.



(b)

Fig. 4 The magnetic field strength: (a) magnetic field at the observation point. (b) the vector diagram in Equation (2).

90°~180°. To reduce the leakage magnetic field, the phase difference between $\mathbf{I_{TX}}$ and $\mathbf{I_{RX}}$ should be 90°~180°. Meanwhile, the magnetic field strength is proportional to the number of turns (N_{TX}, N_{RX}) and the current ($\mathbf{I_{TX}}$, $\mathbf{I_{RX}}$), and inversely proportional to the distance between the observation point and the center of each coil (d_{TX}, d_{RX}) as shown in Fig. 4(a). That relationship is expressed as in Equation (2).

$$|\mathbf{B_{total}}|= |\mathbf{B_{TX}}+\mathbf{B_{RX}}| \propto \left|\frac{N_{TX}\mathbf{I_{TX}}}{{d_{TX}}^3}+\frac{N_{RX}\mathbf{I_{RX}}}{{d_{RX}}^3}\right|= F \tag{2}$$

The objective of the proposed method is to minimize the magnetic field as expressed in Equation (2). To find the optimum value for minimizing the leakage magnetic field, we should define the relationship between $\mathbf{I_{TX}}$ and $\mathbf{I_{RX}}$. $\mathbf{I_{RX}}$ can be expressed in Equation (3).

$$\mathbf{I_{RX}}= I_{RX}\angle\left(-\frac{\pi}{2}-\tan^{-1}\frac{X_{RX}}{R_L}\right) \tag{3}$$

For comparing the leakage magnetic field with the same output power, we assume the I_{RX} is constant value. After defining the $\mathbf{I_{RX}}$, we can define $\mathbf{I_{TX}}$ as the Equation (4) with referring to Equation (1).

$$\mathbf{I_{TX}}= \frac{\sqrt{{R_L}^2+{X_{RX}}^2}}{\omega_o M_{TX-RX}} I_{RX}\angle 0 \tag{4}$$

As a result, the total magnetic field strength in Equation (2) can be expressed as in Equation (5) as expressed in Fig. 4.

$$F^2 = I_{RX}{}^2\left(\frac{N_{TX}{}^2}{d_{TX}{}^6}\frac{X_{RX}{}^2+R_L{}^2}{\omega_o{}^2 M_{TX-RX}{}^2} + \frac{N_{RX}{}^2}{d_{RX}{}^6} - 2\frac{N_{TX}N_{RX}}{d_{TX}{}^3 d_{RX}{}^3}\frac{X_{RX}}{\omega_o M_{TX-RX}}\right) \quad (5)$$

The F^2 is the quadratic function with respect to X_{RX}. So when the F^2 is differentiate with respect to X_{RX}, we can find the optimal X_{RX} for minimizing the leakage magnetic field as expressed in Equation (6).

$$\frac{dF^2}{dX_{RX}} = I_{RX}{}^2\left(2\frac{N_{TX}{}^2}{d_{TX}{}^6}\frac{X_{RX}}{\omega_o{}^2 M_{TX-RX}{}^2} - 2\frac{N_{TX}N_{RX}}{d_{TX}{}^3 d_{RX}{}^3}\frac{1}{\omega_o M_{TX-RX}}\right) = 0, \quad (6)$$
$$X_{RX} = \frac{N_{RX}}{N_{TX}}\left(\frac{d_{TX}}{d_{RX}}\right)^3 \omega_o M_{TX-RX}$$

As shown in Equation (6), proposed method can be applied many applications such as electric vehicles (EVs) and automated guided vehicles that have difference in N_{TX} and N_{RX} or d_{TX} and d_{RX}. And, this method only can be applied to resonant WPT systems because the phase difference between $\mathbf{I_{TX}}$ and $\mathbf{I_{RX}}$ can be adjustable using the resonant capacitor.

When applying the proposed method, we also should consider PTE. PTE is defined as the ratio of the input power and output power shown in Fig. 3, and can be calculated as in Equation (7).

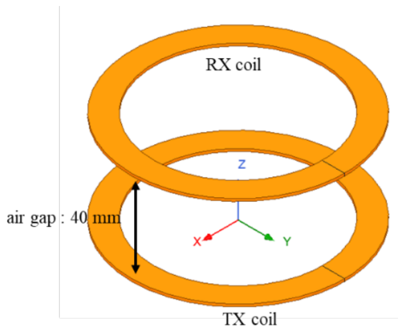
$$\text{PTE} = \frac{P_{out}}{P_{in}} = \frac{\omega_o{}^2 M_{TX-RX}{}^2 R_L}{R_{TX}(X_{RX}{}^2+(R_{RX}+R_L)^2)+\omega_o{}^2 M_{TX-RX}{}^2(R_{RX}+R_L)} \quad (7)$$

As shown in Equation (7), when X_{RX} exists, the PTE will decrease. But, the PTE of other shielding methods such as active and reactive shielding decrease and these methods use additional power source or coils. The proposed method has lower PTE than the conventional WPT system that X_{RX} is 0, but this method can minimize the leakage magnetic field through tuning the resonant capacitor of RX.

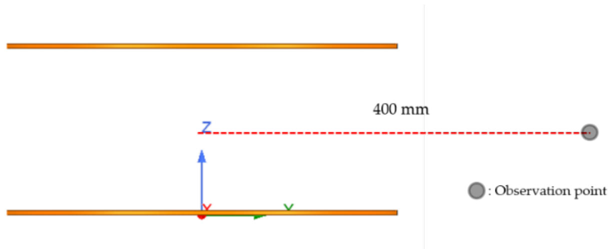
In section 2, we proposed the method for minimizing the leakage magnetic field through finding the optimal X_{RX} values.

3. VERIFICATIONS THROUGH SIMULATIONS

In section 3, we will verity the proposed method through the simulations. Fig. 5 shows the 3D EM simulation setup using the ANSYS Maxwell. As shown in Fig. 5(a) the air gap between the TX coil and RX coil was set to 40 mm, and as shown in Fig. 5(b) the leakage magnetic field was extracted away 400 mm from the center of the coil. In table 1, the inductance of the Tx and RX (L_{TX}, L_{RX}) and mutual inductance (M_{TX-RX}) between the TX and RX coils is expressed. Before explaining the simulation results, the characteristics of the shielding performance should be explained. When referring to the Equation (3) and Equation (4), the phase difference between $\mathbf{I_{TX}}$ and $\mathbf{I_{RX}}$ can be calculated as in Equation



(a)



(b)

Fig. 5 Simulation setup: (a) the aerial view. (b) measurement setup for extracting the EMF

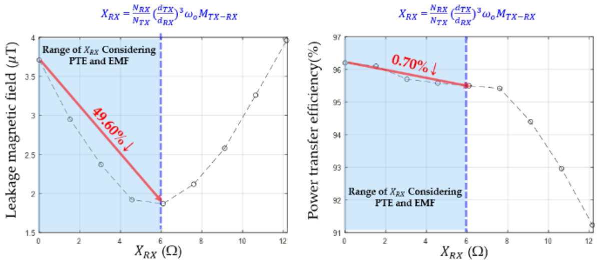
Table 1. Electrical parameters of TX and RX coils

Parameters	Value
L_{TX}	32.73 μH
L_{RX}	32.73 μH
M_{TX-RX}	11.41 μH

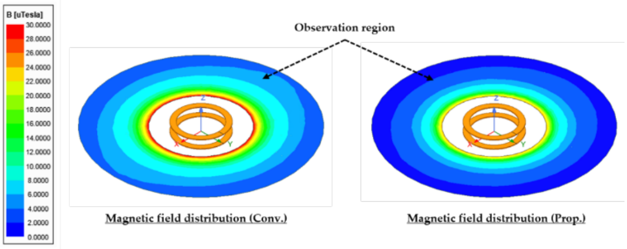
(7). In Equation (7), we define the β as the phase difference between $\mathbf{I_{TX}}$ and $\mathbf{I_{RX}}$.

$$\beta = \frac{\pi}{2} + tan^{-1}\frac{X_{RX}}{R_L} = \frac{\pi}{2} + tan^{-1}\frac{\frac{N_{RX}}{N_{TX}}\left(\frac{d_{TX}}{d_{RX}}\right)^3\omega_o M_{TX-RX}}{R_L} \quad (8)$$

As can be seen in the Equation (8), when N_{TX}, N_{RX}, d_{TX} and d_{RX} are fixed, the lower R_L, and the higher M_{TX-RX}, the shielding performance will increase. So, the proposed method is suitable for the WPT system with small R_L or with small air gap. In Fig. 6 (a), the shielding performance and the power transfer efficiency was compared between the conventional and proposed method. The shielding performance of the proposed method is 49.60% with 0.7% reduction in efficiency. And, as shown in the Fig. 6(b), the color map is the same between the conventional and proposed WPT systems, and the leakage magnetic field of the proposed system is lower than that of the conventional system as shown in the spatial distribution. Through simulation, the proposed method can reduce the leakage magnetic field without any additional materials through finding the optimal X_{RX} value.



(a)



(b)

Fig. 6 Simulation results of the conventional and proposed WPT systems: (a) the leakage magnetic field and PTE. (b) magnetic field distribution.

4. CONCLUSION

In this paper, we proposed a method for minimizing the leakage magnetic field through adjusting the phase difference between $\mathbf{I}_{\mathbf{TX}}$ and $\mathbf{I}_{\mathbf{RX}}$, and the optimal X_{RX} value was calculated. The proposed method was verified through simulations. The proposed WPT system can reduce the leakage magnetic field without any additional materials, so it is suitable for space-limited or weight-limited WPT systems.

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