Theorization of a Compatible Method for Far-field Leakage Magnetic Field Reduction and High Efficiency Power Transfer Using Adjacent Transfer Coil in Dynamic Wireless Power Transfer

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***Abstract*— In order to put dynamic wireless power transfer into practical use, it is necessary to reduce the leakage magnetic field, which has adverse effects on the human body and electronic devices, below the regulated value. At the same time, it is necessary to achieve high efficiency power transfer to utilize energy effectively. In this paper, the far-field leakage magnetic field at 10 m from the reference is reduced below the regulated value without adding any devices that are not necessary for power transfer by setting the input voltage to the adjacent transfer coil in the direction of the electric vehicle to be appropriate for the transfer coil that is supplying power. It is shown that the power transfer efficiency, including adjacent transfer coils, can be increased to more than 95 % without any additional equipment that is not required. This method is applicable to the case where S-S, Double-LCC, or LCC-S is used as the resonance method of the circuit, and the leakage magnetic field can be reduced to a maximum of 0.7 mA/m or less with 20 kW of receiving power in any resonance method. The effectiveness of this method is confirmed by theoretical calculations and electromagnetic field analysis using the method of moments.**

Keywords*— *Dynamic Wireless Power Transfer, Leakage Magnetic Field, EMF, Transfer Efficiency

I. INTRODUCTION

Dynamic wireless power transfer is a technology that transmits electric power to electric vehicles traveling on a feeding road. This technology can change the current situation where electric vehicles are considered effective in improving global environmental problems but are not becoming more widely used. One of the problems facing electric vehicles is how to charge them. Currently, electric vehicles are generally recharged by plugging them in, but this requires a longer time than refueling internal combustion engine vehicles. Electric vehicles are also significantly inferior in terms of cruising range. Dynamic wireless power transfer solve these two problems simultaneously. On the other hand, there are still some problems to be solved for the practical application of dynamic wireless power transfer. Leakage magnetic field and power transfer efficiency are typical examples. Leakage magnetic fields have adverse effects on the human body and electronic equipment, and must be reduced to below the regulated values specified by CISPR and ICNIRP. It is also important to improve power transfer efficiency in order to use limited energy effectively.

The leakage magnetic field reduction methods proposed so far can be roughly classified into two types: active shielding [1]-[5] and passive shielding [6][7]. Active shielding is a method in which a magnetic field-reducing coil including a power supply is added around the transfer coil, and the magnetic field generated by the coil cancels the leakage magnetic field. This method can effectively reduce leakage magnetic fields. However, the power transfer efficiency is generally lowered due to the need of input to the magnetic field reduction coil. In the previous studies[1][2], it is shown that power transfer efficiency can be increased while reducing the near-field leakage magnetic field by using coils not used for power transfer on the left and right sides. In the previous study[3], the far-field leakage magnetic field reduction is performed by changing the positional relationship between the transfer coils and the receiving coils in a situation where there are two transfer coils and two receiving coils, respectively.

In this paper, far-field leakage magnetic fields generated at a distance of 10 m during wireless power transfer in the presence of two transfer coils and one receiving coil are reduced by adjusting the input voltage to the adjacent transfer coil in the direction of the electric vehicle with respect to the transfer coil that is feeding power to the vehicle. At the same time, a power transfer efficiency of more than 95 % including the transfer coils used for the leakage magnetic field reduction is shown to be possible. It is also shown that the above conditions are possible when S-S, Double-LCC, or LCC-S is used as the resonance method of the circuit. The verification is performed by theoretical calculations and electromagnetic field analysis. Theoretical calculations were performed using only the coil design values and input voltages by converting the wireless power transfer system into an equivalent circuit. While the electromagnetic field analysis is time-consuming and requires a powerful PC, the theoretical calculations can be performed on an ordinary notebook PC, which facilitates the system design.

II. OVERVIEW OF ADJACENT TRANSFER COILS

In this paper, a magnetic resonance method is used as a wireless power transfer method. Each coil is an air-core coil without magnetic materials such as ferrite. It is assumed that all transfer coils are the same and are installed on the roadway at intervals of 50 % in a straight line. In this situation, the adjacent transfer coil is defined as the one adjacent to the transfer coil that is transmitting power to the receiving coil installed in the electric vehicle in the direction of travel. Since they are the same transfer coils, they can transmit power when the receiving coil approaches, and the

Fig.1 Diagram of adjacent transfer coils

transfer coil one ahead of the receiving coil becomes the new adjacent transfer coil to reduce the leakage magnetic field.

III. Theoretical Formulae

First, the method for obtaining the magnitude and phase of the current flowing through each coil, which is used in the calculation of leakage magnetic field and power transfer efficiency is shown below. Fig.2 shows the equivalent circuit diagram of a LCC-S circuit with two transfer coils and one receiving coil. The power transfer coil is L_{Tx1}, the adjacent transfer coil is L_{Tx2}, and the receiving coil is L_{Rx}. V_1 and V_2 are the voltages applied to the transfer coil and the adjacent transfer coil respectively, and R_L is the load attached to the receiving coil. L_{0Tx1} and L_{0Tx2} are resonant inductors, C_{Tx1s}, C_{Tx2s} and C_{Rx} are series capacitors, and C_{Tx1p} and C_{Tx2p} are parallel capacitors. The relationship between the magnitudes of each capacitor is expressed by equation (1) using the resonant angular frequency ω_0.

$$\omega_0 = \frac{1}{\sqrt{L_{0x}C_{xp}}} = \sqrt{\frac{C_{xp}+C_{xs}}{L_x C_{xp} C_{xs}}} (x = Tx1, Tx2) = \frac{1}{\sqrt{L_{Rx}C_{Rx}}} \quad (1)$$

R_x is the internal resistance of L_x, and R_{ox} is the internal resistance of the resonant inductor L_{ox}. As for the mutual inductance, L_{ma} is between the transfer coil and the receiving coil, L_{mb} is between the adjacent transfer coil and the receiving coil, and L_{mt} is between the transfer coil and the adjacent transfer coil. These are obtained from Neumann's equation expressed in equation (2). The parameters are shown in Fig.3.

$$L_m = \frac{\mu_0}{4\pi}\oint_{C_1}\oint_{C_2}\frac{dl_1 dl_2}{D} \quad (2)$$

When all coils are in resonance, the circuit equations are expressed in matrix form as equation (3). By obtaining the inverse matrix of equation (3), the currents flowing in each coil can be derived. Since the value of each current is obtained in complex number form, its magnitude and phase can be obtained.

$$\begin{bmatrix} V_1 \\ 0 \\ V_2 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{Tx01} & j\frac{1}{\omega_0 C_{Tx1p}} & 0 & 0 & 0 \\ j\frac{1}{\omega_0 C_{Tx1p}} & R_{Tx1} & 0 & j\omega_0 L_{mt} & j\omega_0 L_{ma} \\ 0 & 0 & R_{Tx02} & j\frac{1}{\omega_o C_{Tx2p}} & 0 \\ 0 & j\omega L_{mt} & j\frac{1}{\omega_o C_{Tx2p}} & R_{Tx2} & j\omega L_{mb} \\ 0 & j\omega L_{ma} & 0 & j\omega L_{mb} & R_{Rx}+R_L \end{bmatrix} \begin{bmatrix} I_{in1} \\ I_1 \\ I_{in2} \\ I_2 \\ I_L \end{bmatrix} \quad (3)$$

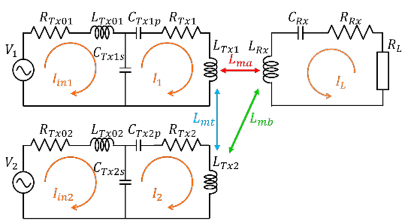

Fig.2 LCC-S equivalent circuit

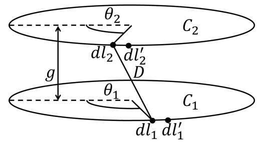

Fig.3 Parameters of the Neumann equation

The theoretical equations for determining the magnetic field and power transfer efficiency are presented below. The magnetic field is derived from the vector potential. The magnetic fields generated by the transfer coil L_{Tx1}, the adjacent transfer coil L_{Tx2}, and the receiving coil L_{Rx} to an arbitrary point $P(x,y,z)$ shown in Fig.4 are represented by equations (4), (5), and (6). Where r_{Tx1}, r_{Tx2}, and r_{Rx} are the distances to an arbitrary point P. Where the distances r_{Tx1}, r_{Tx2}, and r_{Rx} to any point P are sufficiently longer than the lengths a_k, b_k, c_k, d_k, e_k and f_k of each side.

$$H_{Tx1} = \begin{cases} H_{Tx1x} \\ H_{Tx1y} \\ H_{Tx1z} \end{cases} = \begin{cases} \frac{\sum_{k=1}^{n} a_k b_k}{4\pi}\frac{3xz}{r_{Tx1}^5} I_1 \\ \frac{\sum_{k=1}^{n} a_k b_k}{4\pi}\frac{3yz}{r_{Tx1}^5} I_1 \\ \frac{\sum_{k=1}^{n} a_k b_k}{4\pi}\frac{2z^2-x^2-y^2}{r_{Tx1}^5} I_1 \end{cases} \quad (4)$$

$$H_{Tx2} = \begin{cases} H_{Tx2x} \\ H_{Tx2y} \\ H_{Tx2z} \end{cases} = \begin{cases} \frac{\sum_{k=1}^{m} c_k d_k}{4\pi}\frac{3(x-s)z}{r_{Tx2}^5} I_2 \\ \frac{\sum_{k=1}^{m} c_k d_k}{4\pi}\frac{3yz}{r_{Tx2}^5} I_2 \\ \frac{\sum_{k=1}^{m} c_k d_k}{4\pi}\frac{2z^2-(x-s)^2-y^2}{r_{Tx2}^5} I_2 \end{cases} \quad (5)$$

$$H_{Rx} = \begin{cases} H_{Rxx} \\ H_{Rxy} \\ H_{Rxz} \end{cases} = \begin{cases} \frac{\sum_{k=1}^{m} e_k f_k}{4\pi}\frac{3x(z-g)}{r_{Rx}^5} I_L \\ \frac{\sum_{k=1}^{m} e_k f_k}{4\pi}\frac{3y(z-g)}{r_{Rx}^5} I_L \\ \frac{\sum_{k=1}^{m} e_k f_k}{4\pi}\frac{2(z-g)^2-x^2-y^2}{r_{Rx}^5} I_L \end{cases} \quad (6)$$

Since I_1, I_2, and I_L have magnitude and phase the equation (7) can be expressed as follows, where I_1, I_2, and I_L are the magnitude and phase, respectively, and θ_1, θ_2, and θ_L are the phase.

$$I_x = I_x \cos\theta_x + jI_x \sin\theta_x \quad (x = 1,2,L) \quad (7)$$

I_x and θ_x can be expressed using the magnitude and phase of the input voltage and the coil design value from equation (3). The magnitude of the magnetic field H at an arbitrary point P can be derived from the composite of H_{Tx1}, H_{Tx2}, and H_{Rx}. From equations (4), (5), (6), and (7), the magnitude of the magnetic field H can be expressed by equation (8).

$$H = \sqrt{\begin{array}{l} (H_{Tx1x}\cos\theta_1 + H_{Tx2x}\cos\theta_2 + H_{Rxx}\cos\theta_L)^2 \\ +(H_{Tx1x}\sin\theta_1 + H_{Tx2x}\sin\theta_2 + H_{Rxx}\sin\theta_L)^2 \\ +(H_{Tx1y}\cos\theta_1 + H_{Tx2y}\cos\theta_2 + H_{Rxy}\cos\theta_L)^2 \\ +(H_{Tx1y}\sin\theta_1 + H_{Tx2y}\sin\theta_2 + H_{Rxy}\sin\theta_L)^2 \\ +(H_{Tx1z}\cos\theta_1 + H_{Tx2z}\cos\theta_2 + H_{Rxz}\cos\theta_L)^2 \\ +(H_{Tx1z}\sin\theta_1 + H_{Tx2z}\sin\theta_2 + H_{Rxz}\sin\theta_L)^2 \end{array}} \quad (8)$$

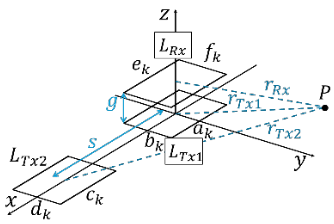

Fig.4 Parameters for magnetic field calculation

Power transfer efficiency η is expressed by equation (9) using the parameters in Fig.2.

$$\eta = \frac{R_L |I_L|^2}{|V_1||I_{in1}| + |V_2||I_{in2}|} \quad (9)$$

From the above theoretical equation, it is possible to obtain the magnitude of leakage magnetic field and power transfer efficiency from the magnitude and phase of the input voltage and the coil design value. The following is a comparison of the results of electromagnetic field analysis for the same circuit configuration and the results obtained by the theoretical equation. Fig.5 shows the magnitude of leakage magnetic field and Fig.6 shows the power transfer efficiency. The figures show the validity of the theoretical equations. The theoretical equations can also be used for SS and double-LCC circuits.

IV. Combination of Leakage Magnetic Field Reduction and High Efficiency Power Transfer

The magnitude of leakage magnetic field and power transfer efficiency are obtained using equations (8) and (9), and it is shown that leakage magnetic field reduction and high efficiency power transfer are possible by adjusting the input voltage to the adjacent transfer coils, regardless of whether the resonance method equation is SS, Double-LCC, or LCC-S. The definition of the compatibility range is as follows. The regulated value of leakage magnetic field is 13.8 mA/m (82.8 dBμA/m) as given in SAE J2954. The criterion for high power transfer efficiency is 95 % or higher. The size of each coil is the same for each resonant system, and the transfer coil is a 7turn coil of 1300×600 mm, and the receiving coil is a 16turn coil of 580×420 mm. The value of the resonant inductor in the LCC circuit is set to be the value that gives a Q value of 500. The magnitude of input voltage and load resistance for each resonance method are shown in Table 1. The magnitude of V_1 is set so that the received power is about 20 kW, and the magnitude of V_2 is set so that the leakage magnetic field can be reduced most. The magnitude of the load resistance is the maximum efficient load for each resonance scheme. The maximum efficient load is obtained by partial differentiation of equation (9) by R_L.

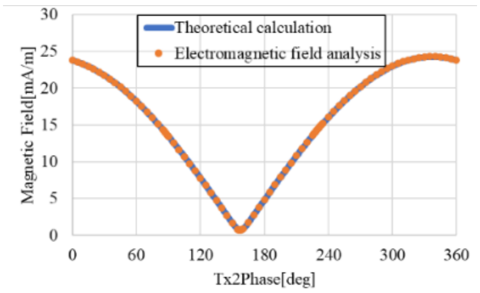

Fig.5 Comparison of leakage magnetic field

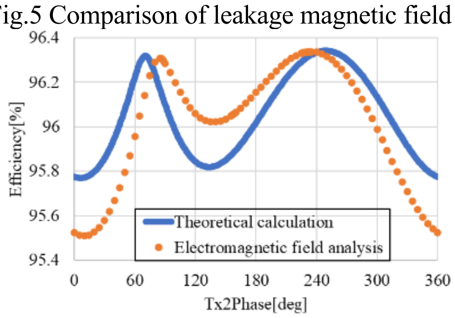

Fig.6 Comparison of power transfer efficiency

Table1 Input voltage and load resistance

	S-S	Double-LCC	LCC-S
V_1	414 V	424 V	435 V
V_2	6 V	493 V	479 V
R_L	6.24 Ω	50.60 Ω	7.35 Ω

Fig.7 shows the compatibility range when the phase of V_2 is changed in the SS circuit, Fig.8 shows the Double-LCC circuit, and Fig.9 shows the LCC-S circuit. The compatible range is the area not colored. The sizes of the vertical axes of each graph are aligned. Fig.7, 8, and 9 show that the compatibility range exists for all resonance methods. The compatible ranges are shown in Table 2. The blue areas are the ranges where the leakage magnetic field is above the regulated value, the orange areas are the ranges where the transmission efficiency is below 95%, and the striped areas are the overlapping ranges.

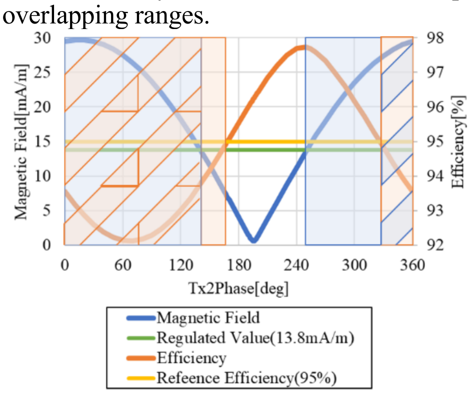

Fig.7 Compatibility range in SS circuit (V_2 phase change)

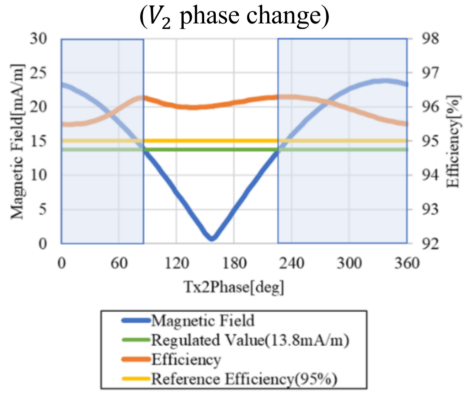

Fig.8 Compatibility range in Double-LCC circuits (V_2 phase change)

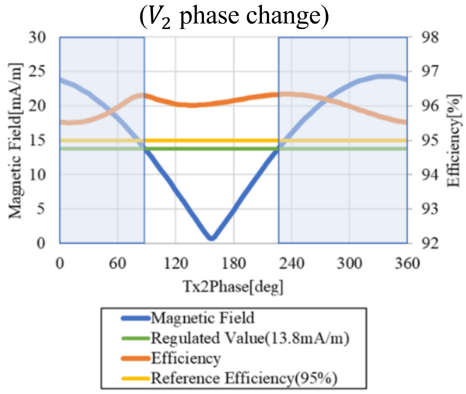

Fig.9 Compatibility range in LCC-S circuits (V_2 phase change)

Table2 Compatibility range for V_2 phase change

	S-S	Double-LCC	LCC-S
Tx2Phase	169–250 deg	86–227 deg	89-226 deg

Table 2 shows that the Double-LCC circuit has the widest compatibility range when the phase of V_2 is varied. In addition, for the Double-LCC and LCC-S circuits, there is no range where the power transfer efficiency falls below 95 % under the conditions used in this paper. In addition, the leakage magnetic field is smaller than that of the SS circuit, which indicates that the SS circuit is more compatible with this leakage magnetic field reduction method. Fig.10 shows the compatibility range of the SS circuit, Fig.11 shows the Double-LCC circuit, and Fig.12 shows the LCC-S circuit when the magnitude of V_2 is varied. V_1 and R_L are set to the values shown in Table 1, and the phase of V_2 is set to 195 deg, 156 deg, and 157 deg, respectively, which is the phase that can reduce the leakage magnetic field the most.

Fig.10, 11, and 12 show that the range of the magnitude of V_2 is wider for the LCC resonance method of the transfer coil than for the S case. This is because a large current flows in the S case but not in the LCC case due to the characteristic of the state with a small coupling coefficient k. From this

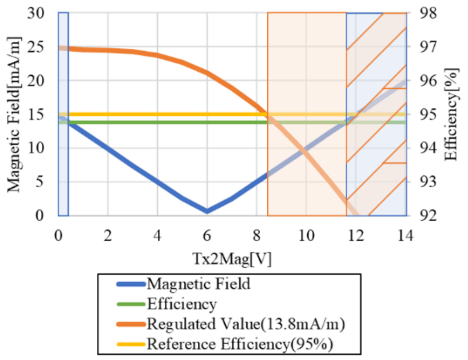

Fig.10 Compatibility range in SS circuit (V_2 magnitude change)

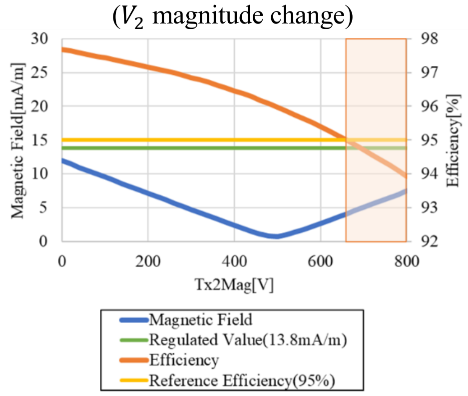

Fig.11 Compatibility range in Double-LCC circuit (V_2 magnitude change)

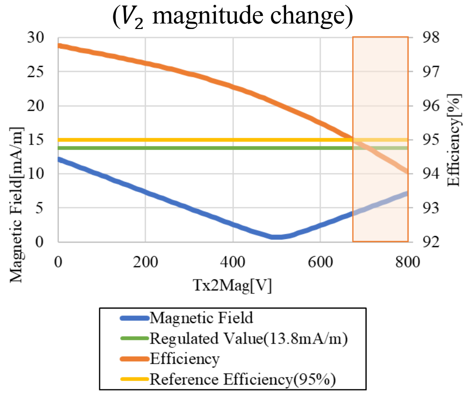

Fig.12 Compatibility range in LCC-S circuit (V_2 magnitude change)

point of view, this method is compatible with the one that uses the LCC resonant circuit on the transmission side. From the above, it can be said that this method is feasible for practical use by focusing on the voltage phase without too strict control of the magnitude of the voltage.

V. Conclusion

It is shown that the leakage magnetic field and power transfer efficiency in the LCC-S circuit of dynamic wireless power transfer systems can be obtained theoretically from the input voltage and coil design values. Theoretical calculations are faster and easier than electromagnetic field analysis. Theoretical calculations can be performed by converting the system into an equivalent circuit, and the same method can be used for SS and Double-LCC circuits.

Theoretical calculations and electromagnetic field analysis show that it is possible to reduce the leakage magnetic field to 0.7 mA/m by adjusting the input voltage to adjacent transfer coils in the direction the electric vehicle is traveling, and in doing so, it is possible to achieve both power transfer efficiency of 95% or higher and low leakage magnetic field. This method is applicable to SS, Double-LCC, and LCC-S resonant circuits.

As future work, this input voltage adjustment method will be combined with vehicle detection and control methods used in actual devices to study the overall system for dynamic wireless power transfer.

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