A Study of Leakage Magnetic Field Reduction by Active Shielding for Receiver Coil Moving in DWPT Using Air-core Coils

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***Abstract*— Leakage magnetic field reduction is one of the challenges for the practical application of DWPTs. It must be reduced because of concerns about its adverse effects on the human body and electronic equipment. In DWPT, the position of the receiver coil changes as the vehicle runs, so a reduction method corresponding to this is necessary. In this paper, the transfer coil installed next to the coil transmitting power to the EV is used as a cancel coil, and the leakage magnetic field is reduced by adjusting the magnitude and phase of the input voltage to the cancel coil according to the position of the receiver coil. The input voltage to the transfer coil is set to the value at which the received power becomes 25 kW. Using SS, LCC-S and Double-LCC as the resonance method, the leakage magnetic field could be reduced to less than the regulated value of 13.8 mA/m in the range from -770 to 800 mm with the center of the transfer coil as the origin. It was also confirmed that the transfer efficiency including the canceling coil can be over 90% for SS and LCC-S, and about 90% for Double-LCC. These were shown using theoretical equations and electromagnetic field analysis using the moment method.**

Keywords— ***Leakage Magnetic Field, Wireless Power Transfer, Reduction, EMF***

I. Introduction

DWPT (Dynamic Wireless Power Transfer) has attracted attention as a technology to facilitate the transition from internal combustion engine vehicles to electric vehicles, which is one method to solve global environmental problems [1]-[3]. Reasons for the lack of progress in the transition include the shorter range of electric vehicles compared to internal combustion engine vehicles and the time required for recharging, which can be solved by DWPT. There are various challenges to the practical application of DWPT, the leakage magnetic field problem being one of them. This refers to the magnetic field that leaks into the surroundings during wireless power transfer. It is concerned that leakage magnetic fields may have adverse effects on the human body and electronic equipment, and regulated values have been established by CISPR and ICNIRP. This is an essential technology because DWPT requires nearly 10 times more power transfer than SWPT (Static Wireless Power Transfer).

In previous studies, leakage magnetic field reduction has been carried out using active shielding [4]-[6] and passive shielding [7]-[10] for situations where the receiver coil is installed at a certain location such as directly above the transfer coil. For situations where the receiver coil moves, studies have been carried out to suppress the current pulsation [11], etc., but few studies have been carried out to reduce the leakage magnetic field. Therefore, in this paper, a method for reducing leakage magnetic fields by using adjacent transfer coils as a cancel coil is proposed for situations where the position of the receiver coil fluctuates. This method has successfully reduced the leakage magnetic field to less than the regulated value of 13.8 mA/m in the range from -790 to 800 mm with the center of the transfer coil as the origin, under the input condition where the received power is 25 kW. Verification was carried out by theoretical calculations and electromagnetic field analysis using the moment method.

II. DWPT SYSTEM CONFIGULATION

In this paper, the magnetic resonance method is used as the wireless power transfer method. Each coil is an air-core coil without magnetic materials such as ferrite. It is assumed that all the same transfer coils are installed on the traffic roadway at intervals of 50 % in a straight line. In this situation, the transfer coil adjacent to the transfer coil transmitting power to the receiver coil installed in the electric vehicle is used as the adjacent transfer coil and is operated as the cancel coil. The overall system is shown in Fig. 1.

The transfer coil is 1300 x 600 mm with 7 turns and the receiver coil is 580 x 420 mm with 16 turns. The transmission distance is 200 mm and the receiving load is 10 Ω. The range of movement of the receiver coil is shown in Fig. 2. The range is -1300 mm to 1300 mm in the direction of the vehicle with the center of the transfer coil as the origin. The leakage magnetic field strength was analyzed at (x,y,z)=(0,11.9 m,1 m) with the center of the transfer coil as the origin.

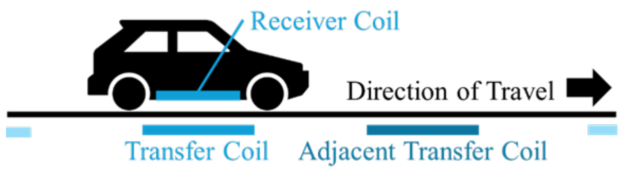

Fig.1 DWPT system configuration diagram

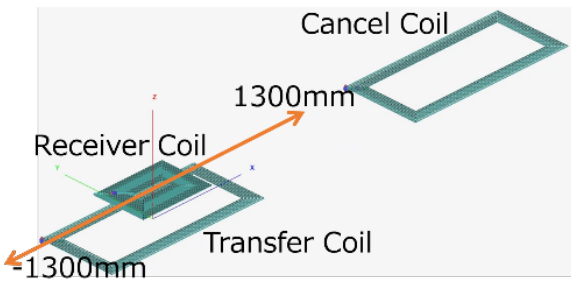

Fig.2 Receiver coil movement range

III. THEORETICAL EQUATIONS

First, the theoretical equations for determining the magnitude and phase of the current flowing in each coil at SS resonance are shown. Fig.3 shows the equivalent circuit including the three coils: transfer coil, receiver coil and cancel coil. Since the positional relationship of each coil appears in the value of mutual inductance, it can be expressed as an equivalent circuit in the same way when the receiver coil is moved. The mutual inductance can be obtained from the Neumann equation shown in equation (1).

$$L_m = \frac{\mu_0}{4\pi}\oint_{C_1}\oint_{C_2}\frac{dl_1 dl_2}{D} \tag{1}$$

Equation (2) is a matrix representation of each of the circuit equations when the three coils are in resonance.

$$\begin{bmatrix} V_1 \\ V_2 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 & j\omega L_{mt} & j\omega L_{ma} \\ j\omega L_{mt} & R_2 & j\omega L_{mb} \\ j\omega L_{ma} & j\omega L_{mb} & R_3 + R_L \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{2}$$

The input voltage V_1 to the transfer coil and the input voltage V_2 to the cancel coil have magnitude and phase respectively, so by substituting them in complex form as shown in equation (3), the current values can be obtained in complex form as shown in equation (4). In this way, the magnitude and phase of the current flowing in each coil can be obtained. The same procedure can be used for other resonance systems.

$$\begin{aligned} V_1 &= V_1\cos\varphi_1 + jV_1\sin\varphi_1 \\ V_2 &= V_2\cos\varphi_2 + jV_2\sin\varphi_2 \end{aligned} \tag{3}$$

$$I_1 = \frac{\begin{array}{c}[\{R_2(R_3+R_L)+(\omega L_{mb})^2\}V_1\cos\varphi_1 - (\omega L_{ma})(\omega L_{mb})V_2\cos\varphi_2 + (\omega L_{mt})(R_3+R_L)V_2\sin\varphi_2] \\ +j[\{R_2(R_3+R_L)+(\omega L_{mb})^2\}V_1\sin\varphi_1 - (\omega L_{ma})(\omega L_{mb})V_2\sin\varphi_2 + (\omega L_{mt})(R_3+R_L)V_2\cos\varphi_2]\end{array}}{R_1R_2(R_3+R_L)+(\omega L_{mb})^2R_1+(\omega L_{ma})^2R_2+(\omega L_{mt})^2(R_3+R_L)+j\{-2(\omega L_{ma})(\omega L_{mb})(\omega L_{mt})\}} \tag{4}$$

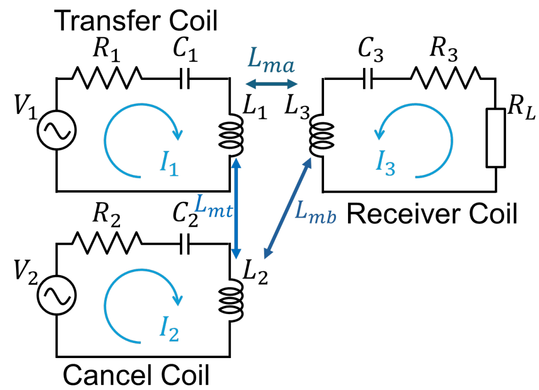

Fig.3 equivalent circuit

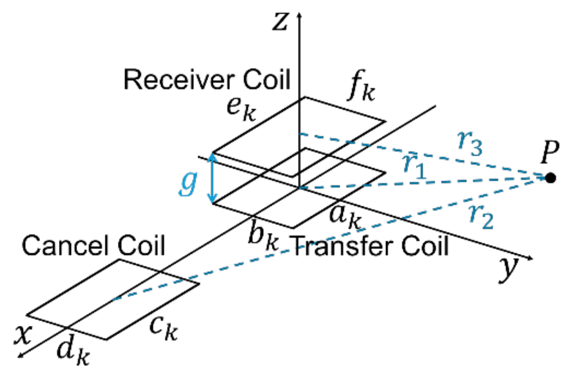

Fig.4 Magnetic field calculation parameters

Next, the theoretical equation for determining the magnetic field strength is presented. This was derived from Biot-Savart's law. The magnetic field generated from the transfer, cancelling and receiver coils to the magnetic field measurement point P(x,y,z) shown in Fig. 4 can be expressed by equation (5)-(7).

$$H_{Tx} = \begin{Bmatrix} H_{Txx} \\ H_{Txy} \\ H_{Txz} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\sum_{k=1}^{n} a_k b_k}{4\pi}\dfrac{3xz}{r_1^5}I_1 \\ \dfrac{\sum_{k=1}^{n} a_k b_k}{4\pi}\dfrac{3yz}{r_1^5}I_1 \\ \dfrac{\sum_{k=1}^{n} a_k b_k}{4\pi}\dfrac{2z^2 - x^2 - y^2}{r_1^5}I_1 \end{Bmatrix} \tag{5}$$

$$H_{Cx} = \begin{Bmatrix} H_{Cxx} \\ H_{Cxy} \\ H_{Cxz} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\sum_{k=1}^{m} c_k d_k}{4\pi}\dfrac{3(x-x_2)z}{r_2^5}I_2 \\ \dfrac{\sum_{k=1}^{m} c_k d_k}{4\pi}\dfrac{3yz}{r_2^5}I_2 \\ \dfrac{\sum_{k=1}^{m} c_k d_k}{4\pi}\dfrac{2z^2 - (x-x_2)^2 - y^2}{r_2^5}I_2 \end{Bmatrix} \tag{6}$$

$$H_{\mathrm{Rx}} = \begin{cases} H_{\mathrm{Rx}x} \\ H_{\mathrm{Rx}y} \\ H_{\mathrm{Rx}z} \end{cases} = \begin{cases} \dfrac{\sum_{k=1}^{l} e_k f_k}{4\pi} \dfrac{3x(z-g)}{r_3^5} I_3 \\ \dfrac{\sum_{k=1}^{l} e_k f_k}{4\pi} \dfrac{3y(z-g)}{r_3^5} I_3 \\ \dfrac{\sum_{k=1}^{l} e_k f_k}{4\pi} \dfrac{2(z-g)^2 - x^2 - y^2}{r_3^5} I_3 \end{cases} \quad (7)$$

By combining the results, the magnetic field intensity generated at the magnetic field measurement point can be obtained. Since the positional relationship of each coil appears as the distance to the magnetic field measurement point, the magnetic field intensity can be calculated even when the receiver coil moves by combining it with the calculation results of the current value in equation (4).

IV. VERIFICATION OF LEAKAGE MAGNETIC FIELD REDUCTION EFFECT

Figs. 5, 6 and 7 show the results of the analysis under the conditions where the leakage field is reduced the most while receiving 25 kW of power at SS, LCC-S and Double-LCC resonance. The leakage magnetic field strength is reduced to below the regulated value by applying an appropriate voltage to the canceling coil, although this is not shown in all the resonance methods used, as the leakage magnetic field strength was well above the regulated value when the canceling coil was not used. The positions of the receiving coils that can be reduced below the regulation values are -790~800 mm for SS and LCC-S and -770~800 mm for Double-LCC. This means that the leakage magnetic field can be reduced regardless of the resonance method when the receiving coil is moved. In addition, since the positions of the receiving coils at which the leakage magnetic field can be reduced below the regulation value are symmetrical in the front and rear directions of the vehicle, it can be said that the same effect is achieved regardless of whether the coils adjacent to the front or rear of the vehicle are used as the cancellation coils.

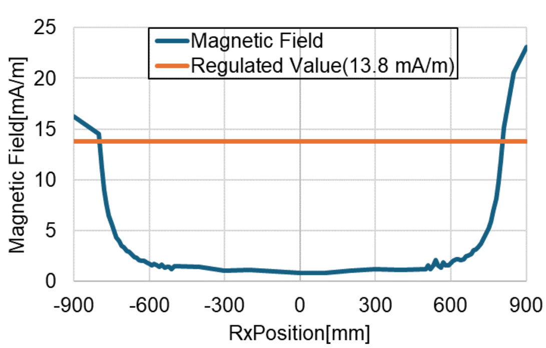

Fig.5 Results of magnetic leakage field analysis(SS)

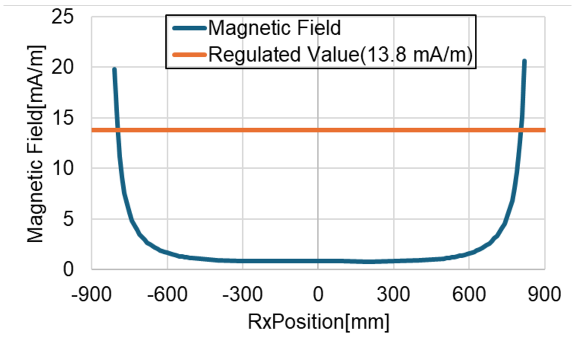

Fig.6 Results of magnetic leakage field analysis(LCC-S)

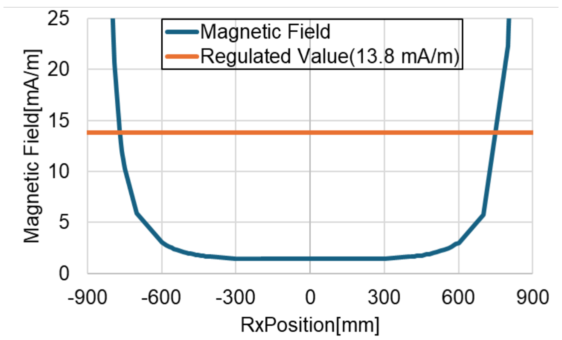

Fig.7 Results of magnetic leakage field analysis(Double-LCC)

Figs.8, 9 and 10 show the power transmission efficiency under the condition where the leakage field is reduced the most while receiving 25 kW power at SS, LCC-S and Double-LCC resonance. The approximate shape of the graph of transmission efficiency for the total resonant system coincides with the approximate shape of the coupling coefficient between the transmitting and receiving coils. The graph of the coupling coefficient is shown in Fig. 11. Since the transmission efficiency in wireless power transmission is expressed as the product of the Q-value of the coil and the coupling coefficient k, the validity of this result is confirmed. The transmission efficiency includes the cancellation coil. At SS and LCC-S resonance, the transmission efficiency is more than 80% in the range of -640~640 mm and more than 90% in the range of -560~560 mm for the position of the receiving coil. Since the range of the receiving coil position is narrower than the range where the leakage magnetic field strength is below the regulation value, power transmission in the range of high transmission efficiency can be compatible with leakage magnetic field reduction. In the case of Double-LCC resonance, the transmission efficiency is 89.9% at maximum and power transmission at about 90% is possible. The reason why the range of high transmission efficiency is narrower than other resonance methods is that the voltage applied to the cancellation coil to reduce the leakage magnetic field is large. In addition, since the inductance design in the resonance circuit is aimed at increasing the power received, it is thought that it can be improved by using an inductance aimed at high transmission efficiency.

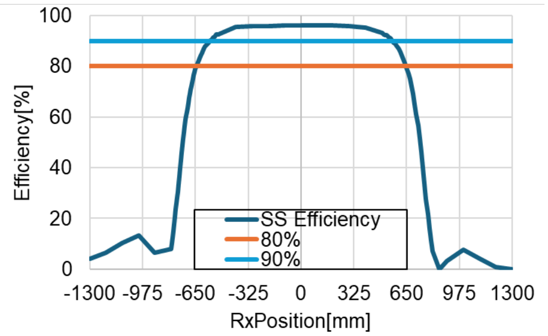

Fig.8 Results of transfer efficiency analysis(SS)

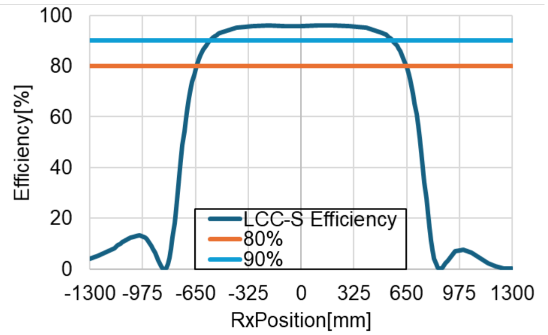

Fig.9 Results of transfer efficiency analysis(LCC-S)

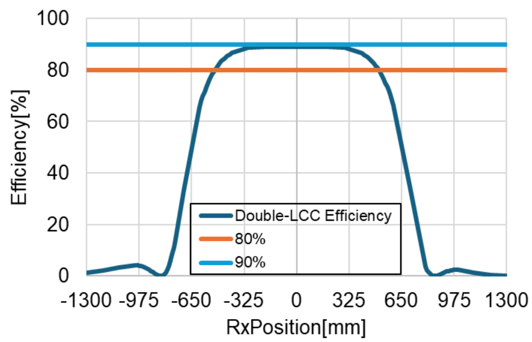

Fig.10 Results of transfer efficiency analysis(Double-LCC)

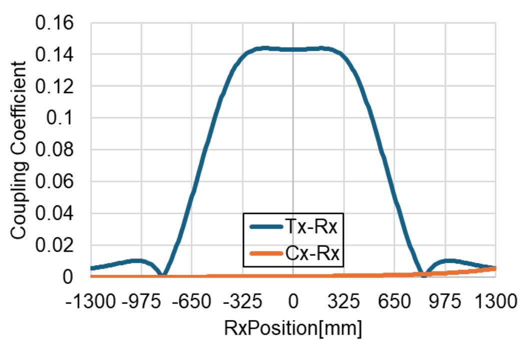

Fig.11 Coupling Coefficient

Finally, a comparison of the range of magnitude and phase of the voltage that can reduce the leakage magnetic field below the regulated value is made to investigate whether SS or LCC-S is more suitable for this method. Fig.12 and 13 show the results of the SS resonance when the magnitude or phase of the input voltage to the cancellation coil is fixed at the optimum value at each receiving coil position and the other parameter is varied, and Fig.14 and 15 show the results of the LCC-S resonance and Fig.16 and 17 show the results of the Double-LCC resonance.

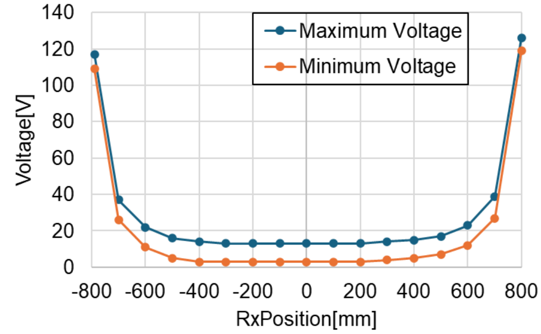

Fig.12 Amplitude range (SS)

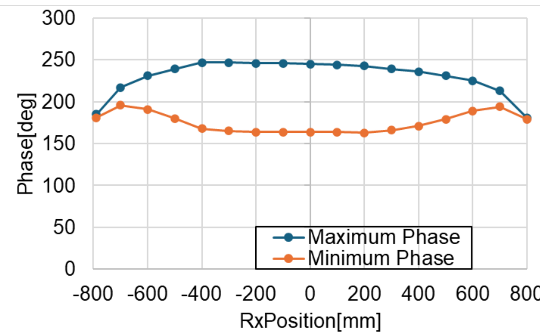

Fig.13 Phase range (SS)

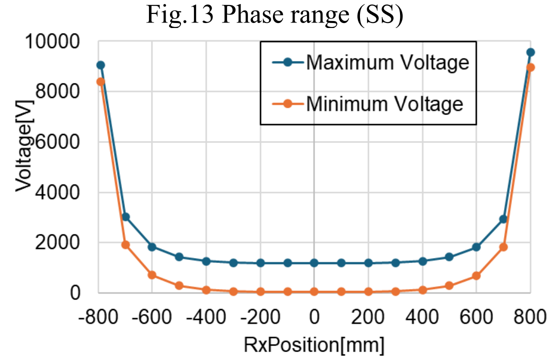

Fig.14 Amplitude range (LCC-S)

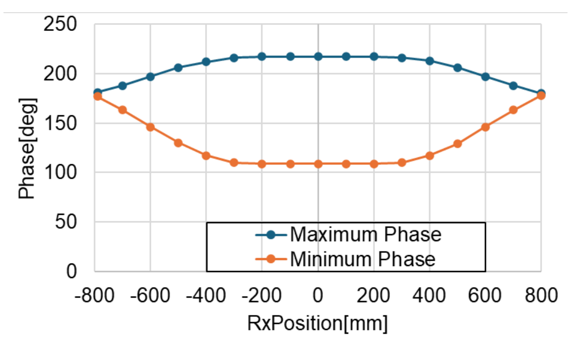

Fig.15 Phase range (LCC-S)

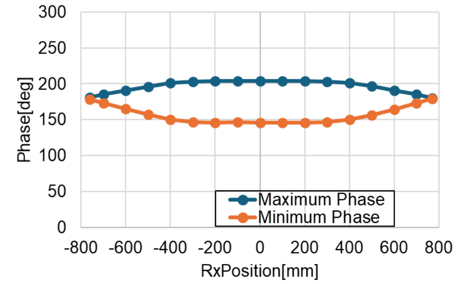

Fig.16 Amplitude range (Double-LCC)

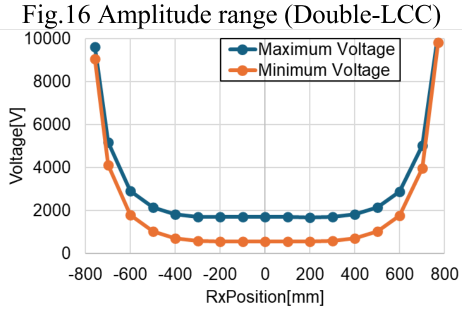

Fig.17 Phase range (Double-LCC)

For all resonance schemes, the range of phase and amplitude is larger when the receiving coil is closer to the center. The difference in the range of the phase is small depending on the resonance method. On the other hand, the amplitude ranges of SS, LCC-S and Double-LCC differ by a factor of about 100. This is since the change in the magnitude of the flowing current with respect to the magnitude of the input voltage is small when the resonance method of the transmission coil is LCC. Considering the practical application of this system, LCC is suitable for the resonance method of the transmission coil because of the larger control margin. On the other hand, there is a risk of the input voltage becoming too large, so SS, which can be used at relatively low voltages, is also considered acceptable. Also, by controlling the amplitude to a small value within the width of the voltage amplitude, the transmission efficiency can be further improved while reducing the leakage magnetic field to below the regulated value.

V. CONCLUSIONS AND FUTURE WORK

In this paper, it is shown that the leakage field reduction method by adjacent transmission coils is effective in the case of SS, LCC-S and Double-LCC resonance for the situation where the receiving coil position fluctuates, and that it is possible to achieve both high transmission efficiency in this situation. The leakage magnetic field can be reduced to less than the regulation value specified by J2954, and a transmission efficiency of 90% can be achieved at the same time. Although it is possible to use all three resonance methods, the LCC is suitable for the resonance method on the transmission side because of its larger control margin. It is shown that these can be calculated theoretically from the individual parameters of the DWPT system without the use of electromagnetic field analysis. This is useful when designing the system, as it facilitates studies under various conditions. Future tasks include the verification of the effectiveness of this method through experiments on actual equipment, the real-world environment of the control and the inclusion of the car body, and the response to the case where there are multiple power receiving coils. It is also necessary to consider the case where the total amount of power received in the transmission section is matched, instead of always transmitting at 25 kW.

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