Theorizing and Demonstrating Far-Field Leakage Magnetic Field Reduction Using Adjacent Transfer Coils in Double-LCC Circuit for Dynamic Wireless Power Transfer

Kaito Takashima
Faculty of Science and Technology
Tokyo University of Science
Noda, Japan
takashima.kaito22@gmail.com

Takehiro Imura
Faculty of Science and Technology
Tokyo University of Science
Noda, Japan

Yoichi Hori
Faculty of Science and Technology
Tokyo University of Science
Noda, Japan

***Abstract*—Several problems remain in the practical application of dynamic wireless power transfer to electric vehicles. It creates the leakage magnetic field that can be bad for people and devices nearby. There are some ways to make the leakage magnetic field smaller, like adding extra coils or materials, but they also add extra weight and cost. This paper proposes a new method to make the far-field leakage magnetic field at 10 m from the reference point smaller without additional equipment. This is a method of reducing the far-field leakage magnetic field by controlling the adjacent power transfer coils in the direction of travel of the power transfer coil that is transmitting power in a double LCC circuit. The currents flowing in the two transfer coils and the receiver coil are derived from the calculation of equivalent circuits considering the coupling between the coils. The effectiveness of the proposed method is confirmed by theoretical calculations using MATLAB and electromagnetic field analysis using Altair FEKO, and it is found that the far-field leakage magnetic field can be reduced below the regulated value without additional equipment.**

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

I. Introduction

Dynamic wireless power transfer is attracting as a technology to promote the transition from internal combustion engine vehicles to electric vehicles, which is one of the ways to solve global environmental problems. Problems with using electric vehicles are that they have a shorter cruising range than internal combustion engine vehicles and take more time to recharge. Dynamic wireless power transfer can solve this problem. In addition, dynamic wireless power transfer can ensure a sufficient cruising range while reducing the battery capacity of the electric vehicle, thus contributing to weight reduction and price reduction. However, there are various problems involved in the practical application of dynamic wireless power transfer. One of them is the problem of leakage magnetic field, which is the magnetic field generated during wireless power transfer that leaks to the outside without coupling. The leakage magnetic field is concerned to have bad effects on the human body and electronic devices, and the CISPR and ICNIRP[1] have established the regulation values.

Leakage magnetic field reduction methods proposed so far can be roughly classified into two types: active shielding and passive shielding. In the active shield [2]-[6], a loop coil with a power supply is added to the circuit configuration, or the wiring method of the transfer coil is devised. Passive shielding [7]-[8] suggests the addition of ferrite or aluminum plates. In all these methods, most of them target the near-field leakage magnetic field. In addition, previous studies have shown that the proposed method reduces the leakage magnetic field from experimental and electromagnetic field analysis results, Not shown using theoretical equations. This paper proposes a new method to make the far-field leakage magnetic field at 10 m from the reference point smaller without additional equipment. This is a method of reducing the far-field leakage magnetic field by controlling the adjacent power transfer coils in the direction of travel of the power transfer coil that is transmitting power in a double LCC circuit. Verifying its effectiveness through theoretical calculations and electromagnetic field analysis. The validity of the theoretical equation is verified by comparison with the results of electromagnetic field analysis.

II. Overview of Leakage Magnetic Field Reduction Method

Magnetic field resonance method is used as a wireless power transmission method, which is high power and high efficiency.

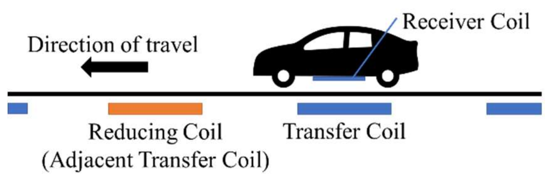


Fig.1 Diagram of the proposed method

Also, the double-LCC method with an air core was adopted as the resonance method. The same power transfer coils are assumed to be installed in a straight line on the roadway with a 50% installation ratio. In this situation, the adjacent power transfer coil in the direction of travel that is transmitting power to the receiver coil attached to the vehicle body is used as a coil for reducing the leakage magnetic field. By adjusting the magnitude and phase of the voltage applied to the adjacent power transfer coil in the direction of travel to an appropriate value, obtain the leakage magnetic field reduction effect. In this paper, this coil is called an adjacent power transfer coil. Fig. 1 shows an illustration of this coil. Also, the case where the receiver coil is located on the center of the transfer coil is considered.

III. Current Derivation by Equivalent Circuit

In this chapter, the magnitude and phase of the current flowing through each coil are derived from the equivalent circuit when there are three coils. The equivalent circuit is shown in Fig. 2. The power transfer coil is L_1, the adjacent transfer coil is L_2, and the receiver coil is L_3. V_1 and V_2 are the voltages applied to the transfer coil and the adjacent transfer coil. R_L is the load attached to the receiver coil. L_{0x} for each coil is a resonant inductor, C_{xs} is a series capacitor, and C_{xp} is a parallel capacitor, and the relationship between their magnitudes is expressed by equation (1) using the resonant angular frequency ω_0.

$$\omega_0 = \frac{1}{\sqrt{L_{0x}C_{xp}}} = \sqrt{\frac{C_{xp}+C_{xs}}{L_x C_{xp} C_{xs}}} \quad (x = 1,2,3) \tag{1}$$

R_x is the internal resistance of L_x, and R_{0x} is the internal resistance of the resonant inductor L_{0x}.

As for the mutual inductance, L_{ma} is between the transfer coil and the receiver coil, L_{mb} is between the adjacent transfer coil and the receiver 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.

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

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.

$$\begin{bmatrix} V_1 \\ 0 \\ V_2 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{01} & j\frac{1}{\omega C_{1p}} & 0 & 0 & 0 & 0 \\ j\frac{1}{\omega C_{1p}} & R_1 & 0 & j\omega L_{mt} & j\omega L_{ma} & 0 \\ 0 & 0 & R_{02} & j\frac{1}{\omega C_{2p}} & 0 & 0 \\ 0 & j\omega L_{mt} & j\frac{1}{\omega C_{2p}} & R_2 & j\omega L_{mb} & 0 \\ 0 & j\omega L_{ma} & 0 & j\omega L_{mb} & R_3 & j\frac{1}{\omega C_{3p}} \\ 0 & 0 & 0 & 0 & j\frac{1}{\omega C_{3p}} & R_{03}+R_L \end{bmatrix} \begin{bmatrix} I_{in1} \\ I_1 \\ I_{in2} \\ I_2 \\ I_3 \\ I_L \end{bmatrix} \tag{3}$$

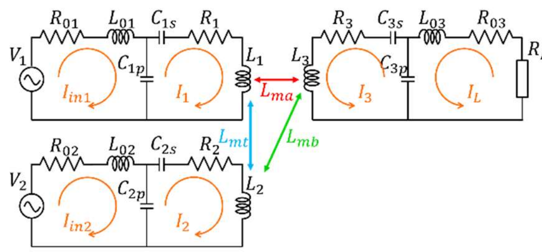


Fig.2 Equivalent circuit of two transfer coils and one receiver coil

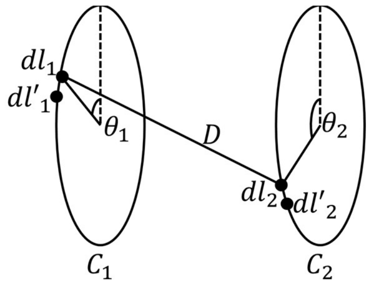


Fig.3 Parameters of Neumann's equation

IV. Magnetic Field Derivation by Vector Potential

After The magnetic field is derived from the vector potential [9]. The magnetic fields generated by the transfer coil L_1, the adjacent transfer coil L_2, and the receiver coil L_3 to an arbitrary point $P(x, y, z)$ shown in Fig.4 are denoted as H_1, H_2, and H_3, respectively, and are expressed by equations (4), (5), and (6), respectively. Here, the distances r_1, r_2, and r_3 to point P are sufficiently longer than the lengths a_k, b_k, c_k, d_k, e_k, and f_k of each side.

$$H_1 = \begin{cases} H_{1x} \\ H_{1y} \\ H_{1z} \end{cases} = \begin{cases} \dfrac{\sum_{k=1}^{n} a_k b_k}{4\pi}\dfrac{3xz}{r_1^5} I_1 \\ \dfrac{\sum_{k=1}^{n} a_k b_k}{4\pi}\dfrac{3yz}{r_1^5} I_1 \\ \dfrac{\sum_{k=1}^{n} a_k b_k}{4\pi}\dfrac{2z^2 - x^2 - y^2}{r_1^5} I_1 \end{cases} \tag{4}$$

$$H_2 = \begin{cases} H_{2x} \\ H_{2y} \\ H_{2z} \end{cases} = \begin{cases} \dfrac{\sum_{k=1}^{m} c_k d_k}{4\pi}\dfrac{3(x-s)z}{r_2^5} I_2 \\ \dfrac{\sum_{k=1}^{m} c_k d_k}{4\pi}\dfrac{3yz}{r_2^5} I_2 \\ \dfrac{\sum_{k=1}^{m} c_k d_k}{4\pi}\dfrac{2z^2 - (x-s)^2 - y^2}{r_2^5} I_2 \end{cases} \tag{5}$$

$$H_3 = \begin{cases} H_{3x} \\ H_{3y} \\ H_{3z} \end{cases} = \begin{cases} \dfrac{\sum_{k=1}^{m} e_k f_k}{4\pi}\dfrac{3x(z-g)}{r_3^5} I_3 \\ \dfrac{\sum_{k=1}^{m} e_k f_k}{4\pi}\dfrac{3y(z-g)}{r_3^5} I_3 \\ \dfrac{\sum_{k=1}^{m} e_k f_k}{4\pi}\dfrac{2(z-g)^2 - x^2 - y^2}{r_3^5} I_3 \end{cases} \tag{6}$$

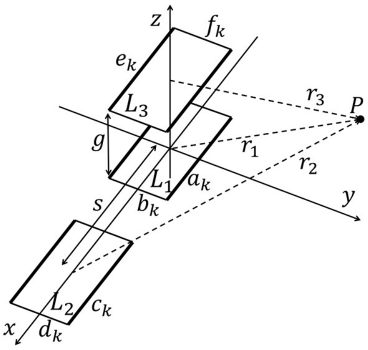


Fig.4 Magnetic field derivation using vector potentials

In addition, I_1, I_2, and I_3 have magnitude and phase, respectively. Denoting I_1, I_2, and I_3 as magnitudes and θ_1, θ_2, and θ_3 as phases, respectively, the equation (7) is expressed as follows.

$$I_x = I_x \cos\theta_x + jI_x \sin\theta_x \quad (x = 1,2,3) \tag{7}$$

The magnitude H of the magnetic field at an arbitrary point P can be derived by composing H_1, H_2, and H_3. From equations (4), (5), (6), and (7), the magnitude of the magnetic field H is expressed by equation (8).

$$H = \sqrt{\begin{aligned} &(H_{1x}\cos\theta_1 + H_{2x}\cos\theta_2 + H_{3x}\cos\theta_3)^2 \\ &+(H_{1x}\sin\theta_1 + H_{2x}\sin\theta_2 + H_{3x}\sin\theta_3)^2 \\ &+\left(H_{1y}\cos\theta_1 + H_{2y}\cos\theta_2 + H_{3y}\cos\theta_3\right)^2 \\ &+\left(H_{1y}\sin\theta_1 + H_{2y}\sin\theta_2 + H_{3y}\sin\theta_3\right)^2 \\ &+(H_{1z}\cos\theta_1 + H_{2z}\cos\theta_2 + H_{3z}\cos\theta_3)^2 \\ &+(H_{1z}\sin\theta_1 + H_{2z}\sin\theta_2 + H_{3z}\sin\theta_3)^2 \end{aligned}} \tag{8}$$

V. Magnetic Field Derivation by Vector Potential

After The validity of the theoretical equations and the effectiveness of the far-field leakage magnetic field reduction method are verified by comparing the results of the theoretical calculations and the electromagnetic field analysis. Theoretical calculations are performed using MATLAB by MathWorks. The electromagnetic field analysis is performed by the MoM method using Altair FEKO. The analytical model is shown in Fig. 5, and the values of each parameter are shown in Table 1. The self-inductance L_x and internal resistance R_x of each coil are the values obtained by electromagnetic field analysis. The measured values are also used in the case of the actual device. The resistance R_{0x} of each resonant inductor is designed so that the Q value of the resonant inductor is 500.

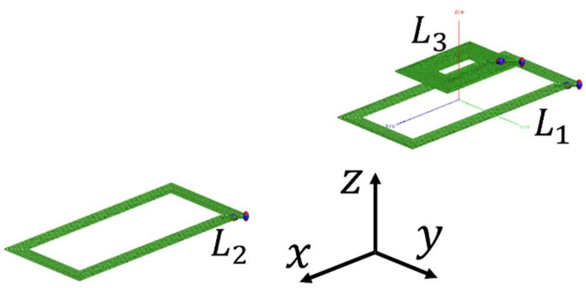


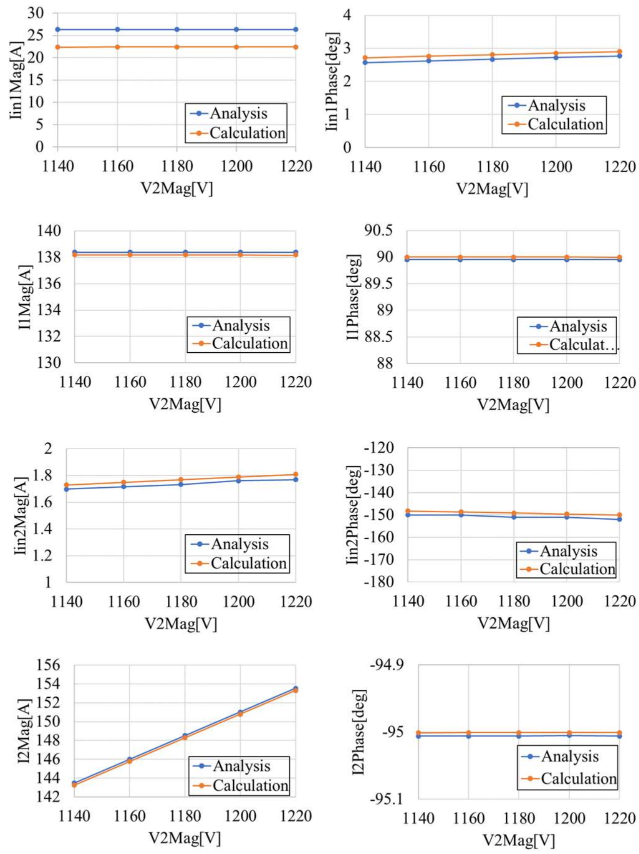
Fig.5 Analysis Model

Table1 Analysis Set Up

	L_1	L_2	L_3
Size[mm]	1300×600		580×420
Pitch[mm]	14.85		10.85
Turn	7		16
V_1 [V]	1100	—	—
Gap[mm]	—	—	200
Spacing[mm]	—	2600	—
R_{0x} [mΩ]	15.9		37.9
R_x [mΩ]	77.5		69.7
L_{0x} [μH]	14.9		35.5
L_x [μH]	89.3		97.4
C_{xp} [nF]	235		98.8
C_{xs} [nF]	47.1		56.6
R_L [Ω]	—	—	10

A. Current

Fig.6 shows the magnitude and phase of each current when V_1 is 1100 V 0 deg and V_2 is 1180 V and the phase is varied, and Fig.7 shows the magnitude and phase of each current when V_2 is 175 deg and the phase is varied, which are obtained from electromagnetic field analysis and theoretical calculation. Fig.6 and 7 show that the magnitude and phase of each current are obtained both when the magnitude of V_2 is varied and when the phase is varied. This shows the validity of the theoretical equation for the current derivation.



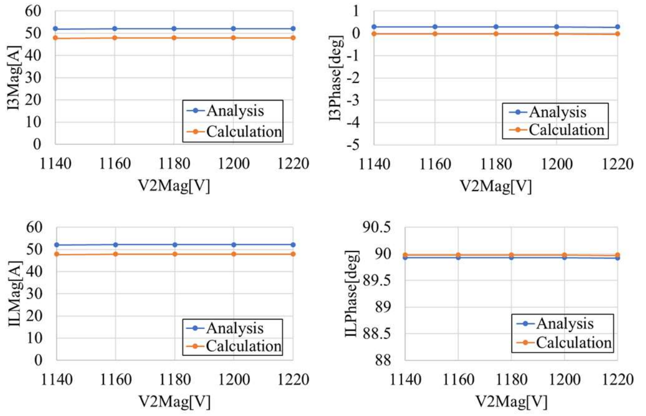
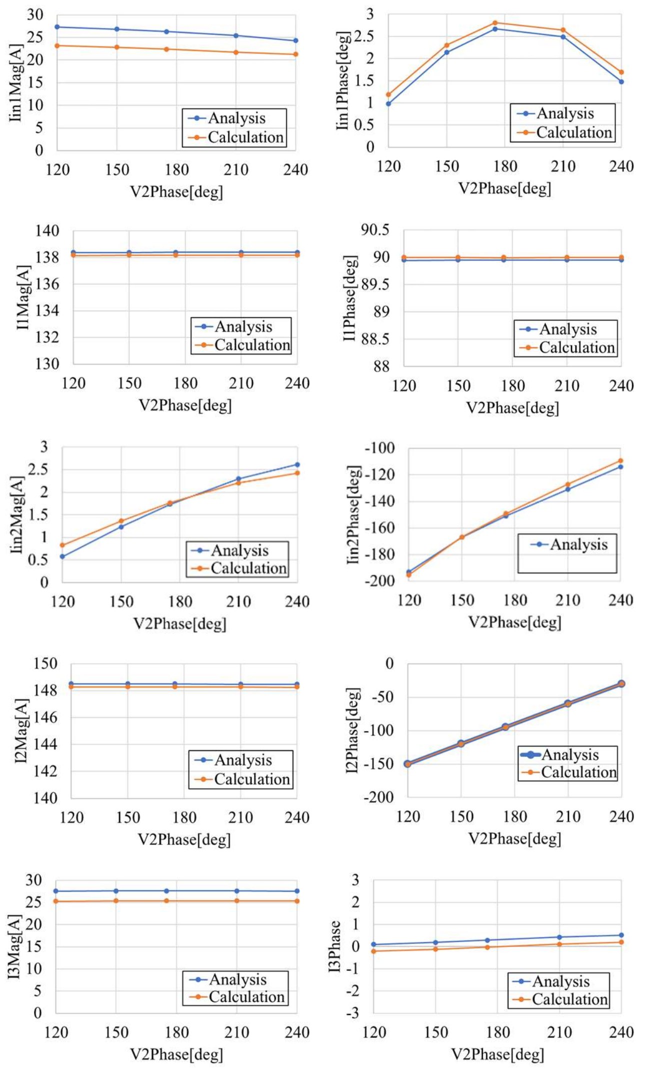


Fig.6 Magnitude and phase of each current when the magnitude of V_2 is varied



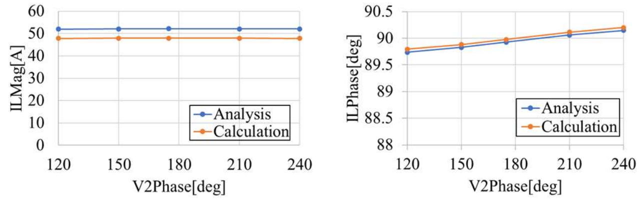


Fig.7 Magnitude and phase of each current when the phase of V_2 is varied

B. Far-Field Leakage Magnetic Field

1) Verification of Suppression Effect

The magnetic field measurement points are x=0 m, y=11.9 m, and z=1 m in the coordinate system which origin is the center of L_1 shown in Fig. 8. The reason for this 11.9 m is that the SAE standard defines a radius of 1.9 m from the center of the receiving coil as the WPT Measurement Boundary where the power supply and other devices are installed, and the analysis point is 10 m away from this radius, which is far-field leakage magnetic field. The leakage magnetic field at the measurement point was compared with the regulation value of 82.8 dBμA/m (13.8 mA/m) given in SAE J2954.

Theoretical calculations show that the magnetic leakage field at the measurement point reaches its minimum at 1180 V 175 deg for V_2 when the voltage V_1 applied to L_1 is 1100 V 0 deg. Fig.9 shows the magnitude of the magnetic field when the magnitude of V_2 is varied, and Fig.10 shows when the phase of V_2 is varied. From Figs.9 and 10, it was possible to obtain the leakage magnetic field at the measurement point both when the magnitude of V_2 was varied and when the phase was varied. The maximum error is 1.4 %. This shows the validity of the theoretical equation for the current derivation. "No Cancel" indicates a situation where adjacent transfer coil L_2 is present but power is not applied. In this situation, the magnetic field generated at the measurement point is 29.3 mA/m, which is higher than the regulated value of 13.8 mA/m. When V_2 is 1100 V 175 deg, which is the point where the leakage magnetic field is most suppressed, the magnetic field is 1.58 mA/m, which is 27.7 mA/m (88.9 dBμA/m) less than the regulation value.

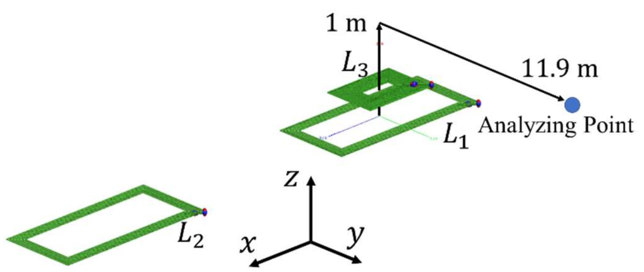


Fig.8 Magnetic Field Analyzing Point

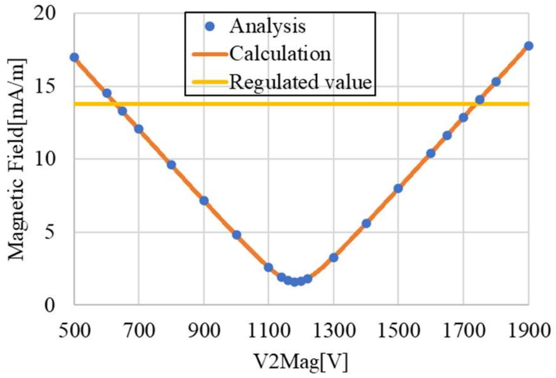


Fig.9 Magnitude of the magnetic field when the magnitude of V_2 is varied

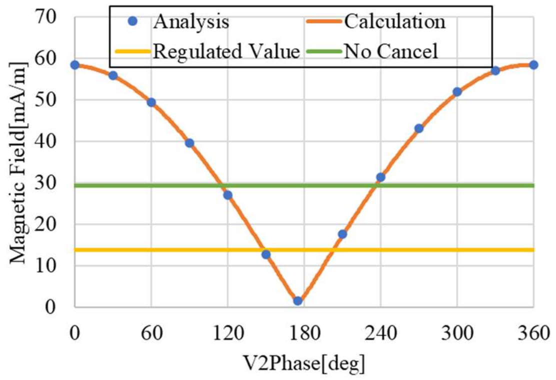


Fig.10 Magnitude of the magnetic field when the phase of V_2 is varied

2) Magnetic Field at Maximum Reduction Outside of the Measurement Point

The magnitude of the magnetic field generated outside the measurement point is shown for the condition that the leakage magnetic field at the measurement point is reduced the most. First, Fig.12 shows the results for a radius of 11.9 m and a height of 1 m around the transfer coil L_1 shown in Fig.11. Most of the areas are below the limited value, and the limited value is exceeded only in the direction of travel. The values are also lower than those without reduction only in the presence of adjacent transfer coils over a wide range. From this result, it can be said that there is an effect of leakage magnetic field reduction except in the region of about 60° in the direction of travel. However, this is not considered to be a problem because it is considered possible to reduce the leakage magnetic field by using a coil further ahead of the adjacent transfer coil, and because no one can enter the area because it is in the direction of travel. From Fig.9, there is a certain range of the magnitude of V_2 that can reduce the leakage magnetic field at the measurement point below the regulated value. Since the magnitude of the magnetic field is linear with the magnitude of the current, and the magnitude of the current is linear with the magnitude of the voltage, it is considered possible to reduce the surrounding leakage magnetic field while keeping the measurement point below the regulation value by reducing V_2.

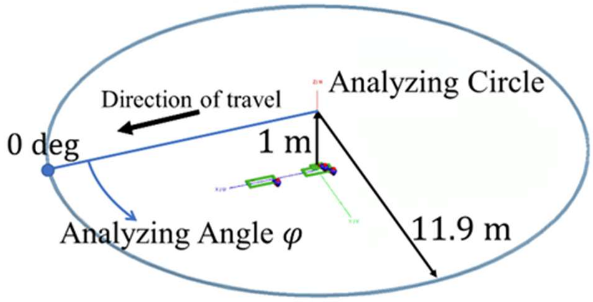


Fig.11 Analyzing Circle

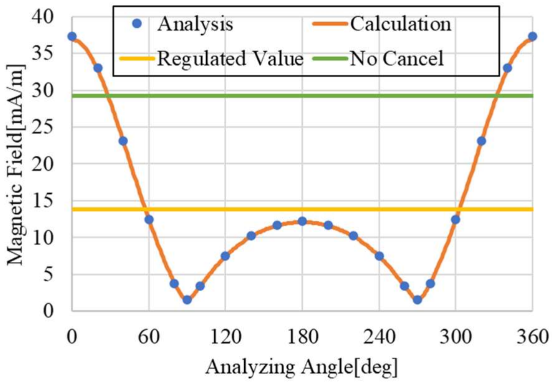


Fig.12 Leakage magnetic field around the transmission coil

Fig.14, 15, and 16 show the results at locations where the x, y, and z directions were changed from the measurement points shown in Fig.13. In the coordinate system with the center of L_1 as the origin, the x side of Fig.13 is (-15 m, 11.9 m, 1 m) ~ (15 m, 11.9 m, 1 m), the y side is (0 m, 0 m, 1 m) ~ (0 m, 15 m, 1 m), and the z side is (0 m, 11.9 m, 0 m) ~ (0 m, 11.9 m, 2 m). From Fig.15, the error in the y direction from y=0 to 2 m is larger. This is due to the approximation that the distance to the measurement point is sufficiently longer than the coil edge when the magnetic field is calculated from the vector potential. When the distance to the measurement point becomes shorter, the approximation no longer holds, and this is the reason for the error. As for the x-side and z-side, it can be said that the magnetic field can be derived from the theoretical calculation from Fig.14 and 16.

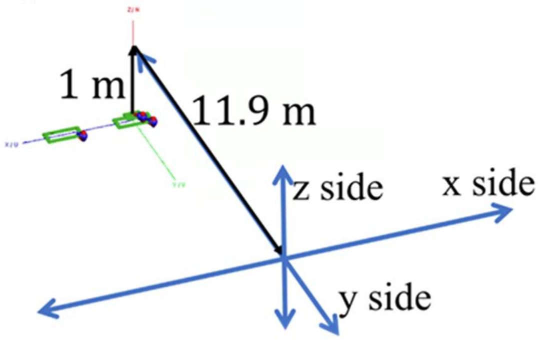


Fig.13 Analyzing Line

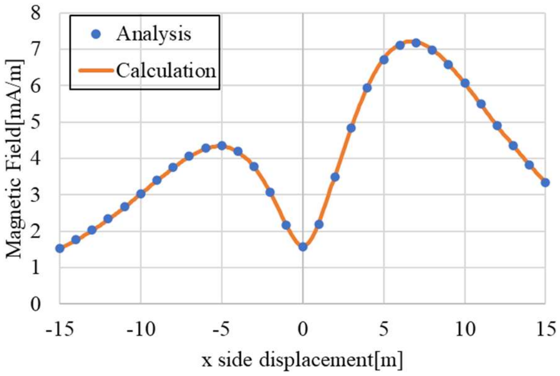


Fig.14 x side displacement

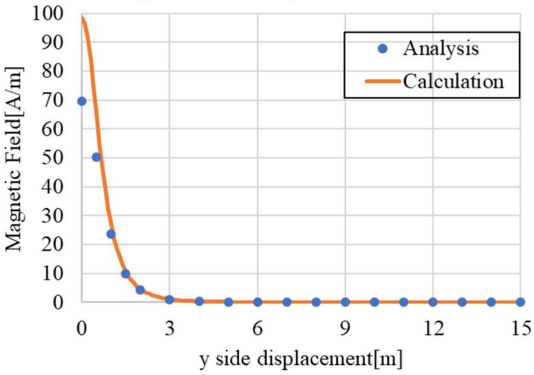


Fig.15 y side displacement

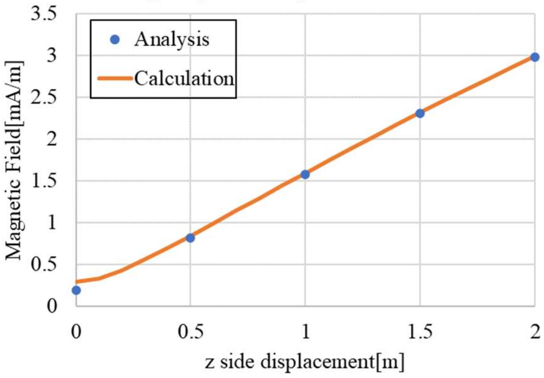


Fig.16 z side displacement

VI. Conclusion

The magnitude and phase of the current flowing through each coil during dynamic wireless power transfer in double-LCC circuit can be derived from the input power and coil configuration. Using the currents, the far-field leakage magnetic field can be derived from the theoretical equation of vector potential, which agrees with the electromagnetic field analysis, showing the validity of the theoretical calculations. The current and magnetic field can be derived in the same way when the number of coils is increased further. The availability of the theoretical calculations will be useful for system design since it will allow to examine various conditions earlier than by electromagnetic field analysis. One of the future issues is to develop a theoretical equation that considers the effects of the real environment, such as the car body and the ground.

As a method to reduce the leakage magnetic field, this paper proposed the method of using adjacent transfer coil in the direction of travel. The leakage magnetic field reduction is achieved by adjusting the magnitude and phase of the voltage of the adjacent transfer coil. By applying a voltage of 1180 V 175 deg to the adjacent transfer coil when the input voltage of the transfer coil is 1100 V 0 deg, the far-field leakage magnetic field at 11.9 m from the transfer coil can be reduced by a maximum of 27.7 mA/m (88.9 dBμA/m). It was also confirmed that this method can reduce the leakage magnetic field over a wide range. The advantage of this method is that it can be performed without any additional equipment. One of the future issues is how to change the magnitude and phase of the input voltage to each transfer coil.

Acknowledgement

This paper is based on results obtained from a project, JPNP21028, subsidized by the New Energy and Industrial Technology Development Organization (NEDO)in cooperation with DAIHEN Corporation.

References

[1] SAE International, “Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology J2954," Issued2016-05, Revised 2020-10.

[2] W. Songcen et al., "Electromagnetic shielding design for magnetic coupler of N-type dynamic electric vehicle wireless power transfer systems," 2019 22nd International Conference on Electrical Machines and Systems (ICEMS), Harbin, China, 2019, pp. 1-7

[3] M. Mi, Q. Yang, Y. Li, P. Zhang and W. Zhang, "Multi-Objective Active Shielding Coil Design for Wireless Electric Vehicle Charging System," in IEEE Transactions on Magnetics, vol. 58, no. 2, pp. 1-5, Feb. 2022

[4] J. Kim and S. Ahn, "Dual Loop Reactive Shield Application of Wireless Power Transfer System for Leakage Magnetic Field Reduction and Efficiency Enhancement," in IEEE Access, vol. 9, pp. 118307-118323, 2021

[5] S. Sato, Y. Tanaka, Y. Tsuruda and S. Nakamura, "Basic Investigation on Wireless Power Transfer System via Magnetic Resonant Coupling with Magnetic Field Suppression at an Any Point," IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, Singapore, 2020, pp. 1555-1560

[6] A. D. Scher, M. Mohammad, B. Ozpineci and O. Onar, "Design and optimization of cancellation coil topologies for a ferrite-less wireless EV charging pad," 2021 IEEE Transportation Electrification Conference & Expo (ITEC), Chicago, IL, USA, 2021, pp. 1-7

[7] M. Mohammad, O. C. Onar, V. P. Galigekere, G. -J. Su and J. Wilkins, "Magnetic Shield Design for the Double-D Coil-Based Wireless Charging System," in IEEE Transactions on Power Electronics, vol. 37, no. 12, pp. 15740-15752, Dec. 2022

[8] S. Hayato, T. Eisuke, Y. Nobuhisa, T. Keisuke, N. Sakahisa, F. Toshiyuki and F. Hiroshi, "Novel Evaluation Method for Leakage Electromagnetic Field Using Coil Scaling Law for Wireless Power Transfer System for Electric Vehicle," 5th International Electric Vehicle Technology Conference (EVTeC2021), May.2021

[9] Soma Hasegawa, Takehiro Imura, Yoichi Hori, "Theory Development of Far-field Leakage Magnetic Field in Dynamic Wireless Power Transfer for Electric Vehicles Charging and Influence of Ferrite", 2022 Asian Wireless Power Transfer Workshop (AWPT2022), Hybrid, Dec. 2022.