

A Fundamental Study on Leakage Magnetic Field Reduction Using Adjacent Coils in Dynamic Wireless Power Transfer

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Abstract— The widespread adoption of electric vehicles (EVs) is expected as a means of reducing CO₂ emissions. Dynamic wireless power transfer (DWPT) has therefore attracted attention as a promising solution to the problems of limited driving range and long charging times. On the other hand, leakage magnetic fields in DWPT systems are a concern because of their potential effects on the human body and electronic equipment, and mitigation methods that satisfy regulatory limits such as CISPR 11 are required. In this paper, coils adjacent to the transmitter coil are used as cancellation coils during power transfer, and a dual-sided cancellation scheme using both adjacent coils is investigated. The input voltage applied to the circuit containing a cancellation coil is referred to as the cancellation voltage, and the optimal conditions for its amplitude ratio and phase difference are theoretically derived on the basis of the characteristics of the Double-LCC circuit. Electromagnetic-field analysis using the derived conditions confirms that the leakage magnetic field is reduced by more than 20 dB in selected directions and falls below the regulatory limit. Furthermore, in the omnidirectional evaluation, the single-sided cancellation scheme still leaves azimuthal directions that exceed the regulatory limit even under the optimal condition, whereas the dual-sided cancellation scheme achieves a peak value of 68.30 dB(μ A/m), which is below the regulatory limit of 68.4 dB(μ A/m) in all directions. Compared with the case without cancellation, the reduction is 4.5–24.4 dB(μ A/m) for the single-sided scheme and 14.2–28.3 dB(μ A/m) for the dual-sided scheme, demonstrating the superiority of the dual-sided approach.

Keywords—Dynamic Wireless Power Transfer, Leakage Magnetic Fields

I. INTRODUCTION

In recent years, the transition from gasoline-powered vehicles to electric vehicles has been accelerating in order to reduce CO₂ emissions. However, electric vehicles still face several issues, such as limited driving range and the inconvenience of charging. Dynamic wireless power transfer (DWPT) has attracted attention as a promising solution to these problems.

One of the major challenges in realizing DWPT is leakage magnetic fields. Leakage magnetic fields can be classified into near-field leakage magnetic fields, which occur at distances from several centimeters to approximately 3 m from the coils and are mainly a concern with respect to human exposure, and far-field leakage magnetic fields, which are evaluated at a point 10 m away from a reference location and are mainly a concern with respect to electronic equipment. Regulatory limits for these fields are specified by standards such as CISPR 11 [1]. Therefore, leakage magnetic fields must be reduced below the regulatory limits in order to realize DWPT.

Representative methods for leakage magnetic field reduction that have been studied so far can be broadly classified into two categories: active shielding [2]–[6] and passive shielding [7], [8]. As shown in previous studies [2], [3], active shielding reduces leakage magnetic fields by using magnetic-field mitigation coils, or cancellation coils. On the other hand, adding dedicated cancellation coils may increase cost and maintenance requirements and may also have adverse effects on the road surface. In [4], leakage magnetic fields are reduced by using the transmitter coil adjacent to the active transmitter coil in the traveling direction as a cancellation coil.

This paper considers a DWPT system in which coils adjacent to the transmitter coil are used as cancellation coils, and investigates a dual-sided cancellation scheme using both adjacent coils in comparison with a single-sided scheme using only one adjacent coil. When only one side is used, the cancellation effect tends to be directionally biased, whereas using both sides enables magnetic-field cancellation over a wider region. In addition, while the previous study [4] focused on leakage magnetic field reduction at a specific direction, this study evaluates the leakage magnetic field over the full azimuthal range around the reference point in order to suppress uncanceled directions. Furthermore, based on the characteristics of the Double-LCC circuit, the optimal

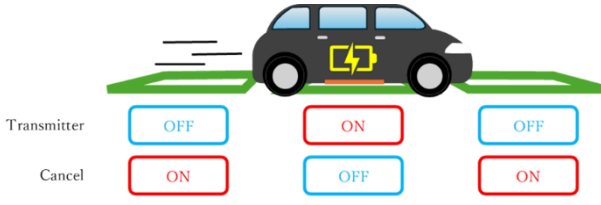


Fig. 1. DWPT system under consideration

conditions of the cancellation voltage are derived, and the effectiveness of leakage magnetic field reduction is verified through theoretical calculations and electromagnetic-field analysis.

II. THEORY

A. DWPT System

Fig. 1 shows the DWPT system considered in this paper. When an EV equipped with a receiver coil passes over multiple transmitter coils embedded in the road, electric power is transferred from the transmitter coil located directly beneath the vehicle. At the same time, the coil adjacent to the active transmitter coil is operated as a cancellation coil for leakage magnetic field reduction, and the roles of the transmitter coil and the cancellation coil are sequentially switched as the EV moves. In this study, a fundamental investigation of leakage magnetic field reduction using cancellation coils is carried out for an air-core coil model.

B. Magnetic Field Equations in a Double-LCC Circuit

Fig. 2 shows the Double-LCC circuit including the adjacent coils. As shown in Fig. 2, the input voltage of the circuit including the transmitter coil is defined as the transmitter voltage, $V_{Tx} = V e^{j0}$, the input voltage of the circuit including the receiver coil is defined as the receiver voltage, $V_{Rx} = \alpha_{Rx} V e^{j\theta_{Rx}}$, and the input voltages of the circuits including the cancellation coils are defined as the cancellation voltages, $V_{Can1} = \alpha_{Can1} V e^{j\theta_{Can1}}$, $V_{Can2} = \alpha_{Can2} V e^{j\theta_{Can2}}$. Here, α_{Rx} , α_{Can1} , and α_{Can2} denote the voltage amplitude ratios with respect to the transmitter voltage, and θ_{Rx} , θ_{Can1} , and θ_{Can2} denote the corresponding phase angles referenced to the transmitter voltage. The current flowing through each coil, neglecting the internal resistance of the coils, is given by (1), where $i = T, R, C1, C2$, $l = T, R$, and $m = Tx, Rx, Can1, Can2$.

$$I_i = -j \frac{1}{\omega_0 L_{0l}} \alpha_m V e^{j\theta_m} \quad (1)$$

Fig. 3 shows the positional relationship between the coils and the measurement point. For magnetic field calculation, the method based on the vector potential presented in [9] is used. Let the total areas of the transmitter coil and receiver coil be S_T and S_R , respectively, and let the center-to-center distance between adjacent transmitter coils be s . Equation (2) gives the approximate magnetic field generated by each coil, and (3) gives the composite magnetic field.

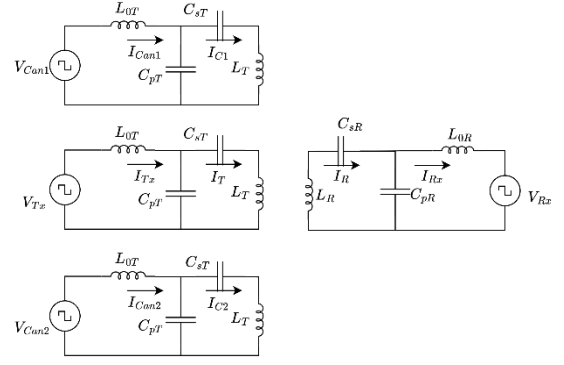


Fig. 2. Double-LCC Circuit

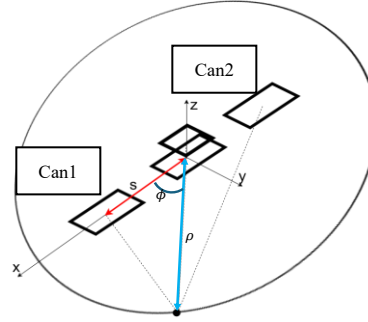


Fig. 3. Positional relationship between coil and measurement position

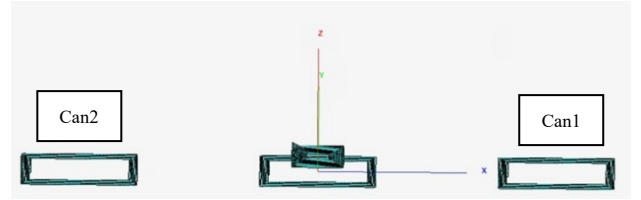


Fig. 4. Analytical model

$$H_x^m = \frac{S_l}{4\pi} \frac{3z(\rho \cos \phi \pm ns)}{\{\rho^2 + z^2 \pm 2ns\rho \cos \phi + (ns)^2\}^{\frac{5}{2}}} I_i$$

$$H_y^m = \frac{S_l}{4\pi} \frac{3z\rho \sin \phi}{\{\rho^2 + z^2 \pm 2ns\rho \cos \phi + (ns)^2\}^{\frac{5}{2}}} I_i \quad (2)$$

$$H_z^m = \frac{S_l}{4\pi} \frac{2z^2 - \{\rho^2 \pm 2ns\rho \cos \phi + (ns)^2\}}{\{\rho^2 + z^2 \pm 2ns\rho \cos \phi + (ns)^2\}^{\frac{5}{2}}} I_i$$

$$H = \sqrt{|H_x^{Tx} + H_x^{Rx} + H_x^{Can1} + H_x^{Can2}|^2 + |H_y^{Tx} + H_y^{Rx} + H_y^{Can1} + H_y^{Can2}|^2 + |H_z^{Tx} + H_z^{Rx} + H_z^{Can1} + H_z^{Can2}|^2} \quad (3)$$

In the Double-LCC circuit, as indicated by (1), the current of each coil does not depend on the coupling coefficient. Therefore, the magnetic field expressed by (2) can also be evaluated independently of the coupling coefficient, in the same manner as the coil currents. In addition, because the current of each coil is proportional to the applied voltage, the far-field leakage magnetic field can be controlled through the

amplitude ratio and phase difference of the cancellation voltage. As a result, the contribution of each coil can be separated more easily, which facilitates deriving the optimal amplitude and phase of the cancellation voltage.

III. LEAKAGE MAGNETIC FIELD REDUCTION USING ADJACENT COILS

When both adjacent coils, Can1 and Can2, are used, the scheme is referred to as dual-sided cancellation, whereas the case using only Can2 is referred to as single-sided cancellation. In this section, the amplitude ratio and phase difference of the cancellation voltage are treated as design variables on the basis that the coil currents in the Double-LCC circuit are determined by the input voltages. For the dual-sided cancellation case, a left-right symmetric arrangement is assumed, and the two cancellation coils are driven with identical applied voltages. Accordingly, the problem is formulated as a two-variable optimization problem based on the cancellation-voltage amplitude ratio and phase difference referenced to the transmitter voltage, $\alpha_{Can} = \alpha_{Can1} = \alpha_{Can2}$, $\theta_{Can} = \theta_{Can1} = \theta_{Can2}$, and the optimal conditions for leakage magnetic field reduction are investigated. The optimal values are obtained for both the dual-sided and single-sided schemes, and their validity is confirmed by electromagnetic-field analysis. In addition, the results are compared with the regulatory limit based on CISPR 11, namely 68.4 dB(μ A/m). For the single-sided case, the adjacent coil located at $\phi = 180^\circ$ in Fig. 3, namely Can2, is used as the cancellation coil.

Electromagnetic-field analysis is performed using the method of moments (MoM) in FEKO. Fig. 4 shows the analysis model. The resonant frequency of the coils is set to 85 kHz, which is identical to the operating frequency. The transmitter and receiver input voltages are both fixed at 600 V, yielding an output power of approximately 25 kW. The output power remains nearly constant even when the cancellation voltage is varied. The center-to-center coil spacing is set to $s = 2.6$ m, which is twice the long side of the transmitter coil so that the installation ratio becomes 0.5. The magnetic-field evaluation point is defined in the coordinate system shown in Fig. 3, whose origin is the center of the transmitter coil, as $\rho = \sqrt{x^2 + y^2} = 11.9$ m and $z = 1$ m. The distance of 11.9 m is determined by placing the analysis point 10 m outside the WPT Measurement Boundary, which has a radius of 1.9 m from the center of the receiver coil according to the SAE standard.

A. Reduction Focused on a Specific Direction

This subsection derives the cancellation voltage when the reduction is focused on selected directions. The target directions for reduction are set to $\phi = 0^\circ$, 90° , and 180° in Fig. 3. Table I lists the amplitude ratio α_{Can} and phase θ_{Can} of the cancellation voltage that minimize the leakage magnetic field at each direction.

Figs. 5-7 show the analysis results obtained using the cancellation voltages listed in Table I. In the dual-sided case, the values of the cancellation voltage at $\phi = 0^\circ$ and 180° become identical owing to symmetry. As shown in Fig. 5, the leakage magnetic field at $\phi = 0^\circ$ is significantly

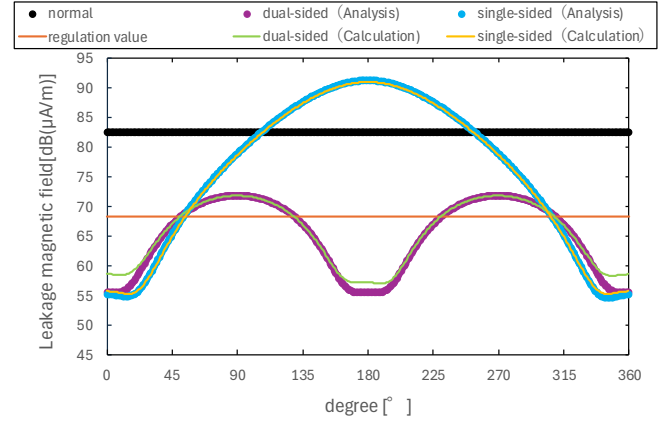


Fig. 5. Comparison of leakage magnetic field with the cancellation voltage optimized at $\phi = 0^\circ$.

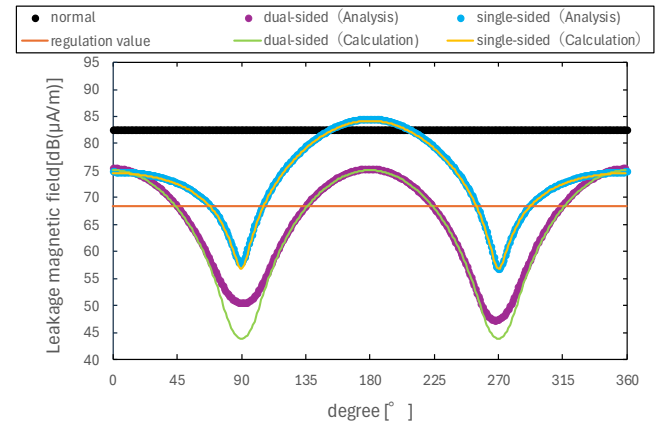


Fig. 6. Comparison of leakage magnetic field with the cancellation voltage optimized at $\phi = 90^\circ$.

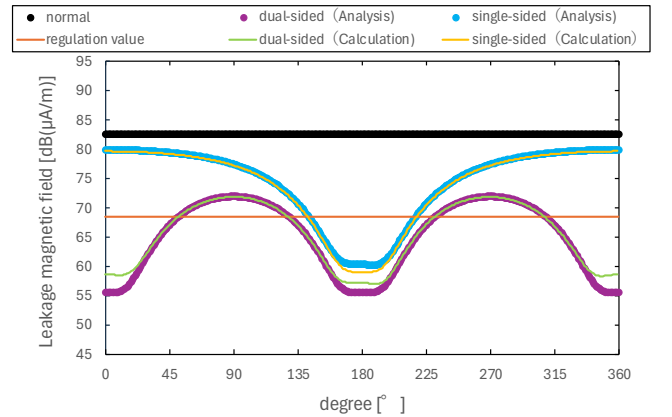


Fig. 7. Comparison of leakage magnetic field with the cancellation voltage optimized at $\phi = 180^\circ$.

reduced in both the dual-sided and single-sided cases, and the single-sided case achieves a greater reduction at this angle. As shown in Fig. 6, the leakage magnetic field at $\phi = 90^\circ$ is significantly reduced in both cases; however, the dual-sided case provides a greater reduction and a wider angular range below the regulatory limit. As shown in Fig. 7, the leakage magnetic field at $\phi = 180^\circ$ is also significantly reduced in

TABLE I. CANCELLATION VOLTAGE

ϕ [deg]	Cancellation Coil	α_{Can}	θ_{Can} [deg]
0	dual-sided	0.425	153.0
	single-sided	0.535	153.0
90	dual-sided	0.605	153.0
	single-sided	1.205	153.0
180	dual-sided	0.425	153.0
	single-sided	2.000	153.0

both cases, and the dual-sided case provides a greater reduction and a wider angular range over which the leakage magnetic field remains below the regulatory limit. Overall, Figs. 5-7 indicate that even when the reduction is optimized only for a specific direction, the magnetic field at the target direction is reduced by more than 20dB($\mu\text{A/m}$) compared with the case without cancellation and falls below the regulatory limit.

B. Omnidirectional Reduction

Whereas the previous subsection focused on leakage magnetic field reduction only at specific directions, this subsection investigates the cancellation voltage that satisfies the regulatory limit over the full azimuthal range, $\phi = 0^\circ$ to

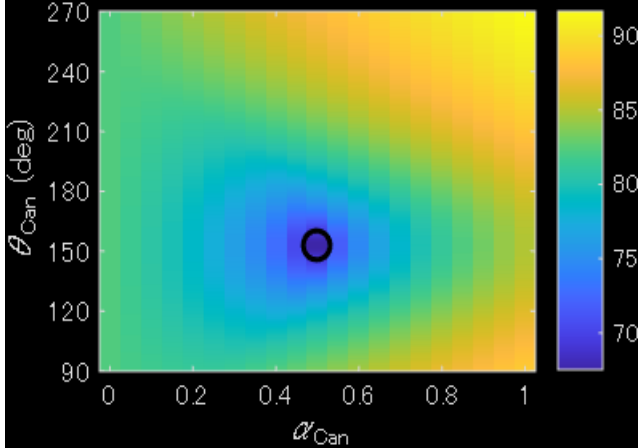


Fig.8. Peak leakage magnetic field over $0^\circ \leq \phi < 360^\circ$ as a function of α_{Can} and θ_{Can} (dual-sided cancellation).

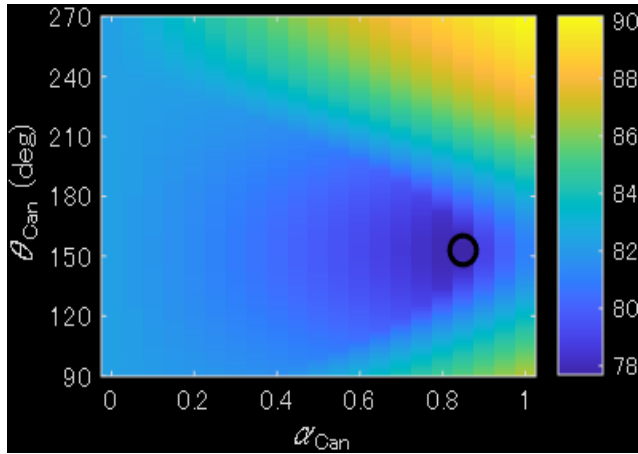


Fig.9. Peak leakage magnetic field over $0^\circ \leq \phi < 360^\circ$ as a function of α_{Can} and θ_{Can} (single-sided cancellation).

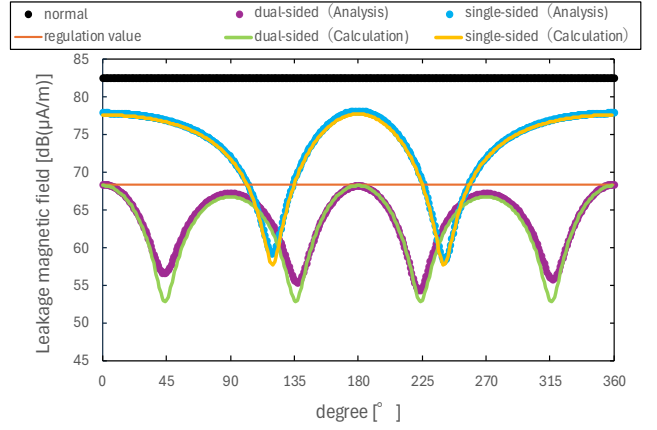


Fig. 10. Comparison of omnidirectional leakage magnetic field using the optimal cancellation voltage.

360° , shown in Fig. 3. For this purpose, the peak value of the leakage magnetic field along the azimuthal direction is used as the evaluation metric, and the pair $(\alpha_{Can}, \theta_{Can})$ that minimizes this peak value is defined as the optimal condition.

Figs. 8 and 9 show the peak value of the leakage magnetic field as a function of the two variables α_{Can} and θ_{Can} for the dual-sided and single-sided cases, respectively. The optimum values are $\alpha_{Can} = 0.500$ and $\theta_{Can} = 153.0^\circ$ for the dual-sided case, and $\alpha_{Can} = 0.850$ and $\theta_{Can} = 153.0^\circ$ for the single-sided case. These optimum values indicate that the dual-sided scheme achieves the optimal condition with a smaller amplitude ratio than the single-sided scheme. Fig. 10 shows the leakage magnetic field obtained using the optimum cancellation voltage for each case. As shown in Fig. 10, the electromagnetic-field analysis and the calculated values agree well overall, although a discrepancy is observed near the minimum value of the leakage magnetic field in the dual-sided case. In the single-sided case, some azimuthal directions still exceed the regulatory limit even when the peak value of the leakage magnetic field is minimized. In contrast, in the dual-sided case, the peak value is 68.30 dB($\mu\text{A/m}$) at $\phi = 0^\circ$, and the leakage magnetic field remains below the regulatory limit of 68.4 dB($\mu\text{A/m}$) in all directions. Compared with the case without cancellation, the reduction is 4.5-24.4 dB($\mu\text{A/m}$) for the single-sided case and 14.2-28.3 dB($\mu\text{A/m}$) for the dual-sided case. This difference is considered to arise because, in the single-sided case, the leakage magnetic field is cancelled by only one adjacent coil and the reduction effect tends to be biased toward selected directions, whereas in the dual-sided case, two adjacent coils can share the cancellation effect, making it possible to reduce the directional bias of the leakage magnetic field around the full azimuth. Therefore, the dual-sided scheme is effective not only for reducing the leakage magnetic field in selected directions but also for satisfying the regulatory limit over the entire azimuthal range.

IV. CONCLUSION

This paper has considered a DWPT system in which adjacent coils are used as cancellation coils and has derived the optimal conditions of the cancellation voltage, namely its amplitude ratio and phase difference, by theoretical calculation based on the Double-LCC circuit. Under the

reduction conditions optimized for selected directions, both the single-sided and dual-sided schemes achieved reductions of more than 20 dB(μ A/m) compared with the case without cancellation, and the leakage magnetic field fell below the regulatory limit in the target directions. In addition, the dual-sided scheme provided a greater reduction effect and a wider angular range below the regulatory limit. Under the omnidirectional reduction condition, the single-sided scheme still left directions that exceeded the regulatory limit, whereas the dual-sided scheme remained below the regulatory limit in all directions. Furthermore, compared with the case without cancellation, the reduction was 4.5-24.4 dB(μ A/m) for the single-sided scheme and 14.2-28.3 dB(μ A/m) for the dual-sided scheme, demonstrating the superiority of the dual-sided scheme. These results show that, compared with the single-sided scheme, the dual-sided scheme can realize more uniform leakage magnetic field reduction over the azimuthal range and is effective in satisfying the regulatory limit in all directions.

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