Leakage Magnetic Field Suppression Method Using the Next Transmission Coil as a Cancel Coil with Ferrite and Shield in Dynamic Wireless Power Transfer

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ABSTRACT: In recent years, from the perspective of carbon neutrality, the spread of Electric Vehicles (EVs) is progressing worldwide. However, it is not widely used due to its cruising distance and battery weight. Therefore, attention is focused on Wireless Power Transfer (WPT), especially Dynamic Wireless Power Transfer (DWPT), which supplies power to a running EV. The leakage magnetic field is a problem in spreading this technology. If the magnetic field used in WPT using magnetic resonance coupling leaks outside, it may adversely affect the human body and electronic devices. Therefore, in this paper, we consider leakage magnetic field suppression. Although the method of using a canceling coil or changing the coil structure is common, this paper proposes a leakage magnetic field suppression method that does not require additional coils and does not change the coil structure by controlling only the phase of the voltage applied to the cancel coil. Simulations on the proposed method show that it is possible to suppress the leakage magnetic field. It was also confirmed that the magnetic field suppression is effective even when the position of the receiving coil is shifted.

KEY WORDS: Electric Vehicle (EV), Wireless Power Transfer (WPT), Dynamic Wireless Power Transfer (DWPT), Leakage Magnetic Field, Coil Misalignment

1. INTRODUCTION

In recent years, the promotion of Electric Vehicles (EVs) from the perspective of carbon neutrality has been actively pursued. However, EVs have not yet become popular due to issues such as the heavy weight of on-board batteries and short driving ranges. One solution that has gained attention is Wireless Power Transfer (WPT), specifically Dynamic Wireless Power Transfer (DWPT), which charges EVs wirelessly while in motion. This technology has the potential to solve the problems and ultimately contribute to the spread of EVs, and research is being actively pursued in this area.

However, there are various challenges to the practical implementation of DWPT. One of them is the leakage magnetic fields when using magnetic resonance coupling for WPT. Leakage magnetic fields are divided into near-field and far-field leakage magnetic fields, which have the potential to adversely affect the human body and electronic devices, so it is essential to suppress leakage magnetic fields to achieve DWPT. Previous research has suggested methods such as using a magnetic shield [(1)-(3)] or coil arrangements with canceling coils [(4)-(6)] to suppress leakage magnetic fields. However, these methods are not desirable from the perspective of increased complexity of structure or cost associated with coil creation and burial. Additionally, there are more papers that focus on suppressing near-field leakage magnetic fields compared to far-field leakage magnetic fields [(7)-(9)].

Therefore, this paper proposes a new method that suppresses far-field leakage magnetic fields using only the power transmission and receiving coils, including the forward power transmission coil, without the need for additional canceling coils. The leakage field suppression effect of the proposed method was verified by electromagnetic field analysis software. In this paper, Chapter 2 describes the proposed method, Chapter 3 presents simulation results based on the proposed method, and Chapter 4 concludes the paper.

2. DWPT Assumption System

Firstly, an illustration of DWPT is shown in Fig.1.

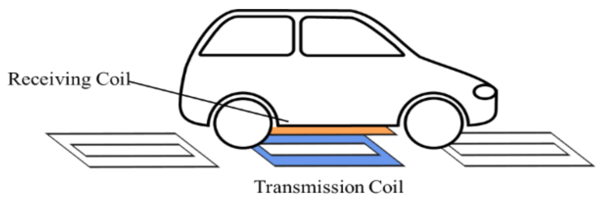


Fig.1 DWPT System

The power transmission method uses magnetic resonance coupling and is an on-board type with coils attached to the underside of the vehicle. The circuit configuration is an S-S (Series-Series) circuit, in which a capacitor is connected in series to the coil. When the receiving coil (Rx) comes above the transmission coil (Tx), power transmission is performed by coupling the transmission and receiving coils. As the EV moves, the coupling coils change, and the transmission coil that performs power transmission is switched based on the detection by the transmitting side. Fig.2 shows the method proposed in this paper.

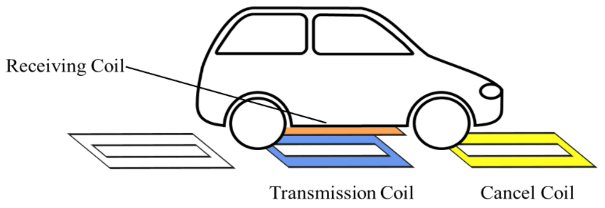


Fig.2 Proposed DWPT Method

The proposed method is a technique for suppressing leakage magnetic fields by simultaneously activating the forward power transmission coil as a cancel coil (Cx) for the coupled power transmission and receiving coils used in the power transmission method employing magnetic field resonance coupling and on-board coils installed under the vehicle. In this paper, the voltage and phase applied to the cancel coil are referred to as the cancel voltage and cancel phase, respectively. By synchronizing the power sources connected to the main coil and cancel coil and outputting a cancel voltage with a varying amplitude and phase at the same time the main power source is activated, this method suppresses leakage magnetic fields.

3. SIMULATION

3.1. Analytical Model

The analysis model created based on the proposed method is shown in Fig.3, and the parameters for each are presented in Table 1.

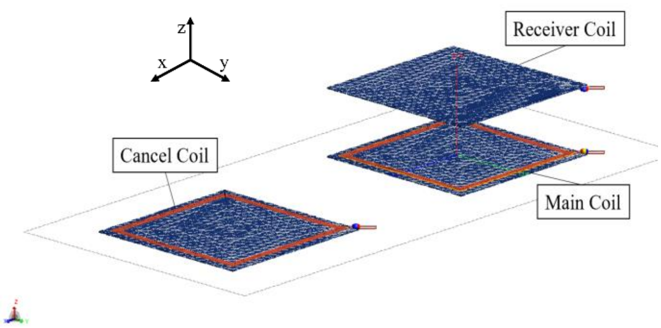


Fig.3 Created Model

Table 1 Coil Parameter in Simulation

Number of coils n	11
pitch [mm]	3
L [μH]	251.8
Q	1010
C [nF]	13.9
f [Hz]	85,000
gap [mm]	150

In this study, electromagnetic field simulations were performed using the electromagnetic field analysis software "FEKO" from Hyper Works. The software uses the Method of Moments (MoM) for electromagnetic field analysis calculations. In this paper, the parameters of the transmission and receiving coils and cancel coil were all assumed to be the same. To avoid coupling between the main coil and the cancel coil, they were placed 400 mm apart, equivalent to one coil pitch. Ferrite and aluminum shields were used for each coil. The ferrite used was PC95 specified in J2954.

3.2. Leakage Magnetic Field Analysis Method

The analysis range refers to the 11.9 m point from the center of the power receiving coil specified in SAE J2954 [10]. This sets the radius 1.9 m point as the WPT measurement boundary, with a measurement range of 10 m from there.

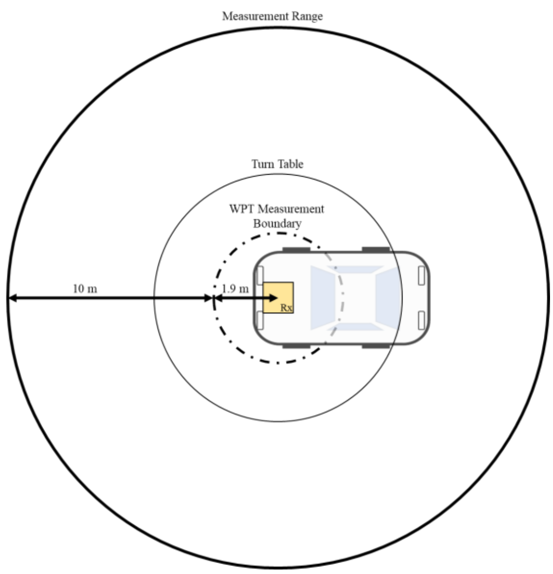


Fig.4 Measurement Range Defined by SAE J2954

The measurement area was determined by excluding areas where people do not enter, such as the Traveling Direction of the car, from the range shown in Fig.4, and is shown in Fig.5. In this paper, we will discuss the location where the maximum value was observed in this analysis area.

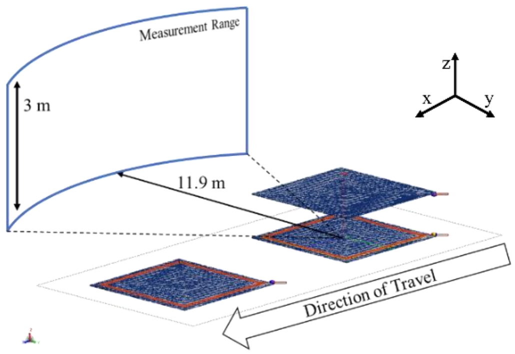


Fig.5 Measurement Point

The measurement area shown in Fig.5 is defined as the range excluding the areas where people do not enter, such as the direction of vehicle travel. This paper discusses the location where the maximum value is obtained in this analysis area.

Regarding the regulation values, the maximum allowable value of 68.4 dBμA/m specified in Paragraph 4 [(11)] of the Ministry of Internal Affairs and Communications Notification No. 207 is used. In this paper, the magnetic field intensity at the 11.9 m point in the proposed method is compared with this regulation value, and simulations are performed.

The analysis procedure is as follows: first, the transmission voltage is fixed at 600 V to achieve a received power of 20~30 kW. Then, while fixing the cancel voltage to 10 V, only the cancel phase is changed. Next, while fixing the phase that showed the most significant suppression effect, the cancel voltage is varied. The leakage magnetic field suppression effect is evaluated using this method.

3.3. Analysis Result

The simulation results for the far-field leakage magnetic fields intensity are shown in Fig.6, which illustrates the maximum magnetic field intensity point in the measurement range when only the cancel phase is varied.

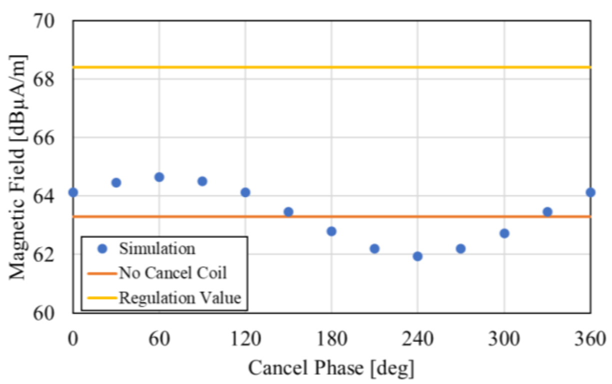


Fig.6 Simulation Result for Voltage Phase

Based on the results shown in Fig.6, it was confirmed that the magnetic field intensity is the lowest when the cancel phase is 240 deg, indicating that the leakage magnetic field is suppressed. Therefore, with the cancel phase fixed at 240 deg, the maximum magnetic field intensity within the measurement range was analyzed by varying only the cancel voltage. The results are shown in Fig.7.

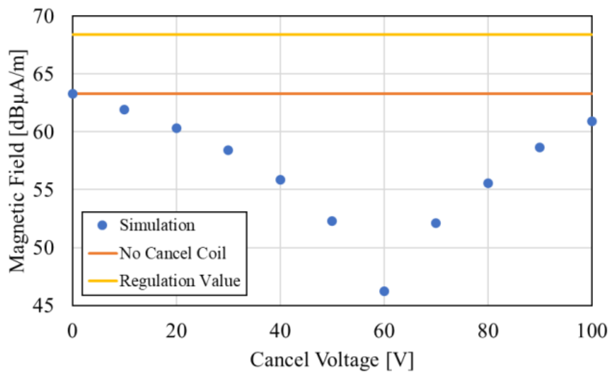


Fig.7 Simulation Result for Voltage Change

From Fig.6 and Fig.7, it was confirmed that the leakage magnetic field can be suppressed the most by applying a voltage of 60 V and 240 deg to the cancel coil when the main power supply is 600 V. Next, the following color map summarizes the size of the magnetic field other than the voltage magnitude and phase analyzed in Fig.6 and Fig.7.

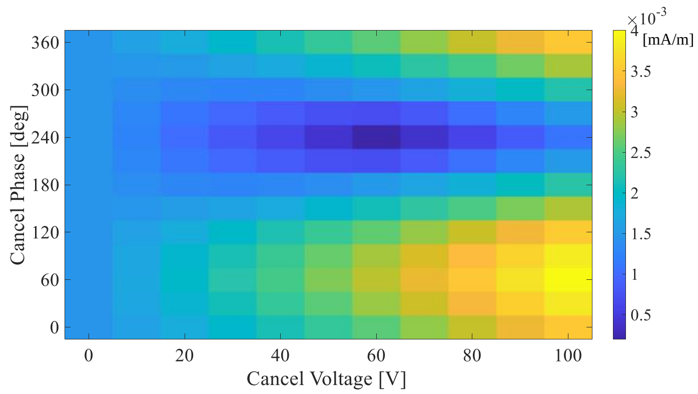
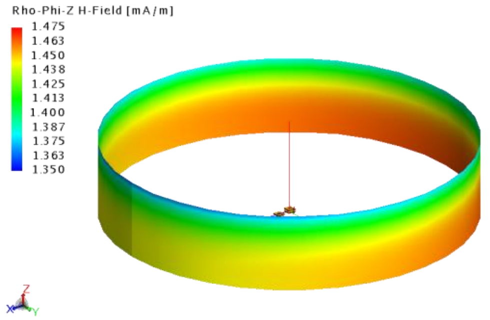


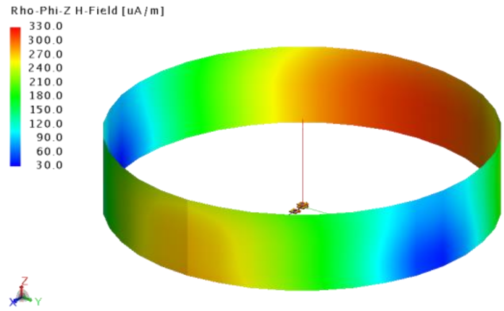
Fig.8 Color Map of Simulation Results

From Fig. 8, it was confirmed once again that applying a voltage of 60 V and 240 deg cancel phase to the cancel coil provides the best suppression of leakage magnetic fields. It was also observed that increasing the cancel voltage leads to an increase in the overall magnetic field. This is because the cancel coil used to suppress leakage magnetic fields generates a large magnetic field, which in turn increases the overall magnetic field.

Fig.9 shows the magnetic field in all directions without cancel voltage applied and with the voltage values of 60 V and 240 deg, which were the highest values obtained from Figs. 6 and 7, applied to the cancel coil to suppress the leakage magnetic field. Fig.10 shows the magnetic fields with and without the cancel coil and the difference at each point.

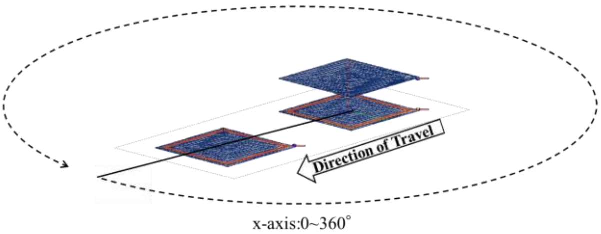


(a) without Cancel Coil

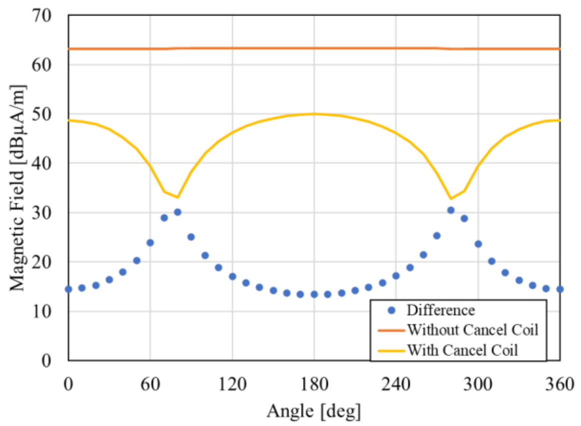


(b) with Cancel Coil

Fig.9 Appearance of Magnetic Field with Cancel Coil



(a) About x-axis



(b) Magnetic Field Difference

Fig.10 Magnetic Field Difference at Each Point

From the magnitude of the suppression, the color scale has different ranges, but Fig.9 confirms that applying a voltage of 60 V and 240 deg to the cancel coil can significantly suppress the leakage magnetic field not only within the measurement range defined in Fig.5, but also in all directions. Additionally, Fig.10 shows that suppression of 15~30 dBμA/m is achieved in all directions. Especially well suppressed in the 90 deg and 270 deg directions, where pedestrians are most likely to be present.

Finally, Fig.11 shows the transmission efficiency and received power between the transmitter and receiver when the cancel coil was operated at the voltage values of Fig.6 and 7. Note that (1) was used to calculate the efficiency.

$$\eta = \frac{P_R}{P_T + P_C} \quad (1)$$

Here, P_R represents received power, P_T represents transmitted power, and P_C represents canceled power.

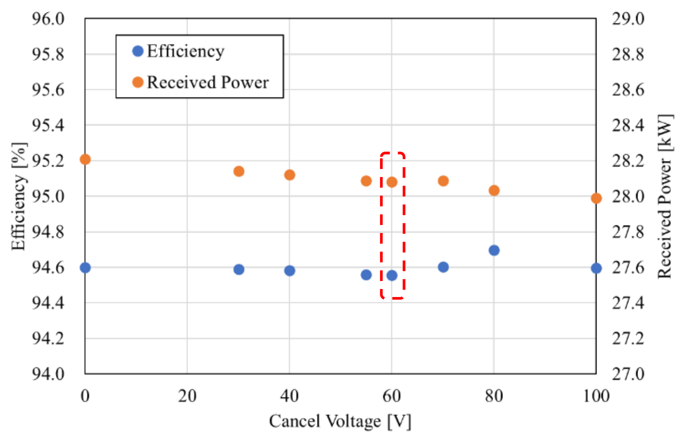


Fig.11 Simulation Result for Efficiency and Received Power

From Fig11, it can be seen that changes in cancel voltage and cancel phase have little effect on the efficiency. Moreover, it can be confirmed that sufficient power is being transmitted with little decrease in power. This is because the transmission and receiving coils and the cancel coils are sufficiently separated, so there is little coupling effect. Even at 60 V and 240 deg (highlighted in red), where the suppression effect of the leakage magnetic field at a distance can be confirmed, the efficiency is hardly affected, and high-efficiency transmission of high-power electricity can be achieved.

Based on these results, it can be confirmed that the proposed method can suppress distant leakage magnetic fields without significantly affecting power transmission efficiency or received power. This demonstrates the usefulness of the proposed method.

3.4. Coil Misalignment

Next, we investigated the effect of misalignment of the receiving coil on the suppression of leakage magnetic fields in the proposed method through simulations. We analyzed two different scenarios of misalignment.

① ±150 mm in the Traveling Direction.

② ±100 mm in the Width Direction.

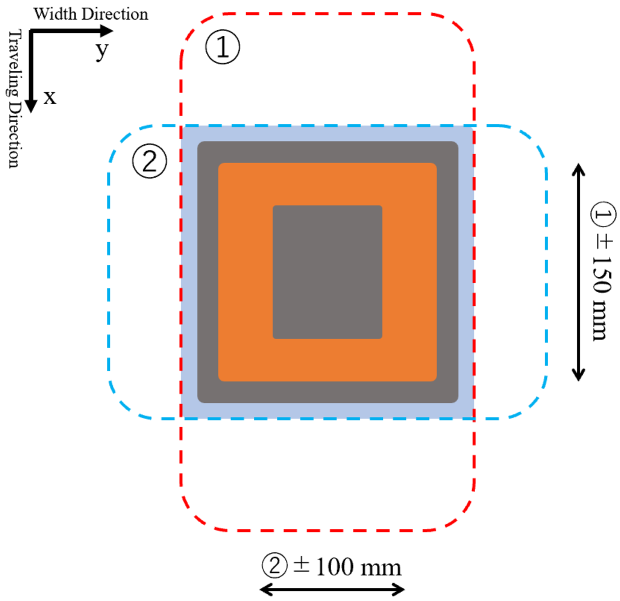
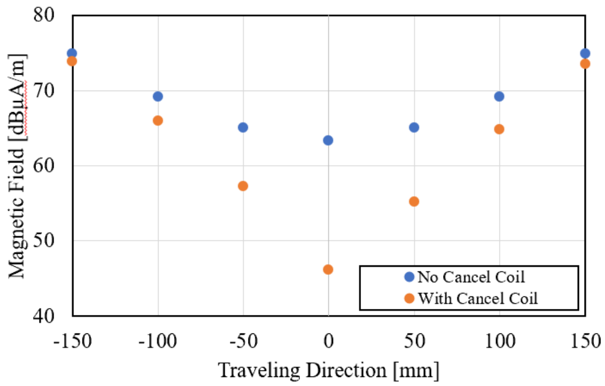
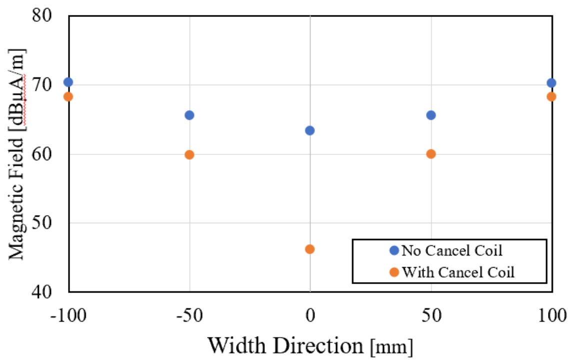


Fig.12 Coil Misalignment Pattern

We conducted simulations for two patterns shown in Fig. 12, each with a displacement of 50 mm. We compared the simulations with and without the cancel coil, using the same values for the transmitting voltage and cancel voltage as in Section 3.3, i.e., 60 V 240 deg. The results are presented in Fig. 13.



(a) Traveling Direction Deviation

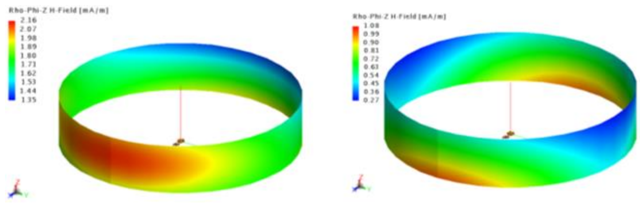


(b) Width Direction Deviation

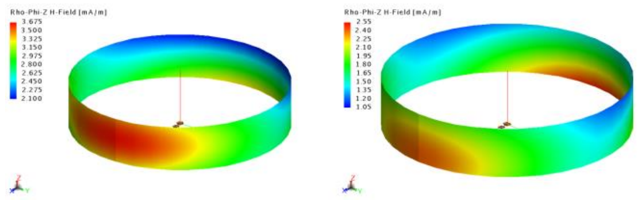
Fig.13 Simulation Results for Misalignment

According to Fig.13, it was confirmed that even when there is a positional deviation, the proposed method can suppress the leakage magnetic field. When the positions of the transmission and receiving coils deviate significantly, the canceling effect is hardly observed, but this is believed to be due to an increase in the amount of leaked magnetic flux and an increase in the current flowing due to changes in the coupling coefficient.

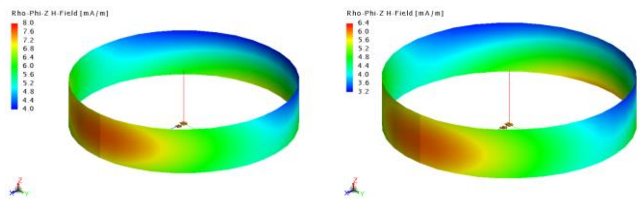
Finally, Fig. 14 and 15 summarize the distribution of magnetic fields when the position of the power receiving coil is shifted in the forward and lateral directions. Please note that the magnitude of the magnetic field varies depending on the presence of the cancel coil and the position of the power receiving coil, so the color scale is different.



(a)x=50 mm

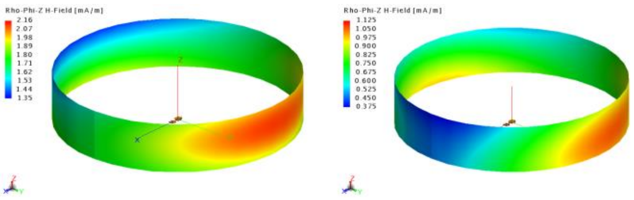


(b)x=100 mm

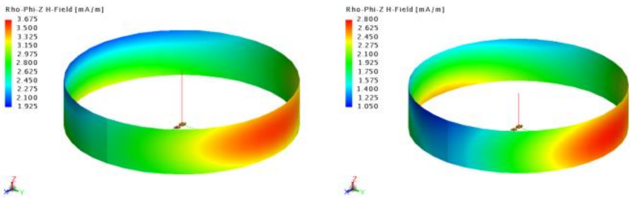


(c)x=150 mm

Fig.14 Magnetic Field Distribution in Misalignment of Traveling Direction (Left: Without Cancel Coil, Right: With Cancel Coil)



(a)y=50 mm



(b)y=100 mm

Fig.15 Magnetic Field Distribution in Misalignment of Width Direction (Left: Without Cancel Coil, Right: With Cancel Coil)

As shown in Fig. 14 and 15, the magnetic field in the direction where the power receiving coil is shifted increases. However, it was confirmed that the overall magnetic field can be reduced by the cancel coil.

4. CONCLUSION

In this paper, we proposed a leakage magnetic fields suppression method using a cancel coil as the transmission coil in front. By analyzing the far-field leakage magnetic fields while changing the cancel voltage and cancel phase, with the transmitting power fixed at 600 V, we verified the magnetic field suppression effect. As a result, simulation showed that a cancel voltage of 60 V and 240 deg could suppress far-field leakage magnetic fields by approximately 20 dBμA/m, without significantly affecting power and efficiency. We also confirmed that magnetic field suppression is possible even when the receiving coil is displaced.

For future research, we need to consider other parameters, such as the position relationship between the transmission coil and the cancel coil, as well as different sizes of transmission and receiving coils. Therefore, we need to conduct simulations and experiments to find the optimal values. We also aim to measure the actual leakage magnetic fields when running an EV and perform experiments assuming DWPT.

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