Study on high-power wireless power transfer for EVs using multiple SAE J2954 coils

- Reduction of Leakage Magnetic Field in Combined Driving of WPT Coils -

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ABSTRACT: In wireless power transfer, it is possible to increase power by using multiple coils. However, there is an issue that the leakage magnetic field is larger than that of a single coil power transfer. In this research, we examined the reduction methods of leakage magnetic field when multiple SAE J2954 WPT3/Z3 coils were driven simultaneously, focusing on the changes in current phase and the use of passive shield type cancel coils. By combining these two reduction methods, we were able to further reduce the leakage magnetic field.

KEY WORDS: Wireless power transfer, SAE J2954, Leakage magnetic field, Current phase, Efficiency, Cancel coil.

1. INTRODUCTION

Recently, contactless wireless power transfer (WPT) technology, which involves no electrical contact, has attracted attention due to its safety, maintainability, and convenience compared to the conductive method(1). The Society of Automotive Engineers (SAE) has issued SAE J2954(2) as a standard for wireless power transfer systems for electric vehicles, and research(3) and product development are progressing based on this standard, which is used as a standard for EV wireless power transfer in Japan and Europe. It is possible to increase the power by using multiple coils as specified in SAE J2954(4), but in that case, there is an issue that the leakage magnetic field becomes larger compared to single coil power supply.

Various circuit topologies, modulation methods, and transmitter-receiver coil structures have been proposed to reduce leakage magnetic fields(5)-(10). Among them, a method of reducing leakage magnetic field in polyphase power supply by preparing N sets of coils and supplying power with a phase difference has been proposed(9). By using air-core circular coils and a frequency of 13.56 MHz, the magnetic field was considered as a far field, and theoretical analysis was performed. However, there has been no study using multiple practical SAE coils with an aluminum shield or a laminated ferrite structure.

Focusing on the coil structure, a method has been proposed to place a shorted or externally powered cancellation coil around the transmission and reception coils, and to cancel the leakage magnetic field by the current flowing through the cancellation coil(10). In the method of short-circuiting the cancellation coil (passive shielding method), the current flowing so that the change in magnetic flux inside the loop of the cancellation coil becomes zero is used to reduce the leakage magnetic field around the cancellation coil. On the other hand, in the method of connecting the cancellation coil to an external power source (active shielding method), the leakage magnetic field generated by the transmission and reception coils is canceled by flowing a current with an opposite phase from the external power source to the cancellation coil. Since the current flowing through the cancellation coil can be controlled in this method, it is more effective in reducing leakage magnetic fields than the passive shielding method, but it requires an additional power source, increasing the cost.

In this paper, we assume that two SAE J2954 WPT3/Z3 coils are used for power supply. In this case, we investigated the reduction of leakage magnetic field by changing the phase of the coil current and the reduction by the cancellation coil of the passive shielding method.

2. COMBINED DRIVING OF SAE J2954 WPT3/Z3 COILS

2.1. SAE J2954 WPT3/Z3 power supply circuit

Fig.1 shows the SAE J2954 WPT3/Z3 circuit(2). The capacitance values of capacitors C_1 to C_{10} and the inductance values of coils L_1 to L_4 are specified in the standard. The coil shape and coil constants of the transmission and reception coils are also specified. Designers are provided with variable impedances of $jX_{GA}/2$ and $jX_{VA}/2$, allowing for adjustment of input and output due to load and gap length variations.

According to the SAE J2954 standard, the transmission coil is referred to as the Ground Assembly Coil (GA coil) and the reception coil is referred to as the Vehicle Assembly Coil (VA coil). This paper follows the same nomenclature. The GA coil consists of an aluminum plate, three layers of ferrite, and an eight-turn circular coil connected in parallel, while the VA coil consists of an eight-turn circular coil, one layer of ferrite, and two aluminum plates of different sizes.

2.2. Circuit Combined Driving Method

This paper deals with the combined driving of two SAE J2954 WPT3/Z3 standard coils. Even when two sets of coils are placed as close as possible, the cross-coupling between adjacent coils is very small and can be ignored(4). There are two circuit configurations for combining two sets of coils: series connection and parallel connection. In this paper, we use parallel connections, which reduces losses during rectification. Fig.2 shows a circuit diagram of the parallel synthesis of SAE J2954 WPT3/Z3 circuits. The values of $jX_{GA}/2$ and $jX_{VA}/2$ were determined by simulation. To obtain the specified output power within the expected gap length change and battery load range, $jX_{GA}/2$ = 8.0 Ω and $jX_{VA}/2$ = 0Ω were set(4). The AC input is defined as the power immediately after the coil $jX_{GA}/2$ in Fig.2, the AC output is defined as the input power to the rectifier circuit, and the DC output is defined as the output power of the rectifier. The two circuits are denoted as Circuit A and Circuit B, with corresponding coils designated as Coil A and Coil B. The current phase is regulated by an inverter, and the input current phase difference is set to either 0° (in-phase) or 180° (anti-phase). The appearance of the two sets of coils (Coil A and Coil B) that were fabricated is shown in Fig.3, and their coils constants are shown in Table 1.

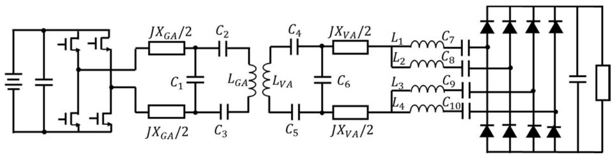


Fig. 1 WPT3/Z3 power supply circuit

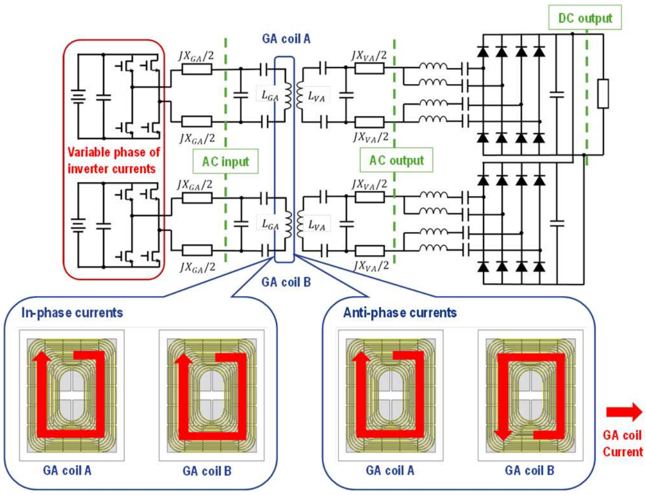


Fig. 2 SAE J2954 WPT3/Z3 parallel composite drive circuit

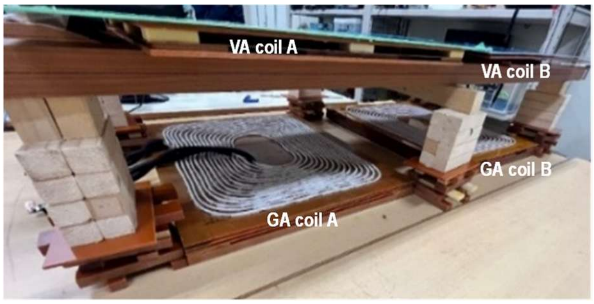


Fig.3 Photo of the parallel combined drive coils

Table 1 Coil constant

	Coil A			Coil B		
gap [mm]	170	210	250	170	210	250
L_{GA} [μH]	38.1	38.5	38.9	38.0	38.5	38.8
R_{GA} [mΩ]	23.8	25.4	25.8	27.8	27.9	27.4
L_{VA} [μH]	40.6	40.4	40.4	40.2	40.0	39.9
R_{VA} [mΩ]	29.1	30.5	32.0	30.4	30.9	31.8
M [μH]	6.60	4.70	3.38	6.51	4.61	3.33
k	0.168	0.119	0.0854	0.167	0.117	0.0848

3. LEAKAGE MAGNETIC FIELD REDUCTION

3.1. Reduction by changing coil current phase

In this paper, we investigate the combined driving of two SAE J2954 WPT3/Z3 standard coils. Under the following assumptions, the electromagnetic field generated by a loop current can be expressed by Equations (1) to (4) (9):

- No free charges exist in the air, i.e., there is no shielding.
- The electric field, magnetic field, and current oscillate at an angular frequency ω, and the time-varying and time-invariant terms can be separated.
- The wave source is much smaller than a sphere with a radius of $1/k$.
- The observation point is much farther from the source than a sphere with a radius of $1/k$.

$$E_r = E_\theta = 0, H_\phi = 0 \tag{1}$$

$$E_\phi = j\frac{ISZ_0}{4\pi}e^{-j\omega t+jkr}\left(\frac{k}{r^2} - j\frac{k^3}{r}\right)\sin\theta \tag{2}$$

$$H_r = \frac{IS}{2\pi}e^{-j\omega t+jkr}\left(\frac{1}{r^3} - j\frac{k}{r^2}\right)\cos\theta \tag{3}$$

$$H_\theta = \frac{IS}{4\pi}e^{-j\omega t+jkr}\left(\frac{1}{r^3} - j\frac{k}{r^2} - \frac{k^3}{r}\right)\sin\theta \tag{4}$$

Equations (1) to (4) show that the electromagnetic field is governed by the magnetic dipole moment IS, where I is the loop current, S is the loop area, and Z_0 is the impedance of free space (=120π). Therefore, the strength of the electromagnetic field generated by multiple coil currents depends on the magnitude of the overlap of the magnetic dipoles IS as shown in the following equation.

$$IS = \sum_{n=1}^{N} I_0 \exp\left(j\frac{2n\pi}{N}\right)S_0 = I_0 S_0 \sum_{n=1}^{N} \exp\left(j\frac{2n\pi}{N}\right) = 0 \tag{5}$$

Here, I_0 is the amplitude of the coil current, and S_0 is the area of the closed space when the transmission coil is approximated as a loop.

To analyze the reduction effect of leakage magnetic fields, we employed the electromagnetic field analysis simulator JMAG. Fig.4 shows the results of calculating the magnetic field strength at a point 3m away from the coil by changing the phase difference of the coil current from 0° to 180°. As shown in equation (5), the leakage magnetic field was at its smallest when the phase difference was 180°. Therefore, in this paper, we conducted an experiment to compare the cases when the current phase difference was 0° (in-phase) and 180° (anti-phase phase).

The power supply experiments were conducted with a driving frequency of 85 kHz, a load value of 9.2 Ω, and coil gaps of 170 mm, 210 mm, and 250 mm. The inverter voltage was adjusted so that the DC output was 10kW. The coil currents under in-phase and anti-phase input conditions are depicted in Fig.5. Although variations in component values might cause deviations in the phase of the inverter current relative to the coil current, it was experimentally confirmed that the coil current could be precisely controlled to be in-phase or anti-phase by adjusting the inverter current phase. Fig.6 shows the variation in power transfer efficiency during the synthesized drive experiment. The results

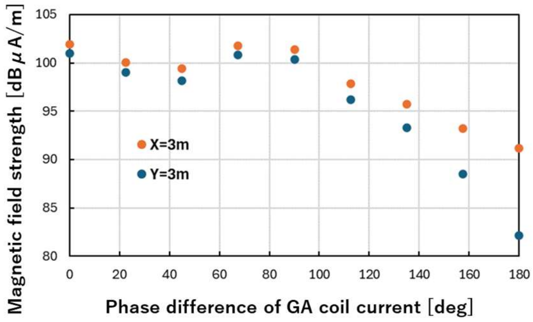
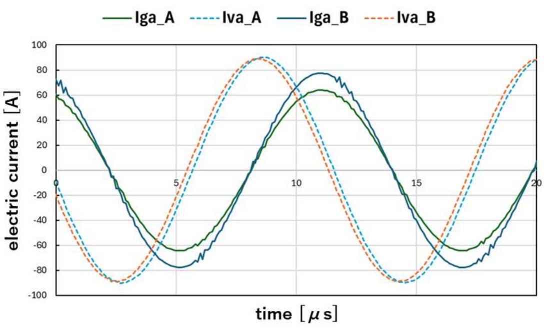
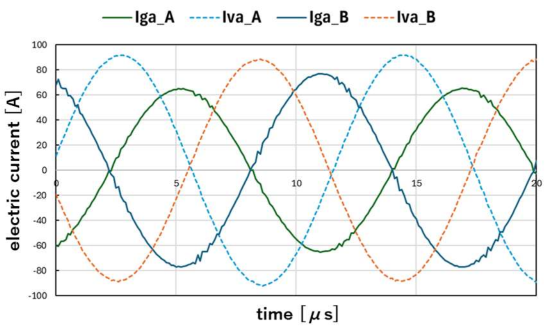


Fig. 4 Magnetic field strength when coil current phase changes



(a) Inverter current waveform for in-phase operation



(b) Inverter current waveform for anti-phase operation

Fig. 5 Coil current waveforms

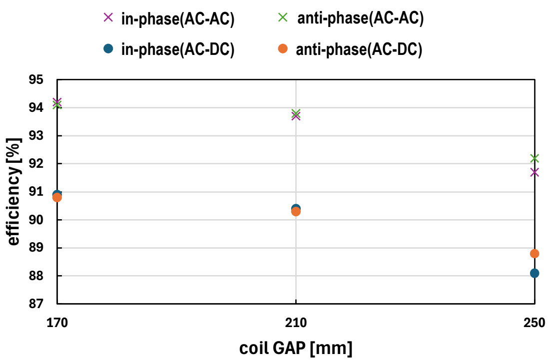


Fig. 6 Change in efficiency due to current phase change

indicate that the power transfer efficiency was unaffected by changes in the current phase.

As shown in Fig. 7, a loop antenna was placed 3m from the center of the coil, and the magnetic fields H_x, H_y, and H_z along each axis were measured according to the conditions specified in SAE J2954, and their root mean square (RMS) value is calculated as the leakage magnetic field strength. Measurements were conducted from 9kHz to 3MHz using peak detection. Fig.8 presents the measured and simulated data at x =3m and y =3m. At x=3m, reductions of 6.47 dBμA/m, 11.1 dBμA/m, and 11.2 dBμA/m in the leakage magnetic field were observed for GAP170mm, GAP210mm, and GAP250mm, respectively. Similarly, at y =3m, reductions of 9.26 dBμA/m, 16.4 dBμA/m, and 17.5 dBμA/m were observed. These findings are consistent with the simulation results. Furthermore, the reduction effect was more pronounced at y =3m compared to x =3m. This is attributed to the fact that the measurement point at y =3m is equally influenced by both coils, whereas at x =3m, the closer coil has a more dominant impact.

2.2. Reduction by cancellation coils

Although this method of reducing leakage magnetic fields by changing the current phase of the coil is very effective, the reduction effect varies depending on the direction. In this section, we discuss the possibility of reducing leakage magnetic fields using a passive shielding type cancellation coil with an additional shorted coil.

Fig. 9 shows a structural diagram and a photo of GA coils and cancellation coils. The cancellation coil is installed only on the GA coil side. The cancellation coil consists of the outer periphery of the GA coil and an extension to either the left or right. The two parts are connected, so the cancellation coil is a closed circuit. When current is passed through the GA coil, magnetic flux is generated and a voltage is induced in the outer periphery of the cancellation coil to cancel out this magnetic flux. As a result, the current flowing through the cancellation coil is of opposite phase to the current flowing through the GA coil. The cancellation coil current also flows in the extended part of the cancellation coil, generating a magnetic flux of opposite phase to the GA coil. The opposite phase magnetic flux generated by the cancellation coil reduces the leakage magnetic field that expands outside the GA coil.

Experiments and simulations were performed under the same conditions as in the previous section, with a GAP of 250mm. The efficiency between the AC input and DC output when the inverter currents were in phase and in opposite phase was 88.3% and 88.7%, respectively, and there was no difference between the two.

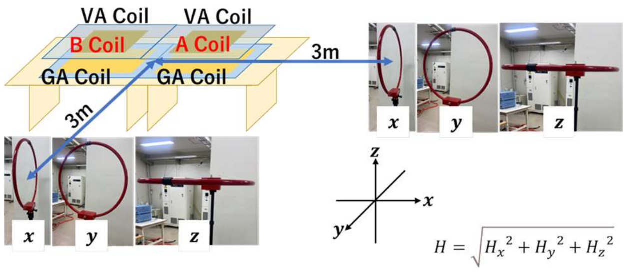
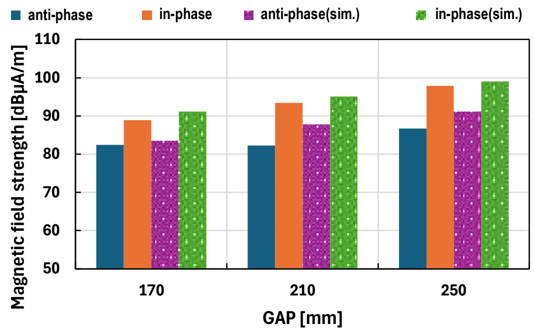
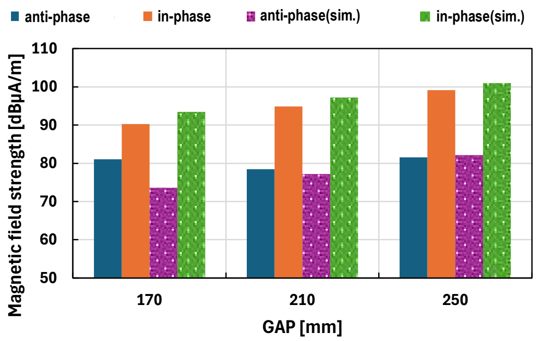


Fig. 7 3-axis measurement method by loop antenna



(a) x =3m



(b) y =3m

Fig. 8 Magnetic field strength when the gap length was changed (without cancel coil)

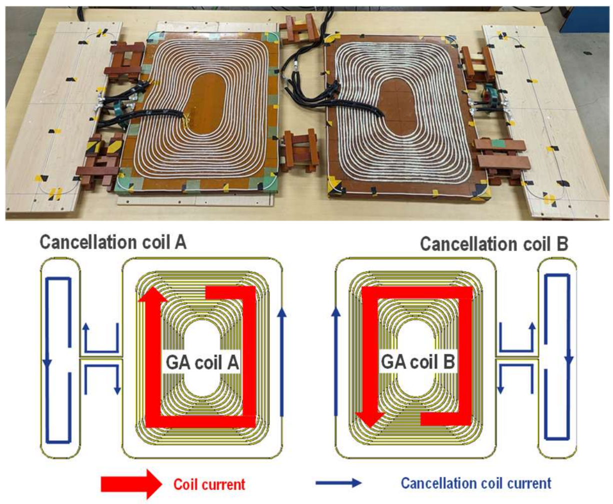
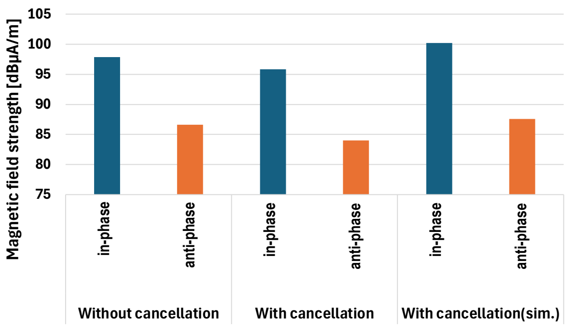


Fig. 9 Structural diagram and a photo of the GA coils and cancellation coils

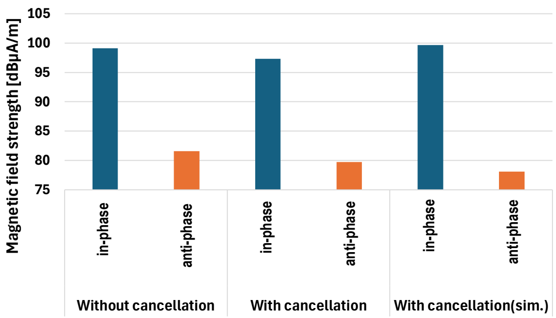
Fig.10 presents the measurement and simulation results for these points. At x =3m, a reduction in leakage magnetic field of 2.01 dBμA/m was observed for in-phase currents and 2.61 dBμA/m for antiphase currents. While the reduction at y =3m was less pronounced, a decrease of 1.80 dBμA/m for in-phase currents and 1.84 dBμA/m for antiphase currents was still observed. Combining this method with the current phase shift technique resulted in a total reduction of 13.8 dBμA/m at x =3m and 19.4 dBμA/m at y =3m.

3. CONCLUSIONS

This paper investigates methods to reduce leakage magnetic fields when multiple SAE J2954 WPT3/Z3 coils are driven simultaneously by changing the current phase and using a passive shielded cancellation coil. It was confirmed that by reversing the current phase of the inverter, the current flowing through the transmitter and receiver coils is also reversed, reducing the leakage magnetic field. While the reduction effect of the leakage magnetic field varies depending on the direction, it was confirmed that by adding a passive shielded cancellation coil in the direction where the leakage magnetic field cannot be reduced, the leakage magnetic field in that direction can also be reduced.



(a) x =3m



(b) y =3m

Fig. 10 Magnetic field strength when gap length is 250mm

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