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Letter

Reduction in Leakage Magnetic Flux of Wireless Power Transfer Systems with Halbach Coils

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This paper proposes wireless power transfer (WPT) system with Halbach coils to reduce leakage magnetic flux. The transmission coil using the Halbach coils generates magnetic flux in the vertical direction and coils that generate a magnetic flux in the horizontal direction. The WPT systems with Halbach and spiral coils are developed and experimentally tested to verify the effect of reducing the leakage magnetic flux density. The experimental results show that the magnetic flux density decreases by 35.6% at maximum.

Keywords : wireless power transfer, Halbach, magnetic flux leakage

1. Introduction

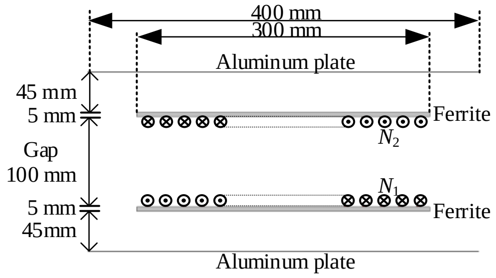
In a wireless power transfer (WPT) system with magnetic induction, it is impossible to prevent leakage of magnetic flux due to its operating principle. From the perspective of human protection, International Commission on Non-Ionizing Radiation Protection (ICNIRP) has published the guidelines for leakage magnetic flux [1]. In order to reduce the leakage magnetic flux, active and passive shielding methods with additional windings have been proposed [2]. However, the additional windings cause the cross-coupling between a main winding and a canceling winding [3].

This letter proposes a wireless power transfer system with Halbach coils which reduce the leakage magnetic flux without cross-coupling. In the Halbach winding, part of the transmission coil also contributes to canceling out the leakage magnetic field.

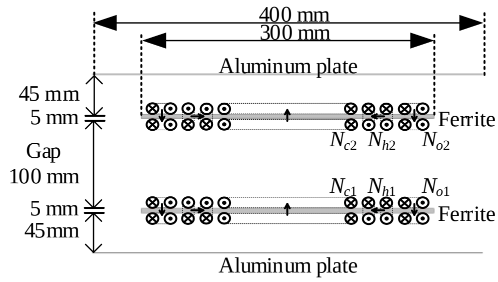
2. WPT system with Halbach coils

Figure 1 shows the cross-sections of the WPT coils. Fig. 1 (a) is the conventional spiral windings. The spiral winding has a winding on the ferrite plate, which generates magnetic flux in only the vertical direction. There is no capability to reduce the leakage magnetic flux. Thus spiral coil needs additional windings for passive or active shielding.

Fig. 1 (b) is the Halbach coils. The Halbach coil replicates the Halbach array [4], which concentrates magnetic flux in one direction through the arrangement of magnets, using coil windings. The Halbach winding has two types of windings, one generates magnetic flux in the vertical direction, and the other generates magnetic flux in the horizontal direction. The horizontal magnetic flux strengthens the vertical magnetic flux between the primary coil and secondary coils. On the other hand, the magnetic flux is canceled out at the top and bottom of the coils. These coils are arranged vertically with ferrite plates sandwiched between them and connected in series. Thus, there is no cross-coupling among the Halbach coils.



(a) Spiral coils.



(b) Halbach coils.

Fig. 1. Transmission coils for WPT.

3. Experimental evaluation

3.1 Evaluation points The evaluation points for leakage magnetic flux density are determined regarding the origin O, located 25 mm above the surface of the buried primary coil, as shown in Fig. 2. The measurement points for the leakage magnetic flux are determined considering the stationary and dynamic charging of EVs. In this study, measurement points 1A and 1B are determined for the protection of occupants in vehicles as a reference to the origin point O. The points 2A and 2B are for the protection of pedestrians standing near the vehicle during stationary charging.

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The points 3A and 3B are for the protection of pedestrians or riders standing slightly away from the vehicle for dynamic charging. Note that the distance from the origin is similarly scaled down, as shown in Fig. 2. The measurement points in the width direction are scaled based on an assumed vehicle width and the width of the aluminum plate used in the experiment. Similarly, in the height direction, the measurement distance is scaled based on the transmission distance for the assumed vehicle and prototype.

3.2 Prototype Figure 3 shows the test environment with a prototype with a rated power of 500 W. The specifications of the prototype are shown in Table I. In the experiment, the number of turns is determined so that the primary and secondary inductances are almost the same for the spiral and Halbach coils for comparison. Each winding is on the laminated PCBs with a size of 300 × 200 × 1.6 mm, with ten layers. The spiral and Halbach coils are configured by changing the wire on the PCBs. Due to the difference in the winding structure, there is a difference in the mutual inductance, nevertheless the same transmission distance. The primary voltage and load resistance are adjusted to ensure that the primary and secondary currents are equal for each winding under the resonance condition. For this reason, the transmission frequency is also adjusted to maintain the resonance condition.

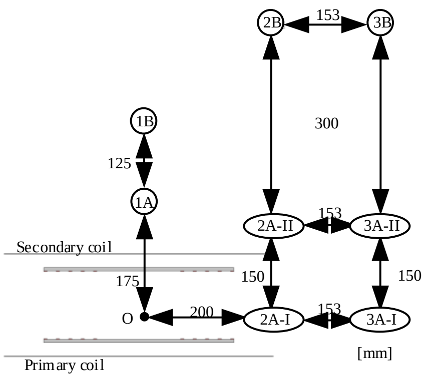
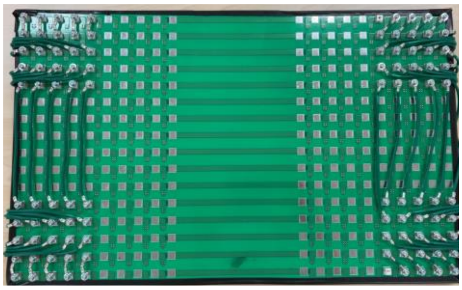
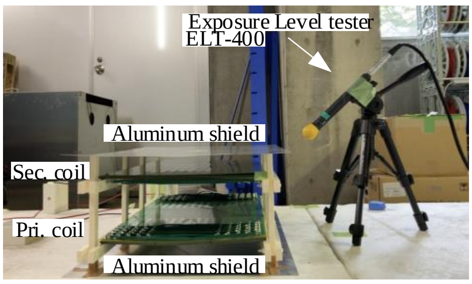


Fig. 2. Evaluation points of leakage magnetic flux for the prototype.



(a) PCB for Halbach coil



(b) Measurement of leakage magnetic flux density

Fig. 3. WPT system with Halbach coils.

Table I. Specifications of the prototype.

	Spiral	Halbach
Number of turn [turn]	N_1, N_2: 25	N_{c1}, N_{c2}: 15
	-	N_{o1}, N_{o2}: 10
	-	N_{h1}, N_{h2}: 10
Self-inductance [μH]	L_1: 520	L_1: 470
	L_2: 530	L_2: 480
Coupling coefficient k	0.34	0.19
Primary current I_1 [A]	2.44	2.44
Primary current I_2 [A]	2.75	2.75
Transmission frequency [kHz]	96	86

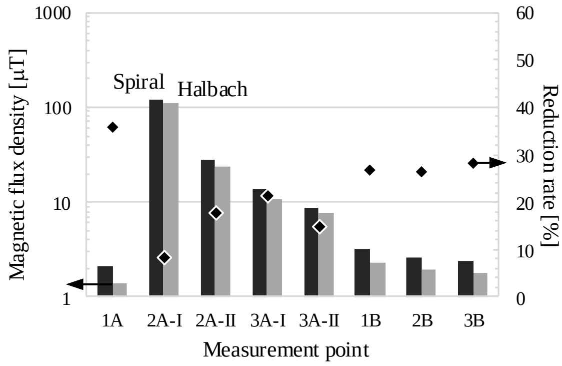


Fig. 4. Magnetic flux density at each measurement point in Fig. 2.

3.3 Experimental results The leakage magnetic flux density of the WPT systems with the conventional spiral coils and proposed Halbach coils are measured and compared. The magnetic flux density is measured with ELT-400.

Figure 4 shows the measured magnetic flux density at each measurement point in Fig .3. In all of the measurement points, the magnetic flux density is reduced. In particular, the effect is maximum at measurement point 1A above the transmission coil, and the magnetic flux density is reduced by 35.6%. The point where the reduction effect is weakest is 2A-I, and the reduction rate is 8.2%. This is because the additional windings for the Halbach coil N_{h1} and N_{h2} produce magnetic flux in the horizontal direction.

4. Conclusion

The WPT system with Halbach coils is proposed to reduce the leakage magnetic flux density in this letter. The magnetic flux density is reduced by 35.6% at maximum compared to the conventional spiral coils.

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