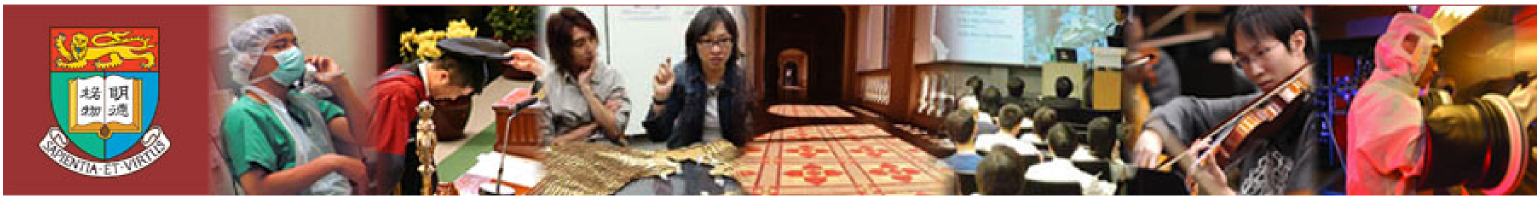

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Modular inductive power transmission system for high misalignment electric vehicle application

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This paper gives a design method of power transmitter for electric vehicle wireless charging applications. Uniform magnetic field is targeted for better modular application and misalignment adaption. Rectangular coil and spiral windings are specially selected for evaluation. The compound winding is chosen for optimization. The magnetic flux density is studied by calculating the mutual inductance per area. By optimally choosing the turns and pitch distances of the spiral winding, a uniform magnetic field is achieved. Using finite element analysis, the performances of the transmitter are evaluated, including its tolerance to misalignment.
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I. INTRODUCTION

Inductive power transmission for electric vehicles (EVs) has made great achievements in the last decade.[1,2] This near-field magnetic field based technology is proved effective for both stationary and dynamic charging applications. The key element in this system is a pair of magnetically coupled coils. When powering a large area, multiple coils can be used to form a single uniform magnetic field. A wide variety of configurations of module layout has been reported, such as multilayer hexagonal coils.[3] For any configurations of layouts, it is important to achieve a uniform magnetic field for each module.

Generally, the coreless planar coil has higher tolerance to misalignment than ferrite core enhanced counterpart although the latter one shows better power transfer ability when perfectly aligned.[4] As for the coil shape, rectangular coil is preferred. The circular coil cannot avoid the absence of coverage when multiple coils are used to form a single surface. By using the multilayer configurations, this problem can be solved but with a much higher cost. As for the receiver, the smaller receiving coil will further improve misalignment tolerance. Therefore, the non-identical transmitting and receiving coils arrangement is selected.

This paper focuses on the design of rectangular transmitting coil structure, which is suitable for modular applications. The most common coil topologies are studied, namely, the coil type and the spiral type. As a result, the coil-spiral compound structure is adopted for generating a uniform magnetic field. For optimal design of the compound structure, a new method based on calculating the mutual inductance per area is proposed. When the calculated mutual inductance per area achieves constant, the magnetic field is considered to be uniform.

This method is applied to the design of a 5 kW, 150 mm air-gap inductive EV charging system. By using finite element analysis (FEA), the magnetic field is evaluated together with the load power under different misalignments.

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II. STUDY ON BASIC TRANSMITTER STRUCTURES

The two systems, using coil and spiral transmitter structures, are shown in Figs. 1(a) and 1(b), respectively. The coil type structure was chosen for the receiver for both systems. These two systems were designed according to the same requirements of a 5 kW, 150 mm air-gap EV charging system. Several parameters were predefined, such as the dimensions and operating frequency. The turns of transmitter and receiver, N_1 and N_2, were chosen to fit the desired battery charging voltage and power. If different combinations of the turns-ratio N_1:N_2 are applicable, the one with least copper mass is favored. The cross-sectional areas of the wires were chosen to satisfy the current density recommendations. In this study, the current density of 3–4 A/mm^2 was selected. The detailed parameters of the coil type transmitter were designed according to Ref. 5. Detailed specifications are summarized in Table I. The spiral type transmitter was constructed using the same specifications, with an identical pitch distance of 10 mm between adjacent turns.

By employing the FEA tool, the models of both coil and spiral type systems were built for comparison. Specifically, the magnetic flux density at the height of 150 mm above the transmitter plane was scanned. The magnetic flux density distribution pattern is shown in Fig. 2. The pattern of coil type transmitter shows a rectangular platform with a concave at the central. On the contrary, the pattern of spiral type transmitter has a single convex at the central but decreases to nearly zero at the border of the transmitter. This study shows a possibility to combine these two types of structures and create a more uniform flux density.

III. OPTIMAL DESIGN OF TRANSMITTER WITH COMPOUND STRUCTURE

When the source and load parameters are defined, the mutual inductance between the transmitter and receiver becomes the major determinant of the load power. If the magnetic flux density is uniform over the whole charging

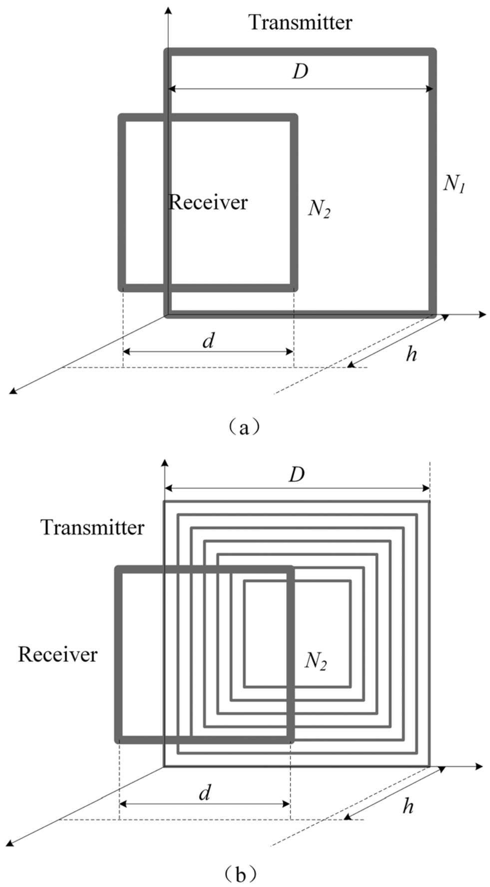

FIG. 1. Sketch and parameters of winding structures: (a) coil type and (b) spiral type.

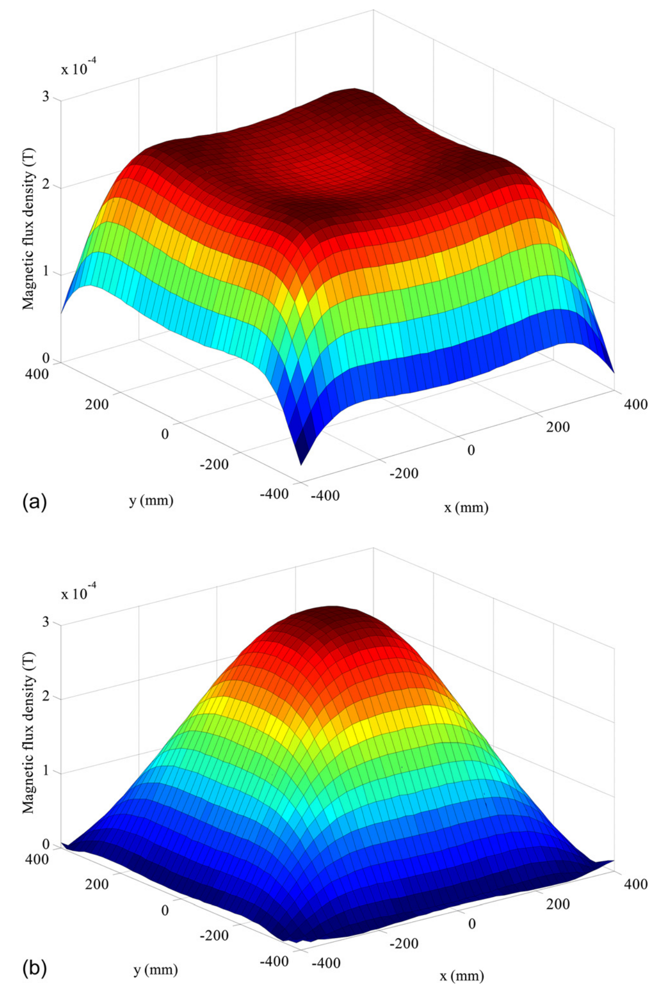

FIG. 2. Magnetic flux density pattern by FEA: (a) coil type and (b) spiral type.

area, the mutual inductance will keep constant, hence achieving best misalignment tolerance. Therefore, the mutual inductance can be conversely used to evaluate the uniformity of magnetic flux density before the transmitter is made.

The mutual inductance is determined by the magnetic flux encircled by the receiver coils. Fig. 3 shows two concentric rectangular coils with different side lengths. Since the coil width is relatively small compared to the dimensions, and Litz wires are used, the coils can be treated as filaments. By using the Biot-Savart law, the mutual inductance is calculated by integrating the magnetic flux within the receiver coils area produced by the four segments: MN, NP, PQ, and QM.[6] For the multi-turn coils, the mutual inductance M is multiplied by the number of turns N_1 and N_2 of both transmitter and receiver

$$
\begin{aligned}
M = \frac{2\mu_0}{\pi} N_1 N_2 \Bigg[& \sqrt{2(D+d)^2 + h^2} + \sqrt{2(D-d)^2 + h^2} \\
& - 2\sqrt{2D^2 + 2d^2 + h^2} \\
& -(D+d)\tanh^{-1}\left[(D+d)/\sqrt{2(D+d)^2 + h^2}\right] \\
& -(D-d)\tanh^{-1}\left[(D-d)/\sqrt{2(D-d)^2 + h^2}\right] \\
& +(D+d)\tanh^{-1}\left[(D+d)/\sqrt{2D^2 + 2d^2 + h^2}\right] \\
& +(D-d)\tanh^{-1}\left[(D-d)/\sqrt{2D^2 + 2d^2 + h^2}\right] \Bigg].
\end{aligned}
\quad (1)
$$

TABLE I. Design specifications for 5 kW EV charging system.

	Coil winding	Spiral winding
No. of the transmitter turns (N_1)	27	
No. of the receiver turns (N_2)	7	
Transmitter dimensions (D*D)	800 × 800 mm	
Receiver dimensions (d*d)	400 × 400 mm	
Air gap (h)	150 mm	
Primary current (I_p)	10 A (RMS)	
Operational frequency (f_0)	100 kHz	
Transmitter coil cross-sectional area (S_1)	3 mm^2	
Receiver coil cross-sectional area (S_2)	10 mm^2	

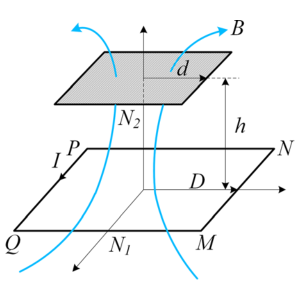

FIG. 3. Concentric multi-turn rectangular filament coils.

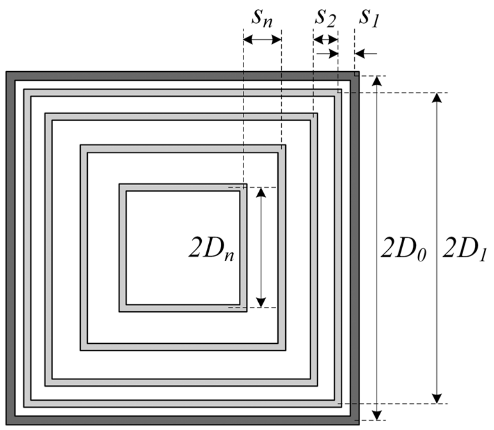

FIG. 4. Layout and parameters of compound wingding structure.

The spiral structure can be treated as a special case of the coil structure. Each turn of the winding is regarded as a single-turn coil, and the mutual inductance can be calculated by (1). The total mutual inductance is obtained by summing the mutual inductance for all turns

$$M_{\text{total}} = \sum_i M(D_i). \tag{2}$$

When the receiver and transmitter are not concentrically aligned, (2) should be extended to the non-concentric condition.[5] However, various testing points should be selected for evaluation, thus increasing the complexity. To simplify the design process, the mutual inductance per area is adopted instead of the mutual inductance itself. By gradually increasing the side length of the receiver d from 0 to D, the mutual inductance per area is calculated as

$$\left(\frac{M_{\text{total}}}{S}\right)_i = \frac{M_{\text{total}}(d_i)}{d_i{}^2}. \tag{3}$$

If the M/S keeps nearly constant at different d, the magnetic flux density is considered to be uniform. For the compound structure transmitter design, the major task is to properly choose the number of turns of the spiral winding, and adjust the optimal pitch distances between adjacent turns, as shown in Fig. 4.

TABLE II. Pitch distance for compound winding.

	Even pitches (mm)	Uneven pitches (mm)
S_1	5	3
S_2	5	4
S_3	5	5
S_4	5	6
S_5	5	7

A compound structure was improved based on the 27-turn coil structure transmitter designed in Sec. II. First, the number of turns of the spiral winding was selected. The number of turns was gradually increased from 1, and the mutual inductance per area was calculated correspondingly for each case. In this study, a 5-turn spiral winding was selected when the magnetic flux density concave at the central of the coil structure was well compensated. Then, the pitch distances were configured. As shown in Fig. 5, the spiral winding with even pitches exhibits a high M/S at the central, but the M/S decreases rapidly at the border of the transmitter. This effect causes a similar drop at the central of the M/S curve for the compound winding. To overcome this shortcoming, the pitch distances were adjusted. The pitch distances closer to the outer borders were tuned smaller. This means that the spiral winding becomes denser at the borders, supporting additional magnetic flux density. As shown in Fig. 5, the compound structure with uneven pitch distances has nearly constant mutual inductance per area at most part of the transmitter, though there are inevitable decreases at the borders for all structures. Table II shows the detailed arrangement of pitch distances.

IV. DESIGN RESULTS AND MISALIGNMENT EVALUATION

The magnetic flux density was again scanned above the transmitter plane at the height of 150 mm using a FEA tool. Compared with the coil structure, the improved compound structure transmitter shows a more uniform flux density

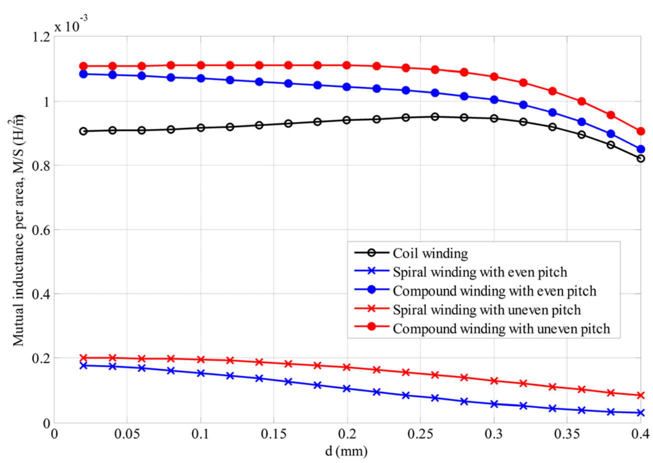

FIG. 5. Calculated mutual inductance per area for coil, spiral, and compound windings.

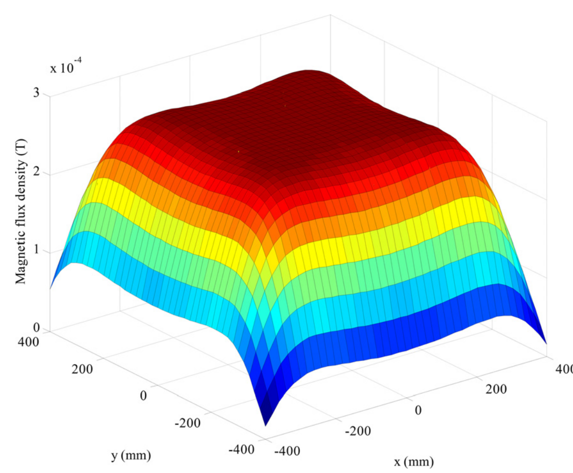

FIG. 6. Magnetic flux density pattern of compound type windings by FEA.

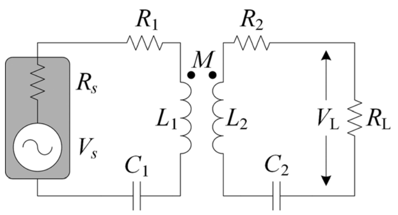

FIG. 7. Equivalent circuit model of S-S compensated IPT system.

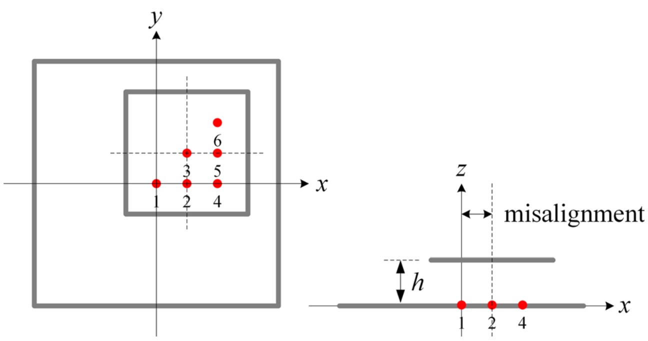

FIG. 8. Testing point for misalignment evaluation.

pattern, especially at the central of the transmitter as shown in Fig. 6. This characteristic is consistent with the mutual inductance calculation results in Sec. III.

When the transmitter and receiver are not concentrically aligned, the mutual inductance will fluctuate because of the unevenly distributed magnetic flux. Fig. 7 shows the equivalent circuit of a serial-serial compensated inductive power transfer (IPT) system, where M denotes the mutual inductance between the transmitter and receiver. Other elements include the internal resistance of the source R_S and the load R_L. The load is assumed purely resistive for simplicity. The load power can be described by (4), which is highly related to M

$$P_L = \frac{\omega_0{}^2 M^2 V_S{}^2 R_L}{\left[(R_S + R_1)(R_L + R_2) + \omega_0{}^2 M^2\right]^2}. \quad (4)$$

The proposed compound transmitter could provide a uniform magnetic flux density at most of the charging area. Nevertheless, it is still important to evaluate the power pickup ability when the receiver is highly misaligned. Six testing positions are selected, taking into account of the misalignments along the lateral and diagonal directions, as shown in Fig. 8, where the red points denote the centers of the receiver. The load power is calculated by FEA along

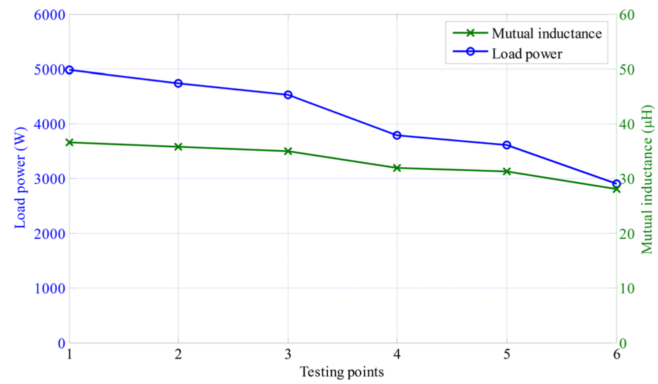

FIG. 9. Load power and mutual inductance at different misalignments.

with the mutual inductance for each case. As shown in Fig. 9, the load power decreases as the misalignment grows. In the worst case scenario, the load power is around 60% of the rated level.

V. CONCLUSION

This paper gives a new transmitter design method for EV wireless charging application. The characteristics of commonly used coil and spiral structures were studied using finite element analysis. A compound structure transmitter for a 5 kW system with an air-gap of 150 mm was designed. Mutual inductance per area was proposed as the index for performance optimization. The magnetic flux density distribution for the designed transmitter is simulated by FEA. The results showed good consistency with the design calculation. The compound transmitter using uneven pitch distances of the spiral winding can offer a uniform magnetic flux density at most of the charging area, though it still exhibits an inevitable reduction at the borders of the transmitter.

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