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Interoperability Study of Wireless Charging System Based on Generalized DD Coil

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Abstract. In recent years, with the popularization of intelligent auxiliary driving technology, wireless charging technology has garnered widespread attention due to its advantages in automation. However, there are still many issues to be resolved before the widespread adoption of wireless charging technology, with a key issue being the interoperability of coupling structures. To achieve adaptive interoperability, this paper proposes a wireless charging system based on dual generalized double-D (DD) coils. The system introduces a receiving structure composed of two generalized DD coils, which can naturally decouple the two coils. At the same time, the system topology employs a series connection of half-bridge rectifiers to enhance the system's equivalent mutual inductance. Mathematical models and simulation verifications are provided. The proposed approach has been validated through simulations, showing that the system can automatically achieve interoperability with unipolar coils, DD coils, and quadrupolar coils.

1 Introduction

In recent years, with the rapid development of intelligent auxiliary driving technology for electric vehicles (EVs), traditional plug-in charging methods have become increasingly insufficient to meet the automated and intelligent demands of EVs. Consequently, wireless charging technology, favored for its safety, convenience, and automation [1-4], has become a focal point of interest in both academia and industry. However, there are still many issues to be resolved before EVs can be fully commercialized, with interoperability issues, especially those related to coupling structures, being a critical concern [5,6].

The interoperability of coupling structures in wireless charging systems refers to the magnetic flux coupling capability between different transmitting (Tx) and receiving (Rx) coils, which determines the system's power transfer capability. Several mainstream coil structures, as shown in Fig. 1, include unipolar coils, double-D (DD) coils, and quadrupolar coils. Due to the inherent characteristics of these coil structures, they are naturally decoupled when aligned, thus completely unable to transfer power, leading to interoperability issues [7,8]. To further promote the adoption of wireless charging technology, it is essential to address this challenge and achieve interoperability of coupling structures.

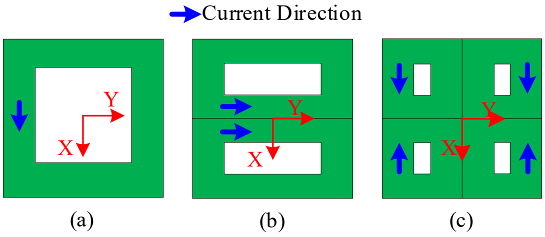

Fig. 1. Conventional coil structures. (a) Square coil. (b) DD coil. (c) Quadrupolar coil.

To achieve interoperability among these coil types, [9] and [10] suggest adjusting the relative position between the Tx and Rx coils to facilitate interoperability between unipolar coils and DD coils. However, this method is only applicable to specific coil structures and requires the coils to be in a particular position to effectively transfer power. Additionally, to enhance the interoperability of common coils, some special coil structures have been proposed. [11] investigates the interoperability between tripolar coils and circular pad (CP) coils as well as bipolar (BP) coils. [12] employs tripolar coils to achieve interoperability with unipolar coils and DD coils. Beyond these, [13] introduces a triple quadrature pad (TQP) coil and studies its interoperability with CP coils and DD coils. Some of the aforementioned literature also discovered that altering the amplitude and phase of the current can improve interoperability. Similarly, [14] achieves interoperability by changing the direction of the current flow. However, these solutions necessitate the prior knowledge of the coil types involved, which requires the addition of complex coil detection devices and control systems, not conducive to reducing system weight and cost.

To achieve adaptive interoperability, this paper introduces a wireless charging system based on dual generalized DD coils. The coil structure design and performance will be detailed in Section II. Section III presents the proposed system topology and mathematical model. System parameters and simulation

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verification are provided in Section IV. Section V summarizes this paper.

2 Magnetic design

To achieve interoperability of coupling structures, this paper proposes a wireless charging system for electric vehicles based on a dual-generalized DD coil structure. The proposed coupling structure is shown in Fig. 2. As can be seen from the figure, the Rx coil structure consists of two generalized DD coils, with the yellow coil representing DD Rx coil 1 and the red coil representing DD Rx coil 2. Each DD Rx coil is composed of two windings, and therefore, the mutual inductance between the two Rx coils is determined by these four windings. Thanks to this unique coil design, the mutual inductance between the four windings cancels out in sign, thus allowing the decoupling of these two generalized DD coils.

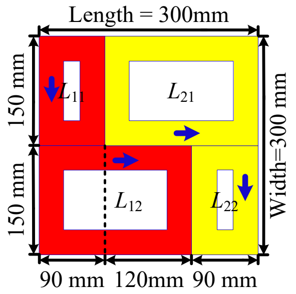


Fig. 2. Proposed Rx coil structure.

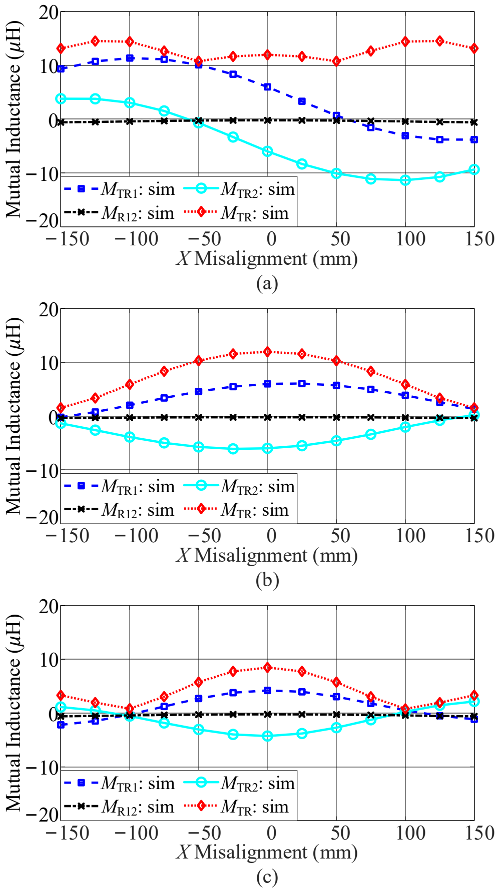


Fig. 3. Simulate the variation of mutual inductance with *X* misalignment when the Tx coils are different. (a) Square Tx coil. (b) DD Tx coil. (c) Quadrupolar Tx coil.

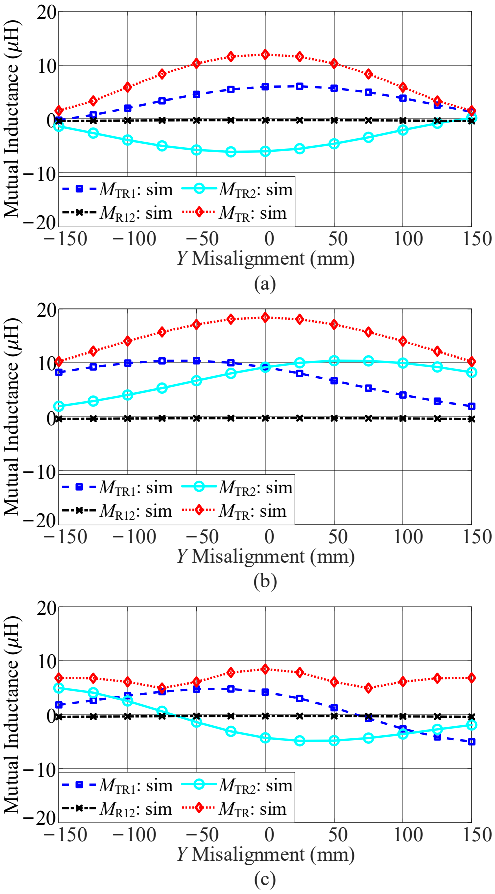


Fig. 4. Simulate the variation of mutual inductance with *Y* misalignment when the Tx coils are different. (a) Square Tx coil. (b) DD Tx coil. (c) Quadrupolar Tx coil.

Different variations of mutual inductance with respect to misalignment are illustrated in Figs. 3 and 4, respectively. It is noteworthy that M_{TR} in the figures represents the equivalent mutual inductance between the entire Rx side and the Tx side, the value of which can be expressed as

$$M_{TR} = |M_{TR1}| + |M_{TR2}| \tag{1}$$

From the figures, it is evident that the mutual inductance between the two Rx coils remains at an extremely low value, negligible enough to be disregarded, thereby effectively verifying that the proposed coil structure can achieve decoupling between the two Rx coils. Additionally, it can be observed that regardless of whether the Tx coil is a unipolar coil, a DD coil, or a quadrupolar coil, the proposed coil structure exhibits a substantial equivalent mutual inductance with each, ensuring the capability to transfer power to coils of different types.

3 Topology and modelling

In order to guarantee that the overall mutual inductance of the system corresponds to the combined total of the individual absolute mutual inductance values, the topology of the system, as presented in this study, is illustrated in Fig. 5.

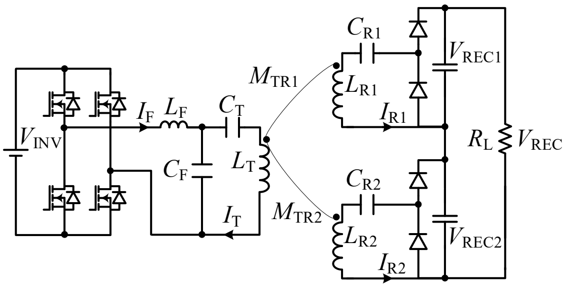


Fig. 5. Proposed system topology.

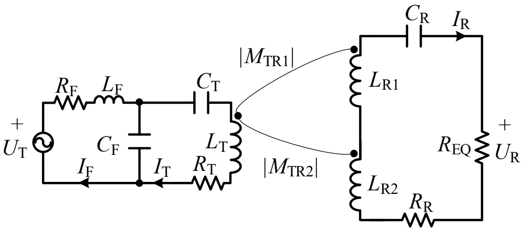


Fig. 6. Equivalent circuit of proposed system.

The dc voltage from the inverter and rectifier is denoted as V_{INV} and V_{REC}, respectively. The self-inductance of the Tx coil is represented by L_T with its corresponding current being I_T. The series compensation inductance of is represented by L_F with its corresponding current being I_F. The self-inductances of the Rx coils are denoted by L_{R1} for the Rx coil 1 and L_{R2} for the Rx coil 2. The currents through these coils are represented by I_{R1} and I_{R2}, respectively. C_T, C_{R1}, and C_{R2} are the series compensation capacitors for the Tx coil, Rx coil 1, and Rx coil 2, respectively, while C_F is the shunt compensation capacitor for the Tx coil. The mutual inductances between the Tx coil and the two Rx coils are represented by M_{TR1} and M_{TR2}, respectively. Due to the coil structure designed to eliminate coupling between the two generalized DD coils, this mutual inductance is neglected. R_L is the load resistance.

The resonant frequency of this system, denoted as ω, is calculated as follows

$$\omega = \frac{1}{\sqrt{L_{R1}C_{R1}}} = \frac{1}{\sqrt{L_{R2}C_{R2}}} = \frac{1}{\sqrt{L_T\dfrac{C_F C_T}{C_F + C_T}}}. \qquad (2)$$

The equivalent circuit of the system is depicted in Fig. 6. The equivalent series resistances (ESRs) of coils L_F and L_T are represented by R_F and R_T, respectively. R_R represents the overall equivalent resistance on the Rx side, while C_R denotes the overall equivalent compensation capacitance on the Rx side. R_R and C_R can be expressed as

$$R_R = R_{R1} + R_{R2}, C_R = \frac{C_{R1}C_{R2}}{C_{R1} + C_{R2}} \qquad (3)$$

The fundamental components of the ac voltages from the inverter and rectifier are denoted as U_T and U_R, respectively. The equivalent load resistance of the system is represented by R_{EQ}. U_T, U_R, and R_{EQ} can be expressed as

$$U_T = \frac{2\sqrt{2}}{\pi}V_{INV}, U_R = \frac{\sqrt{2}}{\pi}V_{REC}, R_{EQ} = \frac{2}{\pi^2}R_L \qquad (4)$$

At the resonant frequency, according to Kirchhoff's Voltage Law (KVL), one can get

$$P_{OUT} = \frac{(\alpha M_{TR}U_T)^2 R_{EQ}}{[R_R + R_{EQ} + \alpha(\omega M_{TR})^2 C_F R_F]^2} \qquad (5)$$

$$\eta = \frac{P_{OUT}}{P_{OUT} + I_F^2 R_F + I_T^2 R_T + I_R^2 R_R}. \qquad (6)$$

where α is defined as follows:

$$\alpha = \frac{1}{L_F + R_T R_F C_F} \qquad (7)$$

4 Simulation verification

To validate the proposed scheme, the simulation model of the system is depicted in Fig. 7. The simulation parameters are shown in Table I. The overall dimensions for all types of the Tx and Rx coils are uniformly 300 × 300 mm, and the charging distance of the system is set to 100 mm.

Figs. 8 to 10 display the output power and efficiency under various misalignments for different Tx coil

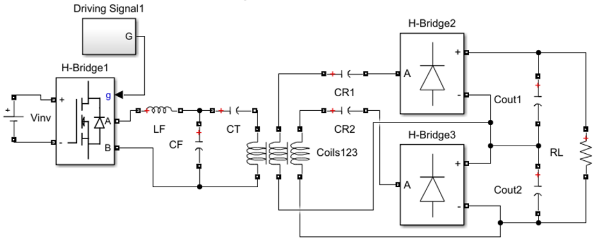
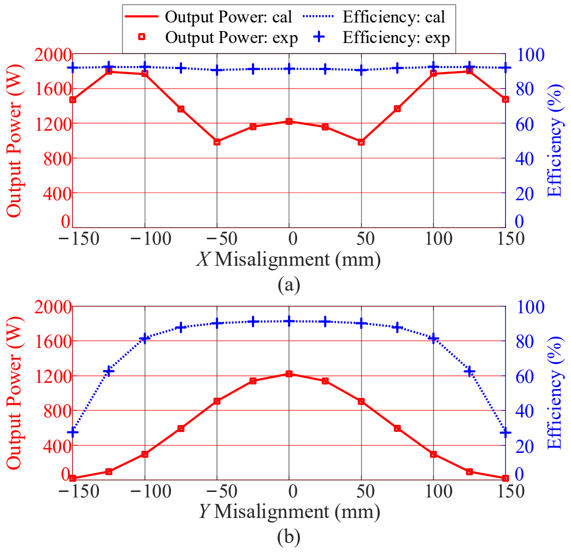


Fig. 7. Model in Matlab/Simulink.

TABLE I
PARAMETERS OF THE PROTOTYPE.

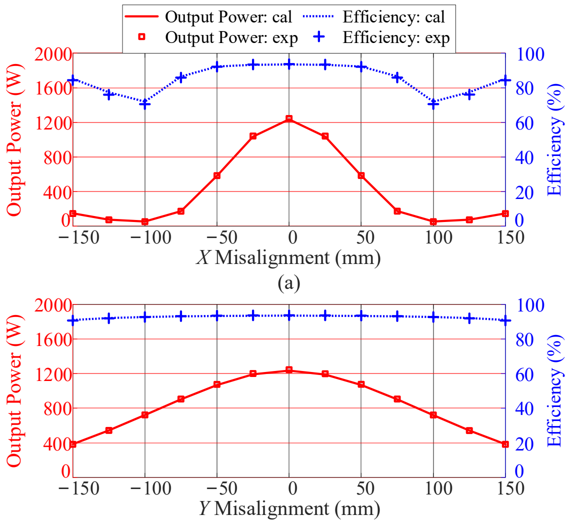
V_{INV}	200 V	L_{R1}	42.31 μH	L_{R2}	42.27 μH
f	85 kHz	R_{R1}	0.1506 Ω	R_{R2}	0.1505 Ω
R_L	30 Ω	C_{R1}	82.87 nF	C_{R2}	82.94 nF
Square Coil		DD Coil		Quadrupolar Coil	
L_F	23.75 μH	L_F	36.34 μH	L_F	16.59 μH
R_F	0.0846 Ω	R_F	0.1294 Ω	R_F	0.0591 Ω
C_F	147.6 nF	C_F	96.48 nF	C_F	211.3 nF
L_T	142.5 μH	L_T	119.9 μH	L_T	116.1 μH
R_T	0.2537 Ω	R_T	0.2135 Ω	R_T	0.2068 Ω
C_T	29.52 nF	C_T	41.95 nF	C_T	35.22 nF



(a)

(b)

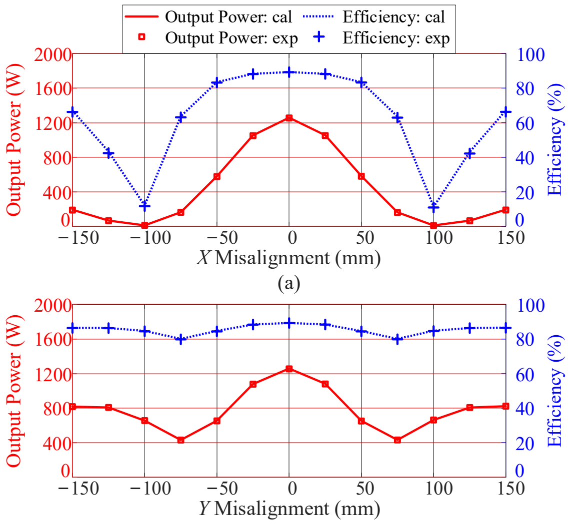
Fig. 8. The variation in output power and efficiency due to misalignments when utilizing a unipolar Rx coil. (a) *X* misalignment. (b) *Y* misalignment.



(a)

(b)

Fig. 9. The variation in output power and efficiency due to misalignments when utilizing a DD Rx coil. (a) *X* misalignment. (b) *Y* misalignment.



(a)

(b)

Fig. 10. The variation in output power and efficiency due to misalignments when utilizing a quadrupolar Rx coil.. (a) *X* misalignment. (b) *Y* misalignment.

configurations: Fig. 8 for a unipolar coil, Fig. 9 for a DD coil, and Fig. 10 for a quadrupolar coil.

From the figure, it can be observed that the system is capable of achieving efficient power transfer for unipolar coils, DD coils, and quadrupolar coils, thereby validating that the proposed solution can effectively realize the interoperability of these three types of coils.

5 Conclusions

To achieve adaptive interoperability, a wireless charging system based on dual generalized DD coils have been proposed in this paper. The Rx coil in this system is composed of two generalized DD coils; by adjusting their winding turns and dimensions, it is possible to attain effective decoupling between them. The Rx side of the system includes two series half bridge rectifiers, resulting in an equivalent mutual inductance that is the aggregate of the mutual inductances, in absolute terms, between each of the Rx coils and the Tx coil. The proposed approach has been validated through simulations, confirming that the system can effectively achieve interoperability with unipolar coils, DD coils, and quadrupolar coils.

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