

Analytical Model of Multicoil Pad Couplers with Ferrite Core Plates in Wireless Electric Vehicle Charging Systems

Wenjie Zhang, Boyu Li, Kejun Wei, Yunguang Gao, Ye Zhang, and Lei Jia

Abstract—Multicoil pad couplers with a bipolar pad (BPP) transmitter and a double-D pad (DDP) receiver have emerged as one of the most promising topologies in wireless power transfer (WPT) systems for electric vehicles (EVs). However, due to their complex structure and variable excitation mode, solving the process of the coupler parameters based on finite element models (FEMs) can be time-consuming and resource-intensive. In this study, the analytical model of the BPP-DDP coupler in different misalignment cases and under different excitation modes is developed based on dual-Fourier transformation. The mutual inductance performance of the BPP-DDP coupler in misalignment is investigated using the proposed analytical model, and the optimized excitation mode of the BPP-DDP coupler in different misalignment cases can be easily obtained. Finally, a prototype of the BPP-DDP coupler with dimensions of 600 mm × 500 mm is constructed, and the experimental results demonstrate that the computational errors of the analytical model and FEM are approximately equal, while the analytical model is 7.6 times faster than the FEM.

Index Terms—Wireless power charging, Multicoil pad coupler, Analytical model, Misalignment tolerance, Excitation mode.

I. INTRODUCTION

WIRELESS power transfer (WPT) has been widely adopted due to its numerous advantages, including the ability to transfer power to the load through electromagnetic coupling without any physical connection, making it safe and convenient [1]-[5]. The application of WPT to wireless charging for electric vehicles (EVs) has attracted considerable research interest owing to its promising potential [6]-[10].

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The structural design and analytical modeling of couplers are crucial for improving the transmission performance of WPT systems. Various coupler structures have been proposed to enhance coupling performance in wireless EV charging. Traditional couplers typically use unipolar coils, such as circular and square couplers [11]-[14]. A unipolar coil realizes energy transmission through coupling magnetic flux in the vertical direction [15]. It exhibits good coupling performance when the pads on both sides are perfectly aligned. However, the coupling coefficient rapidly decreases when misalignment occurs in the horizontal direction. To improve the misalignment tolerance of couplers, the polarized coupler structure called a double-D (DD) coupler is proposed [16]-[18], as shown in Fig. 1(a). Owing to its ability to promote energy transfer by capturing lateral magnetic flux, it can improve the anti-misalignment ability in the x-direction, but its misalignment tolerance in the y-direction becomes worse [15]. To further optimize the coupling performance of couplers under misalignment in any direction, researchers have adopted multicoil pad couplers in WPT systems. In [19], a multicoil pad coupler with a double D (DD) pad transmitter and a double D quadrature (DDQ) pad receiver is proposed. By adding an extra quadrature coil in the DD receiver coil, the anti-misalignment ability of the coupler along the lateral directions is improved. In [20], another multicoil pad coupler, called a bipolar pad (BPP) coupler, which consists of two partially overlapped and decoupled rectangular coils, is proposed, as shown in Fig. 1(b). The misalignment performance of the BPP coupler can be improved by adjusting the excitation modes of the transmitting pad. Among the commonly used multicoil pad couplers, the BPP-double-D pad (DDP) coupler has emerged as one of the most promising topologies in WPT systems for EV charging. The circuit schematic of the WPT system based on the BPP-DDP coupler is shown in Fig. 2. The excitation mode of the BPP-DDP coupler can be flexibly adjusted to improve the misalignment tolerance and reduce the magnetic flux leakage of the coupler [21]. An equation describing the effective coupling factor of the BPP-DDP coupler is proposed to demonstrate how each coil on the transmitting side is energized to control VA transmission [22]. It is evident that a BPP-DDP coupler typically exhibits remarkable mutual inductance and a larger charging zone.

The analytical model has proven to be a more flexible,

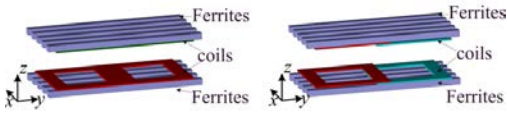


Fig. 1 Structures of the couplers. (a) DDP coupler. (b) BPP coupler.

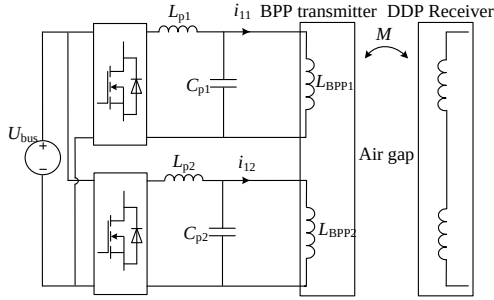


Fig. 2 Schematic circuit of the WPT system with a BPP transmitter.

convenient, and cost-effective tool for analyzing and designing couplers. Various analytical models for different couplers have been proposed in previous studies. In [23], an analytical model for mutual inductance between two circular solenoid coils in lateral and angular misalignment is proposed, and the transmission power of the WPT system is optimized based on the analytical model. In [24], an analytical model is presented for accurately calculating the self-inductance and mutual inductance of two mutually coupled rectangular coils in lateral misalignment. This model can be a reliable tool for designing rectangular hollow magnetic couplers. In [25], an analytical model of mutual inductance is derived based on Neumann's formula, which considers the changes in the angle and position of two rectangular spiral coils to analyze the transmission efficiency of a WPT system. However, couplers used for wireless charging of EVs typically include ferrite layers on both sides, and the ferrite layer is not considered in the above analytical modeling process. To address the limitation, the analytical models of the square and circular planar coils with a ferrite layer are calculated based on the Fourier-Bessel and dual-Fourier transformations [12]. A new empirical equation for the mutual inductance between square coils with ferrite core plates is proposed in [26]. This model can effectively overcome limitations associated with computational time and resources during the design process. In [27], a theoretical model of the square and circular coils between two multilayer media is proposed. This model can calculate the self-inductance and mutual inductance of the two planar coils without requiring excessive computational time. However, these analytical models mainly focus on unipolar coils with ferrite cores, and it is crucial to pay more attention to the modeling of multicoil pad couplers with superior coupling performance. In [28], an analytical model for couplers composed of DD coils or bipolar coils without ferrite layers on both sides is proposed, and the mutual inductance characteristics of the two couplers in misalignment are investigated. In [29], a three-dimensional analytical model of a multicoil pad coupler consisting of a BPP transmitter and a square receiver is established based on the superposition of two-dimensional subdomain analytical models. However,

given the complex structure and the variable excitation mode of the BPP-DDP coupler, there are still some challenges associated with the modeling and analysis of the couplers in different misalignment cases and under different excitation modes.

To overcome these problems, this study proposes an analytical model for the BPP-DDP coupler. The main contributions of this study are summarized as follows:

1) An analytical model of the multicoil pad couplers in different misalignment cases and under different excitation modes is developed based on dual-Fourier transformation. The experimental results show that the calculation accuracy of the proposed analytical model and the finite element model (FEM) is approximately equal, while the computational time of the proposed analytical model is 7.6 times faster than that of the FEM, which facilitates the design and analysis of multicoil pad couplers.

2) The mutual inductance performance of the coupler in different misalignment cases and under different excitation modes can be obtained using the analytical model; it is easy to obtain the optimized excitation modes of BPP-DDP couplers under different misalignment conditions, which can improve the misalignment tolerance of the couplers.

The remainder of the paper is organized as follows: In Section II, the analytical model of the BPP-DDP coupler in different misalignment cases and under different excitation modes is proposed. In Section III, the misalignment performances of the BPP-DDP coupler along different directions are investigated using the proposed analytical model, and the optimized excitation mode of the BPP-DDP coupler in different misalignment cases is obtained. In Section IV, a prototype of the BPP-DDP coupler with dimensions of 600 mm × 500 mm is developed, and the experimental results are presented to verify the theoretical analysis. In Section V, the computational costs and accuracy of the two methods are compared and discussed. Finally, Section VI presents the conclusion.

II. MODELING OF THE BPP-DDP COUPLER

In this section, an analytical model of the BPP-DDP coupler is established based on dual-Fourier transformation. The structure of the BPP-DDP coupler with a single-turn coil in Cartesian coordinates is shown in Fig. 3. The surrounding space of the coupler consists of six regions, where Regions 1 and 6 correspond to the lower and upper areas of the coupler, respectively. The permeability and conductivity of the air medium in these regions are denoted as μ_0 and σ_0 , respectively. Regions 2 and 5 correspond to the ferrite layers on both sides, and the initial permeability is $\mu_{i2} = \mu_{i5} = 2400$. The thickness of Regions 2 and 5 are t_2 and t_5 , respectively, and the vertical distance between the two regions is d . Region 3 corresponds to the area between the lower ferrite layer and the transmitter coil. Region 4 corresponds to the area between the upper ferrite layer and the transmitter coil.

According to classical electromagnetic theory, since the current frequency is less than 100 kHz, the size of the

magnetic pads on both sides are $600 \text{ mm} \times 500 \text{ mm} \times 8 \text{ mm}$, and the coil adopts AWG38 800-strand Litz wire with a diameter of 4 mm, the magnetic field around the coupler can be regarded as a magnetoquasistatic system, and the mutual inductance between the magnetic pads on both sides can be calculated using the quasi-static electromagnetic formula. Because the coils are wound with Litz wire with multiple strands, the current flowing through a single-turn coil is considered a filamentary current. The calculation method of the square coupler can be cited in [12].

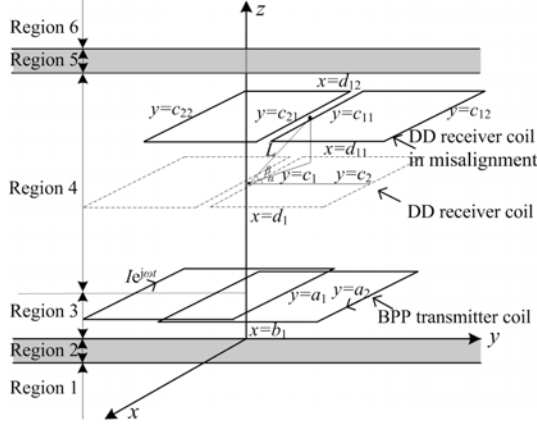


Fig. 3 Schematic of the BPP-DDP coupler.

The positions of each wire in the BPP-DD coupler are shown in Fig. 3. The upper surface of the ferrite plate on the transmitting side is located at the $z = 0$ plane, and the vertical coordinates of the transmitter and receiver coils are $z = z_1$ and $z = z_2$, respectively. Since the mutual inductance of the coupler is independent of the coil currents, only the excitation current $i_1 = Ie^{j\omega t}$ is considered in the analysis, where I is the amplitude, ω is the angular frequency, t is time, and j is the imaginary unit. Moreover, the BPP transmitter can be driven by varying excitation modes [15], and this study focuses on the in-phase excitation and opposing-phase excitation modes.

A. Regions 3 and 4

The magnetic flux density in Regions 3 and 4 includes $\mathbf{B}_n$ ($n = 3$ and 4) excited by the excitation current and $\mathbf{B}_r$ generated by the induced eddy current. By neglecting the displacement current and using the Coulomb gauge condition, the relation between the magnetic flux density $\mathbf{B}_n$ ($n = 3$ and 4) and the magnetic vector potential $\mathbf{A}$ is given by (1). By integrating the point source (x', y', z') along the transmitter coil, the magnetic vector potential $\mathbf{A}$ of an arbitrary point $p(x, y, z)$ can be obtained, as shown in (2). For ease of analysis, only the magnitudes of the magnetic vector potential $\mathbf{A}$ and magnetic flux density $\mathbf{B}$ are considered in (1) and (2):

$$\mathbf{B}_n = \nabla \times \mathbf{A} \quad (1)$$

$$\mathbf{A}(x, y, z) = \frac{\mu_0}{4\pi} \int_v \frac{\mathbf{J}(x', y', z') dv}{R} \quad (2)$$

where v is the infinitesimal unit of the current distribution in the transmitter coil, and R is the distance from an arbitrary point $p(x, y, z)$ to the source point $p'(x', y', z')$, which is given as (3):

$$R = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2} \quad (3)$$

Dual-Fourier transformation and its inverse methods (4) and (5) can be used to solve the magnetic vector potential and magnetic flux density in the following calculations, where ξ and η are the integral variables, and j is the imaginary unit.

$$b(\xi, \eta, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} B(x, y, z) \cdot e^{-j(x\xi + y\eta)} dx dy \quad (4)$$

$$B(x, y, z) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} b(\xi, \eta, z) \cdot e^{j(x\xi + y\eta)} d\xi d\eta \quad (5)$$

By applying dual-Fourier transformation (4) to (1), the components of the magnetic flux density $\mathbf{B}_n$ ($n = 3$ and 4) in the spatial frequency domain can be calculated as (6):

$$b_{nx} = -j\eta a_z - \frac{\partial a_y}{\partial z}, \quad b_{ny} = j\xi a_z + \frac{\partial a_x}{\partial z}, \quad b_{nz} = -j\xi a_y + j\eta a_x \quad (6)$$

Further, by applying dual-Fourier transformation (4) to (2), the magnetic vector potential $\mathbf{A}$ in the spatial frequency domain can be derived as shown in (7), where $k = \sqrt{\xi^2 + \eta^2}$.

$$a(\xi, \eta, z) = \frac{\mu_0}{2} \int_v e^{-j(x'\xi + y'\eta)} J(x', y', z') \frac{e^{-k|z - z_1|}}{k} dv' \quad (7)$$

1) Under in-phase excitation mode

For the BPP transmitter coil under the in-phase excitation mode, the current paths parallel to the x -axis are shown in Fig. 3. By integrating the current density $J_1(x', y', z')$ along the current paths, the x component of the magnetic vector potential a_x generated by the excitation current can be calculated as (8):

$$a_x = \frac{-j2\mu_0 I e^{-k|z - z_1|} \sin b_1 \xi (\sin \eta a_1 + \sin \eta a_2)}{k \xi} \quad (8)$$

The y component of the magnetic vector potential excited by the excitation current can be derived using the same method as (9):

$$a_y = \frac{j2\mu_0 I e^{-k|z - z_1|} \sin b_1 \xi (\sin \eta a_2 + \sin \eta a_1)}{k \eta} \quad (9)$$

Substituting (8) and (9) into (6), the components of the magnetic flux density in different directions can be expressed as (10):

$$\begin{cases} b_{3x} = -\frac{\partial a_y}{\partial z} = \frac{-2j\mu_0 I \sin b_1 \xi (\sin \eta a_2 + \sin \eta a_1) e^{k(z - z_1)}}{\eta} = C_{3x} e^{kz} \\ b_{3y} = \frac{\partial a_x}{\partial z} = \frac{-2j\mu_0 I \sin b_1 \xi (\sin \eta a_1 + \sin \eta a_2) e^{k(z - z_1)}}{\xi} = C_{3y} e^{kz} \\ b_{3z} = -j\eta a_y + j\xi a_x = \frac{2\mu_0 I \sin b_1 \xi (\sin \eta a_1 + \sin \eta a_2) e^{k(z - z_1)}}{\xi \eta} = C_{3z} e^{kz} \end{cases} \quad (10)$$

$$\begin{cases} b_{4x} = -\frac{\partial a_y}{\partial z} = \frac{2j\mu_0 I \sin b_1 \xi (\sin \eta a_2 + \sin \eta a_1) e^{-k(z - z_1)}}{\eta} = C_{4x} e^{-kz} \\ b_{4y} = \frac{\partial a_x}{\partial z} = \frac{2j\mu_0 I \sin b_1 \xi (\sin \eta a_1 + \sin \eta a_2) e^{-k(z - z_1)}}{\xi} = C_{4y} e^{-kz} \\ b_{4z} = -j\eta a_y + j\xi a_x = \frac{2\mu_0 I \sin b_1 \xi (\sin \eta a_1 + \sin \eta a_2) e^{-k(z - z_1)}}{\xi \eta} = C_{4z} e^{-kz} \end{cases} \quad (11)$$

2) Under opposing-phase excitation mode

Similarly, for the BPP transmitter coil under the opposing-phase excitation mode, the current paths parallel to the x -axis can be obtained from the current distribution in the BPP transmitter coil. By integrating the current density $J_1(x', y', \text{ and } z')$ along the current paths, the x component of the magnetic vector potential generated by the excitation current can be derived as (12):

$$a_x = \frac{2\mu_0 I e^{-k|z-z_1|} \sin b_1 \xi (\cos \eta a_1 - \cos \eta a_2)}{k \xi} \quad (12)$$

The y component of the magnetic vector potential excited by the excitation current can be derived using the same method as (13):

$$a_y = \frac{2\mu_0 I e^{-k|z-z_1|} \sin b_1 \xi (\cos \eta a_2 - \cos \eta a_1)}{k \eta} \quad (13)$$

Substituting (12) and (13) into (6), the components of the magnetic flux density in different directions can be obtained as (14):

$$\begin{cases} b_{3x} = -\frac{\partial a_y}{\partial z} = \frac{-2u_0 I \sin \xi b_1 (\cos \eta a_2 - \cos \eta a_1) e^{k(z-z_1)}}{\eta} = C_{3x} e^{kz} \\ b_{3y} = \frac{\partial a_x}{\partial z} = \frac{2u_0 I \sin \xi b_1 (\cos \eta a_1 - \cos \eta a_2) e^{k(z-z_1)}}{\xi} = C_{3y} e^{kz} \\ b_{3z} = -j\epsilon a_y + j\eta a_x = \frac{2ju_0 I k e^{k(z-z_1)} \sin \xi b_1 (\cos \eta a_1 - \cos \eta a_2)}{\xi \eta} = C_{3z} e^{kz} \end{cases} \quad (14)$$

$$\begin{cases} b_{4x} = -\frac{\partial a_y}{\partial z} = \frac{2u_0 I \sin \xi b_1 (\cos \eta a_2 - \cos \eta a_1) e^{-k(z-z_1)}}{\eta} = C_{4x} e^{-kz} \\ b_{4y} = \frac{\partial a_x}{\partial z} = \frac{-2u_0 I \sin \xi b_1 (\cos \eta a_1 - \cos \eta a_2) e^{-k(z-z_1)}}{\xi} = C_{4y} e^{-kz} \\ b_{4z} = -j\epsilon a_y + j\eta a_x = \frac{2ju_0 I e^{-k(z-z_1)} \sin b_1 \xi (\cos a_1 \eta - \cos a_2 \eta) k}{\xi \eta} = C_{4z} e^{-kz} \end{cases} \quad (15)$$

According to (10), (11), (14), and (15), the relation between the x and z components of the magnetic flux density can be expressed as (16) and (17):

$$b_{3x} = -j \frac{\xi}{k} b_{3z} \quad (16)$$

$$b_{4x} = j \frac{\xi}{k} b_{4z} \quad (17)$$

By neglecting the displacement current, the reflected magnetic flux density $\mathbf{B}_r$ generated by the induced eddy current satisfies (18) and (19):

$$\nabla^2 \mathbf{B}_r = 0 \quad (18)$$

$$\nabla \cdot \mathbf{B}_r = 0 \quad (19)$$

By applying dual-Fourier transformations (4) and (5) to (18) and (19), b_r in the spatial frequency domain satisfies (20) and (21):

$$\frac{\partial b_r}{\partial z^2} - k^2 b_r = 0 \quad (20)$$

$$-j\xi b_{rx} - j\eta b_{ry} + \frac{\partial b_{rz}}{\partial z} = 0 \quad (21)$$

For the second-order partial differential equation (20), the general solution of the reflected magnetic flux density can be expressed as (22):

$$b_{rz} = C_{rz} e^{kz} + C'_{rz} e^{-kz} \quad (22)$$

As $\nabla \times \mathbf{B}_r = 0$ in Regions 3 and 4, the relation between b_{rx} and b_{ry} can be expressed as (23):

$$\xi b_{ry} = \eta b_{rx} \quad (23)$$

Based on (21) and (23), the relation between b_{rx} and b_{rz} can be derived as (24):

$$b_{rx} = \frac{\xi}{jk^2} \cdot \frac{\partial b_{rz}}{\partial z} \quad (24)$$

B. Regions 2 and 5

Regions 2 and 5 correspond to the ferrite layers on both sides. The magnetic flux density $\mathbf{B}_n$ ($n = 2$ and 5) in these regions can be expressed as (25) and (26):

$$\nabla^2 \mathbf{B}_n - j\omega\mu_0\mu_n\sigma_n \mathbf{B}_n = 0 \quad (25)$$

$$\nabla \cdot \mathbf{B}_n = 0 \quad (26)$$

By applying dual-Fourier transformations (4) and (5) to (25) and (26), b_n in the spatial frequency domain satisfies (27) and (28):

$$\frac{\partial^2 b_n}{\partial z^2} - (k^2 b_r + j\omega\mu_0\mu_n\sigma_n) b_n = 0 \quad (27)$$

$$-j\xi b_{nx} - j\eta b_{ny} + \frac{\partial b_{nz}}{\partial z} = 0 \quad (28)$$

For the second-order partial differential equation (27), the general solution of the magnetic flux density can be obtained as (29), where $\lambda = \sqrt{k^2 + j\omega\mu_0\mu_n\sigma_n}$.

$$b_{nz} = C_{nz} \cdot e^{\lambda z} + C'_{nz} \cdot e^{-\lambda z} \quad (29)$$

Due to $\nabla \cdot \mathbf{J} = 0$ in Regions 2 and 5, the current density J_z does not exist, and the relation between b_{nx} and b_{ny} can be obtained as (30):

$$\xi b_{ny} = \eta b_{nx} \quad (30)$$

Based on (28) and (30), the relation between b_{nx} and b_{nz} can be derived as (31):

$$b_{nx} = \frac{\xi}{jk^2} \cdot \frac{\partial b_{nz}}{\partial z} \quad (31)$$

C. Regions 1 and 6

These regions are similar to Regions 2 and 5, except that the relative permeability and conductivity of the medium are different. Therefore, b_n ($n = 1$ and 6) in these regions satisfies (32):

$$\frac{\partial^2 b_n}{\partial z^2} - k^2 b_n = 0 \quad (32)$$

The general solution of the magnetic flux density can be expressed as (33):

$$b_{nz} = C_{nz} e^{kz} + C'_{nz} e^{-kz} \quad (33)$$

Similarly, the relation between b_{nx} and b_{nz} can be obtained as (34):

$$b_{nx} = \frac{\xi}{jk^2} \frac{\partial b_{nz}}{\partial z} \quad (34)$$

D. Boundary Conditions

According to the electromagnetic field theory, the z component of the magnetic flux density B and the x , y

components of the magnetic field intensity H must be continuous at the $z = -t_2$, $z = 0$, $z = d$, $z = d + t_5$ planes. The boundary condition equations can be obtained as (35):

$$\begin{cases} b_{3z} + b_{rz} = b_{2z}, b_{3x} + b_{rx} = \frac{b_{2x}}{\mu_2} (z = 0) \\ b_{1z} = b_{2z}, b_{1x} = \frac{b_{2x}}{\mu_2} (z = -t_2) \\ b_{4z} + b_{tz} = b_{5z}, b_{4x} + b_{tx} = \frac{b_{5x}}{\mu_5} (z = d) \\ b_{5z} = b_{6z}, b_{5x} = \frac{b_{6x}}{\mu_5} (z = d + t_5) \end{cases} \quad (35)$$

The general solutions of the z component of the magnetic flux density can be expressed by (10), (11), (14), (15), (22), (29), and (33). As a result, four boundary condition equations can be obtained by substituting these expressions into (35). Similarly, the general solutions of the x component of the magnetic flux density can be expressed by (16), (17), (24), (31), and (34). Another four boundary condition equations can be derived by substituting these equations into (35). Further, by solving the above eight equations, the matrix equation for the coefficients C_{tz} , C'_{tz} , C_{1z} , C_{2z} , C'_{2z} , C_{5z} , C'_{5z} , and C'_{6z} can be obtained, as shown in (36). Because the magnetic flux density tends to zero as z tends to infinity, the coefficients C'_{1z} and C_{6z} must be zero.

$$\begin{pmatrix} 1 & 1 & 0 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & e^{-kt_2} & -e^{-kt_2} & -e^{-kt_2} & 0 & 0 & 0 \\ e^{2kd} & 1 & 0 & 0 & 0 & -e^{2kd} & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & e^{k(d+t_5)} & e^{-k(d+t_5)} & -e^{-k(d+t_5)} \\ 1 & -1 & 0 & \frac{-1}{\mu_{t2}} & \frac{1}{\mu_{t2}} & 0 & 0 & 0 \\ 0 & 0 & e^{-kt_2} & \frac{-e^{-kt_2}}{\mu_{t2}} & \frac{e^{-kt_2}}{\mu_{t2}} & 0 & 0 & 0 \\ e^{2kd} & -1 & 0 & 0 & 0 & \frac{-e^{2kd}}{\mu_{t5}} & \frac{1}{\mu_{t5}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-e^{k(t_5+d)}}{\mu_{t5}} & \frac{e^{-k(t_5+d)}}{\mu_{t5}} & -e^{-k(t_5+d)} \end{pmatrix} \begin{pmatrix} C_{tz} \\ C'_{tz} \\ C_{1z} \\ C_{2z} \\ C'_{2z} \\ C_{5z} \\ C'_{5z} \\ C'_{6z} \end{pmatrix} = \begin{pmatrix} -C_{3z} \\ 0 \\ -C_{4z} \\ 0 \\ C_{3z} \\ 0 \\ -C_{4z} \\ 0 \end{pmatrix} \quad (36)$$

The analytical formulas of the coefficients C_{tz} , C'_{tz} , C_{1z} , C_{2z} , C'_{2z} , C_{5z} , C'_{5z} , and C'_{6z} can be obtained by solving the above matrix equation.

$$M_{11} = \frac{\Psi}{I} = \frac{1}{4\pi^2 I} \cdot \left| \begin{aligned} & \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [C_{tz} e^{kz} + (C_{4z} + C'_{tz}) e^{-kz}] \left(\frac{e^{jd_{11}\xi} - e^{jd_{12}\xi}}{j\xi} \right) \left(\frac{e^{jc_{12}\eta} - e^{jc_{11}\eta}}{j\eta} \right) d\xi d\eta \\ & - \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [C_{tz} e^{kz} + (C_{4z} + C'_{tz}) e^{-kz}] \frac{e^{jd_{11}\xi} - e^{jd_{12}\xi}}{j\xi} \left(\frac{e^{jc_{21}\eta} - e^{jc_{22}\eta}}{j\eta} \right) d\xi d\eta \end{aligned} \right|$$

Therefore, the mutual inductance M of the BPP-DDP coupler with transmitter turn number N_1 and receiver turn number N_2 can be expressed as (43):

$$M = \sum_{p=1}^{N_1} \sum_{q=1}^{N_2} M_{pq} \quad (43)$$

Here, M_{pq} represents the mutual inductance between the p -th turn of the transmitter coil and the q -th turn of the receiver coil, and s_1 and s_2 represent the line spacing (distance between each turn) of the transmitter coil and receiver coil,

E. Mutual Inductance Calculation

By applying the dual-Fourier transformations (4) and (5), the z component of the magnetic flux density in Region 4 can be expressed as (37):

$$B_z = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [C_{tz} e^{kz} + (C_{4z} + C'_{tz}) e^{-kz}] \cdot e^{j(x\xi + y\eta)} d\xi d\eta \quad (37)$$

In the case of the BPP-DDP coupler with different misalignments, as shown in Fig. 3, specific wire positions can be identified. Wires parallel to the x -axis in the receiver coil are located at $y = c_{11}$, $y = c_{12}$, $y = c_{21}$, and $y = c_{22}$, and the wires parallel to the y -axis are located at $x = d_{11}$ and $x = d_{12}$. The above parameters can be expressed as (38), where L represents the offset distance, β is the angle between the offset direction and the x - o - y plane, and α is the angle between the x -axis and the projection of the offset direction on the x - o - y plane.

$$\begin{aligned} c_{11} &= c_1 + L \cdot \cos(\beta) \cos(\alpha) \\ c_{12} &= c_2 + L \cdot \cos(\beta) \cos(\alpha) \\ c_{21} &= -c_1 + L \cdot \cos(\beta) \cos(\alpha) \\ c_{22} &= -c_2 + L \cdot \cos(\beta) \cos(\alpha) \\ d_{11} &= d_1 + L \cdot \cos(\beta) \cos(\alpha) \\ d_{12} &= -d_1 + L \cdot \cos(\beta) \cos(\alpha) \\ z &= z_2 + L \cdot \sin(\beta) \end{aligned} \quad (38)$$

The magnetic fluxes coupled by the two square coils of the DD receiver coil in the z -direction can be obtained as (39) and (40):

$$\Psi_1 = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [C_{tz} e^{kz} + (C_{4z} + C'_{tz}) e^{-kz}] \left(\frac{e^{jd_{11}\xi} - e^{jd_{12}\xi}}{j\xi} \right) \left(\frac{e^{jc_{12}\eta} - e^{jc_{11}\eta}}{j\eta} \right) d\xi d\eta \quad (39)$$

$$\Psi_2 = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [C_{tz} e^{kz} + (C_{4z} + C'_{tz}) e^{-kz}] \frac{e^{jd_{11}\xi} - e^{jd_{12}\xi}}{j\xi} \left(\frac{e^{jc_{21}\eta} - e^{jc_{22}\eta}}{j\eta} \right) d\xi d\eta \quad (40)$$

According to the superposition principle, because the two square coils of the DD receiver coil are wound in opposite directions, the net magnetic flux coupled by the DD receiver coil can be expressed as (41):

$$\Psi = |\Psi_1 - \Psi_2| \quad (41)$$

Moreover, the mutual inductance of the single-turn BPP-DDP coupler can be obtained as (42):

$$M_{11} = \frac{\Psi}{I} = \frac{1}{4\pi^2 I} \cdot \left| \begin{aligned} & \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [C_{tz} e^{kz} + (C_{4z} + C'_{tz}) e^{-kz}] \left(\frac{e^{jd_{11}\xi} - e^{jd_{12}\xi}}{j\xi} \right) \left(\frac{e^{jc_{12}\eta} - e^{jc_{11}\eta}}{j\eta} \right) d\xi d\eta \\ & - \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} [C_{tz} e^{kz} + (C_{4z} + C'_{tz}) e^{-kz}] \frac{e^{jd_{11}\xi} - e^{jd_{12}\xi}}{j\xi} \left(\frac{e^{jc_{21}\eta} - e^{jc_{22}\eta}}{j\eta} \right) d\xi d\eta \end{aligned} \right| \quad (42)$$

respectively. The positions of each wire in the p -th turn of the transmitter coil are $x = \pm b_{p1}$, $y = \pm a_{p1}$, and $y = \pm a_{p2}$. The positions of each wire in the q -th turn of the receiver coil are $x = d_{q11}$, $x = d_{q12}$, $y = c_{q11}$, $y = c_{q12}$, $y = c_{q21}$, and $y = c_{q22}$, as shown in (44):

$$\begin{cases} a_{p1} = a_1 - s_1(p-1), a_{p2} = a_2 - s_1(p-1), b_{p1} = b_1 - s_1(p-1) \\ c_{q11} = c_{11} + s_2(q-1), c_{q12} = c_{12} - s_2(q-1), c_{q21} = c_{21} - s_2(q-1) \\ c_{q22} = c_{22} + s_2(q-1), d_{q11} = d_{11} - s_2(q-1), d_{q12} = d_{12} + s_2(q-1) \end{cases} \quad (44)$$

Based on the above analytical model, the mutual inductance of the BPP-DDP coupler in different misalignment cases can be calculated. This calculation is useful for designing and analyzing the BPP-DDP coupler. It is worth noting that the finite ferrite plate in practice is replaced by an infinite ferrite plate in the above analytical model. Therefore, it is necessary to revise the equivalent relative permeability in the model based on the experimental results to improve the accuracy of the calculation results.

III. MISALIGNMENT PERFORMANCE OF BPP-DDP COUPLER BASED ON ANALYTICAL MODEL

In this section, the misalignment performance of the BPP-DDP coupler is analyzed based on the analytical model and compared with the results based on the FEM. The FEM of the coupler is established using the JMAG analysis tool as shown in Fig. 4(a). The dimensions of the BPP transmitter pad and DDP receiver pad are shown in Figs. 4(b) and 4(c), respectively. Based on the practical application scenarios of wireless charging for EVs, the parameters are selected as shown in Table I. The mutual inductances of the BPP-DDP coupler in different misalignment cases and under different excitation modes are investigated as shown in Fig. 5. Specifically, the in-phase excitation and opposing-phase excitation modes are focused on. The solid lines in the graph represent the calculation results, and the dotted lines correspond to the simulation results. The results of the analytical model are obtained by the numerically evaluated integral, and the meshes of the coupler and air areas in the FEM are selected as 6 and 60 mm, respectively.

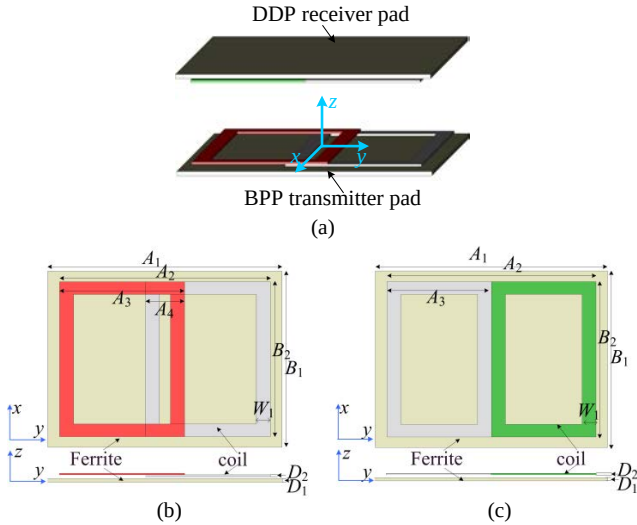


Fig. 4 Finite element models of the BPP-DDP coupler. (a) Overall structure. (b) BPP transmitter pad. (c) DDP receiver pad.

Fig. 5(a) shows the mutual inductance of the BPP-DDP coupler when misalignment occurs in the x-direction. The mutual inductance remains approximately zero under the in-phase excitation mode. This phenomenon can be attributed to the vertical magnetic flux excited by the BPP transmitter under this condition, and the net magnetic flux coupled by the two square coils of the DD receiver is always approximately

Parameters	BPP transmitter pad	DDP receiver pad
A_1/mm	600	600
A_2/mm	540	540
A_3/mm	320	270
A_4/mm	100	—
B_1/mm	500	500
B_2/mm	440	440
W_1/mm	36	36
D_1/mm	8	8
D_2/mm	4	4

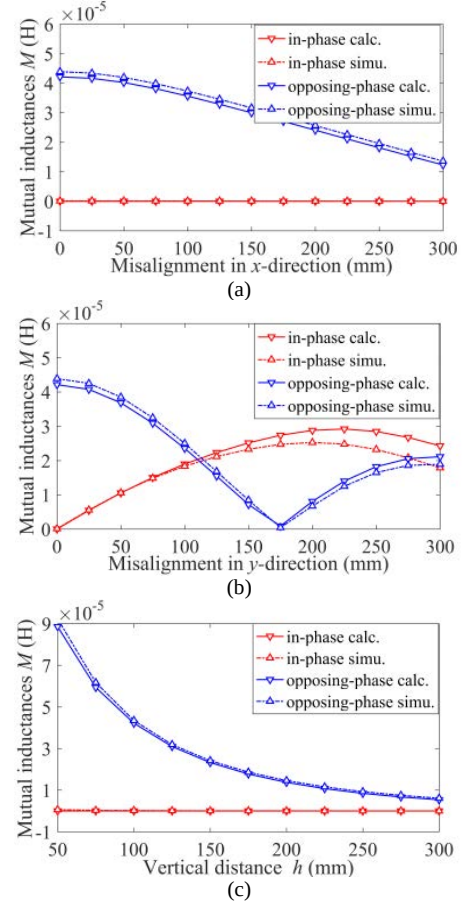


Fig. 5 Mutual inductance of the BPP-DDP coupler in different misalignment cases and under different excitation modes. (a) Misalignment in the x-direction. (b) Misalignment in the y-direction. (c) Displacement in the z-direction.

zero. Moreover, under the opposing-phase excitation mode, the mutual inductance of the BPP-DDP coupler decreases monotonically when misalignment occurs in the x-direction. This behavior indicates that the BPP transmitter under this condition generates horizontal magnetic flux, and the net magnetic flux coupled by the DD receiver decreases when misalignment occurs in the x-direction.

Fig. 5(b) illustrates the mutual inductance of the BPP-DDP coupler when misalignment occurs in the y-direction. The results indicate that mutual inductance increases first and then decreases under the in-phase excitation mode. This behavior can also be attributed to the vertical magnetic flux excited by

the BPP transmitter, and the net magnetic flux coupled by the DD receiver initially increases and then decreases. Additionally, the results also show that the mutual inductance of the BPP-DDP coupler demonstrates an initial decrease followed by an increase under the opposing-phase excitation mode. This phenomenon arises from the horizontal magnetic flux generated by the BPP transmitter, and the net magnetic flux coupled by the DD receiver first decreases and then increases.

Fig. 5(c) illustrates the mutual inductance of the BPP-DDP coupler when displacement occurs in the z -direction. The mutual inductance remains approximately zero under the in-phase excitation mode. This is because the BPP transmitter excites vertical magnetic flux, and the net magnetic flux coupled by the DD receiver at different vertical distances is always approximately zero. In addition, the mutual inductance under the opposing-phase excitation mode decreases monotonically as the vertical distance increases. This behavior is because the BPP transmitter generates the horizontal magnetic flux, and the net magnetic flux coupled by the DD receiver decreases as the vertical distance increases.

According to the above analysis, the mutual inductance of the BPP-DDP coupler changes with different excitation modes and misalignment cases. Therefore, the misalignment tolerance of the BPP-DDP coupler can be improved by adjusting the excitation mode in different misalignment cases.

IV. EXPERIMENTAL VERIFICATION

A. Experimental Setup

The BPP-DDP coupler is fabricated to verify the theoretical analysis, as shown in Fig. 6(a). The BPP transmitter and DD receiver pads are shown in Figs. 6(b) and 6(c), respectively. The mutual inductances of the coupler in misalignment are measured to validate the accuracy of the proposed analytical model, and the parameters of the coupler are listed in Table I. The experimental prototype of the WPT system has been established.

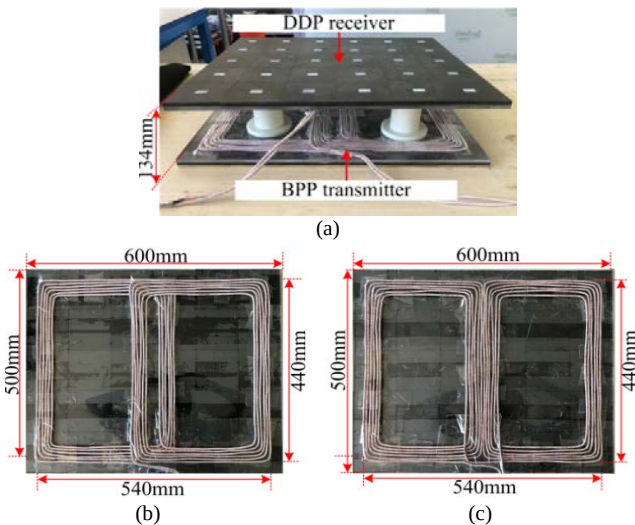


Fig. 6 Experimental prototype of (a) BPP-DDP coupler. (b) BPP transmitter pad. (c) DD receiver pad.

The AWG38 800-strand Litz wire with a diameter of 4 mm is used to fabricate the coupler coils to reduce skin effect losses. The DMR44 ferrite obtained from Dongci Corporation is selected to assemble the ferrite plate, with an initial relative permeability of 2400. The mutual inductances and self-inductances are measured using the LCR meter TONGHUI 2827A.

B. Experimental results and excitation mode selection

The mutual inductances of the BPP-DDP coupler are measured in different misalignment cases and under different excitation modes, and compared with the calculation results and the simulation results, as shown in Figs. 7(a)–7(c). The solid lines, dotted lines, and dashed lines correspond to the calculation, simulation, and experimental results, respectively. Furthermore, to improve the calculation accuracy of the analytical model, the equivalent relative permeabilities are adjusted to $\mu_{i2} = \mu_{i5} = 600$ based on the experimental results.

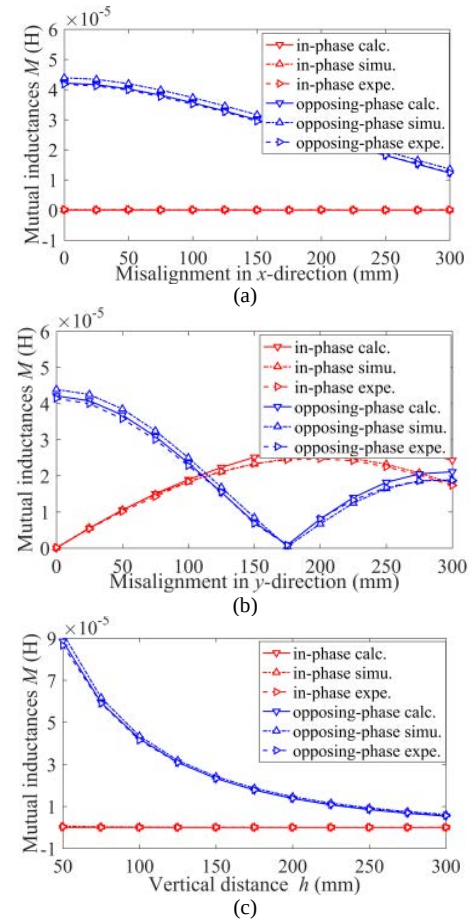


Fig. 7 Experimental results of the mutual inductance of the coupler in different misalignment cases and under different excitation modes. (a) Misalignment in the x -direction. (b) Misalignment in the y -direction. (c) Displacement in the z -direction

Fig. 7(a) shows that the mutual inductance of the BPP-DDP coupler in the opposing-phase excitation mode is always greater than that in the in-phase excitation mode when misalignment occurs in the x -direction. Therefore, to improve the misalignment tolerance of the coupler, the excitation mode of the BPP transmitter can be adjusted to the opposing-phase

excitation mode in the misalignment cases.

Fig. 7(b) suggests that the mutual inductance of the coupler under the opposing-phase excitation mode is greater than that under the in-phase excitation mode when the misalignment distance along the y -direction falls within 0–115 mm. However, this trend is reversed when the misalignment distance is in the range of 115–300 mm. Therefore, the excitation mode of the BPP transmitter can be adjusted based on the misalignment distance along the y -direction to improve the misalignment tolerance of the coupler.

Fig. 7(c) suggests that the mutual inductance of the BPP-DDP coupler under the opposing-phase excitation mode consistently surpasses that under the in-phase excitation mode at varying vertical distances. Therefore, the excitation mode of the BPP transmitter coil can be adjusted to the opposing-phase excitation mode in the case of displacement in the z -direction, which can also optimize the misalignment tolerance of the coupler.

Based on the above experimental results, the optimized excitation mode selection of BPP-DDP coupler at different misalignment positions is shown in Fig. 8. The mutual inductance of the coupler is calculated when the misalignment positions of the DD receiver are $x = 100, 200, \text{ and } 300 \text{ mm}$, $y = 100, 200, \text{ and } 300 \text{ mm}$, and $z = 100, 200, \text{ and } 300 \text{ mm}$, respectively. The circular dots represent the misalignment positions where the opposing-phase excitation mode is preferred, while the square dots represent the misalignment positions where the in-phase excitation mode is preferred. The experimental results show that at the misalignment positions $y = 200$ and 300 mm , the mutual inductance of the coupler is greater under the in-phase excitation mode, while at other misalignment positions, the mutual inductance of the coupler is greater under the opposing-phase excitation mode. It can be inferred that adjusting the excitation mode under different misalignment cases can improve the misalignment tolerance of the coupler. Moreover, the calculation results obtained from the analytical model are consistent with the experimental results, validating the effectiveness of the proposed analytical model. The computational time and accuracy of the analytical model will be discussed in detail in Section V.

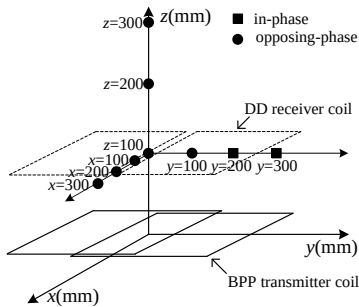


Fig. 8 Optimized excitation mode selection of BPP-DDP coupler at different misalignment positions

In general, the loss of a multicoil coupler consists of two parts: core loss and coil loss. The core loss includes magnetic hysteresis loss, excess loss, and eddy current loss, and the winding loss is mainly composed of skin-effect loss,

proximity-effect loss, and DC conduction loss. Due to the focus of this paper on establishing an analytical model for multicoil couplers, there has been no in-depth study on the losses of couplers.

V. DISCUSSION ON COMPUTATIONAL TIME AND ACCURACY

To evaluate the computational time and accuracy of the analytical model, the mutual inductances of the BPP-DDP coupler in different misalignment cases and under different excitation modes are obtained based on the analytical model and FEM, and compared with the experimental results. According to the application scenario of wireless charging for EVs, five misalignment distances ($L = 0, 25, 50, 75, \text{ and } 100 \text{ mm}$) and five vertical distances ($h = 100, 125, 150, 175, \text{ and } 200 \text{ mm}$) are selected. The two calculations are performed on a computer equipped with an Intel Core processor operating at a 3.3 GHz clock frequency and 4 GB RAM. In addition, it should be noted that the coordinates of each Litz wire in the analytical model are taken as the coordinates of the centerline of the Litz wire, while in the FEM, all Litz wires are regarded as a copper pad with a size equal to the entire Litz coil of the analytical model. In the analytical model, the ferrite layer is regarded as an infinite ferrite layer with a thickness equal to the ferrite thickness of the experimental prototype, which is 8 mm. In the FEM, the ferrite layer is regarded as a finite copper pad with a size equal to $600 \text{ mm} \times 500 \text{ mm} \times 8 \text{ mm}$, which is the same size as the ferrite layer of the experimental prototype. The analytical model is calculated in MATLAB software, and the FEM is calculated in JMAG software, and the meshes for the coupler and air areas in the FEM are 6 and 60 mm, respectively. The mutual inductances at five positions and the total computational time using the two models are shown in Tables II and III.

Table II shows that for the BPP-DDP coupler under the in-phase excitation mode, the maximum errors of the calculation results using the analytical model along the x , y , and z directions are 0.25, 0.84, and 0.11 μH , respectively, and the corresponding percentage values are —, 5.9%, and —. The maximum errors of the simulation results based on the FEM along the x , y , and z directions are 0.86, 0.64, and 0.14 μH , respectively, and the corresponding percentage values are —, 4.5%, —. It should be noted that when displacement occurs along the x and z directions, the experimental results of the mutual inductance value are close to zero, so only the maximum error can be given, and the percentage value cannot be given, which is represented by (—) in Table II.

Table III illustrates that for the BPP-DDP coupler under the opposing-phase excitation mode, the maximum errors of the calculation results along the x , y , and z directions are 0.52, 1.06, and 0.69 μH , respectively, and the corresponding percentage values are 1.4%, 3.0%, and 1.7%. The maximum errors of the simulation results along the x , y , and z directions are 2.24, 2.73, and 2.01 μH , respectively, and the corresponding percentage values are 5.4%, 7.6%, and 4.8%. It can be observed that the computational accuracy of the analytical model is

TABLE II
COMPARISON OF MUTUAL INDUCTANCES UNDER THE IN-PHASE EXCITATION MODE BASED ON TWO MODELS

Misalignment in x-direction/mm	0	25	50	75	100	Total time	Maximum error/percentage value
Calculation results/ μH	0	0	0	0	0	359 s	0.25 μH /—
Simulation results/ μH	0.11	0.11	0.10	0.88	0.79	2739 s	0.86 μH /—
Experimental results/ μH	0.22	0.08	0.25	0.02	0.12	—	—
Misalignment in y-direction/mm	0	25	50	75	100		
Calculation results/ μH	0	5.45	10.54	15.05	18.96	354 s	0.84 μH /5.9%
Simulation results/ μH	0.11	5.57	10.57	14.85	18.35	2730 s	0.64 μH /4.5%
Experimental results/ μH	0.17	5.38	10.15	14.21	18.41	—	—
Displacement in z-direction/mm	100	125	150	175	200		
Calculation results/ μH	0	0	0	0	0	364 s	0.11 μH /—
Simulation results/ μH	0.19	0.11	0.05	0.05	0.03	2748 s	0.14 μH /—
Experimental results/ μH	0.05	0.02	0.112	0.092	0.04	—	—

TABLE III
COMPARISON OF MUTUAL INDUCTANCES UNDER THE OPPOSING-PHASE EXCITATION MODE BASED ON TWO MODELS

Misalignment in x-direction/mm	0	25	50	75	100	Total time	Maximum error/percentage value
Calculation results/ μH	42.14	41.64	40.22	38.14	35.62	359 s	0.52 μH /1.4%
Simulation results/ μH	43.91	43.39	41.96	39.85	37.32	2735 s	2.24 μH /5.4%
Experimental results/ μH	41.75	41.15	39.85	37.62	35.15	—	—
Misalignment in y-direction/mm	0	25	50	75	100		
Calculation results/ μH	42.14	40.76	36.84	30.88	23.54	354 s	1.06 μH /3.0%
Simulation results/ μH	43.91	42.51	38.51	32.45	25.00	2727 s	2.73 μH /7.6%
Experimental results/ μH	41.42	39.96	35.78	30.00	22.79	—	—
Displacement in z-direction/mm	100	125	150	175	200		
Calculation results/ μH	42.14	30.96	23.26	17.75	13.72	364 s	0.69 μH /1.7%
Simulation results/ μH	43.46	31.89	24.15	18.63	14.58	2743 s	2.01 μH /4.8%
Experimental results/ μH	41.45	30.83	23.25	17.84	13.80	—	—

typically the same as that of the FEM. Meanwhile, the total computational time based on the FEM is 7.6 times that of the analytical model. The computational time can be shortened, but the computational accuracy is reduced when the mesh of the FEM is larger.

Finally, the proposed analytical model is compared to some other recent coil analytical model research in Table IV. As can be observed, the proposed analytical model takes into account the more complex coil structure of the BPP transmitter and DD pad receiver, as well as the ferrite layer

magnetic cores on both sides. In addition, the analytical model also considers the lateral and vertical misalignment cases. Therefore, the proposed analytical model can be considered a reliable and time-saving tool for analyzing the BPP-DDP multicoil coupler. It is essential to highlight that although this study focused on analyzing the mutual inductance performance of the coupler in misalignment along the x , y , and z directions, the mutual inductance performance when misalignment occurs in any direction can be analyzed based on the proposed analytical model.

TABLE IV
COMPARISON BETWEEN THE PROPOSED MODEL AND THE PREVIOUS REFERENCES

Reference	Coil type	Magnetic core type	Misalignment cases	Frequency	Coupler size	Airgap
[23]	Circular solenoid coils on both sides	Air core	Lateral and angular misalignment	202 kHz	Coil radius 11 cm	Distance 24 cm
[12]	Square and circular planar coils on both sides	Ferrite layer magnetic core	Lateral misalignment	80 kHz	External side length of square coils 600 mm, external radius of circular coils 300 mm	Vertical distance 200 mm
[27]	Square and circular coils on both sides	Ferrite layer magnetic core	Lateral misalignment	80 kHz	Outer radius of circular coils 300 mm, length of side of square coils 600 mm	Vertical distance 200 mm
[29]	BPP transmitter and square pad receiver	Ferrite layer magnetic core	Lateral misalignment	85 kHz	Outer length of receiver square coil 250 mm, outside length of two square subcoils of bipolar transmitter 300 mm with an overlap of 70 mm	Vertical distances 140/160 mm
Proposed model	BPP transmitter and DD pad receiver	Ferrite layer magnetic core	Lateral and vertical misalignment	85 kHz	Outer length of two rectangular subcoils of receiver DDP 270 mm $\times$ 440 mm, outer length of two rectangular subcoils of transmitter BPP 320 mm $\times$ 440 mm with an overlap of 100 mm	Vertical distance 100 mm

VI. CONCLUSION

This study proposes an analytical model of the BPP-DDP coupler in different misalignment cases and under different excitation modes based on dual-Fourier transformation. The mutual inductance performance of the coupler in misalignment can be investigated using the proposed model, and the optimized excitation mode of the BPP-DDP coupler in different misalignment cases can be easily obtained. The experimental results indicated that the computational time based on the FEM is 7.6 times that of the analytical model, while the computational accuracy is approximately equal; the results also revealed that the misalignment tolerance of the coupler can be improved by adjusting the excitation mode of the coupler. Therefore, the proposed analytical model can be considered a reliable and time-saving tool for analyzing the BPP-DDP coupler. It is worth noting that the modeling method proposed in this study is not only applicable to the BPP-DDP coupler, but also to other multicoil pad couplers.

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