Letters

An Improved Compensation Method Reducing Displacement Current Loss for Multilayer Coils in IPT System

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***Abstract*—Dual-layer or multilayer coils are often used to increase the power density of inductive power transfer systems. However, compared to single-layer coils, multilayer coils suffer from additional loss caused by interlayer displacement current (IDC), which can reduce system transmission efficiency. Therefore, this letter establishes a general mathematical model for IDC loss in multilayer coils regardless of whether the adjacent layers are symmetric. The traditional centralized compensation capacitor is split into two capacitors (interlayer and auxiliary capacitors), and a novel parameteric design method for the interlayer capacitor is proposed to optimize the IDC losses. The auxiliary capacitor is used to adjust the resonance state of the circuit. The experimental results show that compared to the traditional method, the prototype with the double-layer symmetrical coil achieves efficiency improvements of 0.5% under light load and 2.27% under heavy load. The double-layer asymmetrical coil prototype achieves efficiency improvements of 0.58% under light load and 2.11% under heavy load compared to the traditional method.**

***Index Terms*—Inductive power transfer (IPT), interlayer displacement current (IDC) loss, multilayer coil.**

I. Introduction

INDUCTIVE power transfer (IPT) technology has attracted widespread attention in various fields due to its advantages of flexibility and security. Mutual inductance is one of the key technical indicators of the IPT system, and the system's power transfer performance is closely related to it [1], [2]. Constructing multilayer coils is one of the common ways to increase mutual inductance, which has been widely applied in various fields such as implantable biomedical applications [3], consumer electronics [4], domino-resonator IPT systems [5], and so on.

Unlike single-layer coils, the losses in multilayer coils include not only power losses caused by skin effect and proximity effect but also interlayer displacement currents (IDC) loss. When current flows through multilayer coils, there is a potential difference between any two turns in different layers, causing displacement current in the interlayer insulation material. The power loss caused by the displacement current flowing through the interlayer insulation material is called IDC loss. So far, sufficient research has been conducted on power losses caused by skin effects and proximity effects [6], [7]. However, the research on IDC loss in multilayer coils is not sufficient. For example, Yang et al. [8] proposed a distributed parameter calculation method for the coil, such as interturn capacitance, parasitic capacitance, and the mutual inductance between turns. Especially, the effect of the displacement current is considered to calculate the equivalent series resistance of the coil. Besides, this article indicated that increasing interlayer spacing can reduce interturn capacitance and IDC. In addition, Mai et al. [9] proposed an interesting method to reduce IDC loss by making the winding coils follow the same sequence from outside to inside in each layer and using layer compensation. However, this method only considered symmetric multilayer coils and lacked analysis of cases where adjacent layers are asymmetric (different sizes or turns).

The main contributions of this letter are highlighted as follows.

1) This letter establishes an equivalent circuit model of multilayer coils with distributed parameters, regardless of whether the adjacent layers are symmetric. Based on this, the voltage distribution between adjacent layers of multilayer coils can be calculated.
2) Unlike the traditional approach of using a single centralized capacitor for compensation, in this letter, the centralized compensation capacitor is deliberately divided into two series capacitors: one is called the interlayer capacitor located between the two coil layers, and the other is named the auxiliary capacitor situated at the terminal of the overall coil. The auxiliary capacitor is used to adjust the resonance state of the circuit. Based on this, a novel parameteric design method for the interlayer capacitor is proposed to improve the distribution of IDC and reduce IDC loss.

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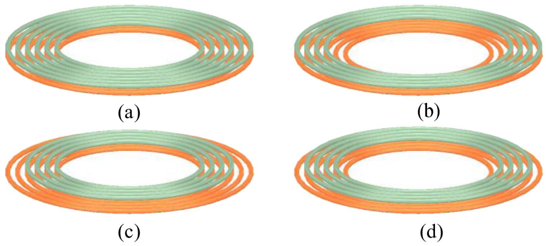


Fig. 1. Schematic diagram of different double-layer coils. (a) Same inner and outer diameters. (b) Same outer diameter and different inner diameter. (c) Different outer diameter and same inner diameter. (d) Different outer diameter and inner diameter. (a) a = 0, b = 0. (b) a = 0, b > 0. (c) a > 0, b = 0. (d) a > 0, b >0 .

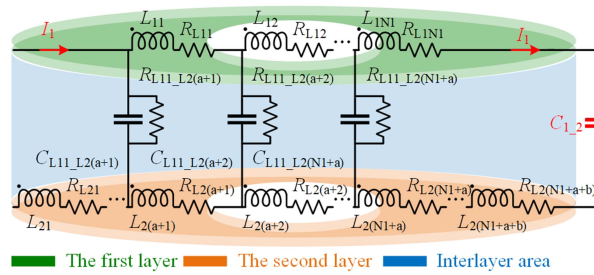


Fig. 2. Equivalent model of a double-layer coil with distributed parameters.

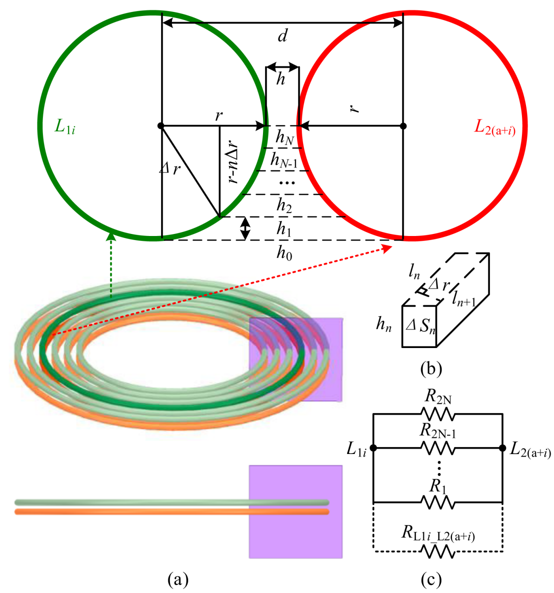


Fig. 3. Model of IDC loss. (a) Schematic of interturn medium segmentation. (b) Equivalent medium element. (c) Equivalent circuit of dielectric resistance.

The rest of this article is organized as follows. In Section II, the equivalent model of the double-layer coil with distributed parameters is proposed and the interlayer dielectric resistance is calculated. Section III provides an optimized design method for the interlayer series compensation capacitor C_{1_2}. Experimental results are provided in Section IV to validate the proposed method. Finally, Section V concludes this article.

II. Analysis of Multilayer Coil

A. Modeling of Double-Layer Coil

Since the IDC loss is generally only considered between adjacent layers in multilayer coils, this article takes the case of a double-layer circular coil as an example. The dual-layer coils are wound in opposite directions. In practical applications, four types of asymmetry may exist in dual-layer coils, as shown in Fig. 1. The outer and inner diameters of the first layer coil are defined as D_{11} and D_{12}, respectively, and the outer and inner diameters of the second layer coil are defined as D_{21} and D_{22}, with a wire diameter of d_{12}. Under these conditions, a = $(D_{21}$-$D_{11})/(2\times d_{12})$ and b = $(D_{22}$-$D_{12})/(2\times d_{12})$.

To simplify the coil model, multiple single-wire circular coils are used to represent the helical coil equivalently, and each turn of the coil is modeled as a node with unit inductance and ac resistance [8]. The self-inductance of each turn, mutual inductance between turns, and parasitic capacitance between adjacent turns in adjacent layers can be calculated. The IDC induced by the voltage between two turns of the coil will cause power loss when flowing through the dielectric. Especially in the traditional centralized compensation method, the adjacent turns in adjacent layers are close to each other and have a high potential difference, and the loss due to IDC cannot be ignored.

The equivalent model of the double-layer coil with distributed parameters is shown in Fig. 2. L_{1i} ($i = 1,\ldots, N_1$) represents the equivalent inductance of the ith turn in the first layer, R_{L1i} represents the parasitic resistance of L_{1i}, L_{2j} ($j = 1,\ldots, N_{1+a+b}$) represents the equivalent inductance of the jth turn in the second layer, R_{L2j} represents the parasitic resistance of L_{2j}, C_{L1x_L2y} represents the coupling capacitance between the xth(x $= 1,\ldots, N_1$) turn in the first layer and the yth(y $=$ a+1, …, a+N_1) turn in the second layer, R_{L1x_L2y} represents the equivalent resistance of IDC loss between the xth turn in the first layer and the yth turn in the second layer, C_{aux} represents the auxiliary capacitor situated at the terminal of the overall coil, and C_{1_2} represents the series compensation capacitance connected between the first layer coil and the second layer coil.

B. Coil Parameters Calculation

When the radius of a single-turn coil loop is R, and the wire radius is r, with $r/R << 1$, its self-inductance can be estimated as follows [10]:

$$L(R, r) = \mu_0 R \left[\text{In}\left(\frac{8R}{r}\right) - 2 \right]. \tag{1}$$

The mutual inductance of two coaxial parallel single-turn coils with loop radii R_1 and R_2 can be estimated using (2), where d is the axial distance between the centers of the wire cross-sections of the two coils, as shown in Fig. 3(a).

$$M(R_1, R_2, d) = \mu_0 \sqrt{R_1 R_2} \left[\left(\frac{2}{k} - k\right) K(k) - \frac{2}{k} E(k) \right] \tag{2}$$

where $K(k)$ and $E(k)$ are the complete elliptic integrals of the first and second kind, respectively [10].

$$k = \sqrt{\frac{4R_1R_2}{(R_1+R_2)^2+d^2}}. \tag{3}$$

The coupling capacitance $C_{\text{L1}i\_\text{L2(a+}i)}$ between the ith turn in the first layer and the (a+i)th turn in the second layer can be estimated as follows [8]:

$$C_{\text{L1}i\_\text{L2(a+}i)} = \varepsilon_0 \int_0^{\pi/4} \frac{\pi D r_0}{r(1-\cos\delta)+0.5h} \text{d}\delta \tag{4}$$

where D is the average diameter of the loop, h is the gap between turns, and ε_0 is the dielectric constant of the interturn medium.

As shown in Fig. 3(a), the dielectric between the ith turn in the first layer and the (a+i)th turn in the second layer is uniformly divided into $2N$ parts along the radius direction of the coil. As shown in Fig. 3(b), when $\Delta r/r<<1$, the dielectric between these two turns can be equivalent to $2N$ trapezoidal bodies with height h_n, thickness Δr, and side lengths ln and l_{n+1} ($n = 0,1, \ldots,2N$). h_n, l_n , and ΔS_m can be calculated as follows:

$$l_n = 2\pi\left(\frac{D}{2} - N\Delta r + n\Delta r\right), \Delta S_m = \frac{\Delta r}{2}(l_n + l_{n+1})$$
$$h_n = h_{2N-n} = 2r + h - 2\sqrt{r^2-(n\Delta r - r)^2},\ 0 \le n \le N \tag{5}$$

where $m = n+1$, $1\le m\le 2N$.

According to Ohm's law, $R_0 = \rho_0 l_0/S_0$, the equivalent resistance R_m of the mth ($m = 1,2,\ldots,2N$) trapezoidal body can be expressed as follows:

$$R_\text{m} = \frac{\rho h_{m-1}}{\Delta S_m}, 1 \le m \le N$$
$$R_\text{m} = \frac{\rho h_m}{\Delta S_m}, \text{N}+1 \le m \le 2N \tag{6}$$

where ρ is the resistivity of the dielectric. As shown in Fig. 3(c), the equivalent resistance of IDC loss between the ith turn in the first layer and the (a+i)th turn in the second layer can be expressed as follows:

$$R_{\text{L1}i\_\text{L2(a+}i)} = \frac{1}{\sum_{m=1}^{2N}\frac{1}{R_m}} = \frac{\rho}{\sum_{m=1}^{N}\frac{2\pi D\Delta r}{h_{m-1}}}. \tag{7}$$

III. Optimization of Displacement Current Loss

The equivalent resistance of the insulation material between two turns increases with the distance between them. Therefore, the total IDC loss of a multilayer coil is the sum of the IDC losses between any two turns with the same inner and outer diameters in adjacent layers. The potential difference $U_{\text{L1}i\_\text{L2(a+}i)}$ between the ith turn in the first layer and the (a+i)th turn in the second layer can be calculated as follows:

$$\begin{aligned} U_{\text{L1}i\_\text{L2(a+}i)} &= I\sum_{x=i}^{N_1}\omega L_{1x} + I\sum_{y=i}^{N_{1+b}}\omega L_{2y} \\ &+ I\sum_{y=1}^{N_1}\sum_{x=i,x\neq y}^{N_1}\omega M_{\text{L1}x\_\text{L1}y} \\ &+ I\sum_{y=1}^{N_{1+a+b}}\sum_{x=i,x=y}^{N_1}\omega M_{\text{L1}x\_\text{L2}y} \\ &+ I\sum_{y=1}^{N_{1+a+b}}\sum_{x=a+i,x\neq y}^{N_{1+a+b}}\omega M_{\text{L2}x\_\text{L2}y} - I\frac{I}{\omega C_{1\_2}} \\ &+ I\sum_{y=1}^{N_1}\sum_{x=a+i,x=y}^{N_{1+a+b}}\omega M_{\text{L2}x\_\text{L1}y} \\ &= I\left(\omega L_{\text{L1}i\_\text{L2(a+}i)} - \frac{1}{\omega C_{1\_2}}\right) \end{aligned} \tag{8}$$

where M represents the mutual inductance between two coils, such as $M_{\text{L1}i\_\text{L2}j}$ representing the mutual inductance between the ith turn in the first layer and the jth turn in the second layer.

The dielectric loss tangent value $\tan\theta_{\text{L1}i\_\text{L2(a+}i)}$ between the ith turn in the first layer and the (a+i)th turn in the second layer can be calculated as follows:

$$\begin{aligned} \tan\theta_{\text{L1}i\_\text{L2(a+}i)} &= \frac{1}{\omega C_{\text{L1}i\_\text{L2(a+}i)} R_{\text{L1}i\_\text{L2(a+}i)}} \\ &= 2\sum_{m=1}^{N}\frac{\Delta r}{h_{m-1}} \times \frac{1}{\omega\varepsilon_0 r_0 \rho \int_0^{\pi/4}\frac{1}{r_0(1-\cos\delta)+0.5h}\text{d}\delta} \end{aligned} \tag{9}$$

According to (9), the tangent of the dielectric loss angle between adjacent single-turn coils in the upper and lower layers is the same. Therefore, the IDC loss in the interlayer between adjacent layers of a multilayer coil can be calculated as follows:

$$P_\text{loss} = \sum_{i=1}^{N_1}\frac{U^2_{\text{L1}i\_\text{L2(a+}i)}}{U^2_{\text{L1}i\_\text{L2(a+}i)}} = \sum_{i=1}^{N_1}\frac{U^2_{\text{L1}i\_\text{L2(a+}i)}}{\frac{1}{\omega C_{\text{L1}i\_\text{L2(a+}i)}\tan\theta_0}}$$
$$\tan\theta_{\text{L1}i\_\text{L2(a+}i)} = \tan\theta_0, i = 1,2,\ldots,N_1. \tag{10}$$

Obviously, when the geometric parameters of the coil and the current flowing through the coil are determined, P_loss is solely dependent on $1/C_{1\_2}$. Equation (10) can be transformed into the following:

$$P_\text{loss} = f\left(\frac{1}{C_{1\_2}}\right) = I^2\left(A_1\frac{1}{C^2_{1\_2}} = A_2\frac{1}{C_{1\_2}} + A_3\right) = I^2 R_\text{loss}$$
$$A_1 = \sum_{i=1}^{N_1}\frac{C_{\text{L1}i\_\text{L2(a+}i)}\tan\theta_0}{\omega} > 0$$
$$A_2 = -2\omega\sum_{i=1}^{N_1}C_{\text{L1}i\_\text{L2(a+}i)}L_{\text{L1}i\_\text{L2(a+}i)}\tan\theta_0$$
$$A_3 = \omega^3\sum_{i=1}^{N_1}C_{\text{L1}i\_\text{L2(a+}i)}L^2_{\text{L1}i\_\text{L2(a+}i)}\tan\theta_0 \tag{11}$$

where R_loss is the equivalent series resistance of IDC loss in a double-layer coil. Unlike the parasitic resistance of reactive

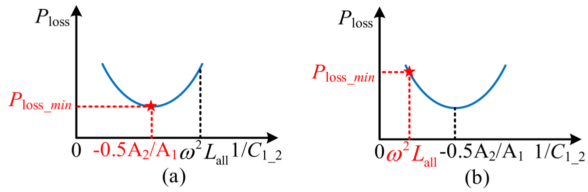


Fig. 4. IDC loss variation curve with C_{1_2}.

components in the traditional sense, R_{loss} cannot be measured directly.

According to (11), when the coil and operating frequency are determined, A_1, A_2, and A_3 are constants independent of C_{1_2}, R_{loss} is only related to the interlayer capacitance C_{1_2}. Therefore, optimizing C_{1_2} can improve the distribution of IDC and reduce IDC loss. From (11), it can be seen that P_{loss} is a quadratic function of C_{1_2} under constant coil current. To maintain the inductive characteristics of the coil impedance (L_{all}-1/(ωC_{1_2})>0), there are two possible conditions of C_{1_2} realizing the minimum value of P_{loss}, as shown in Fig. 4.

As shown in Fig. 4(a), when $\omega^2 L_{\text{all}}$>-0.5A_2/A_1, $P_{\text{loss\_min}} = f$(-0.5A_2/A_1); as shown in Fig. 4(b), when $\omega^2 L_{\text{all}}$<-0.5A_2/A_1, $P_{\text{loss\_min}} = f(\omega^2 L_{\text{all}})$. Therefore, IDC loss can be reduced by designing C_{1_2} within a certain range. In the two cases shown in Fig. 4, the value of C_{1_2} corresponding to $P_{\text{loss\_min}}$ can be calculated as follows:

$$C_{1\_2} = \frac{-2A_1}{A_2}, \text{ if}\frac{A_2}{-2A_1} \leq \omega^2 L_{\text{all}}$$
$$C_{1\_2} = \omega^2 L_{\text{all}}, \text{ if}\frac{A_2}{-2A_1} > \omega^2 L_{\text{all}} \quad (12)$$

Interlayer series distributed compensation capacitor C_{1_2}, distributed auxiliary compensation capacitor C_{aux}, centralized compensation capacitor C_{con}, and multilayer coil self-inductance L_{all} satisfy the following:

$$\frac{1}{\omega C_{\text{con}}} = \frac{1}{\omega C_{1\_2}} + \frac{1}{\omega C_{\text{aux}}} = \omega L_{\text{all}}. \quad (13)$$

IV. Experimental Analysis

A. Experiment Prototype Setup

Two prototypes with 500 W were constructed to verify the proposed method's effectiveness in this article. In both experimental prototypes, the interlayer spacing of the double-layer coils is 0.1 mm, and the wire diameter of the Litz wire used is 0.24 cm. The experimental prototype with a double-layer symmetrical coil is shown in Fig. 5(a), and the corresponding coil is shown in Fig. 5(c). The experimental prototype with a double-layer asymmetrical coil is shown in Fig. 5(b), and the corresponding coil is given in Fig. 5(d).

The equivalent circuit of the system based on SS compensation is shown in Fig. 6. The experimental parameters of the two prototypes are listed in Tables I and II. The subscript "con" represents the parameters of the coupling coil centralized compensation method, while the subscript "dis" represents the parameters of the coupling coil distributed compensation method. For example, $C_{\text{p1\_dis1}}$ and $C_{\text{p1\_dis2}}$ represent the distributed compensation

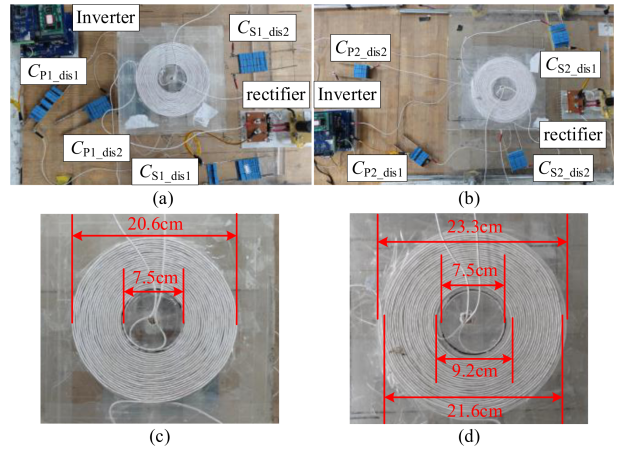


Fig. 5. Experimental prototypes. (a) Dual-layer symmetric coupled coil IPT system. (b) Dual-layer asymmetric coupled coil IPT system. (c) Double layer symmetric 50-turn coil. (d) Double layer asymmetric 54-turn coil.

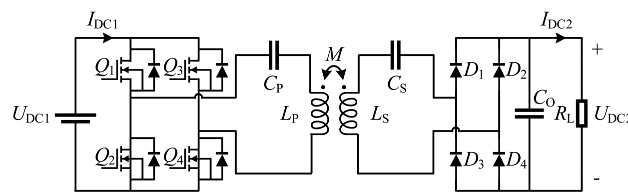


Fig. 6. Equivalent circuit of the system based on SS compensation.

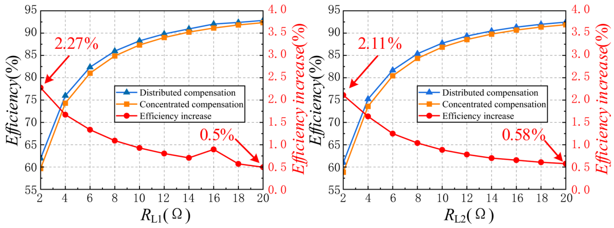
TABLE I
Dual-Layer Symmetric Couple Coil IPT System Experimental Parameters

Symbol	Value	Symbol	Value	Symbol	Value
f_1	100 kHz	$C_{\text{p1\_con}}$	6.99 nF	$C_{\text{p1\_dis2}}$	10.93 nF
U_{IN1}	177 V	$C_{\text{s1\_con}}$	6.87 nF	$C_{\text{s1\_dis1}}$	18.92 nF
L_{p1}	362.37 μH	R_{L1}	2–20 Ω	$C_{\text{s1\_dis2}}$	10.98 nF
L_{s1}	368.71 μH	$C_{\text{p1\_dis1}}$	19.84 nF	M_1	42.26 μH
Turns	25/25	a	0	b	0

TABLE II
Dual-Layer Asymmetric Couple Coil IPT System Experimental Parameters

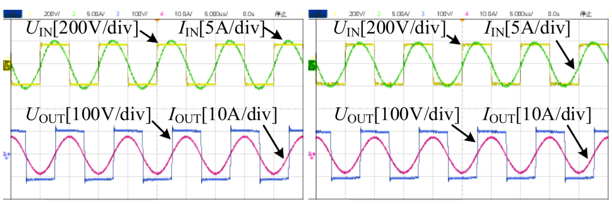
Symbol	Value	Symbol	Value	Symbol	Value
f_2	100 kHz	$C_{\text{p2\_con}}$	5.41 nF	$C_{\text{p2\_dis2}}$	7.34 nF
U_{IN2}	192 V	$C_{\text{s2\_con}}$	5.4 nF	$C_{\text{s2\_dis1}}$	21.95 nF
L_{p2}	467.87 μH	R_{L2}	2–20 Ω	$C_{\text{s2\_dis2}}$	7.27 nF
L_{s2}	468.73 μH	$C_{\text{p2\_dis1}}$	21.88 nF	M_2	44.28 μH
Turns	24/30	a	3	b	3

capacitors for the double-layer symmetrical transmitting coil, $C_{\text{p1\_con}}$ represents the centralized compensation capacitors for the double-layer symmetrical transmitting coil. To follow the principle of controlling a single variable, the parameters of the dual-layer coils in the two experimental prototypes are all constant. Regardless of whether centralized compensation or distributed compensation was used, full compensation condition was maintained for the dual-layer transmitting/ receiving coils. The centralized compensation parameters, the distributed compensation parameters, and the coil self-inductance satisfy (13). Therefore, the system input impedance remained the same in different compensation methods for the same experimental prototype.



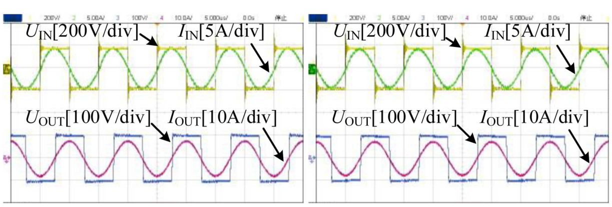
(a) (b)

Fig. 7. Efficiency variation curves with load. (a) Dual-layer symmetric coil IPT system. (b) Dual-layer asymmetric coil IPT system.



(a) (b)

Fig. 8. Experiment waveforms of the dual-layer symmetric coil IPT system. (a) $R_{L1} = 20\,\Omega$ and distributed compensation. (b) $R_{L1} = 20\,\Omega$ and concentrated compensation.



(a) (b)

Fig. 9. Experiment waveforms of dual-layer asymmetric coil IPT system. (a) $R_{L2} = 20\,\Omega$ and distributed compensation. (b) $R_{L2} = 20\,\Omega$ and concentrated compensation.

B. Experiment Result

Fig. 7 shows the two prototypes' efficiency η curves as the load resistance R_L varies. Compared to the traditional centralized compensation method, the distributed compensation method improves the efficiency of the dual-layer symmetric coupled coil IPT system by 2.27% under heavy load ($R_{L1} = 2\ \Omega$) and 0.5% under light load ($R_{L1} = 20\ \Omega$). Similarly, the efficiency of the dual-layer asymmetric coupled coil IPT system is improved by 2.11% under heavy load ($R_{L2} = 2\ \Omega$) and 0.58% under light load ($R_{L2} = 20\ \Omega$). It can be observed that the proposed method effectively improves the voltage distribution of parasitic capacitance between layers significantly reduces IDC loss, and enhances system transmission efficiency.

As shown in Fig. 8, when $R_{L1} = 20\ \Omega$, the circuit waveform phase of the dual-layer symmetric coupled coil IPT system is essentially the same under centralized and distributed compensation methods. Similarly, as shown in Fig. 9, when $R_{L2} = 20\ \Omega$, the circuit waveform phase of the dual-layer asymmetric coupled coil IPT system is nearly the same. Therefore, the efficiency deviation between the two compensation methods in the above two experimental prototypes is approximately independent of the system resonance.

Assuming dielectric resistance is nonexistent, under all other equal conditions, whether using the traditional centralized compensation method or the distributed compensation method, the system transmission efficiency should be the same. However, from the experimental results shown in Fig. 7, it can be observed that by ensuring full compensation conditions for the dual-layer transmitting/receiving coils (maintaining constant system input impedance), replacing the traditional single centralized compensation capacitor with two distributed compensation capacitors can enhance the system's transmission efficiency. This also provides experimental evidence for the presence of interlayer dielectric resistance in multilayer coils.

V. Conclusion

This article establishes a general model for IDC loss in multilayer coils. The relationship between IDC loss and the interlayer capacitor in multilayer coils has been revealed. The interlayer capacitor design method focusing on minimizing IDC loss has been proposed, leading to improved IDC distribution and reduced IDC loss. Finally, two 500-W experimental prototypes were established. The experimental prototype with a double-layer symmetrical coil achieves a maximum efficiency of 92.48%. Compared to the traditional method, the incremental efficiency improvement is 0.5% under light load and 2.27% under heavy load. The experimental prototype with a double-layer asymmetrical coil achieves a maximum efficiency of 92.46%. Compared to the traditional method, the efficiency improvement is 0.58% under light load and 2.11% under heavy load.

References

[1] Z. Zhang et al., "A dynamic wireless power transfer system using DC controlled variable inductor for segment transmitter automatic witching," *IEEE Trans. Ind. Electron.*, early access, Jul. 10, 2024, doi: 10.1109/TPEL.2024.3426100.

[2] Q. Wang et al., "Inductive power transfer system with constant current-constant voltage charging tolerating misalignment based on multi-objective optimization for compensation topology," *IEEE Trans. Power Electron.*, early access, Jul. 30, 2024, doi: 10.1109/TPEL.2024.3435424.

[3] J. Ahn et al., "An out-of-phase wireless power transfer system for implantable medical devices to reduce human exposure to electromagnetic field and increase power transfer efficiency," *IEEE Trans. Biomed Circuits Syst.*, vol. 16, no. 6, pp. 1166–1180, Dec. 2022.

[4] Y. Zhang, S. Chen, X. Li, and Y. Tang, "Design methodology of free-positioning nonoverlapping wireless charging for consumer electronics based on antiparallel windings," *IEEE Trans. Ind. Electron.*, vol. 69, no. 1, pp. 825–834, Jan. 2022.

[5] H. Yang et al., "Efficiency analysis and optimization method of power-relay IPT systems for reefer containers," *IEEE Trans. Ind. Electron.*, vol. 36, no. 5, pp. 4942–4947, May 2021.

[6] J. A. Ferreira, "Improved analytical modeling of conductive losses in magnetic components," *IEEE Trans. Power Electron.*, vol. 9, no. 1, pp. 127–131, Jan. 1994.

[7] Z. Pantic and S. Lukic, "Computationally-efficient, generalized expressions for the proximity-effect in multi-layer, multi-turn tubular coils for wireless power transfer systems," *IEEE Trans. Magn.*, vol. 49, no. 11, pp. 5404–5416, Nov. 2013.

[8] Z. Yang, W. Liu, and E. Basham, "Inductor modeling in wireless links for implantable electronics," *IEEE Trans. Magn.*, vol. 43, no. 10, pp. 3851–3860, Oct. 2007.

[9] J. Mai, X. Zeng, Y. Yao, Y. Wang, and D. Xu, "Improved winding and compensation methods for the multilayer coil in IPT system," *IEEE Trans. Ind. Electron.*, vol. 69, no. 5, pp. 5375–5380, May 2022.

[10] A. K. RamRakhyani, S. Mirabbasi, and M. Chiao, "Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants," *IEEE Trans. Biomed Circuits Syst.*, vol. 5, no. 1, pp. 48–63, Feb. 2011.