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A novel adaptive constant power optimal efficiency control strategy for bidirectional DS-LCC wireless charger

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ABSTRACT

This paper presents a novel adaptive constant power optimal efficiency control (ACPOEC) strategy that enables efficient constant power (CP) charging in a double-sided inductor-capacitor-capacitor (DS-LCC) wireless charger. The proposed control strategy is built upon triple-phase-shift (TPS) modulation and employs a pre-computed lookup table derived from offline optimization to achieve CP charging with corresponding optimal efficiency. The CP charger with the proposed strategy can eliminate switch-controlled capacitors (SCCs) in the topology. The proposed strategy is validated through simulation studies, achieving an efficiency range of 90.72% to 92.46%, which is also competitive with other advanced CP wireless charging systems. Compared with existing state-of-the-art CP wireless charging techniques, the wireless CP charger with the proposed ACPOEC strategy features a simplified topology, bidirectional power transfer capability, and competitive efficiency performance.

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1. INTRODUCTION

In the domain of battery charging, the traditional constant current (CC) charging method remains the predominant approach [1], [2]. However, CC charging does not fully exploit the available power capacity of the power source and charger. As shown in Figure 1(a), the output power is low when the battery voltage is low. This limitation leads to under utilization of the charger's and power supply's capabilities, extending the overall charging duration.

Compared to CC charging, constant power (CP) charging maintains a consistent power transfer throughout the entire charging process [3], as shown in Figure 1(b). This charging method adjusts the output current through control strategies in response to variations in battery voltage. This CP charging can fully utilize the available power capacity of the equipment, thereby accelerating the charging process and reducing the overall charging time. Moreover, CP charging has been shown to alleviate battery degradation issues [4], [5].

Inductive power transfer (IPT) wireless chargers are widely adopted across various industries, such as consumer electronics [6]–[8], biomedical implants [9]–[11], electric bikes [5], [12], [13], and electric vehicles

(EVs) [4], [14], [15], due to their advantages including inherent safety, low maintenance, and high reliability. To realize CP charging in wireless systems, extensive research has been conducted. A common method is incorporating a DC-DC converter on either the input or output side to regulate voltage or current [16], [17]. However, this additional power conversion stage increases system cost, power losses, and overall complexity.

To avoid using an additional DC-DC conversion stage, several single-stage CP wireless charging solutions have been proposed. For example, single-stage CP wireless chargers utilizing series–series (S–S) compensation networks have been explored in the literature [18]–[20]. However, S–S compensated wireless chargers are prone to generating excessive current under the coupler misalignment condition, thereby requiring supplementary safety protection mechanisms.

To deal with this safety concern in wireless power transfer systems, inductor-capacitor-capacitor (LCC) resonant compensation topologies, such as LCC-series (LCC-S) and double-sided LCC (DS-LCC), have emerged as effective solutions. In [5], an LCC-S compensation network combined with pulse-density modulation (PDM) was employed to achieve CP operation and efficiency optimization. However, this charger lacks bidirectional power transfer capability, limiting its suitability for applications aligned with the Energy Internet paradigm.

The DS-LCC compensation topology not only addresses safety concerns but also supports bidirectional power transfer. Owing to this critical advantage, the DS-LCC topology is widely used in IPT systems and is also adopted by industry standards [21]. However, the traditional DS-LCC wireless charger is a kind of CC charger only. To enable the CP charging function in DS-LCC wireless chargers, author in [22] proposed a DS-LCC charger incorporating two switch-controlled capacitors (SCCs). While this approach successfully achieves CP charging, the dependence on multiple SCCs introduces several drawbacks, including increased component costs and additional power losses.

In the IPT field, a DS-LCC wireless charger employing a triple-phase-shift (TPS) modulation strategy was proposed in [23]. This approach enables zero-voltage switching (ZVS) over a wide operating range without the use of any SCCs, resulting in a simplified circuit structure and high efficiency. However, the system is not capable of achieving CP charging for batteries. This paper proposes a novel adaptive constant power optimal efficiency control (ACPOEC) strategy for a DS-LCC bidirectional wireless charger. The ACPOEC strategy is built upon triple-phase-shift (TPS) modulation and employs a pre-computed lookup table derived from offline optimization to achieve CP charging with corresponding optimal efficiency.

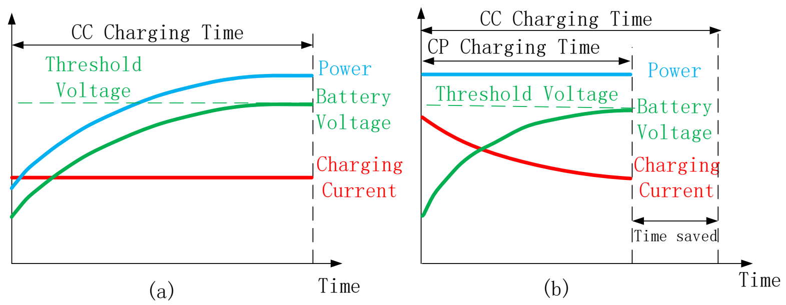

Figure 1. Comparison between (a) CC charging and (b) CP charging

2. THE WIRELESS CP CHARGER WITH THE PROPOSED ACPOEC STRATEGY

2.1. Charging system structure

The topology of the bidirectional DS-LCC wireless charging system is illustrated in Figure 2. On the primary side, an inverter composed of four MOSFETs (S_1 to S_4) is used to generate the AC voltage, while on the secondary side, an active rectifier consisting of four MOSFETs (S_5 to S_8) is employed to convert the AC current into DC current. The compensation network includes series inductors L_1 and L_2, parallel capacitors C_1 and C_2, series compensation capacitors C_p and C_s, and coil self-inductances L_p and L_s.

The C_O is a DC-link capacitor on the secondary side. The input DC voltage and battery voltage are represented by V_1 and V_2. The inverter's output voltage and current are labeled as u_{ab} and i_{L1}, while the rectifier's input voltage and current are denoted by u_{cd} and i_{L2}. The mutual inductance between the couplers is indicated as M, and the coupling coefficient k is defined by $k = M/\sqrt{L_pL_s}$.

The inverter output voltage is denoted as u_{ab}, and the rectifier input voltage is denoted as u_{cd}. Variables u_p and u_s represent the fundamental components of u_{ab} and u_{cd}, respectively. The phase difference between u_p and u_s is denoted by δ. The duty cycles of u_{ab} and u_{cd} are represented by D_p and D_s, respectively. To facilitate the analysis and simplify the equations, a phase shift compensation angle $\Delta\delta$ is defined as $\Delta\delta = \delta - \frac{\pi}{2}$.

The optimum phase shift $\Delta\delta$, denoted as $\Delta\delta_{\mathrm{opt}}$, ensuring that all switches in the system work under ZVS, according to [24], is expressed as (1).

$$\Delta\delta_{\mathrm{opt}} = -D_S\frac{\pi}{2} + \cos^{-1}\left(\Lambda^{-1} \times \left(-2\pi\omega L_1 L_2 I_{\mathrm{ZVS}} + \frac{V_2 L_1}{D_S\frac{\pi}{2} - 8\sin^2(D_S\frac{\pi}{2})}\right)\right) \tag{1}$$

Where $\Lambda = 8MV_1 \sin\left(\frac{\pi}{2}D_p\right)$, and I_{ZVS} is the predefined threshold current required for ZVS, which is used to charge and discharge the MOSFETs' equivalent output capacitance during the dead time. Neglecting losses in the charger, the transferred power can be expressed as (2).

$$P = \frac{M}{\omega L_1 L_2}\left|\dot{U}_P\right|\left|\dot{U}_S\right|\sin\left(\frac{\pi}{2} + \Delta\delta\right) \tag{2}$$

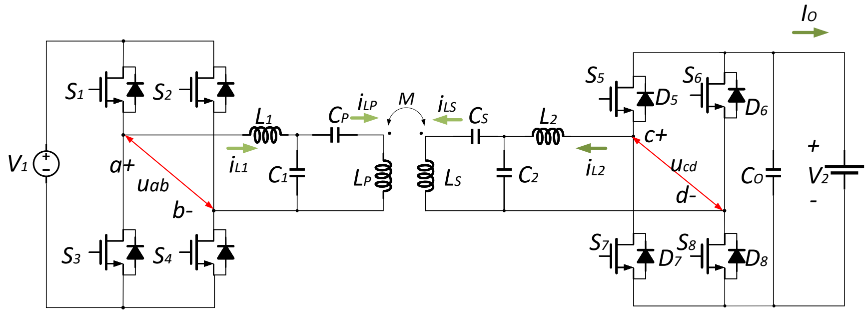

Figure 2. Topology of the bidirectional DS-LCC wireless charger

2.2. Coupling coefficient estimation

In the control strategy, the coupling coefficient needs to be estimated to achieve the adaptive control. A coupling coefficient estimation method is developed. In the estimation method, switches S_7 and S_8 are turned on to force $u_{cd} = 0$, as illustrated in Figure 3.

Ignoring losses, the coupling coefficient k can be expressed as a function of I_{L2} as (3).

$$I_{L2} = \frac{k\sqrt{L_p L_s} \cdot U_{ab}}{\omega L_1 L_2}. \tag{3}$$

Obviously, I_{L2} is proportional to the coupling coefficient k. Therefore, if we want to estimate the coupling coefficient k, we can measure the current I_{L2}. To improve accuracy, I_{L2} can be experimentally measured for discrete values of k, allowing the creation of a lookup table that defines the relationship between I_{L2} and k. This lookup table can then be utilized by the controller to estimate k based on I_{L2}, as illustrated in Figure 3.

I_{L2} can be measured at discrete values of k experimentally, and a lookup table that maps the relationship between I_{L2} and k can be built. The controller can subsequently use this lookup table to estimate k based on the measured I_{L2}, as illustrated in Figure 3.

2.3. ACPOEC strategy for CP charging

The ACPOEC strategy implemented in the proposed CP charger is illustrated in Figure 4. In this strategy, the controller on the secondary side acquires the battery voltage V_2 and retrieves the optimal control variables under this V_2 in the lookup table. This lookup table is produced by the offline optimization method shown in Figure 5, which is explained in the next section. The optimal variables D_{s_opt} and $\Delta\delta_{opt}$ are sent to pulse generators in the secondary side controller as a parameter. In the meantime, the secondary controller sent optimal duty cycle D_{P_opt} to the primary controller by wireless communication. The optimum variable can make the wireless charger achieve CP chargering with corresponding optimum efficiency.

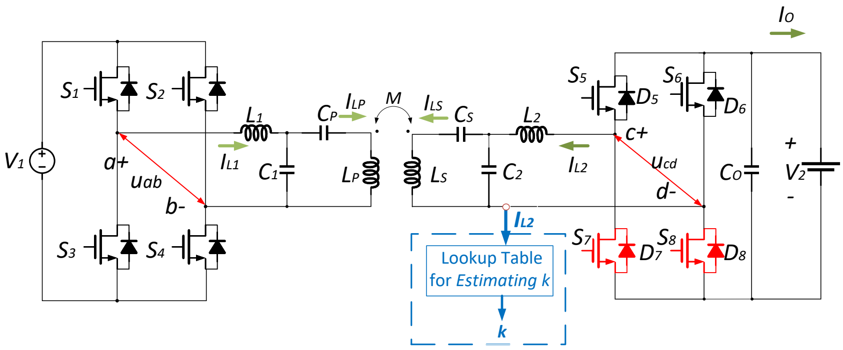

Figure 3. Diagram of coupling coefficient estimation

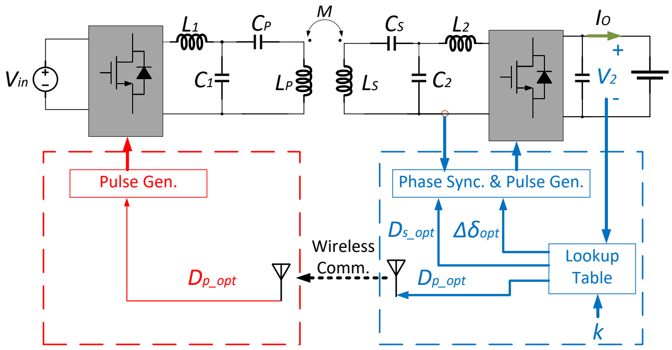

Figure 4. Proposed control strategy

2.4. Offline optimization approach

The optimum variables in the lookup table are generated by the offline optimization approach. The goal of the optimization is to pick the optimal control variables that maximize efficiency while ensuring constant power output across a range of battery voltages. To get maximum efficiency, loss model is built in this section.

The total power loss can be separated into losses in the inverter, losses in the resonant network, and losses in the rectifier. Inverter's losses include conduction losses and switching losses. Since all switches achieve ZVS, the switching losses are very tiny and can be omitted in the overall power loss optimization [23]. The losses in the inverter can be expressed as (4).

$$P_{\text{inv}} = 2R_{\text{ON}}I_{L1}^2 \tag{4}$$

Similarly, the losses from the rectifier are expressed as (5).

$$P_{\text{rec}} = 2R_{\text{ON}}I_{L2}^2 \tag{5}$$

Losses in the resonant circuit are expressed as (6).

$$P_{\text{res}} = I_p^2 R_{L1} + I_s^2 R_{L2} + I_{LP}^2(R_{LP} + R_{CP}) + I_{LS}^2(R_{LS} + R_{CS}) + I_{C1}^2 R_{C1} + I_{C2}^2 R_{C2} \tag{6}$$

Here, R_{CP}, R_{CS}, R_{C1}, and R_{C2} refer to the equivalent series resistances (ESRs) of the capacitors C_P, C_S, C_1, and C_2, respectively.

Thereby, the total losses in the charger can be expressed as (7).

$$P_l = P_{\text{inv}} + P_{\text{rec}} + P_{\text{res}} \tag{7}$$

With the loss model built above, the offline optimization method is proposed, as illustrated in Figure 5. The process involves the following steps: (i) Initialization: Provide system parameters, like input voltage V_1, the range of coupling coefficients $k_{\min}$ and $k_{\max}$, and the range of battery voltages $V_{2\min}$ and $V_{2\max}$, the reference power P_{ref}; (ii) Discretizing coupling coefficient k: Sample the coupling coefficient k over its predefined range using an appropriate step size; (iii) Discretizing battery voltage V_2: Sample the battery voltage V_2 over its predefined range with an appropriate step size; (iv) Control variable searching for CP charging: If the calculated power matches the reference power P_{ref} within a specified tolerance e, the corresponding control variables are retained. If both D_P and D_S already reach the maximum value of 1 and the transferred power still does not meet P_{ref}, the combination $D_P = D_S = 1$ and the associated $\Delta\delta_{\mathrm{opt}}$ are preserved to track the maximum deliverable power with optimal efficiency.

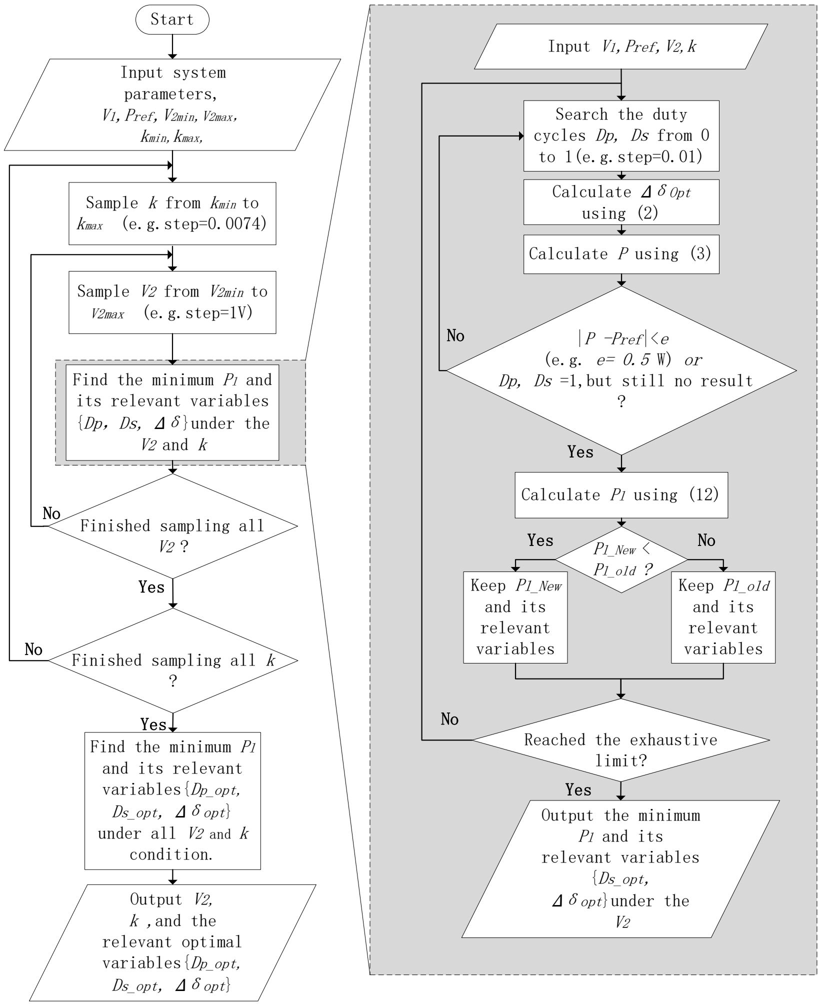

Figure 5. Flowchart for obtaining the optimal variables

3. SIMULATION RESULTS AND DISCUSSION

3.1. Specifications

The performance of the proposed wireless charger is validated through simulations conducted in MATLAB/Simulink. The parameters are designed based on the guidelines provided in [1], and all details are shown in Table 1.

3.2. Simulation results under alignment condition

In the simulation, the coupling coefficient is set as 0.302, and the battery voltage is swept from 72 V to 109 V. As shown in Figure 6, the output power generally remains constant within the range of 210 W to 217 W. The system maintains efficiency between 90.72% and 92.46% throughout the entire charging process. The proposed charger delivers competitive efficiency performance when compared with other state-of-the-art

CP wireless charging systems, as detailed in Table 2.

The wireless charger with the proposed control strategy can make sure all of the switches always work in ZVS conditions during the charging process. The waveforms of the inverter output voltage u_{ab} and the corresponding output current I_{L1} are presented in Figure 7(a), while Figure 7(b) shows the rectifier input voltage u_{cd} and input current I_{L2} under a battery voltage condition of $V_2 = 109$ V.

Table 1. Parameters of the wireless charger

Variable	Speed (rpm)	Power (kW)
V_1	Input DC voltage	73.5 V
V_2	Output battery voltage	72 V – 109 V
k	Coupling coefficient	0.262 – 0.302
L_P, L_S	Transmitting/receiving coil inductance	111 µH
R_{Lp}, R_{Ls}	Transmitting/receiving coil resistance	100 mΩ
L_1, L_2	Primary/secondary compensation inductance	35.2 µH
R_{L1}, R_{L2}	Primary/secondary inductor resistance	100 mΩ
C_1, C_2	Primary/secondary parallel capacitance	115 nF
C_P, C_S	Primary/secondary series capacitance	53.5 nF
R_{C1}, R_{C2}	Primary/secondary parallel capacitance ESR	100 mΩ
R_{Cp}, R_{Cs}	Primary/secondary series capacitance ESR	100 mΩ
R_{ON}	MOSFET on-state resistance	100 mΩ
$f = \frac{\omega}{2\pi}$	Switching frequency	79 kHz
I_{ZVS}	Threshold ZVS current	2 A
P_{ref}	Reference power	230 W

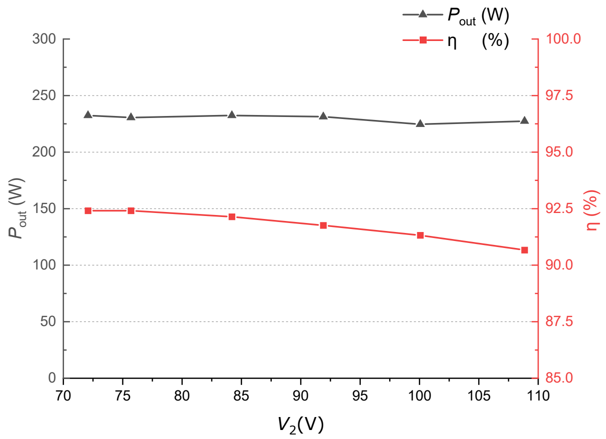

Figure 6. Output power P_o, and efficiency η versus the different battery voltage V_2 when alignment condition

Table 2. Features comparison between the previous single-stage CP chargers and this work

Different works and published year	2020 [19]	2022 [20]	2022 [22]	2024 [5]	This work
Type of compensation network	S-S	S-S	DS-LCC	LCC-S	DS-LCC
No extra auxiliary SCC	No	Yes	No	Yes	Yes
Efficiency optimization	Yes	Yes	No	Yes	Yes
No large current issue when misalignment	No	No	Yes	Yes	Yes
Bidirectional operation	No	Yes	No	No	Yes
No noticeable current fluctuation	Yes	Yes	Yes	No	Yes
Constant operating frequency	Yes	No	Yes	Yes	Yes
DC to DC efficiency	88.8%	87.9%	91.5%	89.8%	92.46%

3.3. Discussion on misalignment condition

To know the performance of the wireless charger under misalignment conditions using the proposed control strategy, a simulation was conducted with the coupling coefficient reduced to 0.262. The output power and efficiency versus battery voltage are illustrated in Figure 8. As observed, the efficiency remains high, ranging from 91.12% to 92.45%, even under misaligned conditions. The output power is maintained between 190.42 W and 217.56 W. When the output voltage V_2 is in the lower range, a drop in output power is observed. This is attributed to the reduced maximum power transfer capability of the DS-LCC charger at lower coupling coefficients. Nevertheless, the proposed control strategy enables the wireless charger to effectively track the maximum power point while maintaining optimal efficiency. When the coupler is properly designed, the variation of the coupling coefficient k is typically confined to a narrow range [25]. Therefore, the impact of misalignment on the output power of the wireless charger is relatively limited.

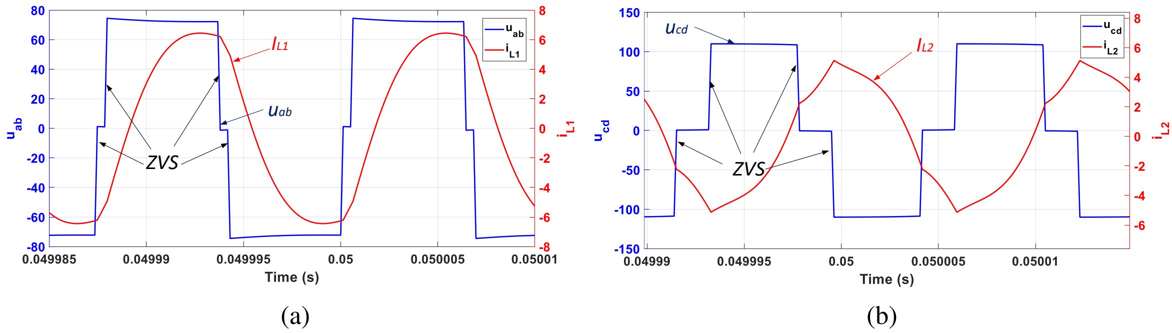

Figure 7. Waveforms of (a) the inverter's output voltage u_{ab} and current i_{L1}, (b) the rectifier's input voltage u_{cd} and current i_{L2} when $V_2 = 109\ V$

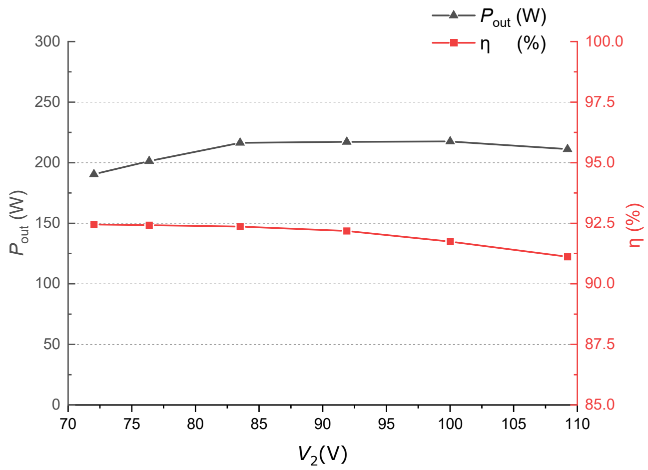

Figure 8. Output current I_o, and efficiency η versus the different battery voltage V_2 in simulation

4. CONCLUSION

This paper proposed an adaptive constant power optimal efficiency control (ACPOEC) strategy for a bidirectional double-sided LCC (DS-LCC) wireless power transfer charger. The proposed approach integrates triple-phase-shift (TPS) modulation with an offline optimization procedure and a precomputed lookup table to regulate the control variables, enabling constant-power charging while maintaining high efficiency over a wide battery voltage range. In addition, a coupling coefficient estimation method based on current measurement is introduced to allow adaptive control under varying magnetic coupling conditions. By eliminating the need for switch-controlled capacitors, the proposed method simplifies the circuit topology and reduces additional component losses while preserving bidirectional power transfer capability. Simulation results demonstrate that the wireless charger can maintain nearly constant output power throughout the charging process while achieving high efficiency in the range of approximately 90–92%. Furthermore, all switching devices operate under zero-voltage switching conditions, which contributes to reduced switching losses and improved overall system efficiency. The performance of the proposed strategy was also evaluated under both alignment and misalignment conditions. The results indicate that the system maintains stable power transfer and high efficiency despite variations in the coupling coefficient, demonstrating the robustness of the proposed control scheme. These characteristics make the proposed ACPOEC-based wireless charger a promising solution for practical inductive power transfer applications, particularly in systems requiring efficient, bidirectional, and reliable wireless charging. Future work will focus on hardware implementation and experimental validation to further investigate the practical performance and dynamic behavior of the proposed control strategy.

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AUTHOR CONTRIBUTIONS STATEMENT

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Nik Rumzi Nik Idris		✓				✓	✓			✓		✓	✓	
Mohammad Al Takrouri						✓				✓	✓			
Tole Sutikno						✓	✓			✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal Analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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