Analysis and Design of Three-Coil Coupler for Inductive Power Transfer System with Automatic Seamless CC-to-CV Charging Capability

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ABSTRACT The three-coil loosely coupled inductive power transfer (IPT) charging system can achieve constant current (CC) to constant voltage (CV) output automatically and smoothly during battery charging process. However, a voltage deviation will generate in CV output compared with the ideal CV charging voltage threshold of battery, because of the cross-coupling that existed between the assistive and receiver coils. In this paper, the practical effect of the cross-coupling between the assistive and receiver coils and the impedance matching at full load for efficiency optimization are further taken into consideration based on coupler design. Four design schemes of the assistive coil are compared by finite-element analysis (FEA) and an effective design approach is provided. Then, the proposed approach is theoretically analyzed to relieve the cross-coupling issue on the CV output even with efficiency optimization. Also, it decreases the space occupancy of the three-coil coupler. An experimental prototype is built to verify the proposed design method and the theoretical analysis.

INDEX TERMS Three-coil coupler, inductive power transfer, battery charging, optimal load matching, compact design.

I. INTRODUCTION

THE inductive power transfer (IPT), without electrical connections, is regarded as a convenient, safety, efficient and promising energy transfer technology throughout the magnetic fields resonance [1]–[4]. It has been widely applied in biomedical implants [5], underwater charging devices [6], and consumer electronics [7]. Currently, an important application of IPT charging system focus on battery wireless charging for electric vehicles (EVs) [8]–[12], which has significant advantages over the traditional plug-in system. As for lithium batteries, in general, there are two main charging profiles, i.e., an initial constant current (CC) charging state and a subsequent wide range of constant voltage (CV) charging state, required to protect and extend battery life [12], [13]. Therefore, an IPT battery charging system should be designed to achieve stable CC and CV output and seamless changing in transition during the charging process as well as maintain high efficiency.

Since the equivalent direct current (DC) load $R_L$ of battery variation is inevitable during the charging profile. A significant challenge of IPT charging system is to operate with load independent current (LIC) and load independent voltage (LIV) in its CC and CV charging process, respectively, and also achieve its seamless changing on transition from CC mode to CV mode. Typically, it is an intuitive to achieve both LIC and LIV output via switchable, reconfigurable or multi-compensation topology [12], [14]–[16]. However, hybrid-topologies result in more conduction loss and component cost because of adding external power switches and passive compensation components. Moreover, some researchers proposed to satisfied the CC and CV charging in the IPT charging system throughout using two different operating frequencies.
Although this method eliminates redundant compensation components and additional power switches, the real-time sensing and wireless feedback communication are indispensable for the variable frequency control, which is not robust caused by the strong electromagnetic interference of the IPT system. Alternatively, some control strategies in [19], [20], which add the additional DC-DC converter in the front-side or the load-side, is proposed to achieve required CC or CV charging threshold by modulating the duty cycle. However, it will increase the complexity of system, and even need a complex control.

In a recent study, a novel scheme adopts a three-coil coupled IPT structure to comply the inherent CC to CV outputs with LIC and LIV [21]. Also, the system is simple that does not require the wireless feedback communication and the charging state detection. Moreover, it has a ability of open circuit protection. However, there still exists a problem on the undesired cross coupling effect between the assistive and receiver coils, which leads to deviation of the CV output.

In [21], it lacks a detailed optimization design method to decreasing the effect of undesired cross-coupling. Moreover, as for IPT charging system, the maximum power point should be load-impedance-matching, otherwise the overall charging efficiency will be degraded. Therefore, to fill the gap, this paper systematically addresses the problem of [21] and proposes an optimization design methodology of the three-coil IPT system via taking the practical effect of cross-coupling issues, and load impedance matching at the full load condition for efficiency optimization. This approach is proposed to reduce the undesired cross-coupling effect, and the three-coil coupler is more compact as well.

The structure of the paper is as follows. The practical effect of cross-coupling in the proposed three-coil coupled IPT charging system and the way to achieve maximum efficiency load impedance matching are analyzed in Section II. In Section III, the design method and the corresponding flowchart of the three-coil coupler is provided. Four design cases of the assistive coil are discussed to find a compact three-coil coupler and eliminate the effect of cross-coupling issue. Finally, in Section IV, an experimental prototype is established to verify the three-coil coupler design methodology and analysis.

II. TWO CRITICAL DESIGN ISSUES OF THREE-COIL IPT CHARGING SYSTEM

A. OVERVIEWS OF THREE-COIL IPT CHARGING SYSTEM WITH AUTOMATIC CC-CV CHARGING PROFILE

Fig. 1(a) depicts the diagram of the three-coil loosely-coupled inductive power transfer (IPT) charging system [21]. Basically, it consists of the transmitter, receiver and assistive circuits, which can be indicated by subscripts T, R and A respectively. The transmitter circuit includes a series compensated transmitter coil driven by a full-bridge inverter, while the receiver circuit has a series compensated receiver coil and a purely passive full-bridge rectifier. It can be observed that, the transmitter and receiver circuits together form a well-known series-series IPT converter. To clamp the transmitter current $i_T$, an additional assistive circuit is used that consists of a series compensated coil and a purely passive full-bridge rectifier. As shown in Fig. 1(a), self inductances of the three coils are denoted as $L_T$, $L_R$ and $L_A$, while the mutual inductances between these three coils are given by $M_{TR}$, $M_{TA}$ and $M_{RA}$. For simplicity, resistances of high-quality-factor coils are ignored in this paper. $C_T$, $C_R$ and $C_A$ are the corresponding compensation capacitors. $V_{IN}$ is the input voltage. The load resistance $R_L$ of the three-coil IPT charging system is determined by the output voltage $V_{bat}$ and output current $I_{bat}$, as given by $R_L = \frac{V_{bat}}{I_{bat}}$.

The three-coil IPT charging system is designed to operate at a fully resonant state, i.e.,

$$\omega = \frac{1}{\sqrt{L_T C_T}} = \frac{1}{\sqrt{L_R C_R}} = \frac{1}{\sqrt{L_A C_A}}. \quad (1)$$

Such that the three circuits all have null reactance at $\omega$, i.e.,

$$\frac{1}{j\omega C_T} + j\omega L_T = \frac{1}{j\omega C_R} + j\omega L_R = \frac{1}{j\omega C_A} + j\omega L_A = 0. \quad (2)$$
Using fundamental approximation, the circuit equations can be highlighted as

$$
\begin{bmatrix}
V_T \\
V_R \\
V_A
\end{bmatrix} = j\omega
\begin{bmatrix}
0 & -M_{TR} & -M_{TA} \\
M_{TR} & 0 & -M_{RA} \\
M_{TA} & -M_{RA} & 0
\end{bmatrix}
\begin{bmatrix}
I_T \\
I_R \\
I_A
\end{bmatrix}.
$$

(3)

where $V_T$, $I_T$, $V_R$, $I_R$, $V_A$ and $I_A$ are corresponding vectors of $v_T$, $i_T$, $v_R$, $i_R$, $v_A$, $i_A$.

Assumed that the mutual coupling $M_{RA}$ is small and insignificant, e.g., $M_{RA} \approx 0$, the basic operating principle of the three-coil IPT charging system can be classified into the follows.

1) $|V_A| \leq V_{IN}$, the assistive rectifier is reverse-blocked.

In this case, the three-coil IPT charging system operates as a common SSIIPT converter to output a constant current for the CC charging. With (3), the CC output can be derived as

$$I_{CC} = \frac{8}{\pi^2} \frac{V_{IN}}{M_{TR}}.$$  

(4)

2) $|V_A| \geq \frac{4}{\pi} V_{IN}$, the assistive rectifier is conducted. In this case, the current $|I_T|$ in the transmitter circuit is clamped by the assistive circuit, as given by

$$|I_T|_{clamp} = \frac{4}{\pi} \frac{V_{IN}}{\omega M_{TA}}.$$  

(5)

Such that, a voltage threshold $V_{CV}$ is induced in the receiver circuit, as given by

$$V_{CV} = \frac{M_{TR}}{M_{TA}} V_{IN}.$$  

(6)

Based on the two key stages above, the three-coil IPT charging system features automatic seamless CC-to-CV charging capability in the ideal case ($M_{RA} = 0$), as indicated by Fig. 2(a). However, $M_{RA}$ is inevitable in the practical case, and even makes an obvious voltage deviation at the CV charging state. It is necessary to minimize this issue via coil design. Moreover, the charging efficiency is another critical issue. Thus, this motivates to further investigate the cross-coupling issue and efficiency optimization of the three-coil IPT system.

### B. EFFECT OF UNDESIRED CROSS-COUPLING ($M_{RA} \neq 0$) ON CV OUTPUT

The cross-coupling $M_{RA}$ between assistive coil and receiver coil can not be ignored in practice. The practical effect of $M_{RA}$ on the CV output is nonlinear throughout the CV charging state, but it can be studied by evaluating two extreme cases as follows.

1) When the assistive rectifier comes to be fully conductive, the assistive circuit begins to be activated and thus the system enter the CV charging state. Moreover, the $i_T$ is still approximated to $I_{CC}$ while $i_A$ is very small that can be regarded as zero. Such that, according to (3), the CV output voltage at the beginning ($R_{L2}$) can be derived as

$$V_{CV,begin} = \frac{M_{TR}}{M_{TA}} V_{IN} \sqrt{1 - \left(\frac{M_{RA}}{M_{TR}}\right)^2.}$$  

(7)

2) As the CV charging process continues, the battery load resistance $R_L$ will increase far from the $R_{L2}$ and gradually approximate to infinity. Followed by the conducting current of receiver side can be restricted to zero. With the phase relationship of the conducting voltages and currents between receiver and assistive circuits, the output voltage at the ending, denoted as $V_{CV, end}$ is given as

$$V_{CV, end} = \frac{M_{TR}}{M_{TA}} V_{IN} \sqrt{1 + \left(\frac{M_{RA}}{M_{TR}}\right)^2.}$$  

(8)

However, the undesired cross-coupling effect can be concluded that, in the practical case ($M_{RA} \neq 0$) as indicated in Fig. 2(b), the CV charging voltage $V_{bat}$ in this three-coil IPT charging system ramps up varying from $V_{CV, begin}$ to $V_{CV, end}$ with the increasing of $R_L$ during the CV charging process. The voltage difference between $V_{CV, end}$ and $V_{CV, ideal}$ is defined as $\Delta V$. Therefore, $\Delta V$ should be minimized via a proper design of the three-coil coupler, and the first design objective can be obtained as

$$\frac{M_{RA}}{M_{TR}} \ll 1.$$  

(9)
**C. Impedance Matching at Full Load for Efficiency Optimization**

Due to wide load range variation throughout the whole charging profile, it is challenging for the three-coil IPT charging system to achieve the efficiency optimization. In general, an IPT converter should obtain a maximum efficiency at the full load condition, which means the full load point matches optimum load impedance [22]. Thus, some effort should be taken to achieve load impedance matching at the full load condition to optimize the charging efficiency.

Since the battery charging process is much slower than the operating period of the SSIPt converter, the battery can be regarded as a resistor which is determined by the charging voltage and the charging current. With (4) and (6), the equivalent battery resistance $R_{bat,max}$ at the full load point is calculated as

$$R_{bat,max} = \frac{\pi^2 \omega M_T^2}{8 M_T A}$$  \hspace{1cm} (10)

The maximum efficiency will be achieved in the proposed IPT charging system, when equivalent load $R_L$ satisfies [22]

$$R_{L,opt} = \frac{\pi^2}{8} \omega M_T \sqrt{\frac{R_T}{R_R}} \approx \frac{\pi^2}{8} \omega M_T \sqrt{\frac{L_R}{L_T}}$$  \hspace{1cm} (11)

$R_T$ and $R_R$ are the equivalent resistance of transmitter coil and receiver coil respectively. Since the equivalent resistance of the coil is proportional to the coil inductance, $R_{L,opt}$ can be further simplified as given in (11). To match the maximum power point and the optimum efficiency point, $R_{L,opt} = R_{bat,max}$, the second design objective can be derived as

$$\frac{M_{TR}}{M_{TA}} \approx 1$$  \hspace{1cm} (12)

Therefore, to obtain load impedance matching at full load for efficiency optimization, the simple and effective method will be applied to regulate the self inductances ($L_T, L_R$) and mutual inductances ($M_{TR}, M_{TA}$) via design the three-coil coupler. More details are given in Section III.

**III. Three-Coil Coupler Design Profile**

**A. Four Possible Design Cases**

As illustrated in Section II-B, the optimal design of the three-coil coupler is required to satisfy with above two objectives (9) and (12) simultaneously, the first one is minimizing the cross-coupling $M_{RA}$ to reduce the $\Delta V$ and the second one is matching optimum impedance at the full load condition.

This optimal design starts with the transmitter and receiver coils that are responsible for main power delivery. Based on (4), the mutual inductance $M_{TR}$ is determined by the CC charging current $I_{CC}$. Typically, a symmetric design is the most cost-effective for the transmitter and receiver coils. Thus, the symmetric design of transmitter and receiver will be adopted that means the self-inductance $L_T$ and $L_R$ are identical using the same diameter of Litz wire. However, the design condition of efficiency optimization in (12) can be simplified as

\[ \frac{M_{TR}}{M_{TA}} \approx 1 \]

Since $L_T=L_R$, the design objective of efficiency optimization (13) can be simply fulfilled once if the assistive coil is exactly the same as the transmitter coil and the air gap $g_{TR} = g_{TA}$, as shown in Fig.3. However, the three-coil coupler occupies the largest installation space under this condition. This upper limitation can be regarded as the initial condition of the three-coil coupler design. Moreover, the transmitter and assistive coils are in a whole as shown in Fig.1. In order to keep the charging system compact, the integration of the the transmitter and assistive coils should be considered to minimize the space occupancy. The out-diameter of the assistive coil is restricted, which cannot exceed that of the transmitter coil. Under such a constraint, the possible designs with respect to diameter, number of turns and turn pitch still can be classified into four cases, as shown in Table 1. Here, the $N$, $W$, $d_{in}$, and $d_{out}$ are number of turns, turn pitch, inner diameter and outer diameter respectively, as shown in Fig.4.

Four possible design cases are simulated by finite-element analysis (FEA) using ANSYS Maxwell. Before the FEA simulation, the battery charging specification is set at 10Ah and 48V. And the transmitter and receiver coils are kept

**TABLE 1.** Assistive coil design methods

| Case   | $N$  | $W$  | $d_{in}$ | $d_{out}$ |
|--------|------|------|----------|-----------|
| Case 1 | Decrease | Constant | Constant | Decrease |
| Case 2 | Decrease | Constant | Increase | Constant |
| Case 3 | Constant | Decrease | Constant | Decrease |
| Case 4 | Constant | Decrease | Increase | Constant |
symmetric with the initial turn pitch, the number of turns, and air gap \( g_{TA} \) being 6 mm, 15 turns, and 40 mm, respectively, and being constant during the following design process. Also, the assistive coil is set at the initial condition that is same as the transmitter coil: \( W = 6 \) mm, \( N = 15 \) turns and \( g_{TA} = 40 \) mm. The simulation results are described as follows.

1) Case 1. As illustrated in Table 1, the inner diameter \( (d_{in}) \) and turn pitch \( (W) \) of the assistive coil are kept constant, but when the number of turns \( N \) is reduced from the outside to the inside, the outer diameter \( d_{out} \) will decrease, as shown in Fig. 5(a). Fig. 5(b), (c), and (d) show the relationships of coupling coefficients \( (K_{TA}, K_{RA}) \) and the air gap \( (g_{TA}) \), \( M_{TR}/M_{TA} \), and \( M_{RA}/M_{TR} \) versus \( N \) by the solid line respectively. Obviously, the coupling coefficient \( K_{TA} \) increases gradually until the number of turns decreases to 9, as shown in Fig. 5(b). And the peak value of \( K_{TA} \) that will be obtained at the \( N \) is about 9. As the \( N \) reduces from 15 to 9, the ratio of \( M_{TR}/M_{TA} \) can keep approximately 1 in Fig. 5(c), by the reductions of \( N \) and the air gap \( g_{TA} \). When \( N \) is less than 9, \( K_{TA} \) has a rapid downward trend of variation resulting in the rapidly increasing of \( M_{TR}/M_{TA} \). Moreover, with the decreasing of \( N \) and \( g_{TA} \), \( M_{RA}/M_{TR} \) reduces gradually. In short, when the number of turns comes to 9, the best design point of Case 1 will be obtained which satisfy two design objectives.

2) Case 2. The outer diameter and turn pitch are kept constant, but the number of turns \( (N) \) of the assistive coil decreases along the inner side towards the outer side, which increases the inner diameter, as shown in Fig. 5 (a). Fig. 5(b), (c), and (d) show the relationships of coupling coefficients \( (K_{TA}, K_{RA}) \) and the air gap \( (g_{TA}) \), \( M_{TR}/M_{TA} \), and \( M_{RA}/M_{TR} \) versus \( N \) by the dotted line respectively. It can be observed from Fig. 5(c) that, the coupling coefficient \( K_{TA} \) increases when \( N \) decreases from 15 to 4, and then decreases when \( N \) is less than 4, which has the same trend as Case 1. Correspondingly, \( M_{TR}/M_{TA} \approx 1 \) can be maintained until \( N \) decreases to 4 as the number of turns \( N \) and the air gap \( g_{TA} \) decrease. And the maximum \( K_{TA} \) will be obtained when the \( N \) is 4 in Case 2. Also,
Case 3
\(d_{\text{in}}\) reduces as \(W\) reduces, \(d_{\text{in}}\) and \(N\) constant

Case 4
\(d_{\text{in}}\) increases as \(W\) reduces, \(d_{\text{in}}\) and \(N\) constant

(a)

(b)

(c)

(d)

FIGURE 6. (a) Design model of assistive coil in case 3 and case 4, (b) Coupling coefficient \(K_{TA}, K_{RA}\) and \(g_{TA}\) versus \(W\), (c) and (d) The ratio of \(M_{TR}/M_{TA}\), \(M_{RA}/M_{TR}\) versus \(W\) respectively.

3) Case 3. The number of turns \(N\) and the inner diameter \(d_{\text{in}}\) are kept constant, but the turn pitch \(W\) of assistive coil is narrowed down from outside, which will reduce the outer diameter \(d_{\text{out}}\), as described in Fig. 6 (a). It can be easily seen that, when wire distance decreases from 6mm to 3mm, the coupling coefficient \((K_{TA})\) keeps increasing, and the maximum \(K_{TA}\) can achieve when \(W\) is 3 mm. Meanwhile, the assistive coil gradually approaches to primary coil along the axial direction to decrease \(g_{TA}\) in this period, so \(M_{TR}/M_{TA} \approx 1\) can be

Both Case 1 and Case 2 can satisfy two design objectives (9) and (13) simultaneously and effectively, but the design range \((N \in [4, 15] \text{ and } g_{TA} \in [0\text{mm}, 40\text{mm}])\) of Case 2 is much wider than that of Case 1 \((N \in [9, 15] \text{ and } g_{TA} \in [0\text{mm}, 40\text{mm}])\), as shown in Fig. 5 (b) and (c). Moreover, \(M_{RA}/M_{TR}\) in Case 2 \((N=4)\) is much lower than that in Case 1 \((N=9)\) as indicated in Fig. 5(d) which means Case 2 has better output performance particularly. As a result, the Case 2 is regarded as the better design method for the assistive coil.

Fig. 5(d) shows \(M_{RA}/M_{TR}\) has a downward tendency and gradually approaches 0 with the decreasing of \(N\) and \(g_{TA}\). In short, the best design point of Case 2 will be achieved when the number of turns reduces to 4.

FIGURE 7. The cross-coupling \(M_{RA}\) versus \(G_{TA}\).
Getting the input parameters of the IPT system and battery charging requirements

Calculating the required $M_{TR}$ using (4) based on input data; Selecting the suitable litz wire based on $I_{CC}$. 

Setting the preferred $K_{TR}$ and determining the self-inductances of the transmitter and receiver coils ($L_T, L_R$) 

Transmitter & receiver coil design

Determining $M_{TA}$ based on the CV threshold of the battery 

Calculating the equivalent battery resistance at the full load condition $R_{Bat,max}$ using (10) 

Calculating the optimum load resistance $R_{L,opt}$ of the IPT converter using (11) 

Load matching for efficiency optimization

Set $R_{Bat,max}=R_{L,opt}$ 

Output the designed parameters of three-coil coupler 

End

FIGURE 8. Design flow of three-coil coupler with clamp coil.

B. SUGGESTED DESIGN AND DESIGN FLOWCHART

Based on above analysis, both Case 2 and Case 3 can be satisfied with two design objectives. In order to distinguish the most effective design of the assistive coil. The relationship between $M_{RA}$ and $g_{TA}$ with Case 2 and Case 3 are studied as shown in Fig. 7 respectively, and both cases have the identical $M_{RA}$ as the initial condition. However, it can be observed that, the value of $M_{RA}$ in Case 2 attenuates faster compared with the Case 3, thus Case 2 is more suitable to reduce the undesired cross-coupling $M_{RA}$ that minimizes voltage derivation. Such that, Case 2 is used for the three-coil coupler design in this paper. To summarize the design method, a completed design flowchart of the three-coil coupler is shown in Fig. 8 and the corresponding description is as follows.

1) Transmitter and receiver coils design

First step is to determine the transmitter and receiver coils that are responsible for main power delivery. According to the input voltage of IPT system and the battery charging specifications, the required $M_{TR}$ is calculated using (4). Also, based on the $I_{CC}$, the diameter of Litz wire with the appropriated current carrying capacity can be determined. Then, setting the preferred coupling coefficient $K_{TR}$. Having $M_{TR}=K_{TR}\sqrt{L_T L_R}$ and $L_T = L_R$, the self-inductances of transmitter coil $L_T$ and receiver coil $L_R$ can be determined. After that, the the design of power transfer coils are completed.

2) Load matching for efficiency optimization

Based on the $R_{Bat,max}=R_{L,opt}$ and the desired CV output threshold $V_{CV, opt}$, $M_{TA}$ is generally calculated, and then, the assistive coil design will be started if the values of $M_{TR}$ and $M_{TA}$ meet the second design objective $M_{TR}/M_{TA} \approx 1$. Otherwise, the design will end.

3) Assistive coil design

$M_{TA}$ has already determined in the previous design stage that can achieve efficiency optimization. The self-inductance of the assistive coil $L_A$ will be adjusted with Case 2 method, decreasing the number of turns $N$ from inside and adjusting $g_{TA}$, until both two design objectives (13) and (9) are satisfied. Then, the design profile of the assistive coil is finished and the designed parameters of the three-coil coupler are generated. Follow by an compact three-coil coupler is achieved, which can weaken the cross-coupling effect and optimize the efficiency.

with the dotted line, although the $M_{TR}/M_{TA} \approx 1$ can be always maintained, the $g_{TA}$ will increase and much larger than the initial condition ($N=15$, $W=6$ mm, $g_{TA}=40$ mm). Then, the effect of cross-coupling will not be minimized because $M_{RA}/M_{TR}$ is gradually towards to 1 that is against the first design objective (9). Therefore, it can confirm that Case 4 is a poor design method.

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TABLE 2. Measured Circuit Parameters

| Items                  | Parameters | Values          |
|------------------------|------------|-----------------|
| Transmitter/Receiver   |            |                 |
| coil                   |            |                 |
|                        | \(d_{in}\) | 20 mm           |
|                        | \(d_{out}\) | 200 mm          |
|                        | Wire distance(W) | 6 mm    |
|                        | Number of turns(N) | 15     |
| Assistive coil         |            |                 |
|                        | \(d_{in}\) | 164 mm          |
|                        | \(d_{out}\) | 200 mm          |
|                        | Wire distance(W) | 6 mm    |
|                        | Number of turns(N) | 4      |
| Circuit values         |            |                 |
|                        | \(L_T\) | 21.44 \(\mu\)H |
|                        | \(L_R\) | 21.30 \(\mu\)H |
|                        | \(L_A\) | 6.12 \(\mu\)H  |
|                        | \(M_{TR}\) | 6.95 \(\mu\)H |
|                        | \(M_{TA}\) | 6.35 \(\mu\)H |
|                        | \(M_{RA}\) | 2.58 \(\mu\)H |
|                        | \(C_T\) | 14.8 nF         |
|                        | \(C_R\) | 14.4 nF         |
|                        | \(C_A\) | 5.8 nF          |
|                        | \(\theta_{TR}\) | 40 mm  |
|                        | \(\theta_{TA}\) | 1 mm   |

FIGURE 9. (a) Three-coil coupler and (b) Experimental prototype of the proposed IPT charging system.

IV. EXPERIMENTAL VERIFICATION

An experimental prototype with the three-coil coupler is built with schematics shown in Fig. 1(a). The capacity of the given battery is 10 Ah and its nominal voltage is 48 V. The charging current is set at \(I_{CC} = 3\) A. Such that, the design of the three-coil coupler can be started with battery charging specifications in line with the flowchart as shown in Fig. 8. The IPT charging system is driven by a DC voltage source with \(V_{IN} = 48\) V, while the battery is emulated by an electronic load. The resonant frequency is fixed at 300 kHz. However, on the basis of the design flowchart, the parameters of the transmitter and receiver coils as well as that of the compensation network can be determined, and also, the assistive coil can be well designed, as shown in Table 2. In addition, the coil winding track of three-coil coupler is printed by a 3D printer using acrylonitrile butadiene styrene (ABS) to set a precise turn pitch of the coil, as shown in Fig. 9(a). The whole prototype of the proposed three-coil IPT charging system is given as Fig. 9(b). Table 3 shows six different assistive coils and the corresponding practical mutual inductance of the three-coil coupler, \(M_{TA}\), \(M_{RA}\) and \(M_{TR}\). The transmitter and receiver coils follow the symmetrical design, so \(M_{TR}\) can keep in 6.95 \(\mu\)H. And the assistive coil complies with the proposed design Case 2, varying from \(N = 15\) to \(N = 1\). Based on above parameters, Fig. 10 shows the simulated and measured ratio of \(M_{TR} / M_{TA}\) of case 2. It can be seen that the measured value is identical with the simulated value. Moreover, \(M_{TR} / M_{TA}\) is approximately closed to 1 as the \(N\) decreases from 15 to 4. Meanwhile, the cross-coupling \(M_{RA}\) of receiver coil and assistive coil can be lower with the decreasing of \(N\) from inside of assistive coil, as indicated in Fig. 11. The experi-
TABLE 3. Measured parameters of assistive coil versus $N$

| Items          | Values |
|----------------|--------|
| $N$            | 1      | 3      | 6      | 9      | 12     | 15     |
| $M_{T_A} (\mu H)$ | 1.78   | 5.65   | 7.20   | 7.11   | 7.15   | 7.08   |
| $M_{R_A} (\mu H)$ | 0.72   | 1.89   | 2.72   | 2.95   | 3.01   | 3.12   |
| $M_{TR} (\mu H)$ |        | 6.95   |        |        |        |        |

(a) CC mode, $R_L = 5 \, \Omega$
(b) Transition process, $R_L = 16 \, \Omega$
(c) CV mode, $R_L = 100 \, \Omega$

FIGURE 12. Experimental waveforms of the proposed IPT charging system with three-coil coupler at the (a) CC mode, $R_L = 5 \, \Omega$; (b) Transition process, $R_L = 16 \, \Omega$; (c) CV mode, $R_L = 100 \, \Omega$.

Fig. 13 plots the measured current $I_{bat}$ (marked with “○”), voltage $V_{bat}$ (marked with “□”), and the measured efficiency $\eta$ (marked with “△”) versus battery load assistance $R_L$. The CC output at 3 A can be achieved when $R_L \leq 9 \, \Omega$, while an approximated CV threshold at 53 V is maintained if $R_L \geq 23 \, \Omega$. In addition, it can be seen that the maximum efficiency of 90.38% is achieved at 16 $\Omega$, which approximates the calculated maximum efficiency load impedance matching point of 16.2 $\Omega$ according to (11). Therefore, the IPT system can achieve the optimum efficiency.

According to Fig. 13, the $V_{CV,begin}$ and $V_{CV,end}$ are 48 V and 53 V, respectively, so that the $V_{CV,begin}$ is slightly lower than the $V_{CV,end}$ and $\Delta V$ can be restricted to 5 V only. In detail, with (6) the calculated ideal CV output voltage $V_{CV,ideal}$ is 52.5 V. The begin voltage of the CV mode $V_{CV,begin}$ is 8.5% lower than ideal voltage $V_{CV,ideal}$ while the end voltage $V_{CV,end}$ is only 0.95% higher than $V_{CV,ideal}$. Thus, the three-coil coupler IPT system with the optimized design can achieve not only efficiency optimization, but also a low voltage deviation during CV charging profile.

V. CONCLUSION

This paper has further analyzed the three-coil loosely coupled IPT system with automatic seamless CC-to-CV transition capacity. To address the existing problems of this IPT system, four coil design schemes have been studied with finite-element analysis. In comparison of these schemes, an effective three-coil design methodology is provided which
can effectively weaken the effect of the cross-coupling issue to decrease the voltage deviation at the CV charging state and achieve load matching efficiency optimization. However, based on the proposed design method, the space occupancy of three-coil coupler is reduced and more compact. Moreover, an experiment topology using the proposed design scheme is built for validation and the experimental results agree well with the analysis.

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