A Novel S–S–LCLCC Compensation for Three-Coil WPT to Improve Misalignment and Energy Efficiency Stiffness of Wireless Charging System

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Abstract—Recent studies have proven that a three-coil wireless power transfer (WPT) design shows better performance and has higher efficiency compared to the two-coil designs, especially when the source resistance and transmission distance between the primary and receiver coil increases. The three-coil WPT system, similar to a two-coil system, is capable of achieving constant output current (CC) and constant output voltage (CV) with ZPA. However, in the CV mode of the conventional three-coil design, the efficiency of the light-load system dramatically decreases as the load becomes smaller. In this article, a new series-series-LCLCC (S–S–LCLCC) compensation design for the three-coil WPT system with load-independent output voltage, which is capable of realizing ZPA characteristics during the entire process of the charging process, is proposed. The new design is capable of significantly improving the energy efficiency stiffness against the load variation, misalignment, increasing the flexibility to optimize the system efficiency, reducing the voltage stress, and increasing the power delivery to load compared to the conventional topology. The experimental design shows that the overall trend of efficiency of the proposed design is higher than the conventional design as the load decreases and the new system has approximately 10% higher efficiency when the battery equivalent load resistance reaches 222 Ω.

Index Terms—Constant voltage, energy efficiency, load variation, misalignment, three-coil wireless power transfer (WPT), voltage stress.

I. INTRODUCTION

WIRELESS charging has been widely recognized due to huge advantages of safety, convenience, environmentally friendly, and high reliability [1]–[7]. Such promising technology has been used in various applications such as smartphones, devices in biomedical implant and electric vehicles (EVs) [8]–[10]. Over the past decade, majority of the studies regarding to wireless charging have been focused on inductive power transfer (IPT) in EVs [11]–[14]. The quality factor, coupling coefficient in coil designs, and compensation circuit are playing a critical role in the system efficiency [15]. It is desired to maximize the quality factor for achieving higher efficiency.

Compensation methods are another approach to improve the overall system efficiency. By regulating the frequency and designing the compensation tank, it is possible to realize a zero-phase angle (ZPA) across the inverter of the WPT system to eliminate or minimize the reactive power, which will decrease the inverter losses, reduce the voltage and current stress, and contribute the system to operate in the soft-switching mode during the entire process of charging. This eventually leads the system to have higher efficiency [16], [17].

Generally, there are two main stages to charge lithium ion batteries, which are considered as one of the most suitable batteries for EV. In the initial stage, the battery voltage rapidly increases while the charger charges the battery in the constant output current (CC) mode until the voltage across the battery reaches its maximum charge. In the second stage, the CC charging process will be replaced with the constant output voltage (CV) mode and eventually, when the current is becoming relatively small, the charging process will stop, as illustrated in Fig. 1.

In order to design a CC/CV charger for EVs, researchers have investigated the characteristics of load-independent output voltage and current of series-series (S–S), parallel-series (P–S), parallel-parallel (P–P), and series-parallel (S–P) topologies at an optimal resonant frequency [18]. Among the all mentioned topologies, only S–S and S–P are capable of realizing both CC and CV. However, in the CV mode, S–S system and CC mode, S–P topology loses their ZPA characteristics, which leads the input impedances of these topologies to be either capacitive or inductive and resulting in reduced efficiency. In [19], a dual topology WPT has been proposed to achieve CC and CV with ZPA during the entire charging process. Later on, in [20], it is shown that the double-sided LCC topology has more advantages...
than SS design in terms of misalignment, voltage stress, achieving zero voltage switching, and flexibility to optimize the system efficiency. On the other hand, SS has higher maximum efficiency when the mutual inductance is set to be large. Moreover, in [17], the proposed two-coil double-sided LCC design achieved CC and CV while having purely resistive input impedance during the entire charging process by operating the system at two different frequencies. Additionally, it is simpler to design, and it requires lesser number of switches in comparison to hybrid topology, which indicates that the design is suitable for charging a battery for EV.

Other approaches have adopted the analysis on the effects of intermediate coils to further increase the transmission distance (Td), power delivery to the load, and the efficiency of a WPT topology. It has been shown in [21] that over the distance of 12 cm, the efficiency and power delivery of three- and four-coil system are significantly higher in comparison to conventional two-coil designs. In [22] and [23], the study suggested that in order to achieve higher efficiency than the two-coil system, the additional intermediate coil can be placed in the same axis as the transmitter coil, which indicates that the system does not require any additional space to implement while having higher efficiency than two-coil design. Additionally, the performance efficiency of a three-coil system becomes even more significant for a larger value of source resistance and when Td increases [24]. Nevertheless, the efficiency and transmitting distance are not the only important factors. The misalignment and characteristics of achieving CC/CV with ZPA are equally important. It has been shown in [22] that the three-coil system can perform better in the case of misalignment. The attempt to achieve high-efficiency three-coil design in [23] resulted in implementation of a high-power wireless charger with CV characteristics. However, this system cannot maintain the soft switching over the entire process of charging, and the idea of having CC characteristics is also missing. In [25], a three-coil wireless charger, which can achieve both CC/CV and is capable of operating in a soft switching mode, is implemented and tested. Achieving CV in [25] has been done by using series-series-series (S–S–S) compensation, which has better performance than S–S compensation in two-coil design [22]. However, the system efficiency dramatically decreases as the load power decreases during this stage.

Generally, the second stage of battery charging is the CV mode as mentioned earlier. Therefore, improving misalignment and efficiency performance during this stage can be beneficial. In this article, in order to improve the CV mode and increase the light-load efficiency, a novel series-series–LCLCC (S–S–LCLCC) three-coil WPT topology is proposed and is shown in Fig. 3(a). In addition, detailed analysis, calculation, simplification, and comparison between conventional S–S–S and new S–S–LCLCC three-coil WPT are presented. The LCLCC compensation contributes the system to maintain the load independent at a specified resonant frequency while realizing ZPA similarly to conventional design. However, with the help of additional two capacitors, the new system becomes more flexible to optimize and shifts the system maximum efficiency by shifting the optimum value of load resistance of the system to the operation area of CV. The conventional design maximum efficiency in the CV mode [25] is placed in the CC stage and the system could not achieve its maximum efficiency while operating at the CV mode. Moreover, the proposed new system contributes the system to have lesser voltage stress, better misalignment performance, improved system light-load efficiency, and increased power delivery to load (PDL) in comparison to conventional S–S–S three-coil design. The detailed analysis to achieve ZPA and comparative analysis of energy efficiency stiffness against load variation are also discussed.

This article consists of six sections. A theoretical analysis of conventional S–S–S and new S–S–LCLCC topologies to achieve load independent output voltage characteristics is presented in Section II. The Section III shows derivation and simplification of efficiency and input impedance equations for both systems. This section also presents the theoretical and simulation comparison in terms of calculation of optimum value of the equivalent load resistance of the battery. Section IV shows the energy stability of the system efficiency in the light-load operation by calculating and analyzing the energy efficiency stiffness for both designs. The design procedure of additional components together with voltage stress and PDL analysis is discussed in Section V. Section VI discusses the misalignment performance of both designs in details. The prototype of both designs is implemented and tested in Section VII in order to demonstrate and to compare the validity of the theoretical analysis. Finally, Section VIII concludes this article.

II. THEORETICAL ANALYSIS OF CV MODE OF S–S–S AND S–S–LCLCC WPT COMPENSATION

A. Analysis of S–S–S Compensation of Three-Coil WPT Systems for Achieving CV With ZPA

The S–S–S compensation circuit is presented in Fig. 2(a). The primary side of the circuit is connected to a full-bridge inverter to convert dc power to high-frequency ac square wave. The battery equivalent load resistance $R_L$ is connected to a full-bridge rectifier on the receiver side of the circuit. By applying the fundamental harmonic approximation (FHA) method, all of the high-order harmonics will be ignored for simplicity. Moreover, every switch operates at 50% duty cycle to maximize the output voltage and $\omega$ represents the operating angular frequency of the inverter. The ac equivalent circuit of S–S–S compensation

![Fig. 1. Lithium ion battery charging characteristics.](image-url)
Based on Fig. 2(b), by applying the Kirchhoff Voltage Law (KVL), the matrix equation of this system can be written as

\[
\begin{bmatrix}
V_1 \\
0
\end{bmatrix} =
\begin{bmatrix}
X_1 + R_1 & j\omega M_{12} & j\omega M_{13} \\
\omega M_{12} & X_2 + R_2 & -j\omega M_{23} \\
\omega M_{13} & -j\omega M_{23} & X_3 + R_3 + R_L
\end{bmatrix}
\begin{bmatrix}
I_{1s} \\
I_{2s} \\
I_{O_s}
\end{bmatrix}.
\]

(4)

In order to show the basic characteristics of S–S–S compensation, based on the experimental setup in Table III, which is from the same three-coil system in [25], the effect of mutual inductance between the source and receiver coil is neglected due to its large distance and its small value of \(M_{13}\), which is very close to zero. In addition, the magnitude of \(M_{13}\) is approximately ten times smaller than other mutual inductances. Recent studies have shown that \(M_{13}\) is capable of bringing the imaginary part into (4) and shifts the phase of the output voltage to above the resonant frequency and decreases the maximum efficiency of the WPT system [26]. In addition, it is also possible to eliminate the imaginary effect of this phenomenon even when the primary and receiver coils are close to each other by using a reactance compensation method [27]. However, the adopting reactance compensation method requires to design capacitors at a specific load resistance, which prevents the designer to design the load independent output voltage with ZPA characteristics during the entire process of charging. Another method has been proposed in [26] to achieve higher efficiency than the conventional design by adopting the compensatory reactance method as well. Nonetheless, this design is also dependent on load resistance. Therefore, in this article, the same coil in [25] is implemented for better comparison analysis and the paper suggested in order to obtain the load independent characteristics, \(M_{13}\) needs to be zero. Moreover, the parasitic resistances are also assumed to be zero and the system is operating at the resonant frequency. Nevertheless, in the following sections, the influences of parasitic resistances are analyzed since they are considered essential parameters for calculating the power efficiency. Therefore, after neglecting \(M_{13}\) and the internal resistances, the matrix equation of this system becomes

\[
\begin{bmatrix}
V_1 \\
0
\end{bmatrix} =
\begin{bmatrix}
0 & j\omega M_{12} & 0 \\
\omega M_{12} & 0 & -j\omega M_{23} \\
0 & -j\omega M_{23} & R_L
\end{bmatrix}
\begin{bmatrix}
I_{1s} \\
I_{2s} \\
I_{O_s}
\end{bmatrix}.
\]

(5)

By solving the matrix in the abovementioned equation, the voltage gain and input current can be derived as [25]

\[
V_{0s} = \frac{M_{23}^2}{M_{12}^2} V_1
\]

\[
I_{1s} = \frac{V_1 M_{23}^2}{R_L M_{12}^2}.
\]

(6)

(7)

The constant output voltage, which is independent of the load resistance with ZPA, can be achieved from the abovementioned equation. However, in this design, the output voltage is only dependent on the mutual inductances, frequency, and input voltage, which makes the design limited to only the mentioned parameters. In addition, it has been shown in [25] that as \(R_L\)
increases in small coil design with small mutual inductances that are mostly used in electric bicycles and small EV vehicles, the system efficiency tends to increase and then dramatically decreases.

B. Design and Analysis of S–S–LCLCC Compensation of Three-Coil WPT Systems for Achieving CV With ZPA

The CV mode is obtained in conventional S–S–S three-coil design, as shown in the previous analyses. In this design, the series compensation, which is connected to the receiver coil, is now replaced by LCLCC design. The S–S–LCLCC compensation has similar characteristics with double-sided LCC design in the two-coil WPT system. The advantages of double LCC over S–S in two-coil design are the power efficiency stability improvement, reducing reactive power and accomplishing load independent output voltage and current output at ZPA, improving misalignment and reducing voltage stress. Therefore, in this section, the S–S–LCLCC system for three-coil design is introduced in Fig. 3 and is analyzed to achieve the load independent CV and further improvement of power efficiency stability, misalignment, and reducing voltage stress in comparison with conventional three-coil design.

The system equations in Fig. 3(b) can be expressed as

\[
\begin{align*}
V_2 &= (X_1 + R_1) I_{1n} + (ZM_{12}) I_{2n} + (ZM_{13}) I_{3n} \\
0 &= (ZM_{12}) I_{1n} + (X_2 + R_2) I_{2n} - (ZM_{23}) I_{3n} \\
0 &= (ZM_{13}) I_{1n} - (ZM_{23}) I_{2n} + (ZL_3 + ZC_3 + ZC_{1p} + R_{3n}) \\
I_{3n} &= - (ZC_{3p}) I_{4n} \\
0 &= - (ZC_{1p}) I_{3n} + (ZC_{1p} + ZL_{1p} + ZC_{3p} + R_{P1}) I_{4n} \\
0 &= - (ZC_{3p}) I_{4n} + (ZL_{3p} + ZC_{3p} + R_{P3} + R_L) I_{0n}.
\end{align*}
\]

For simplicity, similarly, the internal resistances of coils, additional inductors, and capacitors are neglected. The design of additional inductors and capacitor are as follows:

\[
\begin{align*}
ZL_{3p} + ZC_{3p} &= 0 \\
ZC_{1p} + ZL_{1p} + ZC_{3p} &= 0 \\
ZL_3 + ZC_C + ZC_{1p} &= 0.
\end{align*}
\]

By substituting the abovementioned equation into (8), more simplified equations can be transferred to a simpler matrix as follows:

\[
\begin{bmatrix}
V_2 \\
0 \\
0 \\
0
\end{bmatrix} =
\begin{bmatrix}
0 & ZM_{12} & 0 & 0 \\
ZM_{12} & 0 & -ZM_{23} & 0 \\
0 & -ZM_{23} & 0 & -ZC_{1p} \\
0 & 0 & -ZC_{1p} & 0
\end{bmatrix}
\begin{bmatrix}
I_{1n} \\
I_{2n} \\
I_{3n} \\
I_{4n}
\end{bmatrix}
+
\begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix},
\]

Solving the abovementioned matrix, the current relationship and output voltage can be derived as

\[
\begin{align*}
I_{1n} &= \frac{V_o}{L_2} \left[ \frac{ZM_{12}}{ZM_{12}} \right]^{2} \left( \frac{ZC_{1p}}{ZC_{1p}} \right)^{2} = \frac{V_o}{L_2} \left( \frac{M_{23}}{M_{12}} \right)^{2} \left( \frac{C_{1p}}{C_{3p}} \right)^{2} \\
I_{2n} &= \frac{V_o}{ZL_{12}} \\
I_{3n} &= \frac{V_o}{ZM_{23}ZM_{12}} \left( \frac{ZC_{1p}}{ZC_{1p}} \right)^{2} \\
I_{4n} &= \frac{V_o}{L_2} \left[ \frac{ZM_{12}}{ZM_{12}} \right] \left( \frac{ZC_{1p}}{ZC_{1p}} \right) \\
I_{0n} &= \frac{V_o}{L_2} \left[ \frac{ZM_{12}}{ZM_{12}} \right] \left( \frac{ZC_{1p}}{ZC_{1p}} \right) \left( \frac{C_{1p}}{C_{3p}} \right)
\end{align*}
\]

It is found that the input current is purely resistive. Therefore, achieving ZPA is possible. Moreover, load independent CV has been achieved. Unlike the conventional design, where the output voltage is only related to the frequency, the mutual inductances and input voltage, it is clear that the output voltage of LCLCC is also dependent on two additional capacitors $C_{1p}$ and $C_{3p}$.

Based on (6) and last row of (12), the condition when both the S–S–S and S–S–LCLCC systems have the same output voltage and delivering the same amount of output power can be obtained by

\[
\begin{align*}
V_{0n} &= V_{0s} \\
\frac{V_1}{V_2} &= \left( \frac{C_{1p}}{C_{3p}} \right).
\end{align*}
\]
In the following sections, further analyses and comparison are discussed to prove the superior performance of the proposed design.

### III. THEORETICAL EFFICIENCY ANALYSIS OF THREE-COIL WPT

As mentioned earlier, it is not possible to simply neglect the value of internal resistances in calculating the efficiency of the system. Therefore, the following equations are achieved by solving the last two rows of matrix in (4) for S–S–S compensation as

\[
\begin{align*}
I_{0S} & \quad \sqrt{Z_{M12}Z_{M23}} \\
I_{cS} & \quad \frac{Z_{M12}Z_{M23}}{Z_{M23} - R_1(R_3 + R_L)} \\
I_{cC} & \quad \frac{Z_{M23} - R_1(R_3 + R_L)}{Z_{M12}(R_3 + R_L)}.
\end{align*}
\]

By substituting (14) into the first row of matrix in (4), the output current in terms of input voltage can obtained as

\[
I_{0S} = \frac{Z_{M12}Z_{M23}}{R_1Z_{M23} + (R_3 + R_L)(Z_{M23} - R_1R_2)} V_1.
\]

Eventually from (14) and (15), the input impedance and power efficiency of the S–S–S three-coil system can be calculated as [22]

\[
\begin{align*}
\text{Zin}(\omega_0) & = \frac{V_1}{I_{1S}} = \frac{R_1Z_{M23} + (R_3 + R_L)(Z_{M23} - R_1R_2)}{Z_{M23}^2 - R_2(R_3 + R_L)} \\
\eta_{1S} & = \frac{P_{os}}{P_{1S}} = \frac{I_{0S}^2 R_L}{I_{1S} I_{1S}} = \frac{R_L}{qR_L^2 + wR_L + i^2}.
\end{align*}
\]

For better analysis of efficiency, \(q\), \(w\), and \(e\) can be simplified further by assuming

\[
\begin{align*}
Z_{M23} - R_2R_3 & \approx Z_{M23} \\
Z_{M23}^2 - R_1R_2 & \approx Z_{M23}^2 \\
Z_{M23} - R_1R_3 & \approx Z_{M23}^2 \\
R_3 + R_L & \approx R_L.
\end{align*}
\]

This assumption is valid according to [22]. However, small error appears, which is caused by the simplification. Nevertheless, the performance of the simplified curve does not change. Table I describes the actual and simplified values of \(q\), \(w\), and \(e\) for the conventional three-coil system. Based on the simplified model, the input impedance of this system can be further simplified as

\[
\text{Zin}_{3S} = \frac{R_1Z_{M23}^2 + (R_3 + R_L)Z_{M23}^2}{Z_{M23}^2 - R_2R_L}.
\]

Similar approach for calculating and simplifying LCLCC design have been used in this section in order to better differentiate the advantages of this topology in comparison to conventional design. The following equations are achieved by solving the last four rows of (8) and neglecting \(M_{13}\):

\[
\begin{align*}
I_{1n} & = R_2L + R_PZ_{M2} \\
I_{2n} & = -Z_{C3}Z_{P3}(R_1 + R_P)Z_{M2} \\
I_{3n} & = -Z_{C3}Z_{P3}(R_1 + R_P)(R_1 - Z_{C3}Z_{P3}) \\
I_{4n} & = \frac{Z_{C3}Z_{P3}(R_3 + R_2 - Z_{M23})}{Z_{C3}Z_{P3}Z_{M12}} - \frac{(R_L - R_P)(R_P(R_3 + R_2 - Z_{M23}) - Z_{C3}R_2)}{Z_{C3}Z_{P3}Z_{M12}}.
\end{align*}
\]

By substituting (21) into the first row of (8), the power efficiency of the system can be calculated as

\[
\eta_{3S} = R_L \left(\frac{Z_{C3}Z_{P3}Z_{M2}Z_{M12}}{AB}\right)^2.
\]

where \(A\), \(B\), and the input impedance are listed in Table II. Analyzing of (22) is very complex; thus, to make the analysis and comparison simpler, similar simplification technique used in (17) is applied in (22). Therefore, the simplified efficiency expression of S–S–LCLCC design is

\[
\eta_{L} = \frac{P_{os}}{P_{1S}} = \frac{I_{0S}^2 R_L}{I_{1S} I_{1S}} = \frac{R_L}{q_1R_L^2 + w_1R_L + e_1}
\]

where \(q_1\), \(w_1\), and \(e_1\) are expressed in Table II. For the verification of the abovementioned simplification, the curve and characteristic of the power efficiency of the conventional three-coil design and S–S–LCLCC three-coil system are determined by MATLAB using the equations in Tables I, II, (16), (19), and (22). Both tables consist of the complete and simplified equations at resonant frequency to make the analysis and design less complex. The parameters of both designs are listed in Table III. Fig. 4 shows the simulation results of the complete and simplified methods. The results are having approximately 3% error but the
simplified method has very similar trend, characteristics, and shape as the original model. Therefore, it is acceptable to use the simplified equations for analysis of the conventional and LCLCC three-coil designs.

In order to have better understanding at which load resistance the maximum efficiency appears, it is vital to calculate the optimum value of the output load using the partial derivative of the efficiency with respect to the load resistance. For simplicity, the simplified model is used as follows:

$$\frac{\partial \eta}{\partial R_L} = 0.$$ (24)

Solving the abovementioned equation, the optimal value of $R_L$ can be derived for both of the conventional and new designs as follows:

$$R_{L_{opt}} = \sqrt{\frac{c}{q}} \frac{M_{23}}{M_{12}} \sqrt{-\frac{1}{R_2}(ZM^2_{12}R_{3n} + ZM^2_{23}R_1)}$$ (25)

$$R_{L_{opt}}^{3n} = \frac{C_{1P}M_{23}}{C_{3P}M_{12}} \sqrt{rac{(ZC^2_{3P}ZM^2_{23}R_1 + ZM^2_{12}ZC^2_{23}R_{3n} + ZC^2_{1P}R_{P3})}{-R_{P1}ZM^2_{23} + R_{2P}ZC^2_{1P}}}.$$ (26)

Based on the recent charger designs of the WPT battery, the lithium ion battery charging process is divided into two stages. The first stage is happening when the equivalent load resistance of the battery is approximately between 10 and 30 $\Omega$, and in the second stage, the load resistance eventually increases from 30 to 250 $\Omega$ in order to accomplish CC and CV with

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**TABLE II**

<table>
<thead>
<tr>
<th>Complete and Simplified Equations of S–S–LCLCC Three-Coil Topology at Resonant Frequency and Neglecting $M_{13}$</th>
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</thead>
<tbody>
<tr>
<td><strong>Complete Expressions</strong></td>
</tr>
<tr>
<td>$A$ $\left(\frac{ZC^2_{1P}R_{P1}ZM^2_{23}R_1 + ZM^2_{12}ZC^2_{23}R_{3n} + ZC^2_{1P}R_{P3}}{-R_{P1}ZM^2_{23} + R_{2P}ZC^2_{1P}}\right)$</td>
</tr>
<tr>
<td>$B$ $\frac{ZC^2_{1P}R_{P1}ZM^2_{23}R_1 + ZM^2_{12}ZC^2_{23}R_{3n} + ZC^2_{1P}R_{P3}}{-R_{P1}ZM^2_{23} + R_{2P}ZC^2_{1P}}$</td>
</tr>
<tr>
<td>$Z_{in}$ $\frac{R_1 + R_{P1}ZC^2_{1P}R_{P1}ZM^2_{23}R_1 + ZM^2_{12}ZC^2_{23}R_{3n} + ZC^2_{1P}R_{P3}}{-R_{P1}ZM^2_{23} + R_{2P}ZC^2_{1P}}$</td>
</tr>
</tbody>
</table>

**Simplified Expressions**

$A$ $\frac{ZC^2_{1P}R_{P1}ZM^2_{23}R_1 + ZM^2_{12}ZC^2_{23}R_{3n} + ZC^2_{1P}R_{P3}}{-R_{P1}ZM^2_{23} + R_{2P}ZC^2_{1P}}$

$B$ $\frac{ZC^2_{1P}R_{P1}ZM^2_{23}R_1 + ZM^2_{12}ZC^2_{23}R_{3n} + ZC^2_{1P}R_{P3}}{-R_{P1}ZM^2_{23} + R_{2P}ZC^2_{1P}}$

$Z_{in}$ $\frac{R_1 + R_{P1}ZC^2_{1P}R_{P1}ZM^2_{23}R_1 + ZM^2_{12}ZC^2_{23}R_{3n} + ZC^2_{1P}R_{P3}}{-R_{P1}ZM^2_{23} + R_{2P}ZC^2_{1P}}$

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**TABLE III**

<table>
<thead>
<tr>
<th>Impedances and Efficiency of Each Block of the Receiver Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
</tr>
<tr>
<td>$Z_a$</td>
</tr>
<tr>
<td>$Z_b$</td>
</tr>
<tr>
<td>$Z_c$</td>
</tr>
<tr>
<td>$Z_d$</td>
</tr>
<tr>
<td>$Z_e$</td>
</tr>
</tbody>
</table>

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**Fig. 4.** (a) Simulated power efficiency of S–S–S and S–S–LCLCC by using complete and simplified equations. (b) Simulated input impedances of S–S–S and S–S–LCLCC topology by using complete and simplified equations.
ZPA, respectively, [16], [17], [25]. Analyzing (25) yields that the optimum load resistance value of the S–S–S system is proportional to the ratio of $M_2/M_1$. Additionally, since the main purpose of the three-coil system is to have higher efficiency than conventional two-coil design, the study suggested that the relay coil is placed near to the transmitter coil [22]. Optimum load resistance contributes to determine at which load resistance that the maximum efficiency will occur. Accordingly, the $R_{LCLCC}^{opt}$ for S–S–S compensation in small coil designs, following the work in [25], will appear at much smaller value than 24 $\Omega$ in the CV mode. It is clear that the maximum efficiency of the CV of this system will be placed in the CC mode in [25]. Therefore, the system cannot operate at its maximum efficiency. However, in the new S–S–LCLCC design, by using additional capacitors in (26), the optimal $R_{LCLCC}^{opt}$ of S–S–LCLCC can be shifted to much higher load resistance without changing the coils design. This is very significant property since the CV mode is operating at light load (higher equivalent load resistance of the battery) and it is able to achieve its highest efficiency.

This indicates that in order to shift the value of the optimum load resistance for conventional three-coil design to larger value, the relay coil internal resistance should be as small as possible and the mutual inductances should be increased. Increasing the mutual inductance also leads to increasing the size of the coils for S–S–S compensation. In general, S–S–LCLCC can perform well for both larger and smaller mutual inductance designs while the conventional S–S–S topology performs well only when the coil designs are set to be large, where the system can achieve its maximum efficiency at the CV stage.

IV. ANALYSIS OF THE ENERGY EFFICIENCY STIFFNESS

This section illustrates the comparison of load variation and its effect on the energy efficiency stiffness to witness the stability of the energy efficiency of the conventional and proposed design more clearly as the equivalent battery load resistance changes. In order to analyze the energy stability of both systems, the second-order differentiation of the efficiency with respect to load resistance at $\partial^2 \eta / \partial RL^2 = 0$ is [22]

$$\frac{\partial^2 \eta}{\partial RL^2} \bigg|_{RL_{opt}} = -2 \frac{q}{e} \frac{\sqrt{q} e}{(2 \sqrt{q} e + w)^2} .$$

(27)

$$\frac{\partial^2 \eta}{\partial RL^2} \bigg|_{RL_{opt}} = -2 \frac{q_1}{e_1} \frac{\sqrt{q_1} e_1}{(2 \sqrt{q_1} e_1 + w_1)^2} .$$

(28)

By dividing (27) with (28), the relationship of the energy stiffness can be expressed as

$$\frac{\partial^2 \eta_{S-S}}{\partial RL^2} \bigg|_{RL_{opt}} = \frac{\partial^2 \eta_{S-S-LCLCC}}{\partial RL^2} \bigg|_{RL_{opt}} = q_1 e_1 \frac{4 \sqrt{q_1} e_1 + 4 w_1}{4 \sqrt{q} e + 4 w} .$$

(29)

In addition, to have better comparison and more accurate results, both systems are designed to have the same output voltage when delivering the same amount of power. As discussed earlier, in (13), the output voltage of $LCLCC$ topology is proportional to the ratio of $C_{1p}/C_{2p}$. In the experimental design, $C_{1p}$ is set to be approximately 1.42 times larger than $C_{2p}$. Therefore, the input voltage of $LCLCC$ topology is 0.7 times the input voltage of the S–S–S system in (12). Thus, $C_{3p} = 0.7 C_{1p}$ and by substituting this equation into Tables I and II, the relationship between the parameters of power efficiency between S–S–S and S–S–LCLCC can be obtained as

$$\begin{array}{l}
q > q_1 \\
\end{array}$$

(30)

Moreover, the effect of additional capacitors in $e_1/e$ is much larger than $q_1/q$, yielding

$$\frac{\partial^2 \eta_{S-S}}{\partial RL^2} \bigg|_{RL_{opt}} > \frac{\partial^2 \eta_{S-S-LCLCC}}{\partial RL^2} \bigg|_{RL_{opt}} .$$

(31)

The abovementioned equation shows that as the load resistance in the S–S–S three-coil system increases, the energy efficiency stiffness decreases much faster compared to the S–S–LCLCC system as a result of having much larger slope. It has been shown in Fig. 5, which is the graph of the first-order differentiation of efficiency with respect to load resistance, for the small value of load resistance, both systems have a very sharp slope. However, in the S–S–S system, after the system reaches its maximum efficiency at around 7 $\Omega$, the system efficiency tends to decrease rapidly. On the other hand, S–S–LCLCC has much smaller change after 14.2 $\Omega$, where its maximum efficiency appears. Therefore, the efficiency of S–S–LCLCC is much more stable than conventional system, especially at higher load resistance. As mentioned earlier, CV stage operation area is designed for the larger value of the load resistance in the recent studies. Therefore, S–S–LCLCC has significant advantage of power efficiency stability compared to S–S–S topology.

V. DESIGN OF ADDITIONAL COMPONENTS OF THE S–S–LCLCC SYSTEM

It is vital to illustrate the effect of the additional capacitors for having better comparison analysis between conventional and
the new design. Therefore, the ratio between $C_{3P}/C_{1P}$ is defined as $a = C_{3P} / C_{1P}$. By substituting (a) into (23) and Simplified Expressions in Table II, the less complex efficiency equation of the new system can be express as

$$\eta_{3n} = \left( \frac{a^2(\omega^2 M_{23}^2 C_{1P}^2 R_{P1} + R_2)}{\omega^2 M_{23}^2} \right) + 1 + \frac{1}{R_L} \left( \frac{M_{23}^2 R_1}{a^2 M_{12}^2 + R_{3n} + R_{P3}} \right)^{-1}. \quad (33)$$

The abovementioned equation states that the smaller value of (a) can significantly improve the efficiency for the larger values of $R_L$ in the S–S–LCLCC three-coil system.

Fig. 6 shows when $a = 0.3$, the performance efficiency of S–S–LCLCCC becomes much better than conventional design for larger values of $R_L$, which supporting (33). However, according to (12) and (13) as $C_{3P}/C_{1P}$ ratio becomes smaller the voltage gain of the new system increases. Since one of the main objectives of this article is to compare the performance analysis of new S–S–LCLCCC design with S–S–S compensation in [25], the value of $a$ is chosen to be 0.7. This is done so that the input voltage of the new design becomes closer value to the input voltage in [25] and by applying the (13), both designs can deliver the same output power and voltage for the fair comparison. Another approach in this article is choosing the additional inductors to be much smaller than relay and receiver coils since in the recent double-sided LCC design in the two-coil system, additional inductors are usually chosen to be much smaller than the main coils [17], [20]. After selecting the value of additional inductor $L_{3P}$ and a, it is now possible to calculate all other additional components for the new S–S–LCLCCC design by using (10).

A. Voltage Stress

In the recent three–coil S–S–S design, the study in [24] suggested that relay coil ($L_2$) should be much larger than transmitter and receiver coils. Moreover, the primary coil should be placed near or on the same plane as the relay coil in order the system to have higher efficiency than two-coil design [22]. However, this makes the current across the relay coil to be very large compare to other coils, and it also increases the voltage stress across the resonant relay capacitor $C_2$ [24], [25]. Due to the mentioned reasons, the S–S–S system requires a large quantity of the capacitor in order to form the suitable $C_2$. This can be seen clearly in the experimental and measurement setup of [25] and the main losses is due to relay coil and its capacitor. By solving the first row of matrix (5), the relay current ($I_{2s}$) in conventional S–S–S design can be calculated as [25]

$$I_{2s} = \frac{V_1}{ZM_{12}^2}. \quad (34)$$

By using (12), (13), and (34), the relationship between relay current of the new and the conventional design when both systems delivering the same amount of output power can be express as

$$I_{2n} = a(I_{2s}). \quad (35)$$

Since $a = 0.7$, it is obvious that S–S–LCLCCC topology has much smaller current across the relay coil, which indicates that the voltage stress across $C_2$ in the new system is much smaller than conventional design. Since the main losses in the three-coil system happens in the relay coil, reducing current across this coil can be beneficial, which can be done by using smaller a. This also supports (33) and Fig. 6, which prove a better performance of the new design.

B. Analysis of Quality Factor and PDL

Power transfer efficiency (PTE) and PDL of the conventional three-coil system have been discussed in [21] and [28] and they are often considered as important factors in the analysis of new compensation design. In order to derive the PDL of both conventional and new design, it is important to investigate the effect of the reflected impedances.

From Fig. 2, by ignoring the $M_{13}$, the reflected impedance of the receiver coil on the transmitter coil and the reflected impedance of the transmitter coil on the primary coil can be defined as ($Z_{rt\_3s} = (\omega M_{23})^2/(X_3+R_3+R_L)$) and ($Z_{tp\_3s} = (\omega M_{12})^2/(X_2+Z_{rt\_3s}+R_2)$), respectively. Therefore, by using $Z_{tp\_3s}$ and $Z_{tp\_3s}$, the equivalent input impedance and PTE of S-S-S compensation can be derive as [29]

$$Z_{in} = Z_{tp\_3s} + X_1 + R_1 \quad (36)$$

$$\eta_{2s} = \text{PTE}_{3s} = \left( \frac{Z_{tp\_3s}}{Z_{tp\_3s} + R_1} \right) \left( \frac{Z_{rt\_3s}}{Z_{rt\_3s} + R_2} \right) \left( \frac{R_L}{R_L + R_3} \right). \quad (37)$$

Note that when the S–S–S system operates at the resonant frequency ($X_1 = X_2 = X_3 = 0$), (36) and (37) will be the same as (16) and (17), respectively. By substituting ($Q_1 = \omega L_1 / R_1$), ($Q_2 = \omega L_2 / R_2$), ($Q_3 = \omega L_3 / (R_3 + R_L)$), ($M_{12} = K_{12} \sqrt{L_1 L_2}$), and ($M_{23} = K_{23} \sqrt{L_2 L_3}$) into (36) and (37), PTE and PDL of conventional design in terms of the coupling coefficient and
quality factor can be express as [21]

$$\eta_{3s} = \left( \frac{K_{12}^2 Q_1 Q_2}{K_{12}^2 Q_1 Q_2 + K_{23}^2 Q_2 Q_3 + 1} \right) \frac{R_L}{R_L + R_3} \right)$$

(38)

$$\text{PDL}_{3s} = P_{\text{in}} \eta_{3s} = \frac{V_1^2}{R_1} \left( \frac{K_{12}^2 Q_1 Q_2}{K_{12}^2 Q_1 Q_2 + K_{23}^2 Q_2 Q_3 + 1} \right)^2 \times \frac{R_L}{R_L + R_3}.$$  \hspace{1cm} (39)

As can be seen clearly in the abovementioned equations, expression \( (k_{12}^2 Q_1 Q_2) \) and \( (k_{23}^2 Q_2 Q_3) \) are playing a critical role in both PTE and PDL performance of conventional design. Increasing or lowering down the value of \( (k_{12}^2 Q_1 Q_2) \) and \( (k_{23}^2 Q_2 Q_3) \) can be done by varying \( K_{12}, K_{23}, Q_1, Q_2, \) and \( Q_3 \). Quality factor of each coils are dependent on operating angular frequency, ac resistance and inductance of each coil. However, since, the design of the main coils is out of the scope of this article, \( L_1, L_2, L_3 \) and \( R_3 \) have been adopted from the study in [25], and to make the comparison as fair as possible the operating angular frequency is also set to be the same as the mentioned study. This indicates that the value of \( Q_1, Q_2, \) and \( Q_3 \) will be constant. Therefore, the only parameters, which can vary the quality factor are \( K_{12} \) and \( K_{23} \). Note that analysis of PDL and PTE is not simple since decreasing \( (k_{23}^2 Q_2 Q_3) \) causes \( (Z_{r1}' Z_{r2}' R_2 + R_3) \) decreases and it increases the value of \( (Z_{t1}' Z_{t2}' R_1 + R_1) \).

Both of the following expressions have direct effect on PTE and PDL. Therefore, to better illustrate the effect of \( (k_{23}^2 Q_2 Q_3) \), PTE and PDL have been plotted by using (38) and (39) with respect to \( K_{12} \) and \( K_{23} \).

The maximum value of \( K_{12} \) in Fig. 7 is set to be in the condition where the primary coil is placed on the same axis as the transmitter coil, and it reduces when the distance between the mentioned two coils increases. Moreover, further analysis of Fig. 7 indicates that when \( K_{12} \geq K_{23} \), the conventional \( S-S-S \) system is capable of achieving high efficiency. On the other hand, in order to maximize PDL, \( K_{23} \) must be much larger than \( K_{12} \), which is in contrast from maximizing PTE for the \( S-S-S \) system.

Verifying efficiency formula for the conventional system with using a reflected equivalent impedance method and comparing the PDL and PTF equations in terms of quality factor and coupling coefficient have been discussed in the previous analysis. Similar comparison analysis for the new system has been adopted in this section.

The equivalent circuit of the \( S-S-LCLCC \) design is shown in Fig. 8. In order to have detailed analysis, the efficiency and the equivalent impedance of each block diagram are derived and extracted as listed in Table III.

From Fig. 8, the reflected equivalent impedance of the receiver coil on the transmitter coil and the reflected impedance of the transmitter side on the primary side for the new \( S-S-LCLCC \) system can be expressed as \( (Z_{rt} = (\omega M_{23})^2 / Z_c) \) and \( (Z_{tp} = (\omega M_{12})^2 / (X_2 + X_{rt} + R_2)) \), respectively. Consequently, the efficiency of the receiver coil and PTE of the \( S-S-LCLCC \) system are expressed as

$$\eta_{\text{receiver}} = \eta_{Z_a} \cdot \eta_{Z_b} \cdot \eta_{Z_c} \cdot \eta_{Z_d} \cdot \eta_{Z_r}$$  \hspace{1cm} (40)

$$\text{PTE}_n = \left( \frac{Z_{tp}}{Z_{tp} + R_1} \right) \left( \frac{Z_{rt}}{Z_{rt} + R_2} \right) \eta_{\text{receiver}}.$$  \hspace{1cm} (41)

Similar to the previous analysis, by substituting \( Q_1, Q_2, K_{12}, K_{23}, \) and \( (Q_n = \omega L_2 / \text{Re}(Z_r)) \) into (40) and (41), PTE and PDL of the \( LCLCC \) system in terms of coupling coefficient and quality...
factor can be expressed as

$$\eta_n = \eta_{\text{receiver}} \cdot \left( \frac{(K_{12}^2 Q_1 Q_2)(K_{23}^2 Q_2 Q_n)}{(K_{12}^2 Q_1 Q_2 + K_{23}^2 Q_2 Q_n + 1)(K_{23}^2 Q_2 Q_n + 1)} \right)$$

(42)

$$\text{PDL}_n = \frac{V_1^2}{R_i} \cdot \left( \frac{(K_{12}^2 Q_1 Q_2)(K_{23}^2 Q_2 Q_n)}{(K_{12}^2 Q_1 Q_2 + K_{23}^2 Q_2 Q_n + 1)^2} \right)$$

(43)

Fig. 9 shows alike to the conventional design, PDL of the S–S–LCLCC system is maximized when $K_{23}$ is larger than $K_{12}$. Therefore, the similar issue still exists in the new system. However, when $K_{12} \geq K_{23}$ (where both system can achieve high PTE), the S–S–LCLCC system in comparison to conventional design can deliver more power to the load. To better illustrate this effect, Fig. 10 is plotted. Since PTF with respect to $R_i$ has been discussed in the previous sections, in this analysis, $R_L$ is now constant and the input voltage is set to be the same for both systems. Moreover, $K_{12}$ is maximized ($L_1$ is placed on the same plane as $L_2$) and only $K_{23}$ changes in the range of $K_{23} < K_{12}$ so that both systems can achieve high efficiency. According to [22], at this condition, the three-coil system is capable of having higher efficiency than two-coil design. Fig. 10 clearly proves that PDL of S–S–LCLCC is much higher than the conventional S–S–S system, especially when $K_{23}$ is larger and the value of $\alpha$ is smaller. In addition, the efficiency of the S–S–LCLCC compensation topology is higher although lower than that of the conventional topology at higher values of $K_{23}$. Very similar characteristics have been reported in [20], which indicates that the S–S–LCLCC topology is similar to double-sided LCC design in the two-coil system. It can perform much better when the mutual inductances between the transmitter and receiver coil is minimized. Note that in [25], $K_{23}$ is only 0.095 and to make the value of $K_{23}$ to be very large so that S–S–S can have higher efficiency than the proposed S–S–LCLCC system, it is required to use magnetic core materials such as ferrite or to increase the size and the number of turns of the receiver coil. In consequences of that, $K_{13}$ also becomes larger and this makes the value of $M_{12}$ not to be close to zero anymore, which eventually leads the system to lose its ZPA characteristics. Nevertheless, by assuming $K_{23} > 0.2$ while minimizing $M_{12}$ is possible even in that condition, the PDL of S–S–LCLCC will be much higher than the conventional topology. Therefore, it is clear that using S–S–LCLCC instead of the S–S–S system for achieving CV while adopting the coil design in [25] is more beneficial.

PTE in terms of coupling coefficient has been discussed in detail when all the quality factors remain the same as the study in [25]; however, in order to have fair analysis, it is important to investigate the effect of PTE as the coil quality factors changes. Varying the coil quality factors can be done by changing the value of inductance and the internal resistance of each coil. However, the presence of $R_L$ in $Q_3$ equation makes the denominator of the receiver coil quality factor to be large. Due to the mentioned reason, $R_1$ has a negligible effect in $Q_3$ performance; therefore, the only other two parameters, which are capable of incasing the $Q_3$, are $\omega$ and $L_3$. Despite, increasing operating angular frequency is considered one of the main factors and it may contribute to the value of $Q_3$ increases,
but it is not considered a good option because in WPT application the operating frequency is limited around 85 kHz only. Another approach is to increase the size and number of turns in the receiver coil. However, this is also hard to achieve when the Td remains the same as before. Because as $L_3$ becomes larger, $M_{13}$ increases as well. As a consequence of that, the value of $M_{13}$ will not be close to zero anymore and eventually, both systems lose their ZPA characteristics. Moreover, it is in contrast with first the assumption in [25], where $M_{13}$ must be close to Zero. This indicates that if $T_d$ does not increase in [25], all the options which lead the value of $Q_3$ increases will make the first assumption in [25] to be not valid anymore. Therefore, from (38) and (42), the PTE of both topologies have been investigated with respect to the quality factor under two different conditions. Where, in the first condition, $Q_3$ and $T_3$ will remain the same as in [25] and only $Q_1$ and $Q_2$ changes, as it is presented in Fig. 11. In the second condition, $Q_1$ and $Q_2$ vary again, but this time $L_3$ increases to be as large as $L_2$ so that the value of $Q_1$ becomes much larger to provide the wider $Q$ factor analysis, as shown in Fig. 12. In addition, since $L_3$ becomes much larger, ANSYS software has been used to calculate the appropriate $T_d$ so that the value of $M_{13}$ still remains close to zero. Therefore, in this analysis, the value of $K_{23}$ is getting smaller due to increasing the $T_d$. All the other parameters remain the same as [25].

The results in Fig. 11 clearly shows that if the quality factor of the relay coil gets very large for a small value of $R_L$, the conventional system can perform better; however, for the large value of $R_L$ regardless of the value of $Q_1$ and $Q_2$, the PTE of the S–S–LCLCC system is still much better than the conventional topology. On the other hand, analysis of Fig. 12 indicates that the new S–S–LCLCC has higher efficiency than the conventional system when $Q_3$ and $T_d$ get larger for both large and even small value of $R_L$. This is because $K_{23}$ to the power of two in (38) and (42) has a stronger influence on PTE of both topologies in comparison to $Q_3$. Moreover, as it is presented in Fig. 10, the new system performs much better when the coupling coefficient between the relay and receiver coils is minimized and these results agree well with the results obtained and presented in Fig. 12. Therefore, even in the case of using a similar coil design as the study in [22], the proposed new system is capable of significantly improving PTE in comparison to the conventional topology.

VI. ANALYSIS OF THE MISALIGNMENT OF THREE-COIL WPT

The effect of misalignment has been shown in many recent studies for two-, three-, and four-coil systems theoretically and experimentally. Misalignment is mainly depending on the coil and compensation design, and it is inversely proportional to the power efficiency. Moreover, it has been shown in [20] and [22] that the three-coil system and double-sided LCC in the two-coil system perform better than conventional S–S two-coil topology in terms of misalignment. Since misalignment is considered an important factor for WPT applications, the effect of it on the new S–S–LCLCC design is analyzed and compared in this section.

It has been shown in the conventional three-coil system that as the mutual inductance decreases, the output and input power also tend to decrease, which makes the control part of WPT way simpler [22]. Consequently, no additional converter for controlling the output current is required. In a typical three-coil system, the transmitter coil and relay coil are placed at the same plane. Therefore, only $M_{23}$ will change as misalignment occurs. In order to have better comparison, both input current of S–S–S and S–S–LCLCC designs are calculated as

$$\begin{align*}
I_{1S} &= \left| \frac{V_1}{Z_{in}} \right| = \left| \frac{V_1(ZM_{23}\frac{Z_{C3}+Z_{C2}}{Z_{C1}+Z_{C2}+Z_{C3}}+3R_3Z_{M23})}{R_3(ZM_{23}\frac{1}{Z_{C3}+Z_{C2}+Z_{C1}+Z_{C2}+Z_{C3}}+3R_3Z_{M23})} \right| \\
I_{2S} &= \left| \frac{V_1}{Z_{in}} \right| = \left| \frac{V_1(ZM_{23}\frac{Z_{C3}+Z_{C2}}{Z_{C1}+Z_{C2}+Z_{C3}}+3R_3Z_{M23})}{R_3(ZM_{23}\frac{1}{Z_{C3}+Z_{C2}+Z_{C1}+Z_{C2}+Z_{C3}}+3R_3Z_{M23})} \right|
\end{align*}$$

(44)

In this section, similar characteristics happen in LCLCC design. This can be seen from (45) that when $ZM_{23}$ decreases, the nominator becomes smaller and eventually becomes a constant when the maximum misalignment occurs. In addition, as the input current decreases, lesser power will be delivered to the receiver coil, which is the same as the conventional system in (44), where the output current of S–S–LCLCC also decreases in the case of misalignment. Moreover, this phenomenon can be proven from another approach. Based on Table II and (19), as $ZM_{23}$ reduces, the equivalent input impedance will increase, as shown in Fig. 13. Therefore, the input current of both systems decreases. Fig. 13 also indicates that the input current of the
S–S–LCLCC system decreases more rapidly while delivering the same amount of output power as conventional design. Note that the input voltage of S–S–S is 1.42 times larger than S–S–LCC design in (13). For this reason, the input current in S–S–S topology is smaller when both systems deliver the same output power. However, as $M_{23}$ decreases, the input current of the S–S–LCLCC system tends to be closer as S–S–S input current. Since the voltage across the S–S–LCLCC is 0.7 times of the conventional design, S–S–LCLCC requires less input power for delivering the same amount of output power. In other words, the S–S–LCLCC design has less energy losses than S–S–S design when $ZM_{23}$ decreases. This characteristic can be witnessed clearly in Fig. 14(a) and (b), especially for larger values of equivalent load resistance of the battery, which is the main operation area of the CV mode.

VII. EXPERIMENTAL SETUP AND DISCUSSION

To verify the theoretical and simulation results, an experimental setup of the three-coil WPT system is implemented and tested, as shown in Fig. 15. Conduction losses are the main losses of the coils. Therefore, to eliminate it and make it as small as possible, Litz wire with 900 strands and diameter of 4 mm is used due to its low ac resistance magnitude. Further details of the number of turns and the size of coil can be found in [25] since the coil design and structure is adopted from the mentioned study to make a better comparison. However, there is a 5 mm gap between the primary and relay coil to make $M_{13}$ affect smaller. All of the measured values at 200 kHz are provided in Table IV.

In order to compare S–S–S and S–S–LCLCC compensation, $C_{1P}$, $C_{3P}$, and $V_2$ are designed using (13) to maintain the same power level for both topologies. Due to high carrying current potential and low equivalent series resistance (ESR), film capacitors are used. Moreover, air core ac inductors have been adopted in this design since they have good performance compared to magnetic core inductance in the case of operating at high voltage condition [30] and availability in the laboratory. However, it is possible to use magnetic core inductance to minimize the coupling between the coils and to reduce the leakage to metal materials. Consequently, two additional air core ac inductors with a diameter of 5 cm are adopted in this topology. The capacitors, self-inductances, ac resistances, and mutual inductances of the coils are measured using GwInstek-6300 LCR meter, which has the capability to provide accurate measurements.

### Table IV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$L_1$</td>
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<tr>
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<tr>
<td>$R_{L6}$</td>
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Fig. 16. Experimental measurements of waveforms on CV mode at (a) $R_L = 24\,\Omega$ and (b) $R_L = 48\,\Omega$.

measurement up to 300 kHz. From the dc power supply, the power is transferred to the H-bridge inverter with the operating frequency of 200 kHz, the resonator, rectifier, and eventually to the dc load, which acts like a battery charger. In the proposed system, four MOSFETS (C2M0080120D) with 80 mΩ Rds on and fast recovery diodes (DSEI2X101-06A) are used for the inverter and rectifier, respectively. The waveforms are taken by using Tek DPO3014 oscilloscope. For the measurement of power efficiency, a YOKOGAWA WT500 power analyzer is used. The experimental waveforms of the voltage, input current, and output voltage in the constant voltage mode when the load is at 24 and 48 Ω are shown in Fig. 16.

The S−S−LCLCC current is almost in phase with the input voltage and the system can nearly achieve ZPA while operating in the CV mode. The same characteristics can be seen in the conventional design [25], which is supporting the theoretical analysis. A slight change of the output voltage, as can be seen in Fig. 17, is caused by not purely resonance of the system and the slight effect of $M_{13}$, which has been assumed to be zero in the theoretical analysis. Since the increment of the output voltage is less than 2% at about 100 V, the proposed design is acceptable and it can be further improved by designing a new coil with better resonance capacitor compensation and smaller $M_{13}$.

The measurement and simulation of the efficiency of both conventional and new systems at different loads are shown in Fig. 18. In S−S−LCLCC, the additional capacitor helps the system maximum efficiency to occur at 14.2 Ω while the conventional maximum efficiency appears at 7 Ω. It is also possible to further shift the maximum efficiency of S−S−LCLCC to closer to 24 Ω without redesigning the coils structure and by only using a smaller $C_{3p}/C_{1p}$ ratio. However, since one of the main objectives of this article is to use smaller $L_{1p}$, $L_{3p}$ and due to the mentioned analysis in Section V, the ratio of $C_{3p}/C_{1p}$ has been chosen to be 0.7. Nevertheless, the S−S−LCLCC for loads larger than 24 Ω, which is the starting point of the operation of the CV mode in [25], has higher efficiency. Also, when the load reaches 222 Ω, the efficiency of the new system becomes more significant, and it has approximately 10% higher efficiency than the conventional design.

The experimental measurement at different mutual inductions due to the misalignment affect at 24 Ω is shown in Fig. 19, which further proves the superior performance of the newly proposed design at larger equivalent load resistance of the battery when misalignment occurs. The maximum efficiency of the new design reaches to 91.2% at 14.2 Ω and 89.6% at 24 Ω while delivering 420 W power. The measurement efficiency is slightly lower than the calculated values but the overall performance of the system has very similar trend as the theoretical and simulation results. For better comparison, both conventional and new designs are delivering the same amount of output power at approximately 100 V output voltage.

Fig. 17. CV waveform when sudden $RL$ changes from 48 to 24 Ω and changes back to 48 Ω.

Fig. 18. Measurements and simulation of both conventional and new design with respect to load.
Fig. 19. Measurements and simulation of both conventional and new design when the $M_{23}$ changing due to misalignment.

VIII. CONCLUSION

In this article, three-coil S–S–S and S–S–LCLCC WPT topologies have been successfully compared and analyzed theoretically and experimentally. Moreover, simplified models of S–S–LCLCC has been successfully proposed to demonstrate the advantages of this new design. The benefits of S–S–LCLCC compared to the conventional design system are significant improvement of power efficiency at larger values of equivalent load resistance of the battery, reducing energy losses in the case of misalignment, reducing the voltage stress across the relay coil and shifting the optimum value of load resistance to the operating range of CV. Thus, the proposed system can achieve its maximum efficiency. Moreover, additional capacitors contribute to control of the voltage gain of the system together with the mutual inductances, frequency. Although the S–S–S topology has higher maximum efficiency due to having less components, in the case of using a two-switch technique, which contributes the system to operate both in the CC and CV modes with ZPA, the system cannot achieve its maximum efficiency at the CV mode for small coil designs as in [25]. However, the S–S–LCLCC design is capable of shifting its maximum efficiency to the desired equivalent battery load resistance. To validate the superior performance of S–S–LCLCC WPT of three-coil designs, calculation, simulation, simplification, and experimental results have been successfully conducted for the CV mode for only small-coil design for both conventional S–S–S and new S–S–LCLCC design. However, in future works, S–S–LCLCC design combined with S–S–LCC topology, which is capable to realize CV and CC, respectively, will be implemented by using the hybrid two-switch technique to investigate the performance of S–S–LCLCC and its effect on the S–S–LCC in the CC mode.

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REFERENCES


