Cost-effective Compensation Design for Output Customization and Efficiency Optimization in Series/Series-Parallel Inductive Power Transfer Converter

Zhicong Huang, Member, IEEE, Zhijian Fang, Member, IEEE, Chi-Seng Lam, Senior Member, IEEE, Pui-In Mak, Fellow, IEEE, and Rui P. Martins, Fellow, IEEE

Abstract—Load-independent output with zero-phase-angle (ZPA) input is desirable in wireless inductive power transfer (IPT) converters for effective power delivery, but it usually greatly relies on the parameters of the loosely coupled transformer, normally fixed or constrained by space. Thus, load outputs cannot be readily achieved unless a new transformer is redesigned. In this paper, we elaborate the rather complex relationships among compensation parameters, customizable load-independent-voltage (LIV) outputs with ZPA input, power efficiency and overall compensation capacitance cost of the series/series-parallel (S/SP) IPT converter. We present a cost-effective compensation design to free the customization of LIV outputs from a parameter-constrained loosely coupled transformer, with optimization between efficiency enhancement and overall compensation capacitance cost. We conducted the proposed design supported by experimental results in S/SP IPT converters with an identical loosely coupled transformer and various sets of compensation capacitors. Compared with a conventional design, the proposed design provides custom ranges of LIV outputs in both a weak and a relatively strong coupling condition, with over 5.9% and 5% efficiency improvement, respectively. The overall compensation capacitance can also be reduced by up to 37% and 21.5%, respectively.

Index Terms—Efficiency optimization, inductive power transfer, output customization, series/series-parallel compensation, zero phase angle.

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Development in modern power electronics has enabled wireless inductive power transfer (IPT). Benefiting from eliminating physical contact, IPT converters can provide user-friendly and maintenance-free operations of wireless power supply in many applications, such as consumer electronics, electric vehicles, bio-implants, underwater vehicles and so on [1]–[6]. Voltage buses are widely needed in these power electronics applications, and thus IPT converters with load-independent voltage output are widely studied [7]–[11].

Effective power transfer is a critical demand in most IPT application scenarios, where compensation using reactive components for a loosely coupled transformer [12] is usually designed to achieve load-independent output and zero-phase-angle (ZPA) input, thus eliminating the output control [13], [14] and minimizing the voltage-ampere (VA) rating [15], [16] respectively. Moreover, multiple selectable outputs are desired to meet specific requirements in some application scenarios, where the parameters of the loosely coupled transformer are usually fixed or constrained by space, leading to difficulty in output design [17]. As an example, bus voltage on vehicle side may differ in level depending on specifications of the batteries or supercapacitors, but standard SAE J2954™ has suggested a coil and winding geometry specification for wireless electric vehicle charging [18], posing challenges to achieving customizable outputs without redesigning the transformer. Therefore, as a general technical problem in regardless of application scenarios, it is worthwhile optimizing the compensation design for customizable outputs against the constraints of transformer parameters.

From the perspective of minimizing loss and cost, basic compensation topologies are usually adopted, because they only contains minimum number of external capacitive components, i.e., two capacitors, one at each side of the transformer windings, of which the losses are usually negligible. External inductive components, i.e., inductors, with significant copper and core losses are not needed [19]. Four basic compensation topologies are normally identified according to the primary/secondary compensation type, namely series/series (SS), series/parallel (SP), parallel/series, and parallel/parallel. In [15], design for ZPA input to minimize VA rating is studied covering four basic compensation topologies, but output controllability cannot be achieved. In [13], [14], characteristics of load-independent-voltage (LIV) or load-independent-current (LIC) output as well as maximum efficiency are comparatively...
studied for the SS and the SP IPT converter. Nevertheless, output to input transfer functions of the SS and the SP IPT converter greatly rely on transformer parameters, e.g., the LIC transfer function of the SS IPT converter and the LIV transfer function of the SP IPT converter are typically $\frac{v_o}{v_i} \approx \frac{1}{\sqrt{L_{L1,P} S_{P}}} \frac{1}{\sqrt{L_{S} S_{S}}} L_{L1,P} \frac{1}{\sqrt{L_{L2,S} S_{S}}} \frac{1}{\sqrt{L_{S} S_{S}}}$ respectively [13], [14], which are dependent on the primary self inductance $L_{P}$, the secondary self inductance $L_{S}$ and the coupling coefficient $k$ of the transformer. Once the transformer is designed, the converter transfer functions are almost fixed unless a new transformer is used. Therefore, basic compensation may not provide the required current or voltage output in a particular application scenario.

To overcome the constraints imposed by the transformer parameters, higher-order compensation topologies with more reactive components, usually including inductors, can be used to achieve more design freedom for output transfer functions without altering the design of the transformer, such as LC/LC compensation [20] and LCC/LCC compensation [21]. By changing the compensation parameters, customizable LIV or/and LIC transfer functions with ZPA input can be achieved for a wide range of load. Comprehensively, a family of higher-order compensation circuits for IPT converters are proposed in [17]. With these proposed compensation circuits, LIV and LIC outputs can be easily customized by adjusting the compensation parameters, while ZPA input can always be guaranteed to ensure minimum VA rating. However, the efficiency usually suffers from using inductors with significant copper and core losses, which is a major concern of these higher-order compensated IPT converters [19]. Moreover, relationship between compensation parameter design and efficiency performance has rarely been studied.

As a trade-off between basic compensation and higher-order compensation, series/series-parallel (S/SP) compensation without lossy inductors is readily derived for the loosely coupled transformer to easily implement LIV output and ZPA input [7]–[9], with an intuitive design concept illustrated in Fig. 1. The primary leakage inductance $L_{L,P}$, secondary leakage inductance $L_{L,S}$ and mutual inductance $L_{M}$ of the T-circuit model of the loosely coupled transformer are fully compensated by the external capacitors $C_P$, $C_S$ and $C_{S,P}$, respectively, such that the S/SP IPT converter can behave as an ideal transformer with a turn ratio of $\frac{1}{k}$ to achieve LIV output, as well as ZPA input due to pure resistive input impedance. This intuitive design concept fixes the LIV transfer function at an $k$-independent point featuring misalignment-tolerance, but it does not meet the desired requirement of output customization. Moreover, efficiency performance and overall compensation capacitance cost related to compensation parameters are even more worth being further studied to facilitate the design of the S/SP IPT converter.

In this paper, a cost-effective compensation design is elaborated to achieve customizable LIV outputs with ZPA input and optimized power efficiency for the S/SP IPT converter. This paper is organized as follows. In Section II, compensation parameters are indicated by a single design factor $\mu$ and analyzed to generalize conditions allowing any designs for S/SP IPT converters with an identical loosely coupled transformer to achieve customizable LIV transfer functions with ZPA input. Section III gives criteria for theoretical optimum efficiency, with which the relationship of efficiency improvement and design of $\mu$ is revealed, and a critical minimum design value of $\mu$ is derived to ensure load matching for optimized efficiency. Section IV optimizes the custom range of LIV outputs between the efficiency performance and the overall compensation capacitance cost, and puts forward a cost-effective design. The proposed design is experimentally verified in Section V. Finally, Section VI concludes this paper.

II. ANALYSIS OF LIV OUTPUT WITH ZPA INPUT

Fig. 2(a) shows the schematics of an S/SP IPT converter consisting of an input voltage source $V_i$, a full bridge inverter, a resonant tank with S/SP compensation and a rectifier with LC filter. To generalize the analysis of the input and output of the S/SP IPT converter, Fig. 2(b) shows a commonly-used coupled-circuit model based on fundamental approximation [13], [14], where the loosely coupled transformer has primary self inductance $L_{P}$, secondary self inductance $L_{S}$, and mutual inductance $M$. The coupling coefficient is given by $k = \frac{M}{\sqrt{L_{P} L_{S}}}$, $C_{P}$ and $C_{S}$ are the series compensation capacitors in each side, while $C_{S,P}$ is the parallel compensation capacitor in the secondary side. Coil losses in the primary and the secondary are represented by resistors $R_{P}$ and $R_{S}$, $v_{i}$, $v_{o}$ and $R_{L}$ are the equivalent input voltage, output voltage and load.
is highlighted as defined as voltage transfer function 
resistance parameter design and given by respectively. Their ratio is defined as an indicator of compensating for calculations. Similar to that of the SS IPT converter, Fig. 3 shows the customizable LIV transfer function and input phase angle by assuming 

\[ \omega M = \omega L v \] (2), \[ \omega H = \omega S \sqrt{\frac{\mu^2 + 1 + \Delta}{2(1-k^2)}} \] (5), and respectively, where \( \Delta = \sqrt{\left(\mu^2-1\right)^2 + 4k^2\mu^2} \). It should be pointed out that, the S/SP IPT converter can also achieve another LIV transfer function \( E_{\text{LIV}} \) at operating frequency \( \omega_L = \omega_S \sqrt{\frac{\mu^2+1-\Delta}{2(1-k^2)}} \). Similar to the case of S/S IPT converter, operating at \( \omega_H \) is usually preferred because of better efficiency performance and thus chosen for subsequent analyses in this paper [7], [8]. From (7), \( E_{\text{LIV}} \) is customizable with different designs of \( k \) by altering \( C_P, C_S \) and \( C_{SP} \). Fig. 3 shows the customizable \( E_{\text{LIV}} \) versus \( \mu \) under different values of \( k \) with the simulation parameters given in Table. I, which will be used for the rest of this paper unless specified. It can also be observed that, \( E_{\text{LIV}} \) is \( k \)-dependent for most designs of \( k \) except the unity design, i.e. \( k = 1 \).

**B. ZPA Input**

ZPA input is important for the IPT converters to minimize VA rating and improve power transfer capability. The input impedance of the S/SP IPT converter shown in Fig. 2(b) is given by

\[ Z_{in} = jX_P + \frac{\omega^2 M^2}{jX_S + Z_{eq}}. \] (9)

To achieve ZPA input, \( Z_{in} \) should be purely resistive, i.e.,

\[ \Re(Z_{in}) = Z_{in}, \] (10)

for arbitrary load conditions. Substituting (8) into (9) and solving (10), design of \( C_{SP} \) for ZPA input can be derived as

\[ C_{SP} = \frac{C_S}{\omega_S^2 - 1}, \] (11)

which is determined by the design of \( \mu \).

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**TABLE I**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbols</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self inductance</td>
<td>( L_P, L_S )</td>
<td>118 ( \mu H ), 172 ( \mu H )</td>
</tr>
<tr>
<td>Coupling coefficient</td>
<td>( k )</td>
<td>0.15–0.25</td>
</tr>
<tr>
<td>Coils resistance</td>
<td>( R_P, R_S )</td>
<td>0.5 ( \Omega ), 0.72 ( \Omega )</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>( \frac{\omega}{2\pi} )</td>
<td>50 kHz</td>
</tr>
</tbody>
</table>

Although \( R_P \) and \( R_S \) are non-zero for a practical IPT converter, it is valid to simplify subsequent analyses of voltage transfer function and input phase angle by assuming \( R_P = 0 \) and \( R_S = 0 \) [13], [14], [17]. From (5), the condition to achieve LIV transfer function is obviously given by

\[ \mu^2 M^2 - X_P X_S = 0. \] (6)

By solving (6), the LIV transfer function \( E_{\text{LIV}} \) and the corresponding operating frequency \( \omega_H \) are given by

\[ E_{\text{LIV}} = \frac{L_S}{L_P} \frac{k(\mu^2 + 1 + \Delta)}{(2k^2 - 1)\mu^2 + 1 + \Delta}, \] (7)

\[ \omega_H = \omega_S \sqrt{\frac{\mu^2 + 1 + \Delta}{2(1-k^2)}}, \] (8)
However, since the operating frequency $\omega$ invariable S/SP IPT converter towards stationary IPT applications with $\omega_P = \omega_S$. This concern facilitates our implementation of the LIV output and ZPA input in dynamic applications [10], [11], a lot of control effort for the S/SP IPT converter to maintain by control for $k$-variation [22], [23]. Therefore, in practice, it takes $k$-dependent phase-lock loop control is usually needed for frequency tracking against the variation of $k$ [10], [11]. Moreover, $C_S, P$ is $k$-dependent from (11), and additional adaptive control for $C_S, P$ is inevitably required to maintain ZPA input against $k$-variation [22], [23]. Therefore, in practice, it takes a lot of control effort for the S/SP IPT converter to maintain LIV output and ZPA input in dynamic applications [10], [11], [22], [23]. This concern facilitates our implementation of the S/SP IPT converter towards stationary IPT applications with invariable $k$.

### C. Revisiting of Conventional Design for Misalignment-tolerance
Specifically, for the S/SP IPT converters based on conventional design concept [7]–[9], $\mu$ is actually set at unity by properly choosing $C_P$ and $C_S$ to satisfy $\omega_P = \omega_S$. Such that, the LIV transfer function has no relationship with $k$ as given by

$$E_{LIV}|_{\mu=1} = \sqrt{\frac{L_S}{L_P}}, \text{ at } \omega_H|_{\mu=1} = \frac{\omega_S}{\sqrt{1-k}}, \text{ when } \mu = \frac{\omega_P}{\omega_S} = 1. \quad (13)$$

Since the LIV transfer function $E_{LIV}|_{\mu=1}$ in (12) is $k$-independent, it is commonly believed that the S/SP IPT converter with such design is misalignment-tolerant and suitable for dynamic IPT applications with $k$-variation [7]–[9]. However, since the operating frequency $\omega_H|_{\mu=1}$ in (13) is $k$-dependent, phase-lock loop control is usually needed for frequency tracking against the variation of $k$ [10], [11]. Moreover, $C_S, P$ is $k$-dependent from (11), and additional adaptive control for $C_S, P$ is inevitably required to maintain ZPA input against $k$-variation [22], [23]. Therefore, in practice, it takes a lot of control effort for the S/SP IPT converter to maintain LIV output and ZPA input in dynamic applications [10], [11], [22], [23]. This concern facilitates our implementation of the S/SP IPT converter towards stationary IPT applications with invariable $k$.

### III. Efficiency Optimization

#### A. Criteria for Maximizing Power Efficiency
Fig. 4(a) gives an equivalent circuit of Fig. 2(b) for analysis of the power efficiency. $Z_r$ is the reflected impedance from the secondary to the primary given by $Z_r = \frac{\omega^2 P}{X_r + X_r}$. As usual, by separately considering the efficiency $\eta$ in the primary and the efficiency $\eta_S$ in the secondary, overall power efficiency $\eta$ of the S/SP IPT converter can be calculated as

$$\eta = \eta_P \eta_S = \frac{\Re(Z_r)}{R_P + \Re(Z_r)} \cdot \frac{\Re(Z_{eq})}{R_S + \Re(Z_{eq})}. \quad (14)$$

where $\Re$ represents calculation of real component.

To analyze the power efficiency in a more intuitive way, the equivalent impedance $Z_{eq}$ is transformed into a form of series connection as shown in Fig. 4(b) and rewritten as

$$Z_{eq} = jX_{S,P} + jX_{L,eq} + R_{L,eq}. \quad (15)$$

Fig. 5. Calculated results in coupling condition of $k = 0.25$: (a) equivalent resistance $R_{L,eq}$ versus load resistance $R_L$ under different designs of $\mu$, (b) quality factor $Q$ versus $\mu$, (c) power efficiency $\eta$ versus load resistance $R_L$ under different designs of $\mu$. 

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where

\[ R_{L,eq} = \frac{R_L}{Q^2 + 1}, \]  
\[ \Delta X_{L,eq} = \frac{R_{L,eq}}{Q}, \]  
\[ Q = \frac{\omega C_{S,P} R_L}{1}, \]

are defined as equivalent load resistance, equivalent load reactance and load quality factor, respectively. Since the S/SP IPT converter desirably achieves LIV output at \( \omega_H \), it can be observed that

\[ X_S + X_{S,P} = 0, \quad \text{at } \omega_H. \]  

With (14), (15) and (19), the power efficiency at \( \omega_H \) can be calculated and further simplified as

\[ \eta = \frac{1}{\frac{\Delta X_{L,eq}^2 + (R_{L,eq} + \omega_H M)^2}{\omega_H M^2} R_P + \frac{R_S}{R_{L,eq}} + 1}, \]

\[ \approx \frac{1}{\frac{\Delta X_{L,eq}^2 + R_{L,eq}}{\omega_H M^2} R_P + \frac{R_S}{R_{L,eq}} + 1}, \]

with the assumptions \( \omega_H^2 M^2 \gg 0 \) and \( R_{L,eq} \gg R_S \). The optimum values of \( R_{L,eq} \) and \( \Delta X_{L,eq} \) will be found to maximize \( \eta \). From (20), the efficiency can be maximized as

\[ \eta_{opt} \approx \frac{1}{\frac{\Delta X_{L,eq}^2}{\omega_H M^2} R_P + \frac{R_S}{R_{L,eq}} + 1}, \]

\[ R_{L,eq,opt} = \omega_H M \sqrt{\frac{R_S}{R_P}}, \]

\[ \Delta X_{L,eq,opt} = \frac{R_{L,eq}}{Q^2} \rightarrow 0, \]

where \( Q_P = \frac{\omega_H L_P}{R_P} \) and \( Q_S = \frac{\omega_H L_S}{R_S} \) are the quality factors of the primary and secondary winding coils, respectively. Similar to the case of the S/S IPT converter [24], equations (22) and (23) are the criteria of critical load impedance matching point for the S/SP IPT converter to achieve maximum efficiency when operating with LIV output and ZPA input.

**B. Achieving Optimum Equivalent Load Resistance**

From (16) and (18), there may exist a local maximum of \( R_{L,eq} \), which can be calculated by solving \( \frac{d R_{L,eq}}{d R_L} = 0 \) and given by

\[ R_{L,eq,max} = \frac{1}{2 \omega_H C_{S,P}}, \quad \text{at } R_L = \frac{1}{\omega_H C_{S,P}}. \]

Obviously, optimum equivalent load resistance \( R_{L,eq,opt} \) in (22) is achievable only if

\[ R_{L,eq,max} > R_{L,eq,opt}. \]

Therefore, with (22), (24) and (26), the design of \( \mu \) should therefore satisfy

\[ \mu > \mu_{eff} = \sqrt{\frac{1 - k^2}{1 - 2k}} \]

for efficiency optimization, where \( \mu_{eff} \) is defined as the minimum value of \( \mu \) for efficiency optimization.

Fig. 5(a) shows the equivalent load resistance \( R_{L,eq} \) versus the load resistance \( R_L \) under different designs of \( \mu \). \( \mu_{eff} \) can be calculated as 1.36. It can be observed that, when \( \mu \) is less than \( \mu_{eff} \), \( R_{L,eq} \) cannot reach \( R_{L,eq,opt} \) for efficiency optimization.

**C. Minimizing Equivalent Load Reactance**

Supposing the optimum equivalent resistance \( R_{L,eq,opt} \) in (22) is achievable with proper design of \( \mu \) satisfying (27), a large \( Q \) should be further achieved to minimize \( \Delta X_{L,eq} \) as (23). With (16), (18) and (23), the quality factor \( Q \) can be derived as

\[ Q = \frac{\mu^2 - 1 + k^2}{2k \mu^2} + \sqrt{\left(\frac{\mu^2 - 1 + k^2}{2k \mu^2}\right)^2 - 1} \]

and plotted in Fig. 5(b). It can be observed that \( Q \) becomes larger with the increase of \( \mu \), which means the reactance component \( \Delta X_{L,eq} \) in (23) can be further minimized for higher efficiency by designing a larger value of \( \mu \).

It can be concluded that, the S/SP IPT converter can achieve higher power efficiency by designing a larger value of \( \mu \). As an illustration, the operating frequency \( \omega_H \) is fixed to an identical value for fair comparison, and the curves of power efficiency \( \eta \) versus load resistance \( R_L \) are plotted in Fig. 5(c). Compared with conventional design of unity \( \mu \), the peak efficiency is progressively improved with the increase of \( \mu \).

**IV. DESIGN CONSIDERATIONS**

**A. Current Stresses on the Windings**

To achieve optimum efficiency, design of \( \mu \) should allow equivalent load resistance \( R_{L,eq} \) to satisfy (22) and minimize \( \Delta X_{L,eq} \) towards zero as (23). \( \Delta X_{L,eq} \) can be ignored due to high quality factor \( Q \) of the resonant circuit. Therefore, for different designs satisfying (27), i.e., \( \mu > \mu_{eff} \), the equivalent circuit models at maximum efficiency points are nearly identical, with optimum equivalent load resistance \( R_{L,eq,opt} \) and negligible equivalent load reactance \( \Delta X_{S,P} \) as shown in Fig. 4(b). It can be estimated that design of \( \mu \) for efficiency optimization will not affect the current stresses on the primary and secondary windings too much. Such that, LIV transfer functions can be customized by designing the compensation parameters without necessity to redesign the loosely coupled transformer. Moreover, the output power levels are almost identical under different designs of \( \mu \).

**B. Compensation Capacitance Cost**

It is well known that the cost of an IPT converter can be reduced by minimizing its VA rating and improving its power efficiency [15], [16]. The S/SP IPT converter can realize ZPA input and achieve efficiency optimization by designing the compensation parameters indicated by the single factor \( \mu \) discussed above. However, different designs of \( \mu \) may lead to variations of overall compensation capacitance cost, which is thus of interest to be optimized. In general,
the cost of compensation capacitor is affected by the specifications, including capacitance and voltage tolerance, but also affected by the manufacturing factors (e.g., volume) and commercial factors (e.g., order quantity, custom or unique specifications) [25]–[27], making it infeasible to choose unique specifications for each capacitor in practice. Given identical capability of energy storage, metalized polypropylene thin film capacitors with high nominal voltage and small capacitance have better cost performance compared with those with low nominal voltage and large capacitance [25]–[27]. In addition, commercially available capacitors for high-frequency resonant converters (including IPT converters) usually have sufficiently high voltage tolerance for the compensation capacitors of the IPT converter in this work [28]. Such that, the cost of the compensation capacitance can be approximately reflected by the overall compensation capacitance.

Similar to the comparison of power efficiency, the operating frequency \( \omega_H \) is fixed to an identical value under different designs of \( \mu \) by choosing the compensation capacitors \( C_P, C_S \) and \( C_{S,P} \). With (1), (2), (3), (8) and (11), the compensation parameters are approximated as

\[
C_P \approx \frac{1}{1 - k^2 \rho H^2 L_P}, \tag{29}
\]

\[
C_S \approx \frac{\mu^2}{1 - k^2 \rho H^2 L_S}, \quad \text{and} \quad \tag{30}
\]

\[
C_{S,P} \approx \frac{\mu^2}{\mu^2 + k^2 - \frac{1}{\rho H^2 L_S}} \tag{31}
\]

with the assumption \((\mu^2 - 1)^2 > 4k^2\mu^2\). Overall compensation capacitance can be calculated by

\[
C_{\text{total}} = C_P + C_S + C_{S,P}. \tag{32}
\]

Substituting (29) to (31) into (32) and solving \( \frac{dC_{\text{total}}}{d\mu} = 0 \), design of \( \mu \) for minimum capacitance is given by

\[
\mu_{\text{cost}} = \sqrt{2(1 - k^2)}. \tag{33}
\]

As an illustration, Fig. 6 shows the compensation capacitance calculated with parameters given in Table I versus \( \mu \). A design for minimum \( C_{\text{total}} \) exists at \( \mu_{\text{cost}} \).

C. Cost-effective Compensation Design

It has been studied in Section II that a wide-range customizable LIV outputs with ZPA input can be achieved by simply altering the compensation design indicator \( \mu \) of the S/SP IPT converter. It is also revealed in Section III that the maximum efficiency \( \eta_{\text{max}} \) can be progressively enhanced with the increase of \( \mu \), and specifically \( \mu > \mu_{\text{eff}} \) is required for a high efficiency. Moreover, a minimum value of overall compensation capacitance \( C_{\text{total}} \) exists at \( \mu_{\text{cost}} \), and \( C_{\text{total}} \) will increase as \( \mu \) becomes larger when \( \mu > \mu_{\text{cost}} \) as discussed in Section IV-C. Therefore, the trade off between improving power efficiency and minimizing overall compensation capacitance cost imposes constraints to the design range of \( \mu \) for customizable LIV outputs.

The overall compensation capacitance \( C_{\text{total}} \) can be normalized as

\[
\zeta = \frac{C_{\text{total}}}{C_{\text{total}}|_{\mu_{\text{cost}}}}, \tag{34}
\]

with the minimum value \( C_{\text{total}}|_{\mu_{\text{cost}}} \) being the per-unit value. Simulation curves in Fig. 7 show how maximum efficiency \( \eta_{\text{max}} \) and normalized overall compensation capacitance \( \zeta \) vary with \( \mu \). \( \eta_{\text{max}} \) increases with \( \mu \) at a reducing rate (saturates as \( \mu \) becomes large), and \( \zeta \) increases with \( \mu \) at an increasing rate when \( \mu > \mu_{\text{cost}} \). Hence, increasing \( \mu \) will offer diminishing return of \( \eta_{\text{max}} \) and lead to sharp increase of \( \zeta \). To achieve customizable LIV output with efficiency optimization, we may restrict \( \zeta \) to be no greater than that of conventional design, i.e., \( \zeta <= \zeta|_{\mu_{\text{cost}}} \) as a cost-effective design. A limiting value of \( \mu \) for \( \zeta \)-restriction can be given by

\[
\mu_{\text{limit}} = \sqrt{\lambda + \sqrt{\lambda^2 + k^2 + 1}}, \tag{35}
\]

where \( \lambda = \frac{1}{4}(\frac{1}{k} + 1 + k^2 + \frac{1}{k}) \). With (27) and (33), for typical conditions of coupling coefficient of wireless IPT applications, i.e., \( k < 0.25 \), \( \mu_{\text{cost}} \) is guaranteed to be larger than \( \mu_{\text{eff}} \). Therefore, a design range of \( \mu \) is proposed, given by

\[
\mu_{\text{cost}} < \mu < \mu_{\text{limit}}, \tag{36}
\]

to achieve cost-effective compensation design of the S/SP IPT converter for customizable LIV outputs with ZPA input and optimized efficiency, as shown in Fig. 7. The range of LIV
inverter. Both in phase, thus ZPA input can be achieved with different practical parameters are given in Table II. They can be calculated with (1)–(3), (8) and (11), while the design indicators, i.e.,

\[ \mu \]

where conditions of week coupling coefficient
\[ k \]

are used for compensation, under different compensation conditions of coupling coefficient \( k_{\text{min}} \) and relatively strong coupling coefficient \( k_{\text{max}} \) will be considered to evaluate the proposed design. Various sets of \( C_P \), \( C_S \) and \( C_{Z,P} \) are used for compensation, under different compensation design indicators, i.e., \( \mu = 1 \), \( \mu = 1.35 \), \( \mu = 2 \) and \( \mu = 2.5 \). They can be calculated with (1)–(3), (8) and (11), while the practical parameters are given in Table II.

A. Measured Waveforms and LIV Outputs

Fig. 9 and Fig. 10 show the measured waveforms of the S/SP IPT converters with different compensation designs (indicated by different values of \( \mu \)), at \( k_{\text{min}} = 0.17 \) and \( k_{\text{max}} = 0.254 \), respectively. The waveforms include the input voltage \( v_i \), input current (primary winding current) \( i_P \), secondary winding current \( i_S \) and DC output voltage \( V_O \). \( v_i \) and \( i_P \) are kept in phase, thus ZPA input can be achieved with different compensation designs of \( \mu \) to minimize VA rating for the inverter. Both \( i_P \) and \( i_S \) are kept nearly identical for \( \mu = 1.35 \), \( \mu = 2 \) and \( \mu = 2.5 \), which coincides with the analysis in output and the percentage efficiency improvement obtained with the design of \( \mu \) given in (36) should be verified as being satisfactory. Otherwise, a choice of larger \( \mu \) for wider range of LIV output and better efficiency performance is required, with higher overall compensation cost \( \zeta \) as compromise.

V. EXPERIMENTAL VERIFICATION

To verify the proposed cost-effective compensation design of the S/SP IPT converter, prototypes are built as shown in Fig. 8, with detailed parameters given in Table II. The S/SP converters share an identical loosely coupled transformer, where conditions of week coupling coefficient \( k_{\text{min}} \) and relatively strong coupling coefficient \( k_{\text{max}} \) will be considered to evaluate the proposed design. Various sets of \( C_P \), \( C_S \) and \( C_{Z,P} \) are used for compensation, under different compensation design indicators, i.e., \( \mu = 1 \), \( \mu = 1.35 \), \( \mu = 2 \) and \( \mu = 2.5 \). They can be calculated with (1)–(3), (8) and (11), while the practical parameters are given in Table II.

TABLE II Converter Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbols</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>( V_i )</td>
<td>35 V</td>
</tr>
<tr>
<td>Filter</td>
<td>( C_P, C_S, C_{Z,P} )</td>
<td>( 10.42 \text{nF}, 70.58 \text{nF}, 343 \text{nF} )</td>
</tr>
<tr>
<td>MOSFETs</td>
<td>( Q_1-Q_4 )</td>
<td>IPP60R165</td>
</tr>
<tr>
<td>Diodes</td>
<td>( D_1-D_4 )</td>
<td>MBR20200</td>
</tr>
<tr>
<td>Self inductance</td>
<td>( L_P, L_S )</td>
<td>17.47 ( \mu )H, 172.79 ( \mu )H</td>
</tr>
<tr>
<td>Coil resistance</td>
<td>( R_P, R_S )</td>
<td>0.454 ( \Omega ), 0.626 ( \Omega )</td>
</tr>
<tr>
<td>Coupling coefficient</td>
<td>( k_{\text{min}} )</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>( k_{\text{max}} )</td>
<td>0.254</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>( f )</td>
<td>50 ( kHz )</td>
</tr>
</tbody>
</table>

\( k_{\text{min}} \) and \( k_{\text{max}} \) are calculated from (8) and (11) with different compensation conditions of coupling coefficient \( k \). The curves in dark blue indicate the efficiency performance for conventional compensation design, i.e., \( \mu = 1 \), \( \mu = 1.35 \), \( \mu = 2 \) and \( \mu = 2.5 \). It also verifies that although the output voltage and the optimum load resistance vary a lot under different designs of \( \mu \), the output power levels at maximum efficiency points are nearly identical. Thus, it is fair to compare the maximum efficiency points in Section V-B. The output voltage \( V_O \) is customizable with direct readout of the magnitude shown in Fig. 9 and Fig. 10, and the measured DC LIV transfer function \( E_{\text{LIV,DC}} = V_O \) (marked with “□” for \( k_{\text{min}} \) and “○” for \( k_{\text{max}} \)) versus \( \mu \) are shown in Fig. 11. It should be noted that, there exists a scale factor between the DC voltage gain and AC voltage gain, i.e., \( E_{\text{LIV,DC}} = \frac{2}{\mu} E_{\text{LIV}} \). Since the exists practical converter losses, the measured DC voltage gain is slightly lower than the calculated results. However, the trend of \( E_{\text{LIV,DC}} \) with respect to the variation of \( \mu \) coincides with the simulated results shown in Fig. 3.

B. Measured Efficiency and Overall Compensation Capacitance Cost

The input DC power and output DC power are measured by a Yokogawa PX8000 Precision Power Scope. In Fig. 12, the curves plot measured efficiency \( \eta \) versus load resistance \( R \) in different conditions of coupling coefficient \( k \) and with different design values of \( \mu \). The curves in dark blue indicate the efficiency performance for conventional compensation design, i.e., \( \mu = 1 \). Obviously, the efficiency can be enhanced with our proposed compensation design, as indicated by the direct readout of maximum efficiency points of green, red and light blue curves, where the maximum efficiency is progressively improved with the increase of \( \mu \).

In Fig. 13, measured maximum efficiency points (marked with blue “□” for \( k_{\text{min}} \) and blue “○” for \( k_{\text{max}} \)) are plotted, which increase monotonically and saturate as \( \mu \) becomes large. Although the measured maximum efficiencies are slightly lower than the simulated results shown in Fig. 7 due to...
Fig. 10. Steady-state waveforms of the S/SP IPT converters at the measured normalized value\(\zeta\)

Fig. 11. Measured DC LIV transfer function \(E_{\text{LIV, DC}} = \frac{V_o}{I}\) versus compensation design indicator \(\mu\) in different conditions of coupling.

There are 37% and 21.5% reduction of the over compensation capacitance as well as 5.9% and 5% improvement of the efficiency at \(k_{\text{min}}\) and \(k_{\text{max}}\) respectively, compared with those with conventional design, i.e., \(\mu = 1\). To achieve cost-effective compensation design for customizable LIV outputs and optimized efficiency, we restrict \(\zeta\) to be no greater than \(\zeta|_{\mu=1}\). Design ranges of 1.35 < \(\mu < 2.4\) and 1.35 < \(\mu < 2\) are therefore given for \(k_{\text{min}}\) and \(k_{\text{max}}\) as shown in Fig. 13, where \(\eta_{\text{max}}\) will be further improved and \(\zeta\) will increase from its minimum but still locating in a satisfactory range. The custom ranges of LIV transfer function are shown in Fig. 11. It can also be observed in Fig. 13, beyond the proposed design ranges of \(\mu\), \(\eta_{\text{max}}\) becomes saturated while \(\zeta\) increases rapidly, thus the design will not be cost-effective anymore.

### Table III

<table>
<thead>
<tr>
<th>Compensation Topology</th>
<th>No Lossy Compensation Component</th>
<th>Free From Transformer Parameter Constraint</th>
<th>LIV Output Customization</th>
<th>ZPA</th>
<th>Efficiency Enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/SP in Our paper</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
</tr>
<tr>
<td>Conventional S/SP [7]</td>
<td>(\checkmark)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
</tr>
<tr>
<td>Basic S/SP [8]</td>
<td>(\checkmark)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
</tr>
<tr>
<td>Compensation</td>
<td>(\checkmark)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
<td>(\times)</td>
</tr>
<tr>
<td>LP/LP [20]</td>
<td>(\times)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\times)</td>
<td>(\times)</td>
</tr>
<tr>
<td>Higher-order</td>
<td>(\times)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\times)</td>
<td>(\times)</td>
</tr>
<tr>
<td>Compensation</td>
<td>(\times)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\times)</td>
<td>(\times)</td>
</tr>
<tr>
<td>Others [17]</td>
<td>(\times)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\times)</td>
<td>(\times)</td>
</tr>
</tbody>
</table>

Fig. 12. Measured efficiency \(\eta\) versus load resistance \(R\) under different conditions of coupling coefficient.

\[ V_p = 9V, V_p = 63.8V \]

\[ V_p = 93.4V, V_p = 102.7V \]

\[ k_{\text{min}} = 0.17 \]

\[ k_{\text{max}} = 0.254 \]
C. Comparison with the Literature

Table. III summarizes the comparison of the desirable features between our proposed design and those in the literature. All the desirable features can be achieved in our proposed design.

VI. CONCLUSION

In this paper, parameters of three compensation capacitors of a series/series-parallel (S/SP) inductive power transfer (IPT) converter are indicated by a single factor μ, which simplifies the analysis of the relationships among compensation parameters, customizable load-independent-voltage (LIV) outputs with zero-phase-angle (ZPA) input, power efficiency and overall compensation capacitance cost. Critical values of μ ensuring load impedance matching for optimized efficiency, achieving minimum overall compensation capacitance and limiting overall compensation capacitance for effective cost are respectively derived for guiding the design. A cost-effective compensation design achieving customizable LIV outputs with enhanced power efficiency and reduced overall compensation capacitance is elaborated. Experiment results validate the analysis and the proposed cost-effective compensation design in customizing the output and optimizing the efficiency.

REFERENCES


Fig. 13. Measured maximum efficiency $\eta_{\text{max}}$ and normalized overall capacitance $\zeta$ versus compensation design indicator $\mu$. 

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