Primary-Tuning Wireless Constant-Current Charger With Self-Sustained Constant-Voltage Limit Featuring Minimal Secondary Design

Zhicong Huang\textsuperscript{©}, Member, IEEE, Tian Qin, and Herbert Ho-Ching Iu\textsuperscript{©}, Senior Member, IEEE

Abstract—An inductive power transfer (IPT) converter can operate as a constant-current (CC) source for wireless battery charging. Since the output voltage of a CC power supply linearly increases with the load resistance, a constant-voltage (CV) threshold must be incorporated in the IPT converter, so as to protect the CC power supply from open-load condition and prevent the overvoltage from damaging the battery. This article proposes a primary-tuning IPT converter, which operates as a wireless CC charger with a self-sustained CV limit to feature minimal secondary design. The CC-CV behavior is achieved by only adopting and manipulating a switch-controlled capacitor (SCC) in the primary. Secondary-side control and wireless feedback communication are not necessary, and thus, the secondary is minimal and rugged. A voltage divider circuit helps with reducing the voltage stress of the SCC switches. Soft switching is permitted for all switches throughout the operating range. The operating principle and control scheme of the proposed system are explained. Experimental results are presented to demonstrate the CC–CV behavior of the proposed IPT charger.

Index Terms—Constant current (CC), constant voltage (CV), inductive power transfer (IPT), switch-controlled compensation, wireless charging.

I. INTRODUCTION

I

NDUCTIVE power transfer (IPT) is a rapidly developing technology to wirelessly deliver power in applications where getting rid of physical contact is desired, e.g., in a hostile environment with heavy dirt and moisture that are dangerous to plugging and unplugging [1], [2], [3]. With the elimination of physical contact, IPT has found viable prospects in wireless battery charging applications [4], [5], [6], [7], [8]. To charge a depleted battery fast, constant-current (CC) charging is commonly used [9]. Since the battery has a voltage threshold based on its chemistry, once the threshold is reached, further CC charging may damage the battery permanently. Therefore, a constant-voltage (CV) limit must be incorporated in the IPT converter that operates as a CC charger. However, the primary and the secondary of the IPT charger are physically separated, and additional efforts should be made to implement the required CC–CV charging profile, which usually complicates the design and control of the secondary. It is still challenging to implement an IPT charger featuring minimal secondary design.

Some approaches have been carried out to achieve the required CC–CV output in IPT converters. It is straightforward to use a multistage scheme where an additional dc/dc converter is cascaded to the IPT converter for output regulation [10], [11], [12], but the power losses incurred by the additional converter stage is a penalty. To simplify the circuit topology as being single stage, the modulation given by the additional dc/dc converter can be alternatively implemented by an active rectifier where active switches are incorporated, but such schemes require more complex control in the secondary [13], [14]. To further ease the control efforts, load-independent-current (LIC) [15] and load-independent-voltage (LIV) [16] transfer characteristics of single-stage IPT converters have been widely investigated for the CC–CV output. The transition from CC to CV can be achieved by either hoping the operating frequencies from the LIC point to the LIV point in an IPT converter designed with a single compensation topology [17], [18] or altering the compensation topologies in an IPT converter that has hybrid compensation circuits [19], [20], [21], [22]. In these and other listed applications, it is necessary to sense the output voltage and regulate it to the limiting value with wireless feedback communication, which increases the control complexity in the secondary and reduces the control reliability, respectively. In addition, overcurrent protection for the series compensated primary is another issue that should be addressed with less dependence on wireless feedback communication [23].

As demonstrated in Fig. 1, the key to the minimal secondary design is the realization of self-sustained transition from CC output to CV output. Huang et al. [24] proposed a passive approach to inherent CC–CV output. The proposed IPT system is based on a three-coil coupler, among which an extra coil together with a rectifier is utilized to clamp the primary-side current. The induced secondary output voltage, therefore, has a limit without the necessity of secondary-side control and
TABLE I
COMPARISONS WITH STATE-OF-THE-ART WORKS

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<td>not necessary</td>
<td>multiple bidirectional switches</td>
<td>a coupler, compensation circuits, a rectifier</td>
<td>two switches</td>
</tr>
<tr>
<td>minimal secondary design</td>
<td>x</td>
<td>x</td>
<td>x</td>
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</table>

wireless feedback communication. However, cross coupling between the extra coil and the secondary coil, which cannot be fully eliminated even with careful coupler design, leads to a significant deviation in the CV limit [25].

To overcome the difficulty in the design of three-coil coupler [24], [25], this article proposes a novel active approach to the achievement of native CC output and CV limit in an IPT converter. Comparisons with state-of-the-art works are concluded in Table I. To eliminate the complex design of three-coil coupler, the IPT converter adopts a conventional two-coil coupler with series-series (SS) compensation, and it operates as a CC charger. The primary adopts a switch-controlled capacitor (SCC) for active tuning of the primary tank impedance, such that CV limits in the secondary can be readily achieved once the primary tank current reaches its maximum. Such an approach enables minimal and rugged secondary design, because the secondary control and wireless feedback communication are not necessary. Moreover, the proposed scheme can cope with open-circuit protection issue for the primary under the removal of the secondary.

The rest of this article is organized as follows. Section II presents the proposed IPT charger and details its operating principle. Section III optimizes the voltage stress of the SCC switches while ensuring the capability of self-sustained CC–CV charging profile and illustrates the control scheme. In Section IV, in addition to steady-state measurement of the proposed system, transient responses against step-load change, misalignment, and removal of the secondary are also validated. Finally, Section V makes a conclusion.

II. PROPOSED SYSTEM AND OPERATING PRINCIPLE
A. Primary SCC Compensated IPT Converter

Fig. 2 depicts the schematics of the proposed wireless charger. The magnetic coupler has primary self-inductance $L_p$, secondary self-inductance $L_s$, and mutual inductance $M$. Series compensation is adopted on both sides of the magnetic coupler, but different from a conventional SS IPT converter [17], an SCC, as highlighted in the red dashed box, is adopted and manipulated in the primary for active tuning of the primary resonant tank. DC voltage source $V_f$ is chopped into ac voltage $v_p$ to drive the primary tank circuit at a fixed operating frequency $\omega$ by a full-bridge inverter. The secondary ac output is rectified to charge the battery. $V_o$ and $I_o$ are the output voltage and current, respectively. For steady-state analysis, the load can be modeled as a resistor determined by $R_L = (V_o/I_o)$.

For simplicity, the secondary operates as a resonant tank at $\omega$, by fully compensating $L_s$ with $C_s$ that can be designed as follows:

$$C_s = \frac{1}{\omega^2 L_s}. \quad (1)$$

The SCC includes a capacitor $C_p$ in parallel with two antseries connected MOSFET switches $Q_a$ and $Q_b$. Without modulating $Q_a$ and $Q_b$, $C_p$ should resonate with $L_p$ at $\omega$, as given by

$$C_p = \frac{1}{\omega^2 L_p} \quad (2)$$

whereas the control of $Q_a$ and $Q_b$ can steplessly vary the equivalent capacitance $C_{SCC}$.

Modulation of the SCC has been detailed in [26], [27], and [28], and the typical switching sequence and operating waveforms are given in Fig. 3. Gate driving signals of $Q_a$ and $Q_b$ have phase shift $\alpha \in ([\pi/2], \pi)$ from $i_p$ and are complementary to each other. $Q_a$ and $Q_b$ are turned on and off at zero voltage for low switching loss. $v_{C_p}$ is shaped as part of a sine wave, and effective charging/discharging time of $C_p$ in half a cycle is $2(\pi - \alpha)$. As the dashed curve labeled with $v_{C_p,1}$, the increase of $\alpha$ will decrease the peak of the
fundamental component of \(v_{C_p}\). Consequently, the equivalent capacitance \(C_{SCC}\) of the SCC can be varied by the phase-shift angle \(\alpha\). Equivalent \(C_{SCC}\) can be derived by considering the fundamental components of \(v_{C_p}\) and \(i_P\), as given by

\[
C_{SCC} = \frac{C_p}{2 - (2\alpha - \sin 2\alpha)/\pi}. \tag{3}
\]

Using fundamental approximation, an equivalent circuit model of the proposed system is shown in Fig. 4. It is similar to that of the conventional SS IPT converter, except for the switch-controlled primary tank circuit. The secondary tank model of the proposed system is shown in Fig. 4. It is similar to that of the conventional SS IPT converter, except for the switch-controlled primary tank circuit. The secondary tank model has null reactance

\[
X_S = X_{L_S} + X_{C_S} = 0 \tag{4}
\]

where \(X_{L_S} = \omega L_S\) and \(X_{C_S} = -1/(\omega C_S)\). In the rest of this article, \(X_{\text{sub}}\) represents corresponding reactance indicated by its subscript.

Variable reactance of the primary tank circuit controlled by \(\alpha\) is given by

\[
X_P = X_{L_P} + X_{C_{SCC}} = \frac{2\alpha - \sin 2\alpha - \pi}{\pi} X_{L_P} \tag{5}
\]

where \(X_{L_P} = \omega L_P\) and \(X_{C_{SCC}} = -1/(\omega C_{SCC})\). Based on (3) and (6), when \(\alpha\) is varied from 0.5 to \(\pi\), the capacitive reactance \(X_{C_{SCC}}\) can be modulated from \(X_{C_p}\) toward zero, resulting in the monotonic increase of \(X_P\) from zero to \(X_{L_P}\), as shown in Fig. 5.

In Fig. 4, \(V_P, I_P, V_S,\) and \(I_S\) are vectors of fundamentals of \(v_P, i_P, v_S,\) and \(i_S\), respectively. \(R_{eq} = (8/\pi^2)R_L\) is defined as the equivalent load resistance of the rectifier as well as the load. The system equations are given by

\[
V_P = jX_M I_S + jX_P I_P \tag{7}
\]

and

\[
V_S = -R_{eq}I_S = jX_M I_P \tag{8}
\]

where \(X_M = \omega M\).

**B. Native CC Output (\(\alpha = \pi/2\))**

When the primary tank current \(|I_P|\) is within its maximum value, modulation of the SCC is not needed, i.e.,

\[
\alpha = \pi/2, \quad \text{for } |I_P| \leq |I_P|_{\text{max}} \tag{9}
\]

where \(|I_P|_{\text{max}}\) is subject to desired CV threshold \(|V_S|_{\text{th}}\), and with (8), it is given by

\[
|I_P|_{\text{max}} = \frac{|V_S|_{\text{th}}}{X_M}. \tag{10}
\]

By substituting (9) into (6), the primary tank circuit has null reactance as follows:

\[
X_P = 0, \quad \text{for } \alpha = \pi/2. \tag{11}
\]

With (4) and (11), both the primary and the secondary are fully compensated at the operating frequency \(\omega\), such that the proposed system operates as the conventional SS IPT converter. By substituting (11) into (7) and (8), the native CC output can be derived as follows:

\[
|I_S| = \frac{|V_p|}{X_M}, \quad \text{for } \alpha = \pi/2. \tag{12}
\]

The primary tank current given by (13) will linearly increase with the load resistance \(R_{eq}\) during the CC charging process

\[
|I_P| = \frac{|V_p|}{X_M^2} R_{eq} \leq |I_P|_{\text{max}}. \tag{13}
\]

**C. Operating Principle of Self-Sustained CV Limits (Variable \(\alpha > \pi/2\))**

To restrict the primary tank current \(|I_P|\) to its maximum value \(|I_P|_{\text{max}}\) for the desired CV threshold, modulation of the SCC is needed. With (7), variable \(\alpha\) can be derived by solving

\[
\frac{|V_p|}{\sqrt{\left(\frac{X_M^2}{R_{eq}}\right)^2 + X_P^2}} = |I_P|_{\text{max}}. \tag{14}
\]
It can also be illustrated by a phasor diagram shown in Fig. 6(a). Dashed curves represent the amplitude limits of corresponding phasors. The counterclockwise rotation represents the increase of $R_{eq}$. To satisfy (14), $X_P$ should be correspondingly increased to offset the decrease of $(X_M^2/R_{eq})$ caused by the increase of $R_{eq}$ during the CV charging process. From Fig. 5, it can be done via the control of $\alpha$.

Therefore, the overall operating principle for the desired CC–CV behavior is indicated in Fig. 6(b). For the initial CC charging, $\alpha$ is kept at $\pi/2$ when $|I_P| < |I_{P\text{max}}|$. Later, $\alpha$ begins to increase from $\pi/2$ to maintain $|I_P| = |I_{P\text{max}}|$ for the CV threshold given by

$$|V_{S|\text{th}}| = |I_{P\text{max}}| X_M.$$  \hspace{1cm} (15)

III. DESIGN CONSIDERATION AND CONTROL SCHEME

A. Voltage Stress Reduction of SCC Switches

According to Figs. 5 and 6(b), the maximum voltage across the SCC occurs at the transition from the CC output to the CV output, where there is no modulation in the SCC, i.e., $X_{SCC} = X_{C_P}$. Thus, the voltage stress of the SCC switches shown in Fig. 2 can be calculated as follows:

$$|V_{S\text{max}}| = |I_{P\text{max}}| X_{C_P}.$$ \hspace{1cm} (16)

It can be observed that the voltage stress $|V_{S\text{max}}|$ can be optimized via the reduction of $X_{C_P}$.

In order to reduce the voltage stress of the SCC switches, a voltage divider can be designed for the SCC, as shown in Fig. 7. To be specific, the sole SCC in Fig. 2 can be reconfigured as a new SCC with voltage divider. $C_{P}^\prime$ is the new capacitor in the SCC circuit. As usual, $C_{P}^\prime$ is in parallel with two antseries connected MOSFET switches, and the equivalent impedance of the new SCC is donated as $X_{SCC}^\prime$, which is tunable via the phase-shift angle ($\alpha$ and $\alpha'$) versus equivalent load resistance $R_L$.

In addition, the new SCC together with $C_1$ donates an identical impedance to keep the primary resonant as given by

$$X_{C_1} + X_{C_P}^\prime + X_{SCC}^\prime = X_{L_P}.$$ \hspace{1cm} (18)

With (17) and (18), the increase of $X_{C_1}$ can help with the reduction of voltage stress of the SCC switches.

Based on the operating principle of SCC, the impedance of the new SCC varies within

$$X_{SCC}^\prime \in \{X_{C_P}^\prime, 0\}.$$ \hspace{1cm} (19)

The new variable reactance of the primary tank and its range are given by

$$X_P^\prime = X_{L_P} + X_{C_1} + X_{SCC}^\prime \in \{0, X_{L_P} + X_{C_1}\}.$$ \hspace{1cm} (20)

To satisfy the operating principle, as shown in Fig. 6(a), $X_P^\prime$ should be tunable and capable to vary in a sufficiently wide range.
Therefore, a simple PI controller applies the correction to the synchronization signal for the SCC PWM generations. The current zero-crossing point and the amplitude of the primary tank circuit between the primary and the secondary can be eliminated. The proposed charger with wireless feedback communication and only the control of the SCC in the primary is needed in order to achieve a CV output when the load varies, if the operating frequency in the primary is fixed, the ideal SS IPT converter has its own CC output characteristics, as follows.

Thus, once the maximum value of $X_p$ is desired at $P_{\text{max}}$, such that the control scheme is also applicable for an identical CC output. The red solid and dashed curves show the voltage stress of the original SCC and the new SCC with voltage divider during the whole charging process, respectively. It can be observed that the voltage stress can be significantly reduced with the help of $X_{C_1}$.

### Control Scheme

Based on the operation of $\alpha$ given in Sections II-B and II-C, Fig. 9 shows the control diagram in practical implementation. Since the operating frequency in the primary is fixed, the ideal SS IPT converter has its own CC output characteristics, in order to achieve a CV output when the load varies, and only the control of the SCC in the primary is needed for the proposed charger. Wireless feedback communication between the primary and the secondary can be eliminated. The zero-crossing point and the amplitude of the primary tank circuit current $i_p$ are detected. Zero-crossing detection of $i_p$ generates a synchronization signal for the SCC PWM generations. $|I_p|$ takes a monotonic relationship with the control variable $\alpha'$. Therefore, a simple PI controller applies the correction to the

### Experimental Verification

To verify the CC–CV behavior of the proposed system, two experimental prototypes are built with a sole SCC and an SCC with a voltage divider. The parameters are given in Table III, and the experimental setup is shown in Fig. 10. Given a battery with a capacity of 10 Ah and a nominal voltage of 48 V, the desired charge current and the charge threshold voltage can be fixed to $I_{\text{th}} = 4$ A and $V_{O} = 52$ V separately. An electronic load is used to emulate the battery. The closed-loop primary current control scheme demonstrated in Section III-B is implemented in a microcontroller for CC–CV charging throughout the charging process.

#### Table II: Circuit Parameters for Simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbols</th>
<th>Values</th>
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<td>Self inductance</td>
<td>$L_{p-L_S}$</td>
<td>60 $\mu$H, 58 $\mu$H</td>
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<tr>
<td>Mutual inductance</td>
<td>$M$</td>
<td>20 $\mu$H</td>
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<tr>
<td>Equivalent load resistance</td>
<td>$R_e$</td>
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</tr>
<tr>
<td>Operating frequency</td>
<td>$f_{\text{c}}$</td>
<td>85 kHz</td>
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</table>

(1) Sole SCC $C_p$ 53 nF
(2) SCC with voltage divider $C_p'$ 83 nF $C_p$ 150 nF

#### Table III: Parameters of the Experimental Prototype

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbols</th>
<th>Measured Values</th>
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<td>Input voltage</td>
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<td>SCC switches</td>
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<tr>
<td>Operating frequency</td>
<td>$f_{\text{c}}$</td>
<td>85 kHz</td>
</tr>
</tbody>
</table>

(1) Sole SCC $C_p$ 53.4 nF
(2) SCC with voltage divider $C_p'$ 80.2 nF $C_p$ 156.3 nF
A. Steady-State Operating Waveforms and Voltage Stress Reduction

Fig. 11 shows the captured steady-state operating waveforms under different charging modes with a sole SCC. The SCC does not operate in the CC mode, as shown in Fig. 11(a), and thus, the system operates as a conventional SS IPT converter to achieve a CC output. The steady-state waveforms in the CV mode (heavy- and light-load conditions) are shown in Fig. 11(b) and (c), where the primary side current $|I_p|$ is limited to 5.8 A via the tuning of the SCC, such that a CV output being about 52 V is achieved. It can be observed that during CC charging, the phase shift $\alpha = 0.5\pi$, during CV mode, the phase shift $\alpha$ increases with increasing $R_L$. The maximum voltage stress of the SCC switches occurs at the transition from the CC charging to the CV charging, which can be estimated as being about 258.24 V from Fig. 11(b).

Similarly, Fig. 11 shows the captured steady-state operating waveforms under different charging stages with an SCC with a voltage divider. It can be observed that the operation of the phase-shift angle $\alpha'$ against the load variation is similar to that of $\alpha$ in Fig. 11. The maximum voltage stress of the SCC switches occurs at the transition from the CC charging to the CV charging, which can be estimated as being about 69.25 V from Fig. 12(b). Compared with that in Fig. 11(b), the voltage stress is reduced by up to 73.18%.

Curves of voltage stress against the load variation with the sole SCC and the SCC with voltage divider are also plotted in Fig. 13. Measured $\alpha$ and $\alpha'$ are marked with “○” and “□” respectively.
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maximum value 5.8 A, and thus, there is no overcurrent risk for the primary inverter despite the removal of the secondary.

V. CONCLUSION

An active IPT approach to native CC output and CV limit is proposed for battery charging applications. Compared with the existing scheme, complex three-coil coupler is not needed. The CC–CV behavior is achieved by only adopting and manipulating switch-controlled compensation in the primary. It eliminates the necessity of secondary control and wireless communication to make thesecondary minimal and rugged. The primary faces no open-circuit risk, and all switches can realize soft switching. A voltage divider helps with the voltage stress reduction of the SCC switches. Operating principle and control scheme of the proposed system are illustrated in detail. Experimental results validate the theoretical analysis well.

REFERENCES


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Dr. Iu has won two IET Premium Awards in 2012 and 2014. In 2014, he also won the UWA Vice-Chancellor’s Mid-Career Research Award. He received the 2023 IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS Guillemin-Cauer Best Paper Award, the 2021 IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS Prize Paper Award, the 2019 IEEE TRANSACTIONS ON VERY LARGE SCALE INTEGRATION SYSTEMS Prize Paper Award, and the Best Paper Award of 2019 IEEE International Conference on Artificial Intelligence Circuits and Systems. He was appointed as an IEEE CASS Distinguished Lecturer for 2023–2024. He is a Coeditor of Control of Chaos in Nonlinear Circuits and Systems (World Scientific, Singapore, 2009) and a Coauthor of Development of Memristor Based Circuits (World Scientific, Singapore, 2013). He serves as the Editor-in-Chief for the IEEE JOURNAL ON SELECTED AND EMERGING TOPICS IN CIRCUITS AND SYSTEMS and an Associate Editor for the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS II, the IEEE TRANSACTIONS ON POWER ELECTRONICS, the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS ON POWER ELECTRONICS, and the IEEE TRANSACTIONS ON SMART GRID.