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Bi-directional Power Transfer of a Contactless Electric Vehicle Charger Using Direct Three-Phase to Single-Phase AC/AC Converter

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≪Resonant converter≫, ≪Soft switching≫.

Abstract
This paper explains a bi-directional power transfer operation of an inductive charger using a direct three-phase to single-phase AC/AC converter. The converter has a fewer switches than a matrix converter with the same functionality and uses a resonant circuit to utilize zero-current switching. The charger is designed to charge electric vehicle battery, and the transfer operation will be applied to support power grid through a vehicle-to-grid application. The paper focuses on power transfer analysis of a series-series inductive power system with a switching frequency generated from a resonant current. Equivalent circuit and steady-state equations were developed to predict system behavior. Analytical calculations were compared with simulation outcomes for validation purposes. The analysis shows that the coupled system has three resonant frequencies, and power transfer capacity is affected by circuit coupling factor and battery voltage level.

Introduction
A vehicle-to-grid power concept has been proposed in [1] and [2] as an alternative way to provide energy storage system to manage intermittency of solar and wind energies. It uses a group of electric vehicles (EV) to store energy taken from the sources and use it when needed. This concept can also be implemented using inductive-based contactless power transfer (ICPT) system for EV charger. A schematic of a typical bi-directional ICPT system connected to an AC source is given in Fig. 1. On the primary side, the source can be either single-phase or three-phase. The AC/DC converter is connected to the DC/AC converter through \( C_{DC} \). Primary and secondary side are coupled magnetically through two transceiving coils. Leakage and mutual inductances are compensated by two compensation circuits that are symmetrical. The secondary side DC/DC converter is used for power regulation to meet EV’s battery demand [3]-[6]. The system has multiple stages of conversion that introduce power losses as well as increase system size and cost. A direct AC/AC converter can be used to replace the primary side converters to solve the issues [7].

In [8] and [9], the authors proposed a direct three-phase to single-phase AC/AC converter that has a lesser number of switches than a matrix converter with the same capability. However, phase-shift modulation with a constant switching frequency is chosen to drive the resonant circuit which is based on
hard-switching principle. The approach possesses risks of significant power losses at less than $\pi$ phase-shift angle, and inability to maintain high power transfer efficiency in a dynamic environment. Some improvements were proposed in [10]-[12] by changing the modulation method. The method is based on current injection and free-wheeling oscillation which were previously introduced in [7], [13] and [14]. Switching transition is performed at a zero crossing of the primary resonant circuit current to reduce switching power losses. In addition, switching frequency is produced from a resonant frequency of the system to maintain high power transfer efficiency. In this paper, a bi-directional power transfer operation of the ICPT system is presented. The charger is in a series-series configuration with a secondary side connected to a full-bridge topology and an EV battery. The bi-directional power transfer is achieved by changing a phase-shift between voltage and current in both primary and secondary sides while maintaining zero-current switching.

This paper is organized as follows. A brief description of the proposed bi-directional ICPT system using a direct AC/AC converter is given in “Contactless charger system” section. Section of “Converter model” derives resonant frequency and power transfer capacity of the coupled ICPT system. In “Analytical calculation” section, quantities of system characteristics based on mathematical model are provided. Simulation graphs illustrating power transfer either from, or to EV battery are explained in “Simulation results”. Finally, conclusion of the paper is drawn in the last section.

Contactless charger system

ICPT system schematic is given in Fig. 2. The primary circuit side converter contains four bi-directional switches and a resonant circuit ($L_p$ and $C_p$). Three of the switches are connected in series with a three-phase input ($S_{a+}$, $S_{a-}$, $S_{b+}$, $S_{b-}$, $S_{c+}$ and $S_{c-}$) and have a common connection to the fourth switch pair $S_{d-}$ and $S_{d+}$. The switches are controlled by the primary controller and will be used to drive the primary resonant circuit. Secondary circuit side consists of a similar resonant circuit ($L_s$ and $C_s$) connected to a full-bridge topology and an EV battery $v_o(t)$. Both primary as well as secondary sides are magnetically coupled and the ICPT is in a series-series configuration. Their controllers communicate through a wireless communication channel. The usage of AC/AC converter reduces the primary side complexity in a conventional ICPT system shown in Fig. 1.
**Commutation possibility**

Fig. 3 shows four different current commutations of the primary converter. Case (a) and (b) correspond to injection mode where the primary current $i_p(t)$ flows either from or to one of the input source phases. The injection mode for other input phases are also similar. Free-wheeling oscillation mode is described in case (c) and (d), where the resonant current oscillates in the resonant circuit. Positive current flow is defined as a current that goes in a clockwise direction (marked by $+i_p(t)$), while negative flow goes the other way around. Both current flow cases will be used to control transferred power between grid and EV’s battery [10].

![Diagram of AC/AC converter](image)

**Modulation strategy**

Four commutation configurations that were illustrated in Fig. 3 are used in a modulation strategy to drive the primary resonant circuit. A technique called non-successive injection modulation that was introduced...
in [10] and [12] will be used in this paper. It switches the converter during maximum absolute value of the three-phase input or,

\[ \text{Max}(v) = \text{Max}(|v_a(t)|, |v_b(t)|, |v_c(t)|). \]  

(1)

During the period, injection and free-wheeling oscillation are performed alternatingly using one phase that equals Max\((v)\). Illustration of the process is presented in Fig. 4, which highlights an example case where Max\((v) = v_b(t)\). Parameter \(v_p(t)\) symbolizes voltage over primary resonant circuit. It is produced by chopping three-phase input voltage with an amplitude of \(V_{\text{amp}}\). The transition between injection and free-wheeling oscillation (in this case involving \(S_b+\) and \(S_d-\) respectively) is performed at zero-crossings of primary resonant current \(i_p(t)\). It is done to reduce switching power losses. To control power flow from the input to the output side, the ratio of injection and free-wheeling oscillation quantities is varied. Thus the switching becomes intermittent.

![Switching actions during injection modulation](image1)

Fig. 4: A non-successive injection modulation illustration.

On the receiver side, as illustrated in Fig. 5, a similar scheme of inversion modulation using injection and free-wheeling oscillation is applied. The inversion is used to transfer power from the secondary to primary side. The transition between commutations is also performed at zero-crossing of the secondary resonant current \(i_s(t)\). At a controlled power flow from secondary to primary circuit side, the amount of injection with respect to free-wheeling oscillation is varied.

![Switching actions during inversion modulation](image2)

Fig. 5: A secondary side converter modulation illustration.

**Converter model**

The equivalent circuit model of the ICPT system is needed for a steady-state analysis. The model is constructed based on some assumptions which are: all electric components are ideal and the converter
Each circuit side consists of a voltage source \( v_x(t) \), a capacitance \( C_x \) and an inductance \( L_x \) with its coil resistance of \( R_x \). Subscript “x” is replaced by either “p” or “s” to distinguish “primary” and “secondary” sides. The mutual inductance \( M \) between both circuits is equal to \( k \sqrt{L_p L_s} \), where \( k \) is a coupling factor. Steady-state equations that govern the coupled circuit behavior are provided in (2). Both current and voltage amplitudes are in RMS.

\[
\begin{align*}
V_p &= i_p R_p + \frac{i_p \omega^2 M^2 R_s - V_s \omega M (\omega L_s - \frac{1}{\omega C_s})}{R_i^2 + (\omega L_s - \frac{1}{\omega C_s})^2} + \frac{jV_s \omega MR_s}{R_i^2 + (\omega L_s - \frac{1}{\omega C_s})^2} \\
&\quad + j \left[ i_p \left( \omega L_p - \frac{1}{\omega C_p} \right) - \frac{i_p \omega^2 M^2 (\omega L_s - \frac{1}{\omega C_s})}{R_i^2 + (\omega L_s - \frac{1}{\omega C_s})^2} \right].
\end{align*}
\]

Resonant frequency

The resonant frequencies of the coupled resonant circuits can be calculated from equation (2). A combined equation through an elimination of secondary current \( i_s \) is,

\[
\begin{align*}
i_p \left( \omega_0 L_p - \frac{1}{\omega_0 C_p} \right) &= \frac{i_p \omega_0^2 M^2 (\omega_0 L_s - \frac{1}{\omega_0 C_s})}{R_i^2 + (\omega_0 L_s - \frac{1}{\omega_0 C_s})^2}, \\
\left( \omega_0 L_p - \frac{1}{\omega_0 C_p} \right) \left[ R_i^2 + \left( \omega_0 L_s - \frac{1}{\omega_0 C_s} \right)^2 \right] &= \omega_0^2 M^2 \left( \omega_0 L_s - \frac{1}{\omega_0 C_s} \right) = 0, \\
\omega_0^6 L_p L_s (1 - k^2) + \omega_0^4 \left[ L_p R_s^2 - \frac{L_p^2 L_s}{C_s} (2 - k^2) \right] + \omega_0^2 \left[ \frac{L_p}{C_s^2} + \frac{2 L_s}{C_p C_s} - \frac{R_i^2}{C_p^2} \right] - \frac{1}{C_p C_s^2} = 0.
\end{align*}
\]

In the arrangement of bi-directional power transfer scheme in this paper, component values between primary and secondary resonant circuits are set to be equal. This means, \( C_p = C_s, L_p = L_s, \) and \( R_p = R_s \). Thus the sextic polynomial in (6) transforms to,

\[
\begin{align*}
\omega_0^6 L_p^3 C_p^3 (1 - k^2) + \omega_0^4 L_p C_p^3 \left[ R_p^2 - \frac{L_p}{C_p} (3 - k^2) \right] + \omega_0^2 C_p^2 \left( \frac{3 L_p}{C_p} - R_p^2 \right) - 1 &= 0,
\end{align*}
\]
where it can be factored to,

\[
\left( \omega_0 - \frac{1}{\sqrt{L_p C_p}} \right) \left( \omega_0 + \frac{1}{\sqrt{L_p C_p}} \right) \left[ \omega_0^2 L_p^3 C_p^3 (1 - k^2) + \omega_0^2 L_p C_p \left( R_p^2 - \frac{2 L_p}{C_p} \right) + L_p C_p \right] = 0. \tag{8}
\]

All six roots of equation (8) are calculated as follows,

\[
\omega_{0,1,2} = \pm \frac{1}{\sqrt{L_p C_p}}, \quad \omega_{0,3,4,5,6} = \pm \sqrt{\frac{-L_p C_p \left( R_p^2 - \frac{2 L_p}{C_p} \right) \pm \sqrt{\left[ L_p C_p \left( R_p^2 - \frac{2 L_p}{C_p} \right) \right]^2 - 4 L_p^2 C_p^2 (1 - k^2)}}{2 L_p^2 C_p^2 (1 - k^2)}}. \tag{9}
\]

Positive and real roots are the resonant frequencies of the coupled system.

**Power transfer**

The power transfer between primary and secondary sides can be calculated from voltage and current expressions during resonance. By arranging (3), the current equation is obtained as,

\[
i_p = \frac{V_p \left[ R_s^2 + \left( \omega_0 L_s - \frac{1}{\omega_0 C_s} \right)^2 \right] - V_s \omega_0 M [j R_s + \left( \omega_0 L_s - \frac{1}{\omega_0 C_s} \right)]}{R_p \left[ R_s^2 + \left( \omega_0 L_s - \frac{1}{\omega_0 C_s} \right)^2 \right] + R_s \omega_0^2 M^2}. \tag{10}
\]

Average power can therefore be calculated from,

\[
P = \left| V_p i_p \right|^2 = \frac{V_p^2 \left[ R_s^2 + \left( \omega_0 L_s - \frac{1}{\omega_0 C_s} \right)^2 \right] - V_p V_s \omega_0 M [j R_s + \left( \omega_0 L_s - \frac{1}{\omega_0 C_s} \right)]}{R_p \left[ R_s^2 + \left( \omega_0 L_s - \frac{1}{\omega_0 C_s} \right)^2 \right] + R_s \omega_0^2 M^2}. \tag{11}
\]

**Analytical calculations**

ICPT parameter values in Fig. 6 are provided in Table II. Each input three-phase amplitude is marked with \( V_{\text{amp}} \) (see Fig. 4), while its line frequency is denoted by \( f \). Resonant circuit component values are based on specifications given in [11], with an idea to make a comparison analysis between series-only and series-series configurations in future studies. In this case, the system is loosely coupled and in an open-loop configuration. It is designed to provide around 7 kW output power. Battery voltage value is adapted from a range given in [5]. Since both primary and secondary resonant circuits have the same structure, analytical calculations are only performed for primary to secondary side power transfer.

<table>
<thead>
<tr>
<th>( V_{\text{amp}} ) (V)</th>
<th>( f ) (Hz)</th>
<th>( C_p ) (F)</th>
<th>( L_p ) (H)</th>
<th>( C_s ) (F)</th>
<th>( L_s ) (H)</th>
<th>( R_p ) (( \Omega ))</th>
<th>( R_s ) (( \Omega ))</th>
<th>( k )</th>
<th>( V_s ) (( V_{\text{RMS}} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>230 \cdot \sqrt{2}</td>
<td>50</td>
<td>0.2 ( \mu )</td>
<td>200 ( \mu )</td>
<td>( C_p )</td>
<td>( L_p )</td>
<td>0.3</td>
<td>0.1 - 0.3</td>
<td>0.5( V_p ) - 2.5( V_p )</td>
<td></td>
</tr>
</tbody>
</table>

To calculate the resonant frequencies and power transfer, the RMS amplitude of \( V_p \) needs to be calculated in advance. On the primary side, the equivalent peak value for non-successive injection modulation is,

\[
V_p = V_{\text{avg}} \frac{4}{\pi}, \quad V_{\text{avg}} = V_{\text{amp}} \frac{3}{2\pi}, \tag{12}
\]

which is obtained by averaging the voltage over the corresponding resonant circuit side, and then extracting its fundamental component [10]. In the other hand, the secondary side voltage \( v_s(t) \) is a square wave with a peak value of battery voltage \( V_0 \). The peak value of \( v_s(t) \) fundamental component is,

\[
v_s = V_0 \frac{4}{\pi}. \tag{13}
\]
By using input characteristic values in Table II, the RMS value of $V_p$ is 139.806 $V_{\text{RMS}}$. Calculation results of primary to secondary power transfer for different coupling factors and battery voltages are presented in Table III and IV correspondingly. In both cases, other parameter values are also based on Table II. Only positive and real resonant frequencies are selected. Variable $P_1$, $P_2$ and $P_3$ are average power transfer at the first, second and third resonant frequencies respectively.

Table III: Analytical calculation results for different coupling factors ($V_s = 2.5V_p$)

<table>
<thead>
<tr>
<th>$k$</th>
<th>$\omega_0_1$ (rad/s)</th>
<th>$\omega_0_2$ (rad/s)</th>
<th>$\omega_0_3$ (rad/s)</th>
<th>$P_1$ (Watt)</th>
<th>$P_2$ (Watt)</th>
<th>$P_3$ (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>$150.79 \cdot 10^3$</td>
<td>$158.11 \cdot 10^3$</td>
<td>$166.63 \cdot 10^3$</td>
<td>$113.9 \cdot 10^3$</td>
<td>$15.33 \cdot 10^3$</td>
<td>$49.08 \cdot 10^3$</td>
</tr>
<tr>
<td>0.15</td>
<td>$147.46 \cdot 10^3$</td>
<td>$158.11 \cdot 10^3$</td>
<td>$171.47 \cdot 10^3$</td>
<td>$113.96 \cdot 10^3$</td>
<td>$10.26 \cdot 10^3$</td>
<td>$48.96 \cdot 10^3$</td>
</tr>
<tr>
<td>0.2</td>
<td>$144.35 \cdot 10^3$</td>
<td>$158.11 \cdot 10^3$</td>
<td>$176.76 \cdot 10^3$</td>
<td>$113.98 \cdot 10^3$</td>
<td>$7.71 \cdot 10^3$</td>
<td>$48.91 \cdot 10^3$</td>
</tr>
<tr>
<td>0.25</td>
<td>$141.43 \cdot 10^3$</td>
<td>$158.11 \cdot 10^3$</td>
<td>$182.56 \cdot 10^3$</td>
<td>$114 \cdot 10^3$</td>
<td>$6.17 \cdot 10^3$</td>
<td>$48.89 \cdot 10^3$</td>
</tr>
<tr>
<td>0.3</td>
<td>$138.69 \cdot 10^3$</td>
<td>$158.11 \cdot 10^3$</td>
<td>$188.97 \cdot 10^3$</td>
<td>$114 \cdot 10^3$</td>
<td>$5.15 \cdot 10^3$</td>
<td>$48.88 \cdot 10^3$</td>
</tr>
</tbody>
</table>

Table IV: Analytical calculation results for different secondary voltages ($k = 0.1$)

<table>
<thead>
<tr>
<th>$V_s$ (V)</th>
<th>$V_o$ (V)</th>
<th>$P_1$ (Watt)</th>
<th>$P_2$ (Watt)</th>
<th>$P_3$ (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.5V_p$</td>
<td>77.64</td>
<td>$48.81 \cdot 10^3$</td>
<td>$3.12 \cdot 10^3$</td>
<td>$16.42 \cdot 10^3$</td>
</tr>
<tr>
<td>$V_p$</td>
<td>155.29</td>
<td>$65.07 \cdot 10^3$</td>
<td>$6.15 \cdot 10^3$</td>
<td>$2.94 \cdot 10^3$</td>
</tr>
<tr>
<td>$1.5V_p$</td>
<td>232.93</td>
<td>$81.34 \cdot 10^3$</td>
<td>$9.21 \cdot 10^3$</td>
<td>$16.68 \cdot 10^3$</td>
</tr>
<tr>
<td>$2V_p$</td>
<td>310.57</td>
<td>$97.62 \cdot 10^3$</td>
<td>$12.27 \cdot 10^3$</td>
<td>$32.84 \cdot 10^3$</td>
</tr>
</tbody>
</table>

It can be seen that the system has three resonant frequencies that produce three different average powers. Output power is relatively stable under coupling variations on the first and third frequency cases. Higher coupling factor increases the distance between first and third resonant frequencies. Although the second frequency is independent of coupling condition, its output power decreases rapidly as the coupling increases. Plots of average power with respect to resonant frequencies for different primary and secondary voltage ratios are given in Fig. 7, 8 and 9.

Fig. 7: Transferred power plot with respect to resonant frequency for $V_s = 0.5V_p$ with two different coupling factors (0.1 and 0.3). Vertical dashed lines mark resonant frequencies on the x-axis where the corresponding values and related average powers can be seen in Table IV.

The primary to secondary voltage ratio affects the power transfer peak levels especially on $\omega_0_1$. The rightmost peak which belongs to the third frequency disappear when both resonant voltages are equal.
The highest power transfer is achieved using $\omega_0$. It should be noted that the three frequencies might cause instability if converter switching frequency is tracked from primary resonant current. The risk is higher during high coupling condition. This kind of instability has been previously reported in [16].

**Simulation results**

Simulation results are obtained using PLECS software under ideal components condition and an open-loop configuration. System parameters given in Table II are used in the model.

**Primary to secondary side power transfer**

To transfer power from primary to secondary side, switching actions are only performed on the AC/AC converter. Secondary side converter only acts as a passive rectifier. Both resonant voltage and current either in the primary or secondary side are in-phase. Transfer efficiency at a partial load can be increased by introducing an extra converter between battery and rectifier circuit [5] [17]. Simulation results of power transfer based on Table II are presented in Fig. 10. The right graphs are a magnified version of the left side in terms of time scale. It can be seen that voltage and current are on the same phase, therefore the power is transferred from input source or power grid to the battery. The magnified version shows injection process that is performed using phase-c of the input. The frequency and power quantities are close to analytical results given in Table III.
In a closed-loop control mode, secondary side monitors battery conditions and sending them to the primary controller. The controller regulates power flow through intermittent switching of primary resonant voltage.

**Secondary to primary side power transfer**

In this case, both primary and secondary side converter switches are utilized. They operate in a way that resonant voltage and current are 180 degree out-of-phase on both sides. Simulation results are shown in Fig. 11. The right graphs are also a magnified version of the left side in terms of time scale. In an open-loop condition, secondary side converter drives its resonant circuit using only bipolar mode. The transferred power to primary side is absorbed to the input side through bi-directional switches connected to the three-phase source. From the right side of Fig. 11, phase difference between voltage and current is 180 degree in both primary and secondary sides, thus power is transferred from the battery to the grid. Voltage switching transition is also performed at zero-crossing of resonant current on both circuit sides. It is clear that open-loop cases require electrical components with big ratings. In a closed-loop control mode, both sides have to adjust power flow while maintaining resonant current oscillation.

**Conclusion**

A bidirectional power transfer capability of a primary side AC/AC converter ICPT system has been demonstrated at a simulation level. From analytical calculation, the coupled series-series topology has three resonant frequencies. This can cause a system instability at a high coupling condition if converter switching frequency is tracked from a resonant current. Power transfer between primary and secondary sides are affected by a coupling factor as well as both sides voltage source ratio. If the coupling factor can be estimated, a system designer can have more freedom in choosing power transfer operational point. Simulation results show that the power can be transferred either from the grid to EV’s battery or vice versa. Unfortunately, switching frequency instability is not apparent from the results. Experimental setup is currently being built and its behavior will be studied in future publications.

**References**

Fig. 11: Simulation results of secondary to primary power transfer case for $k = 0.1$ and $V_p = 2.5V_q$. At steady-state, the resonant frequency is approximately $166.53 \cdot 10^3$ rad/s or 26,504 kHz, while the average power is around $-48.89 \cdot 10^3$ W. The power is a product of primary resonant voltage and current.