Abstract—A self-tuning controller for contactless electric vehicle (EV) charging systems based on inductive power transfer (IPT) with multiple power levels is proposed. The multiple charging levels (consisting of 10 charging levels) are achieved by controlling the energy injection frequency of the transmitter coil of the inductive power transfer (IPT) system. The proposed controller is capable of self-tuning the switching operations to the natural resonance frequency of the IPT system and benefits from soft-switching operations (zero-current switching), which ensures the maximum performance of the IPT system. The proposed controller has such a simple design which can be implemented based on a simplified control circuit. The simulation of the proposed controller for an inductive charging system at different charging levels is carried out in MATLAB/Simulink. Also, the proposed controller with an AC/DC/AC converter is implemented experimentally on an IPT charging system to verify the effectiveness of the controller at different charging levels. The experimental test results confirm with the simulation results and verify that the proposed controller effectively enables self-tuning capability and soft-switching operations at different charging levels for IPT based contactless EV charging systems.

Index Terms—inductive power transfer, multi-charging-level, self-tuning control, soft-switching, variable frequency control.

I. INTRODUCTION

CONTACTLESS electric vehicle (EV) charging based on inductive power transfer (IPT) systems is a new technology that brings more convenience and safety to the use of EVs. Since it eliminates the electrical contacts, it would not get affected by rain, snow, dust and dirt, it is a safe, reliable, robust and clean way of charging electric vehicles, reduces the risk of electric shock. Therefore, it has recently found a significant interest in residential and commercial sectors [1]–[5]. Contactless EV charging is divided into two main categories: static charging and dynamic (in-motion) charging [6]–[11]. In the static charging the goal is to charge the EV using a contactless charger while the EV is parked in a charging station, which can be used for light-duty or heavy-duty EVs [12]. This is a solution that enables safe, efficient, and convenient automated charging process without the interaction of the driver. On the other hand, a dynamic EV charging system is designed to charge the EVs while they are moving. A typical static inductive EV charging system is shown in Fig. 1. This system is composed of a power supply, primary and secondary converters, transmitter and receiver pad structures, and compensation circuits.

Different control methods for IPT systems and resonant converters have been proposed. These methods include power-frequency control [13], [14], phase-shift and frequency control [15]–[18], load detection [19], power flow control [20], and sliding mode control (SMC) [21]–[24]. In [17], a self-oscillating phase-shift control for regulating the IPT systems is proposed, which matches the switching operation to the resonant current. The phase-shift is achieved by the use of a tunable leading phase-shifter in the current sensing circuit. However, the phase-shift control method leads to deviation of the switching operations from soft-switching points (zero-current and zero-voltage points), which may adversely affect the efficiency of the converter and significantly increase its electromagnetic interference (EMI). The self-tuning capability is specifically essential for dynamic IPT systems where the resonance frequency of the system may have small variations due to load variations on the receiver side. Furthermore, it can find many other applications such as energy encryption in IPT systems [25], where the IPT system has a variable resonance frequency with the use of variable compensation capacitors.

One of the methods that can be employed to effectively adjust the resonant current in an IPT system is the energy-injection and free-oscillation method which has been successfully employed in many studies [26]–[32]. This method can be employed in different converter topologies such as two-stage AC/DC/AC converters [30] and matrix converters [29],
[31]. Using this method, the resonant current is adjusted by controlling the energy injection rate which is transferred to the primary LC tank. This is achieved by constantly switching between two free-oscillation and energy-injection operation modes of the converter.

In this paper, a new variable frequency controller based on energy-injection free-oscillation technique for IPT systems is proposed. This controller provides multiple charging levels for inductive EV charging applications. In this study, the controller is designed for three-phase to single-phase full-bridge two-stage AC/DC/HFAC (high-frequency AC) converters. However, the proposed control method can be applied to other types of converter topologies. The controller enables contactless charging of an EV at multiple charging levels based on a user-defined preset. The charging levels include the standard wireless charging levels for light-duty EVs (Levels 1, 2, 3 and 4) as defined by SAE TIR J2954 [33]. Also, the proposed controller is capable of self-tuning the switching operations to the resonance frequency of the IPT system and benefits from zero-current switching (ZCS), which ensures the maximum power transfer efficiency. The proposed controller can be implemented either based on a digital or analog control circuit. MATLAB/Simulink is used to simulate the proposed controller at different charging levels and the results are presented. Also, the proposed controller is built and tested experimentally to evaluate the effectiveness of the proposed controller at different charging levels.

II. THE PROPOSED CONTROLLER

Using the energy injection method the amplitude of the resonant current in an IPT system can be controlled by varying the rate of the energy injection to the primary coil. On this basis, a self-tuning variable frequency energy injection control method for IPT systems is proposed. The proposed method employs a variable frequency energy injection to the IPT system to achieve multiple charging levels. Fig. 2 shows the proposed controller which is designed for a two-stage AC/DC/HFAC converter. The two-stage converter is composed of a three-phase rectifier and a single-phase full-bridge high-frequency inverter. The operation of the full-bridge inverter can be described in four modes based on the direction of the resonant current (positive or negative) and the type of the (energy injection or free-oscillation) operation mode, as it is presented in Fig. 3 and Table I. Based on Table I, four switching signals of the full-bridge inverter 1, 2, 3, and 4 can be expressed in terms of current direction \(S_{sgn}\) and energy injection \(S_{inj}\) states as follows:

\[
S_1 = S_{sgn}, \quad S_2 = \overline{S_{sgn}}, \quad S_3 = \overline{S_{sgn}} \cdot S_{inj} \quad S_4 = S_{sgn} \cdot \overline{S_{inj}}
\]

(1)

Based on (1), regardless of the type of operation mode (whether it is an energy injection or free-oscillation mode) \(S_1\) is switched ON when the direction of current is positive, and \(S_2\) is switched ON when the direction of current is negative. Furthermore, (1) shows that \(S_4\) is switched ON in positive energy injection modes and \(S_3\) is switched ON in negative energy injection modes.

The presented controller is designed based on a simplified circuit and it is composed of D-type flip-flops, logic gates, a differential comparator, and multi-port switches. The sign of the resonant current \(S_{sgn}\) which has the resonance frequency
In charging levels with different energy injection frequencies for positive and negative half-cycles, the output voltage of the full-bridge inverter will have a DC component. Since the impedance of the series RLC circuit (shown in Fig. 2), for a DC input is infinite (the capacitor acts as an open circuit). In other words, the DC component of the voltage is eliminated. As a result, the output resonant current will only include harmonic (non-DC) components, without any DC component, which will result in a symmetrical resonant current.

In an IPT system if the converter operates at the resonance frequency a perfect matching will be obtained, as the impedance of the compensation capacitors cancels out the equivalent impedance of the transmitter and receiver coils, resulting in a purely resistive network; Thereby, there would be no phase difference between the resonant current and input voltage. As a result, the zero-current switching (ZCS) will ensure the zero-voltage switching (ZVS). Since using the proposed controller the switching operations are synchronized with the resonant current and therefore, the ZCS and ZVS are both achieved. However, if the resonance frequency of the primary and secondary are a little different due to imperfect resonance matching, the equivalent circuit would not be purely resistive. Since the proposed controller uses zero-current crossing points for generating the switching signals, in such a case only ZCS will be achieved.

### III. Theoretical Analysis

In this section theoretical calculation of different measures for the contactless charging system based on the proposed controller is presented. Analytical solutions for the resonant voltage, resonant current and the output power can be found as follows:

#### A. Resonant Current and Resonant Voltage Calculation

The differential equation of a series compensated IPT system can be expressed based on the resonant current $i$ as

$$\frac{di}{dt} = -\frac{1}{L} \left( v_i - v_{	ext{device}} - R_i \cdot i - V_{	ext{es}} \right)$$

where $L$ is the inductance, $v_i$ is the input voltage, $v_{	ext{device}}$ is the voltage across the device, $R_i$ is the internal resistance of the device, and $V_{	ext{es}}$ is the voltage across the compensation capacitors. The resonant current can be expressed as

$$i_r(t) = \frac{V_{	ext{es}}}{\sqrt{L C}} \sin(\omega_r t)$$

where $\omega_r$ is the resonant frequency. The resonant voltage can be expressed as

$$v_{\text{res}}(t) = V_{	ext{es}} \cos(\omega_r t)$$

where $V_{	ext{es}}$ is the voltage across the compensation capacitors. The output power can be found as

$$P_{\text{out}} = \frac{1}{2} L \left( \frac{di}{dt} \right)^2$$
follows:
\[
d\frac{d^2i}{dt^2} + \frac{R_{eq}}{L} \frac{di}{dt} + \frac{1}{LC} i = 0
\]  
(2)

where \( L \) is the self-inductance of the transmitter, and \( C \) is the compensation capacitor of the transmitter, and \( R_{eq} \) is the equivalent resistance of the load on the receiver side, reflected to the transmitter side. At each zero-crossing point of resonant current, the initial conditions of the circuit are as follows:
\[
i_0 = 0, \quad \frac{L}{di/dt}(0) = V_i - v_{c0}
\]  
(3)

where \( i_0 \) is the initial resonant current and \( V_i \) is the output voltage of the inverter. The resonant current and the resonant voltage \( (v_c) \) of the compensation capacitor can be found by solving (2), based on the initial conditions given in (3) [31]:
\[
i(t) = Ke^{-t/\tau} \sin(\omega t)
\]  
(4)

\[
v_c(t) = v_{c0} + \frac{Kr}{C(1 + \tau^2 \omega^2)} \left( \tau \omega - e^{-t/\tau} [\sin(\omega t) + \tau \omega \cos(\omega t)] \right)
\]  
(5)

where \( \tau = 2L/R \) is the damping time constant, \( \omega = 1/\sqrt{LC} \) is the resonant frequency, \( \alpha = R_{eq}/2L \) is the damping coefficient, and the coefficient \( K \) is expressed as:
\[
K = \frac{V_i - v_{c0}}{\omega L}
\]  
(6)

In order to calculate the the initial condition for the resonant voltage \( v_{c0} \) at each current zero-crossing in a steady-state condition, a full control cycle consisting of \( 2n \) half-cycles of the resonant current which includes one energy injection half-cycle (Fig. 5) is considered. The resonant voltage at the end of the energy injection half-cycle \((t = \pi/\omega)\) can be calculated using (5) as follows:
\[
v_{c1} = V_i + \beta (V_i - v_{c0})
\]  
(7)

where \( \beta \) is defined as:
\[
\beta = e^{-\tau/\omega}
\]  
(8)

At the end of free-oscillation half-cycles (half-cycles from 2 to \( 2n \)), the resonant voltage can be calculated based on (5) as follows:
\[
v_{ck} = v_{c1} \beta^{k-1} (-1)^{k-1}
\]  
(9)

### TABLE II

<table>
<thead>
<tr>
<th>Charging Level</th>
<th>Frequency of energy injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1-1</td>
<td>( f_r )</td>
</tr>
<tr>
<td>Level 1-2</td>
<td>( f_r )</td>
</tr>
<tr>
<td>Level 1-4</td>
<td>( f_r )</td>
</tr>
<tr>
<td>Level 1-8</td>
<td>( f_r )</td>
</tr>
<tr>
<td>Level 2-2</td>
<td>( f_r/2 )</td>
</tr>
<tr>
<td>Level 2-4</td>
<td>( f_r/2 )</td>
</tr>
<tr>
<td>Level 2-8</td>
<td>( f_r/4 )</td>
</tr>
<tr>
<td>Level 4-4</td>
<td>( f_r/4 )</td>
</tr>
<tr>
<td>Level 4-8</td>
<td>( f_r/8 )</td>
</tr>
<tr>
<td>Level 8-8</td>
<td>( f_r/8 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charging Level</th>
<th>RMS Resonant Current (A)</th>
<th>THD of Current (%)</th>
<th>Output Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1-1</td>
<td>105.2</td>
<td>0.85</td>
<td>41</td>
</tr>
<tr>
<td>Level 1-2</td>
<td>78.4</td>
<td>2.18</td>
<td>22.1</td>
</tr>
<tr>
<td>Level 2-2</td>
<td>67</td>
<td>3.43</td>
<td>12.3</td>
</tr>
<tr>
<td>Level 4-8</td>
<td>55.1</td>
<td>5.39</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Using (7), equation (9) can be rewritten as follows:
\[
v_{ck} = V_i (1 + \beta) \beta^{k-1} (-1)^{k-1} + v_{c0} \beta^k
\]  
(10)

By assuming that the system has reached a steady-state condition, it can be concluded that the resonant voltage at the beginning of each control cycle \( (v_{c0} \text{ at } k = 0) \) should be equal to the its value at the end of the control cycle \( (v_{ck} \text{ at } k = 2n) \). Therefore, using (10) the following equations can be derived:
\[
v_{c0} = -V_i (1 + \beta) \beta^{2n-1} + v_{c0} \beta^{2n}
\]  
(11)

\[
v_{c0} = \frac{1 + \beta}{1 - \beta^2} V_i
\]  
(12)

Equation (12) is the initial condition for the resonant voltage in the steady-state condition and can be used in (6), (5) to calculate the resonant current and the resonant voltage at any time.

### B. Output Power Calculation

The maximum output power of the converter is achieved when the controller is set to level 1-1. In this case, all of the half-cycles of the resonant current would be in energy injection mode. Using the same method for calculation of the initial condition for the resonant voltage in steady-state conditions which is presented in section III.A, the initial condition for the resonant voltage can be calculated as follows:
\[
v_{c0} = \frac{1 + \beta}{1 - \beta^2} V_i
\]  
(13)

Using (6) and (13), the resonant current \( i \) for any half-cycle can be written as follows:
\[
i = \frac{2V_i}{\omega L (1 - \beta)} e^{-t/\tau} \sin(\omega t)
\]  
(14)

The output power can be calculated using (14) as follows:
\[
P = \frac{\int_0^{\pi/\omega} V_i \frac{2V_i}{\omega L (1 - \beta)} e^{-t/\tau} \sin(\omega t) \, dt}{\pi/\omega}
\]  
(15)

\[
P = \frac{2V_i^2 \tau^2 \omega (1 + e^{-\pi/\tau \omega})}{\pi L (1 - \beta) (1 + \tau^2 \omega^2)}
\]  
(16)

Using (16), the output power can be calculated based on the input voltage and the circuit parameters.
Fig. 6. Inductive electric vehicle battery charging model with the proposed self-tuning controller which is shown in Fig. 2, is simulated in MATLAB/Simulink. The simulation model is presented in Fig. 6 and it is composed of a three-phase power supply, a full-bridge three-phase rectifier, a full-bridge single-phase inverter which is switched by the proposed controller, transmitter and receiver coils with their compensation capacitors, and a battery charger that can operate at constant current (CC) mode at a 360 V battery with 22 kWh capacity. The secondary converter supply is assumed to have a line-to-line voltage of 208 V and compensation capacitors of 0.12 µF. Therefore, the resonance frequency of the IPT system is 35 kHz. The three-phase power supply is assumed to have a line-to-line voltage of 208 V and 60 Hz power frequency. The EV battery is modeled as a 360 V battery with 22 kWh capacity. The secondary converter is modeled as a conventional two-stage (AC/DC/DC) battery charger that can operate at constant current (CC) mode at a desired charging power level.

The simulations are carried out in four charging levels (levels 1-1, 1-2, 2-2 and 4-8 according to Table II) and the results are presented in Table III. Also, the resonant current, inverter output voltage, battery charging current and

IV. Simulation Results

An inductive EV charging system based on the proposed self-tuning controller which is shown in Fig. 2, is simulated
The self-inductance of the power pads is 172 µH. The proposed controller, and a variable load at the secondary. The AC/DC/AC converter as the primary converter connected experimentally and tested on an IPT system. In Fig. 8, the experimental test results on the case study IPT setup consisting of two circular transmitter and receiver power pads, an AC/DC/AC converter as the primary converter and the proposed controller.

**TABLE IV**

<table>
<thead>
<tr>
<th>Charging Level</th>
<th>Frequency of energy injection</th>
<th>Resonant current (A)</th>
<th>Output power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1-1</td>
<td>8 / 2 f / 2</td>
<td>8.00</td>
<td>165.76</td>
</tr>
<tr>
<td>Level 1-2</td>
<td>8 / 4 f / 4</td>
<td>5.81</td>
<td>87.42</td>
</tr>
<tr>
<td>Level 1-4</td>
<td>8 / 8 f / 8</td>
<td>4.74</td>
<td>58.19</td>
</tr>
<tr>
<td>Level 1-8</td>
<td>2 / 2 f / 2</td>
<td>4.19</td>
<td>45.47</td>
</tr>
<tr>
<td>Level 2-2</td>
<td>2 / 4 f / 4</td>
<td>3.64</td>
<td>34.32</td>
</tr>
<tr>
<td>Level 2-4</td>
<td>2 / 8 f / 8</td>
<td>2.59</td>
<td>17.37</td>
</tr>
<tr>
<td>Level 2-8</td>
<td>4 / 4 f / 4</td>
<td>2.12</td>
<td>11.64</td>
</tr>
<tr>
<td>Level 4-4</td>
<td>4 / 8 f / 8</td>
<td>1.70</td>
<td>7.48</td>
</tr>
<tr>
<td>Level 4-8</td>
<td>8 / 12 f / 12</td>
<td>1.29</td>
<td>4.31</td>
</tr>
<tr>
<td>Level 8-8</td>
<td>8 / 16 f / 16</td>
<td>0.82</td>
<td>1.74</td>
</tr>
</tbody>
</table>

The corresponding switching signals are shown in Fig. 7. As it is shown, using the proposed controller, different charging levels can be achieved with low harmonic distortions (THD) in the resonant current. It is important to note that the charging levels 1-2 and 4-8 respectively correspond to the charging levels 4 and 1, as defined by SAE TIR J2954 standard [33].

**V. EXPERIMENTAL ANALYSIS**

The proposed controller for IPT systems is implemented experimentally and tested on an IPT system. In Fig. 8, the IPT test-bed which is comprised of two circular transmitter and receiver power pads, compensation capacitors, a three-phase AC/DC/AC converter as the primary converter connected to the proposed controller, and a variable load at the secondary. The self-inductance of the power pads is 172 µH, and each pad has a 0.12 µF compensation capacitor. As a result, the resonance frequency of the IPT system would be 35 kHz. The three-phase input of the rectifier is connected to a three-phase power supply with a reduced line-to-line voltage of 25 V, with a 60 Hz frequency.

The proposed controller is tested at multiple charging levels according to Table II and the results are presented in Table IV. The resonant current and the energy injection switching signals for each charging level are shown in Fig. 9. This figure shows that due to the self-tuning capability of the converter, the switching operations are all synced with the resonant current (at 35 kHz resonance frequency). Also, Fig. 9 verifies the ZCS operations which occur at the current zero-crossing points.

Therefore, the proposed controller effectively self-tunes the switching operations with the resonant current and achieves soft-switching operations at each charging level.

**VI. CONCLUSION**

This paper has introduced a controller that can be used in inductive EV charging systems to achieve multiple charging levels. The proposed controller has 10 user-defined charging levels and is capable of self-tuning the switching operations of the converter to the resonance frequency of the IPT system, and therefore eliminates the need for switching frequency tuning. Also, it enables soft-switching operations (ZCS) in the converter, which will result in a significant increase in the efficiency of the power electronic converter. Furthermore, the implementation of the proposed controller based on a simplified circuit eliminates the need for DSP/FPGA based solutions and enables high operating frequencies which are usually required in IPT systems. The experimental test results on the IPT test-bed conform with the simulation results and verify the effectiveness of the proposed controller at different charging levels. Although the proposed controller is designed for only 10 charging levels, by increasing the number of frequency divisions of the energy injection signals, the number of charging levels can be further increased.

**REFERENCES**

Fig. 9. Experimental test results on the IPT system setup: the resonant current and energy-injection switching signals at different charging levels: (a) Level 1-1, (b) Level 1-2, (c) Level 1-4, (d) Level 1-8, (e) Level 2-2, (f) Level 2-4, (g) Level 2-8, (h) Level 4-4, (i) Level 4-8, (j) Level 8-8.


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