Abstract— Wireless power transfer (WPT) technology is a promising way for convenient and safe battery charging without any electrical contact, which may cause an unwanted electric spark or deliver dangerous electric current to the users. When transferring power from source to the battery, strong electromagnetic fields (EMFs) are generated. Moreover, the inverter output contains a wide range of harmonics. Therefore, it is important to reduce the EMFs and EMI in a WPT system.

For the first time, in this paper, we propose a new tightly-coupled three-phase resonant magnetic field (TC-TPRMF) charger for drone operating at 60 kHz, which can completely eliminate the 3rd harmonic and its integer multiples in the output voltage. Furthermore, to reduce the selective EMI, the conduction angle control is proposed for the WPT charging system. Through a series of measurements, we verified that the proposed TC-TPRMF with the conduction angle control can reduce the 7th and 11th harmonics of the Tx current by 6.08 dBμA and 11.84 dBμA, respectively. The coil-to-coil power transfer efficiency and total system power transfer efficiency are maintained at 91% and 72%, respectively.

Index Terms— Electromagnetic fields (EMFs), electromagnetic interference (EMI), inductive power transmission, resonant magnetic field, total harmonic distortion (THD), wireless power transfer (WPT).

I. INTRODUCTION

Recently, wireless power transfer (WPT) technology has received global attention as an alternate method to charge batteries in electric devices [1]-[11]. WPT technology is a safe and convenient method for charging batteries because it is unaffected by the external conditions. According to the Teal group’s 2014 market report, drone market will nearly double over the next decade [12]. The current worldwide annual unmanned aerial vehicle (UAV) market of $6.4 billion is expected to increase up to $11.5 billion, totaling almost $91 billion in the next ten years. Due to the development of various types of drones, there are numerous uses for commercial business application such as delivery, agriculture, mapping, oil and gas pipeline monitoring, cinematic filming security monitoring and firefighting. However, the most critical problem with drones is they have limited operating time and range of operation due to limited battery size restricts [13]. Therefore, drones need to be recharged frequently. The WPT technology opens up the possibility of automatic drone landing and takeoff technology to charge the drone batteries conveniently and automatically.

WPT charging methods using magnetic field are also divided into loosely-coupled and tightly-coupled magnetic field charging depending on the coupling coefficient, $k$. Since the loosely-coupled magnetic field chargers with low $k$ have a
relatively larger air gap, the magnetic field leakage generated by the Tx and Rx coils is strong. Thus, heavy shielding materials are required. Moreover, large Tx and Rx coils are GPS, an ultrasonic sensor and an analog-to-digital converter (ADC) [14]. Moreover, the inverter with high operating frequency is typically adopted in high-power WPT systems. The inverter contains a wide range of harmonics, which causes the electromagnetic interference (EMI) issues on the operation of other sensitive electronic devices such as an AM radio antenna. Therefore, it is important to minimize the EMI and EMI in the WPT systems.

The single-phase WPT charging system has been popularly applied to generate magnetic fields in many wireless charging applications [1]-[11]. However, three-phase WPT charging system, as shown in Fig. 1, is an encouraging alternative to the single-phase WPT charging systems due to the great benefits of EMI reduction. This is possible because the output phase voltage of the three-phase inverter is a six-step wave, which completely eliminates the 3\textsuperscript{rd} harmonic and its integer multiples of output phase voltage of the inverter. Moreover, the three-phase WPT charging system with a 4-step Rx input line-to-line voltage waveforms of ac-dc converter has lower current harmonics compared to the single-phase system with a rectangular waveform. Although the three-phase wireless charging system can eliminate the harmonics of the output voltage, the harmonic voltages of the 5\textsuperscript{th}, 7\textsuperscript{th} and other non-triplet odd multiples of fundamental frequency can act as EMI sources. Thus, a selective EMI reduction method is required without increasing the system complexity.

In addition, various methods have been investigated in previous papers to reduce EMI in the inverter, which is the power source of the WPT system. EMI can also be reduced by controlling the rise and fall times [15]. The harmonic energy of the waveform at high frequencies is less than that of an ideal square wave. However, this method increases the system complexity and increases the switching loss. The PWM control, which provide less distorted current and voltage, for EMI reduction can be applied for WPT system [16]; however, it also require a carrier signal with high switching frequency, which also results in high switching loss. Moreover, high frequency filter is required for reduction of high-order harmonics. Although phase-displacement control for generating quasi-square waves can reduce the harmonics of the output of a single-phase power inverter, it is not applicable for a balanced three-phase system. The EMI reduction method introduced in the previous research [17] utilizes spread spectrum technology, which reduces the EMI compared to a fixed-period source system; however, a complex technique is required to implement the spread spectrum source, and the effective bandwidth of the source limits the power transfer efficiency (PTE). An EMI reduction method is required without increasing the system complexity.

In this paper, we propose a new tightly-coupled three-phase resonant magnetic field (TC-TPRMF) charger for drone with the low EMF and EMI. Using the guided magnetic flux in resonance (GMFIR) structure, total weight of the TC-TPRMF charger is reduced by increasing the coupling coefficient between Tx and Rx coils. The proposed TC-TPRMF charger with the IGBT conduction angle control can adjust voltage and current harmonics, which controls the current flowing through freewheeling diodes. Through a series of measurements, we experimentally verified that the proposed TC-TPRMF with conduction angle control can reduce the 7\textsuperscript{th} and 11\textsuperscript{th} harmonics of the Tx current by 6.08 dB\(\mu\)A and 11.84 dB\(\mu\)A, respectively.

II. PROPOSAL AND IMPLEMENTATION OF THE LOW EMF AND EMI TC-TPRMF CHARGER FOR DRONE

A. Proposed Structure of Low EMF and EMI TC-TPRMF Charger for Drone with Commercial Vehicle

Fig. 2 (a) shows a simplified system block diagram for the 150 W-class TC-TPRMF charger system for the drone placed on a commercial vehicle, which consists of the three-phase
In order to realize a WPT system with low EMF and EMI, we implemented the GMFIR structure for the proposed TC-TPRMF charger system. The GMFIR structure can reduce leakage magnetic field by forming a closed path for the magnetic flux. The proposed GMFIR structure can reduce leakage magnetic field by forming a closed path for the magnetic flux. It results in the enhancement of PTE and reduces the EMI.

The proposed TC-TPRMF charger with the three-phase resonant magnetic field has a higher VA rating and lower DC power voltage ripples compared to the single-phase WPT charging system. It results in the enhancement of PTE and output power capability of the proposed TC-TPRMF charging system.

Moreover, the Rx input phase voltage waveforms of the ac-dc converter has lower current harmonics with a six-step waveform compared to the single-phase WPT system. Moreover, the Rx input phase voltage waveforms of the ac-dc converter has lower current harmonics with a six-step waveform compared to the single-phase WPT system.

The operation of the proposed TC-TPRMF charger can be studied by modeling the WPT system as a simple single-phase equivalent circuit shown in Fig. 3 (b) [21].

In order to realize a WPT system with low EMF and EMI, we implemented the GMFIR structure for the proposed TC-TPRMF charger system with the ac-dc converter represented in the block diagram. The circuit components represented by symbols are listed in Table I. The system consists of six mutually coupled coils to transfer required power to the battery in the drone. Both, the Tx and the Rx coil arrangement are Y-connected and compensated statically with capacitors in series. The capacitances in the Tx and Rx parts are inserted to minimize reactive power and to increase the efficiency. The reduced current can also reduce the coil loss and EMF compared to a non-resonant topology.

The capacitances in the series-series (SS) topology can be determined by the following equations:

\[
C_{\text{tx}1} = \frac{1}{\omega_0^2 L_{\text{tx}1}}, C_{\text{tx}2} = \frac{1}{\omega_0^2 L_{\text{tx}2}}, C_{\text{tx}3} = \frac{1}{\omega_0^2 L_{\text{tx}3}}
\]  

\[
C_{\text{rx}1} = \frac{1}{\omega_0^2 L_{\text{rx}1}}, C_{\text{rx}2} = \frac{1}{\omega_0^2 L_{\text{rx}2}}, C_{\text{rx}3} = \frac{1}{\omega_0^2 L_{\text{rx}3}}
\]  

The operation of the proposed TC-TPRMF charger can be studied by modeling the WPT system as a simple single-phase equivalent circuit shown in Fig. 3 (b) [21].

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Since the proposed structure of TC-TPRMF charger have a relatively small air gap, the magnetic field leakage generated by the Tx and Rx coils can be reduced. Thus, heavy shielding materials, such as metal and aluminum, which increase the self- and mutual inductances and decrease the effective series resistance (ESR) of the coils, are not required [18], [19]. In the TC-TPRMF charger, to confine and guide the magnetic field, the Mn-Zn ferrite core with a high permeability (\(\mu = 3200\)) and low conductivity (\(\sigma < 0.142\) S/m) under 200 kHz is used [20].

Litz wire, which consists of 200 thin strands of American-Wire-Gauge (AWG) 38 wires is used to minimize the skin and proximity effects.

The proposed TC-TPRMF charger with the three-phase resonant magnetic field has a higher VA rating and lower DC power voltage ripples compared to the single-phase WPT charging system. It results in the enhancement of PTE and output power capability of the proposed TC-TPRMF charging system. Moreover, the Rx input phase voltage waveforms of the ac-dc converter has lower current harmonics with a six-step waveform compared to the single-phase system with a rectangular waveform of the Rx input voltage.

Fig. 3 (a) shows the equivalent circuit of the TC-TPRMF charger system with the ac-dc converter represented in the block diagram. The circuit components represented by symbols are listed in Table I. The system consists of six mutually coupled coils to transfer required power to the battery in the drone. Both, the Tx and the Rx coil arrangement are Y-connected and compensated statically with capacitors in series. The capacitances in the Tx and Rx parts are inserted to minimize reactive power and to increase the efficiency. The reduced current can also reduce the coil loss and EMF compared to a non-resonant topology.

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\]  

\[
C_{\text{rx}1} = \frac{1}{\omega_0^2 L_{\text{rx}1}}, C_{\text{rx}2} = \frac{1}{\omega_0^2 L_{\text{rx}2}}, C_{\text{rx}3} = \frac{1}{\omega_0^2 L_{\text{rx}3}}
\]  

The operation of the proposed TC-TPRMF charger can be studied by modeling the WPT system as a simple single-phase equivalent circuit shown in Fig. 3 (b) [21].
TPRMF charger, with a closed path for the magnetic field. The proposed TC-TPRMF charger for drone with resonant three-phase magnetic field have eliminated 3rd harmonic and all of its integer multiples of output phase voltage of the inverter. It decreases the EMI compared to a conventional single-phase wireless charger. Moreover, the proposed TC-TPRMF charger has high k value greater than 0.4 due to small effective air gap, and it has high total system PTE due to reduced the number of turns.

B. Implementation and PTE Measurement of the Proposed TC-TPRMF Charger

In order to demonstrate the proposed TC-TPRMF charger, we designed and implemented the 150W-class wireless charger for the drone with the commercial vehicle. The proposed TP-TPRMF charger is designed using 3D FEA tool(ANSYS Maxwell). Also, the proposed design considered the core saturation and EMF regulation. The designed and measured parameters are presented and compared in Table II. The difference between the designed and measured parameters is caused by the difference in physical dimensions of the implemented TC-TPRMF charger. The measured resistance of the coils also includes the additional resistance, which comes from the wire that connects the power inverter and ac-dc converter. Therefore, additional line resistance should be considered.

The Tx and Rx parts of the TC-TPRMF charger, and TC-TPRMF charger system applied on a commercial vehicle are shown in Fig. 4 (a) and Fig. 4 (b), respectively. The 150W-class implemented TC-TPRMF charger system for drone consists of inverter, wireless charging platform, ac-dc converter and Li-Po battery of 22.2 V, as shown in Fig. 4 (a). The PTE is highly sensitive to the coil alignment because k sharply decreases when misaligned. Thus, we designed the shape of wireless charging platform considering the drone landing. When drone with DGPS sensor makes the landing on the wireless charging platform, the drone can slide down the funneled slope. The landing gear with the Rx part is injected into the each hole in the wireless charging platform. It can realize the TC-TPRMF charger with the higher k value, which means that the designs with the low number of turns and light shielding material can be used. It is beneficial for the drone because the flight time of the drone is affected by weight.

To confirm the total system PTE, we simulated and measured the TC-TPRMF charger through a series of simulations and measurements. The total system PTE is an important factor for commercialization. The PTE is also closely related to the range of action, the drone with the commercial vehicle. In order to increase the range of action, the drone TC-TPRMF charger is equipped on a commercial vehicle.

Table II: COMPARISON OF THE ELECTRICAL PARAMETERS IN SIMULATION AND MEASUREMENT

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT x1</td>
<td>55 μH</td>
<td>LT x1</td>
<td>54.12 μH</td>
</tr>
<tr>
<td>LT x2</td>
<td>55 μH</td>
<td>LT x2</td>
<td>55.71 μH</td>
</tr>
<tr>
<td>LT x3</td>
<td>55 μH</td>
<td>LT x3</td>
<td>53.89 μH</td>
</tr>
<tr>
<td>LR x1</td>
<td>45 μH</td>
<td>LR x1</td>
<td>46.34 μH</td>
</tr>
<tr>
<td>LR x2</td>
<td>45 μH</td>
<td>LR x2</td>
<td>44.34 μH</td>
</tr>
<tr>
<td>LR x3</td>
<td>45 μH</td>
<td>LR x3</td>
<td>44.94 μH</td>
</tr>
<tr>
<td>RT x1, RT x2, RT x3</td>
<td>26 mΩ</td>
<td>RT x1, RT x2, RT x3</td>
<td>48 mΩ²²%</td>
</tr>
<tr>
<td>RR x1, RR x2, RR x3</td>
<td>18 mΩ</td>
<td>RR x1, RR x2, RR x3</td>
<td>32 mΩ²²%</td>
</tr>
<tr>
<td>k</td>
<td>0.45</td>
<td>k</td>
<td>0.528²²%</td>
</tr>
</tbody>
</table>

achieved the coil-to-coil PTE more than 91%. The total system PTE between the output power of 12 V battery and the input power of the 22.2 V battery is above 72%.

We demonstrated the 150W-class TC-TPRMF charger applied on a commercial vehicle. It can also be applied in a high power WPT charger because the three-phase resonant magnetic field has higher VA rating and lower DC voltage ripples than a single-phase WPT charging system. The IGBT switching loss and standby power in the inverter and ac-dc converter are also significant contributors to degradation of the total system PTE. To increase the total system PTE, the inverter and ac-dc converter should be designed with the low IGBT switching losses.
III. ANALYSIS AND VERIFICATION OF THE IMPLEMENTED LOW EMI AND EMI TC-TPRMF DRONE CHARGER

Switching methods of the IGBT are divided into hard and soft switching methods. It is well known that the soft switching method can reduce the dv/dt, di/dt and device switching losses. However, soft switching method can increase the system complexity and the system size because of the additional capacitors, inductors, diodes and switching devices. In addition, soft switching method is highly load dependent. Hence, feedback loops and active voltage regulation must be implemented. On the other hand, for the case of hard switching method, the simple switching circuit can result in reduced cost and system complexity. However, the hard switching method has EMI issues because of the high dv/dt or di/dt. In order to reduce the effects of magnetic near-field EMI noise, a reduction in the voltage and current harmonics of the proposed TC-TPRMF system is required in the desired frequency range. The harmonic contents generated by power electronic devices may have significant and detrimental effect on nearby electrical devices [22]-[25]. The magnitudes of the current harmonics are defined by the ratio of the inverter output voltage to the magnitude of the input impedance. The analytical expression of the $Z_{input}$, as shown in Fig. 3, can be defined as

$$Z_{input} = \frac{V_{Tx}}{I_{Tx}} = R_1 + R_2 + j\omega L_1 + j\omega C_1 + \frac{1}{j\omega M^2}$$

(3)

The input impedance curves of the proposed TC-TPRMF charger are plotted in Fig. 5 based on (3). The TC-TPRMF charger with GMFIR structure for high efficiency and light charger are plotted in Fig. 5 based on (3). The TC-TPRMF charger with GMFIR structure for high efficiency and light weight of coils results in three peak frequencies $f_{lower}$, $f_{higher}$, which is known as the frequency splitting phenomenon [26]. Because the current harmonics are determined by the ratio of the magnitude of the input impedance at the resonant frequency to the magnitude in its harmonic frequencies, the current harmonics are increased by the frequency splitting phenomena [26].

To reduce the EMI in the desired frequency range, we propose a selective EMI reduction method with the IGBT conduction angle control, which can control the freewheeling current in the TC-TPRMF charger. Therefore, we proposed three phase wireless charging scheme with the three-phase inverter and three-phase rectifier for the drone which can eliminate 3rd wireless charging scheme with the three-phase inverter and in the TP-TPRMF charger, Therefore, we proposed three phase harmonics are increased by the frequency splitting phenomena to the magnitude in its harmonic frequencies, the current harmonics are increased by the frequency splitting phenomena [26].

The distortion of the current is quantified as total harmonic distortion (THD), which is defined as the ratio of the sum of the current magnitude of all harmonic components to that of the fundamental frequency; a higher THD value indicates greater distortion in Tx and Rx current waveform. The equation for the THD is given by

$$THD = \sqrt{\frac{\sum_{n=1}^{\infty} I_n^2}{I_1}} \times 100 = \sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots + I_n^2} \times 100$$

(4)

where $I_n$ is the RMS current of the $n$th harmonic, where $n = 1$ represents the fundamental frequency. The THD values of the current through the Tx and Rx windings are calculated using (4), and the resulting values are shown in Table III. Since the THD of the Tx current of the TC-TPRMF charger is higher than the Rx current, the THD of the output voltage from the three-phase inverter should be reduced for a low EMI system in the desired frequency band. In this section, we propose a selective EMI reduction method with the IGBT conduction angle control, which can control the freewheeling current in the TC-TPRMF charger.

A. Simulation based EMI Comparison and Analysis of the TC-TPRMF Charger with IGBT Conduction Angle Control

To reduce the EMI in the desired frequency range, we proposed the IGBT conduction angle control in the TC-TPRMF charger. The IGBT conduction angle control has been investigated to reduce the EMI in the resistive load and motor
In case of the proposed TC-TPRMF charger, the results were different because the system operates at the high-frequency with high dv/dt. The horizontal axis of the waveforms has been represented in terms of “rot” where “ro” is the angular frequency. The most common switching type is the 180° conduction angle control, where β is equal to 180°.

In the proposed TC-TPRMF charger, there are magnetically coupled coils to transfer the electrical power to the targeted load. When the IGBT is turned off by the conduction angle control, there is a sharp pulse of voltage across the coil because of high dv/dt. The direction of this voltage is opposite to the applied voltage in accordance with Lenz’s law. Moreover, the resonant capacitors in Tx and Rx parts are inserted to minimize the VA rating and to increase the efficiency. The resonant capacitor also stores the electrical energy as a form of an electric field.

In region I, as shown in Fig. 7 (a), g1, g2, and g3 are all turned on. The currents path through g1 and g3, and the return current path through g2 are shown in Fig. 7 (b). In region II, as shown in Fig. 7 (a), there exists a dead angle of α. In this region, only two IGBTs, which are g1 and g3, are turned on during α. The current flow in region II is shown in Fig. 7 (c). According to the Faraday’s law and Lenz’s law, when g1 is turned on by IGBT conduction angle control, the coils attempt to resist the sudden change in current flow by storing the magnetic field energy resulting in counter-electromotive force. The current generated by the counter-electromotive force flow through the freewheeling diodes, placed across the IGBTs, and the current path is path 1 illustrated in Fig. 7 (d). In addition, the current by temporarily stored electrical energy in the resonant capacitor flow through freewheeling diode, as illustrated as path 2 in Fig 7 (d). Compared to the phase of the voltage, the current across the Tx coil is 90° behind and the current across the Tx resonant capacitors is 90° ahead. The freewheeling current generated by coils and freewheeling current generated by the resonant capacitors appears at different time within the α interval as shown in Fig 8. Fig. 8 shows the simulation results of freewheeling current and voltage across one of the freewheeling diodes, indicated in Fig. 7 (b). The shape of the output voltage waveform of the inverter can be controlled by interval of A and B. The interval of A and B can be obtained using a circuit simulator, ANSYS Simplorer.

The simulation results of the line-to-line voltage, v_{ab}, with
variations of the conduction angle are shown in Fig. 9. The output waveform is expressed by Fourier series expansion and the equation is given as the following [22]:

\[
0 = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t)
\]

(5)

where \(a_0, a_n, b_n\) are Fourier coefficients.

Fig. 9 is 4-step voltage waveform with 180° conduction angle control, where \(\beta = 180°, \alpha = 0°\). The analytical expression of Fig. 9 (a) using Fourier series for line-to-line voltage output, \(v_{ab}\), can be obtained as the following: [22]

\[
1,3,5, \ldots \cos(n\omega t) + b_n \sin(n\omega t) = \frac{4V_{DC}}{n\pi} \sin\left(\frac{\pi}{6}\right) \sin\left(\theta + \frac{\pi}{6}\right)
\]

(6)

From (6), the 4-step voltage waveform with 180° conduction angle control in the proposed TC-TPRMF charger is targeted at eliminating 3rd harmonic and all of its integer multiples and the even harmonics. In the proposed TC-TPRMF charger with operating at high frequency, the 120° and 150° conduction angle control can produce voltage waveform with half wave symmetry, as shown in Fig. 9 (b), (c).

The duration of A and B are determined by inductance of the coils and the capacitance of the resonant capacitor, as shown in Fig. 8. On the other hand, the 167° conduction angle control has quarter wave symmetry. In the voltage waveforms with half wave symmetry, the Fourier coefficients are [28]

\[
a_n = 0,\ a_n = 0 (if \ n \ is \ even),\ b_n = 0 (if \ n \ is \ even)
\]

(7)

In the voltage waveforms with quarter wave symmetry, the Fourier coefficients are [23]

\[
a_n = 0,\ a_n = 0 (all \ n),\ b_n = 0 (if \ n \ is \ even)
\]

(8)

The comparison of THD depending on the conduction angles are shown in Fig. 10. The proposed 167° conduction angle control can reduces the THD by 15.46 %, as shown in Fig. 10. Thus, the 167° conduction angle control resulting in quarter wave symmetry has lower magnitude of harmonics compared to that of half wave symmetry. The expression for Fourier coefficients of a waveform with three switching angles per cycle, as shown in Fig. 9 (d) is given as:

\[
h_n = \frac{4V_{DC}}{n\pi} (\cos(n\theta_1) - \cos(n\theta_2) + \cos(n\theta_3))
\]

(9)

The output waveform can be rewritten in Fourier series expansion as:

\[
v_{ab}(t) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{DC}}{n\pi} \sin\left(\frac{\pi}{6}\right) \sin\left(\theta + \frac{\pi}{6}\right)
\]

(10)

where, \(V_{DC}\) is the available DC voltage and \(\theta\) is the switching angle, which meets the condition of \(\theta_1 < \theta_2 < \theta_3 < \pi/2\).

With inductances and capacitances in TC-TPRMF charger, the 167° conduction angle control can realize quarter wave symmetry in the voltage waveform. The angles of \(\theta_1, \theta_2, \) and \(\theta_3\) in the proposed TC-TPRMF charger system are \(\theta_1 = 23.7°, \theta_2 = 30.2°, \) and \(\theta_3 = 36.6°\).
The simulation results of the line-to-line voltage of the 150 W-class TC-TPRMF charger with the 180° and 167° conduction mode in frequency domain obtained by fast Fourier transform (FFT) are shown in Fig. 11. Since the three-phase inverter with the 180° conduction angle can produce the line-to-line voltage with 4-step wave where the spectrum contains the odd harmonics. The expansion coefficient of a square wave is proportional to 1/f, which causes an amplitude reduction of the harmonics by 20 dB/decade up to a frequency of $1/\pi \tau_r$, where $\tau_r$ is the rise/fall time of the IGBT. The TC-TPRMF charger with the 167° conduction angle can reduce the 7th and 11th line-to-line voltage harmonics by 3.54 dB $\mu$V and 8.42 dB $\mu$V. The Tx voltage harmonics can be reduced by controlling freewheeling current. Using proposed conduction angle control the 11th and 13th harmonics can be reduced by 8.28 dB $\mu$A and 3.47 dB $\mu$A, respectively, as shown in Fig. 12. It is possible to reduce the 5th and 7th harmonics by controlling $\theta_1, \theta_2,$ and $\theta_3$ with conduction angle control and electrical parameters. In order to eliminate the 5th and 7th harmonics, the following condition must be satisfied:

$$\frac{4V_i}{\pi} \left(\cos(\theta_1) - \cos(\theta_2) + \cos(\theta_3)\right) = v_1$$

$$\cos(5\theta_1) - \cos(5\theta_2) + \cos(5\theta_3) = 0$$

$$\cos(7\theta_1) - \cos(7\theta_2) + \cos(7\theta_3) = 0$$

(11)

where, $v_1$ is the magnitude of voltage at fundamental frequency.

We have verified and confirmed that the conduction angle control in the proposed TC-TPRMF charger for the drone can realize selective harmonic reductions by adjusting the freewheeling current without heavy computational burden and a complicated hardware. By appropriate distribution of the conduction angles to turn the IGBT inverter switches on and off, the output waveform of the inverter is controlled the harmonic components in the desired frequency range can be eliminated. Besides the addition of the conduction angle control, further EMI reduction can be realized by multi-level inverters such as diode clamped multi-level inverters and flying capacitor multi-level inverters [21]. Moreover, the input impedance shaping, which increases the magnitude of the input impedance at higher frequencies, can be realized by the addition of LC ladder circuit at the output of the inverter for EMI reduction.

B. Measurement Verification of Selective EMI Reduction of the TC-TPRMF Charger with the Variation of VSI Conduction Mode

For experimental verification of the simulation results, the voltage waveforms with the variations of the IGBT conduction angle in the proposed TP-TCRMF charger are measured. When the SOC of the batteries in the drone was approximately 72%, the measured terminal voltage and load current were 25.2 V and 5.8 A, respectively. As reported in the previous chapter, the conduction angle control can realize the reduction of selective current harmonics. Thus, we implemented the TC-TPRMF charger with the functionality to change the conduction angle for selective harmonics reduction.

Fig. 13 (a) and Fig. 13 (b) show the measurement results of the Tx line-to-line voltage in the TC-TPRMF charger with the 180° and 167° conduction angle, which has symmetries in the output voltage symmetry, which can eliminate the even harmonics.

[Figures and equations are referenced in the text.]
voltage waveform, respectively. During the α dead-angle period of the TC-TPRMF charger, the Tx current flow through the freewheeling diodes, placed across IGBTs. Thus, Tx line-to-line voltage shown in Fig. 13 (b) can be obtained. Marginal difference between the simulation results and the measurement results are present due to several reasons. First, the voltage and current waveforms are affected by the duty ratio which depends on SOC of the battery and k between the Tx and Rx coils. Moreover, the physical dimensions of the implemented TC-TPRMF charger had minor discrepancies with the physical dimensions used in the simulation.

Fig. 14 (a) and Fig. 14 (b) show the frequency spectrum of the measured Tx and Rx current between 167° and 180° conduction modes. Since the positive and negative half cycles of the voltage waveforms are not perfectly symmetrical, there are small even harmonics in the measurement results. Moreover, the equivalent load resistance is changed according to the duty ratio, which depends on SOC of battery. As a result, the input impedance curve changes and causes some discrepancy between the simulation and the measurement results. Moreover, the non-linear hysteresis curve of ferrite core produces a non-sinusoidal excitation current. The proposed TC-TPRMF charger with the 167° conduction angle can reduce the \(7^{th}\) and \(11^{th}\) Tx current harmonics by 6.08 dBμA and 11.84 dBμA, respectively. Thus, the selective harmonics reduction can be possible by conduction angle control, as shown in Fig 14. (b).

We have verified that the TC-TPRMF charger can eliminate the 3\(^{rd}\) harmonic and all of its integer multiples of output voltage. Moreover, the conduction angle control for the selective EMI reduction can effectively reduce the current harmonics in the desired frequency range. Moreover, to increase the accuracy, the EM simulation should include the harmonic loss, as well as the temperature and frequency dependent properties of the core material. With further research to optimize structure, the proposed TC-TPRMF charger can be widely adapted to high-power applications such as robotics, industrial manufacturing and test systems, which require high PTE and low EMI WPT chargers.

IV. CONCLUSION

In this paper, we firstly proposed and demonstrated a new 150 W-class low EMF and EMI TC-TPRMF charger operating at 60 kHz with commercial vehicle. The measurement results confirm that coil-to-coil PTE and total system PTE from the source to the battery remain above 91% and 72%, respectively. We proposed and experimentally verified that the TC-TPRMF charger can eliminate 3\(^{rd}\) harmonic and all of its integer multiples and even harmonics of the current flowing through Tx and Rx coils. Moreover, the proposed TC-TPRMF charger with 167° conduction angle can reduce the \(7^{th}\) and \(11^{th}\) Tx current harmonics by 6.08 dBμA and 11.84 dBμA, respectively. Thus, the selective harmonics reduction is possible through proposed conduction angle control. The results presented in this paper may provide solutions for high-power WPT applications, which require PTE and low EMF/EMI WPT chargers.

REFERENCES


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signal integrity, power integrity, ground integrity, timing integrity, and radiated emission in 3-D IC, through silicon- via (TSV), and interposer. He has authored or co-authored over 404 technical papers in refereed journals and conference proceedings. He has authored a book entitled Electrical Design of Through-Silicon-Via (Springer, 2014). His current research interests include electromagnetic compatibility (EMC) modeling, design, and measurement methodologies of 3-D IC, TSV, interposer, system-in-package, multilayer PCB, and wireless power transfer (WPT) technology for 3-D IC, electric vehicle and mobile phone.

Dr. Kim was the Symposium Chair of the 2015 IEEE EDAPS, Seoul, Korea, and Joint Conference Chair of the Japan-Korea Microwave Society in 2015. He was also the Conference Chair of the 2014 IEEE Wireless Power Transfer Conference (WPTC), Jeju, Korea, and the Symposium Chair of the 2008 IEEE EDAPS and the Technical Program Committee (TPC) chair of the 2011 APEMC. He was appointed as the IEEE EMC Society Distinguished Lecturer from 2009 to 2011. He is a TPC Member of Electrical Performance of Electronic Packaging and System. He is an Associate Editor of the IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY. He served as a Guest Editor of the Special Issue of the IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY for PCB level signal integrity, power integrity, and electromagnetic interference/compatibility in 2010, the Special Issue of the IEEE TRANSACTIONS ON ADVANCED PACKAGING for TSV in 2011, and the Mini-Special Issue on the 2014 IEEE WPTC of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES in 2014. He was a recipient of the Outstanding Academic Achievement Faculty Award of KAIST in 2006, the KAIST Grand Research Award in 2008, the National 100 Best Project Award in 2009, the KAIST International Collaboration Award in 2010, the KAIST Grand Research Award in 2014, respectively, and the Technology Achievement Award from the IEEE Electromagnetic Society in 2010.