A High Power Interleaved Parallel Topology Full-Bridge LLC Converter for Off-Board Charger

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ABSTRACT A interleaved parallel LLC converter is proposed as a DC/DC converter for a digital off-board charger in accordance with the high output power requirements of modern electric vehicle chargers. The proposed converter utilizes a hybrid control strategy of pulse frequency modulation (PFM) and pulse width modulation (PWM) that can greatly increase the adjustable output voltage range. As a result of these designs, a silky target voltage can be achieved. The proposed LLC converter has been rigorously analyzed and parametrically designed. To verify the design parameters of the proposed LLC converter, a laboratory prototype with an output voltage range of 40-110 V and a maximum output power of 20 kW was fabricated. The rated output voltage and rated output current are 80 V and 200 A, respectively, while its switching frequency range is 100-250 kHz and its resonant frequency is 153 kHz. This prototype exhibits incredible robustness and stability, and achieves a flexible, stability and sensitivity to automatically adapt the target output voltage value.

INDEX TERMS High Power, LLC, Interleaved Parallel Topology, Off-Board Charger

I. INTRODUCTION
The vehicle, an incredible invention, has always been shaping and impacting the civilization of Mankind and has been driving the progress of human society for centuries[1]. In the overwhelming majority of the planet, the automobile has been an extremely significant transportation vehicle[2, 3]. Regrettably, in the recent century, the use of conventional vehicles has increased to the extent that it has caused environmental and human life hazards[4]. This is because these cars burn gasoline, diesel or natural gas, producing carbon dioxide (CO2), carbon dioxide (SO2) and oxides of nitrogen as harmful exhaust components[5]. For this reason, electric vehicles (EVs) have been proposed as a preferable alternative. In the last decade, electric vehicles(EVs) have been commercialized to reduce the demand for fossil fuels [6].

In modern plug-in electric vehicles, off-board chargers (OBC, off-board charger) are widely used in electric vehicles where an off-board charger is installed to charge a high-voltage battery, while the performance of the OBC is essential for the charging time. Fig.1 shows a typical structure of an off-board charger [7]. The structure of the most common off-board charger consists of an EMI filter and a two-stage converter [8]. In this two-stage converter, a boost AC-DC converter is used as a power factor correction (PFC) module to isolate harmonic pollution from the grid and provide pure supply of direct voltage to the next stage module. In addition, an isolated DC/DC converter is used to directly handle complex load conditions to accommodate the linear load characteristics and wide adjustable output voltage range of the EV’s high-voltage battery [9]. Therefore, the characteristics of this two-stage converter are largely influenced by the DC/DC converter, which means that the design of the DC/DC converter is particularly important for off-board chargers. Among the many topologies of DC/DC converters, LLC resonant converters are highly anticipated because of their high efficiency, high power density, low EMI and wide voltage range. Pulse frequency modulation (PFM) is commonly used in LLC converters to regulate the output power[10]. In order to further increase the adjustable
while maintaining a stabilized target output voltage value control accuracy over the specified output range and enables stability[15]. The proposed LLC converter has excellent stringent industry specifications with amazing robustness and 20 kW, and the proposed converter’s test machine passes the strategy dramatically increases the adjustable output voltage used for the proposed LLC converter[14]. This control modulation (PFM) and pulse width modulation (PWM) is this paper, a hybrid control strategy of pulse frequency chargers and to meet the relevant industry specifications. In accommodate the market demand for electric vehicle parameters. An ultra-high power converter is also required to realization of the converter control strategy and control supply technology provides a more flexible and strategic decrease current ripple optimally[13]. The digital power topology can effectively reduce voltage stress as well as parameters of the resonant tank is affected by the complex saturation. In addition, the relational function of the voltage gain of the resonant tank is affected by the complex parameters of the resonant cavity and presents a mathematically sophisticated relationship. Generally, the change of one parameter will have certain impact on several other parameters, so the design of resonant tank parameters is a very difficult engineering problem. In this paper, the proposed converter attempts to utilize a rational analysis method to solve these problems in order to design and fabricate a digitally off-board charger that can satisfy high power output requirements.

A laboratory prototype with an output voltage range of 40-110 V and a maximum output power of 20 kW was fabricated to verifying the design parameters of the proposed LLC converter. Its rated output voltage and rated output current are 80 V and 200 A, respectively, while its switching frequency range is 100-250 kHz and its resonance frequency is 153 kHz. The proposed LLC converter is employed as a DC/DC converter for a digitally off-board charger and forms a two-stage converter with an additional power factor correction (PFC) module.

II. PROPOSED CONVERTER

A. CIRCUIT CONFIGURATION

Fig.2 illustrates the schematic diagram of the proposed converter formed by two parallel LLC resonant converters, where each parallel LLC resonant converter is performed by a switch network and a resonant tank. The parallel LLC resonant converter is operated in control strategy of interlace phase. [20]

Since the proposed converter adopts an interleaved parallel topology, the design and selection of component parameters on each side are simplified.

To simplify the analysis, it is assumed that both of each parallel LLC resonant converters are identical. Additional, both of isolated transformers are possess same turn ratio and magnetizing inductances.

The switch network consists of switching devices Q1-Q8, with their parasitic anti-parallelled diodes Dds1-Dds8. The each LLC resonant is composed of a resonant inductor (Lr1 and Lr2), a magnetizing inductor (Lm1 and Lm2) and a resonant capacitance (Cr1 and Cr2).

T1 and T2 are two same isolated transformers, with same turn ratio, and linked to interlace full wave rectifier be applied to output circuit respectively.
It should be noted that both LLC resonant tank of the proposed converter are identical (i.e. \( L_r1=L_r2, \ Cr_1=Cr_2 \)) to ensure balanced resonant tank variables and to produce equal resonant frequencies to simplify the design consideration of parameter requirement.

Furthermore, switching frequency of switch network is required to operate at a range less than the resonant frequency and greater than the second resonant frequency. Hence, all inverter switching devices will be able to achieve manner of Zero Voltage Switch (ZVS) if LLC resonant tank impedance can behave inductively.

In addition, Wide load variation can be obtained on account of utilizing variable frequency control with hybrid control of pulse frequency modulation and pulse width modulation (PFM&PWM). This control strategy enhances the voltage output range, allowing the proposed converter to operate at soft switching under the conditions of most loads.

In order to alleviate current ripple, two switch network utilizing method of interlace phase, which the one of driveing voltage will be 90° out of phase than the other one. Hence, waveform of full wave rectifier also will be 90° out of phase than the other one.

Also, the aim of utilizing two parallel LLC resonant converters is to reduce voltage stress of each switching devices.

By reason of these disposal methods, not only the current ripple and temperature rise of proposed converter had been greatly reduced, but also output power has been dramatically enhanced. The improvement of these parameters can effectively improve the performance of the proposed converter and make it more suitable for application condition of high-power output, such as charging for electric vehicles.

### B. CIRCUIT CHARACTERISTICS AND ANALYSIS

The input voltage of LLC resonant tanks, \( V_s \) of the voltage source shown in Fig.3 that generated by the switching network. Based on Fourier analysis that builted by adopting first harmonic approximation (FHA) [21]. It is obvious that feeds the resonant tanks can be expressed using the formula as follows:

\[
V_s(t) = \frac{4V_g}{\pi} \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{n} \sin(n\omega_s t)
\]

Where \( V_g \) is the peak value of the switch network output square-wave voltage and \( \omega_s \) is the angular switching frequency. The input voltage of LLC resonant tanks contains harmonics of order 2n-1 (n=integer).

The circuit configuration and parameters of the LLC resonant tank on each side are identical. Therefore, the calculation process of the circuit parameters for each side of identical proposed converter can also be analogous. Assume that the input voltage \( V_s \) is applied to one of LLC resonant tanks as shown in the equivalent circuit in Fig.3 [22]. The AC voltage gain of the LLC resonant tanks can be obtained by splitting the voltage between the input and the output impedance[23]. The converter gain equation can be expressed as the following equations:

\[
Z_i = X_{Lr} + X_{Cr} + \frac{X_{Lm} + R_{ac}}{X_{Lm}R_{ac}}
\]

\[
Z_o = \frac{X_{Lm}R_{ac}}{X_{Lm} + R_{ac}}
\]

\[
G = \frac{V_o}{V_s} = \frac{\frac{N_i}{N_p}}{Z_i} = \frac{\frac{j\omega L_{mR}}{j\omega L_{m} + R_{ac}}} + \frac{\frac{j\omega L_{mR}}{j\omega L_{m} + R_{ac}}}{j\omega C_r + j\omega L_{m} + R_{ac}}
\]

Where \( R_{ac} \) is the effective ac resistance, \( \omega_0 \) is the angular switching frequency and \( N_s/N_p \) is the turn ratio of secondary to primary part. The effective resistance \( R_{ac} \) is converted from the secondary to primary part by using the transformer winding ratio, and determined by:

**FIGURE 3. Equivalent circuit of resonant tanks**

**FIGURE 4. Voltage gain versus the load-quality factor for characteristic of the proposed LLC converter**

**FIGURE 5. Voltage gain versus the inductance ratio for characteristic of the proposed LLC converter**
Similarly, the voltage gain of the other LLC resonant tanks can be obtained with the similar derivation, as both side LLC resonant tanks of proposed converter are thoroughly identical. Hence, the resonant tank parameters can be defined by the following expressions:

Resonance frequency:
\[ f_r = \frac{1}{\sqrt{2\pi L_r C_r}} \]  
(6)

Magnetizing frequency:
\[ f_m = \frac{1}{\sqrt{2\pi (L_r + L_m) C_r}} \]  
(7)

Characteristic impedance:
\[ Z_0 = \frac{L_r}{C_r} = 2\pi f_r L_r = \frac{1}{2\pi f_r C_r} \]  
(8)

Inductance ratio:
\[ K = \frac{L_r}{L_m} \]  
(9)

Load-quality factor:
\[ Q = \frac{Z_0}{R_{ac}} = \frac{2\pi f_r L_r}{R_{ac}} \]  
(10)

Where \( L_r \) is the resonant inductance, \( L_m \) is the magnetizing inductance and \( C_r \) is resonant capacitance. Further, the expressed equations of converter voltage gain can be derived as:

\[ G(x) = \frac{N_s}{N_p} K x^2 \left( 1 + K x^2 - (QK x(x^2 - 1))^2 \right)^{-1/2} \]  
(11)

Where the load-quality factor \( Q \) is defined to be the ratio between the characteristic impedance \( Z_0 \) and effective resistance \( R_{ac} \). Inductance ratio \( K \) is the ratio between resonance frequency and magnetizing frequency. Therein, normalized frequency \( x \) is the ratio between switching frequency and resonant frequency, that is \( x = f_s/f_r \).

From (11), it is known that the voltage gain is related to \( f_s \), \( Q \) and \( K \). In order to confirm the parameters of the LLC resonant tank, such as resonant inductance \( L_r \), magnetizing inductance \( L_m \) and resonant capacitance \( C_r \). The effect of \( Q \) and \( K \) on voltage gain need to be analyzed by using control variable method.

First of all, this is necessary that to determine a resonant frequency that is constrained by the appropriate size of the inductor device and the temperature rise of power module can be subjected, and then the range of switching frequency can be confirmed. Based on previous engineering experience, the resonant frequency \( f_r \) is chosen as 153 kHz and the turns ratio \( N_s/N_p \) is chosen as 3/14. Afterwards, the appropriate value that requires \( Q \) of proposed converter needs to be selected in order to determine the appropriate resonant inductance \( L_r \). A family of plots of the the voltage gain curve versus switching frequency for different values of \( Q \), with fixed \( K (K=0.225) \) is shown in Fig.4. A family of plots of the the voltage gain curve versus switching frequency for different values of \( K \), with fixed \( Q \) (Q=3.0) is shown in Fig.5. The voltage gain curve of this both condition is plotted by MATLAB to analyze and select the parameters of proposed

**FIGURE 6. Operation modes of proposed LLC converter**

**FIGURE 7. Relevant waveforms of the proposed converter**
To achieve the performance requirements of the proposed converter as illustrated in Table 1. The corresponding \( f_m \), dotted in blue, for each curve is marked in Fig.4-Fig.5 respectively, and they all have exactly the same \( f_r \) which dotted in green. \( K \) and \( Q \) can be selected by combining the voltage gain curve with calculation.

Based on Fig.4, it can be clearly seen that the choice of Load-quality factor \( Q \) is determined by a combination of factors such as voltage gain range and linearity of voltage gain curve. The voltage gain range of 0.03-0.4 was selected to meet the requirements of the output parameters and to reserve ample design margin. Hence, the curve with \( Q \) of 3.0 is selected as the optimal curve of proposed converter.

After \( Q \) and \( K \) are determined, the specific parameters of the LLC resonant tank, such as resonant inductance, magnetizing inductance and resonant capacitance, can be calculated, respectively. These specific parameters of the LLC resonant tank are theoretically proved to be able to satisfy the engineering design requirements of the maximum output power of 20kW for digital switching power supply module which is utilized for automobile charging pile. The specifications of the converter components are shown in Table 2.

Changing \( K \) under a fixed \( Q \) as shown in Fig.5, the difference between resonance frequency and magnetizing frequency \( (\Delta f = f_s - f_m) \) increases firstly and then decreases with the increase of switching frequency. Specially, when \( k \) is approximately 0.3, the \( \Delta f \) of voltage gain curve achieve the maximum. After sufficient considering the requirements of manufacturing process and design margin, the inductance ratio \( k \) is defined as 0.225.

### III. OPERATION PRINCIPLE

The operation of proposed converter, consist of two parallel LLC resonant converter, can be summed up as the control strategy of interlace phase. As a result of this control strategy of interlace phase, the operation principle of two parallel resonant converters are identical. It should be pointed out that one of them will be a quarter of a cycle later than the other [24].

To simplify the analysis the proposed converter system, we only discuss operation principle of the one for the
proposed converter. Empirically, the operation principle of the other side of the converter is operated analogously [25].

The hybrid control of pulse frequency modulation (PFM) and pulse width modulation (PWM) is employed to regulate output voltage of the proposed converter [26]. When the converter is attached to a lighter load range, the switching network turns on and off with 50% duty cycle at switching frequency $f_s$ [27]. When the converter is attached to a heavier load range, the switching network modulated the duty cycle of the driving square wave at a certain fitted frequency [28]. When $f_s > f_r$, the circuit has 6 operation modes in one cycle, the key waveforms of the proposed converter are shown in Fig.7. Furthermore, the topological equivalent circuits of one side are given in Fig.6.

Operation modes 1 (t0-t1): In the first operation modes shown in Fig.6(a), while the input impedance characteristics of resonator is perceptual, Q1 and Q3 are gated simultaneously. As a result of the clamping action of the parasitic anti-parallelled diodes, ZVS turn-on of switching device Q1 and Q3 are realized. In addition, the voltage drop of $L_m$ is relatively low and unable to provide sufficient conduction drop to secondary part in this operation modes.

Operation modes 2 (t1-t2): In the second operation modes shown in Fig.6(b), the resonant current still does not change direction. The energy is transmitted from primary side of transformers to the secondary side, the voltage of $L_m$ increases linearly. Distinctly, ZCS turn-on of rectifier diode are realized.

Operation modes 3 (t2-t3): In the this operation modes shown in Fig.6(c), while Q1 and Q3 still are gated simultaneously, the resonant current $I_{Lr}$ starts to reverse dexterously. The energy of load originates from magnetizing current and resonance current, collectively.

Operation modes 4 (t3-t4): In the this operation modes shown in Fig.6(d), while Q1 and Q3 still are gated simultaneously, the magnetizing current $I_{Lm}$ starts to reverse dexterously. The energy of load and magnetizing inductance derived from resonance current. When this operation modes is finished, the rectifier current on the side of secondary part will drop to zero sinusoidally, thus achieving ZVC.

Operation modes 5 (t4-t5): In the this operation modes shown in Fig.6(e), while Q1 and Q3 still are gated simultaneously, the energy quit the transfer between the primary side of transformers to the secondary side as the reason of energy of the LLC resonant tank is excessive low.

Operation modes 6 (t5-t6): In the last operation modes shown in Fig.6(f), while Q1 and Q3 are shuted simultaneously, the proposed converter operating in dead

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**FIGURE 9.** Laboratory prototype

**FIGURE 10.** Gate voltage of MOSFET for switching network

**FIGURE 11.** Dynamic Response

**FIGURE 12.** Resonant current inside the resonant tank

Hence, it is obvious that no current passes through the full wave rectifier circuit on the side of secondary part.

Operation modes 2 (t1-t2): In the second operation modes shown in Fig.6(b), the resonant current still does not change direction. The energy is transmitted from primary side of transformers to the secondary side, the voltage of $L_m$ increases linearly. Distinctly, ZCS turn-on of rectifier diode are realized.

Operation modes 3 (t2-t3): In the this operation modes shown in Fig.6(c), while Q1 and Q3 still are gated simultaneously, the resonant current $I_{Lr}$ starts to reverse dexterously. The energy of load originates from magnetizing current and resonance current, collectively.

Operation modes 4 (t3-t4): In the this operation modes shown in Fig.6(d), while Q1 and Q3 still are gated simultaneously, the magnetizing current $I_{Lm}$ starts to reverse dexterously. The energy of load and magnetizing inductance derived from resonance current. When this operation modes is finished, the rectifier current on the side of secondary part will drop to zero sinusoidally, thus achieving ZVC.

Operation modes 5 (t4-t5): In the this operation modes shown in Fig.6(e), while Q1 and Q3 still are gated simultaneously, the energy quit the transfer between the primary side of transformers to the secondary side as the reason of energy of the LLC resonant tank is excessive low.

Operation modes 6 (t5-t6): In the last operation modes shown in Fig.6(f), while Q1 and Q3 are shuted simultaneously, the proposed converter operating in dead
zone. Furthermore, the residuary energy of parasitic anti-parallelled diodes derived from resonance current.

IV. SIMULATION RESULTS
The simulation results for different operating conditions are shown in Fig.9-Fig.11. They are the simulated waveforms at 25%, 50%, 75% and 100% output power, respectively. Q1 and Q4 are the driving voltages for one of the switching networks, while Q6 and Q7 are the starting voltages for the other set of switching networks. iLr is the resonant current and iLm is the magnetizing current, which are drawn in the same figure to facilitate the analysis. iD1 and iD2 are the rectifier diode currents from the rectifiers of the two parallel circuits respectively. From these simulation figures, it can be clearly observed that the proposed converter operates in the identical pattern to the one we previously analyzed. All figures are simulated at an output of 100V, and the output currents corresponding to Fig.9- Fig.11 are 50A, 100A, 150A and 200A respectively. It is obviously seen that as the output power increases, the resonant and magnetizing currents and rectifier diode currents increase, but also the switching frequency decreases accordingly.

V. EXPERIMENTAL RESULTS
An laboratory prototype of the proposed converter with an output voltage range of 40-110V was designed and fabricated for experimentations and testing, which has a maximum output of 20kW (As shown in Fig.9). It has a resonant frequency of 153 kHz and a switching frequency range of 100-250 kHz, in addition to the parameters of its resonant tank as what was discussed previously, as shown in Table 1.

Due to the wide output range of the proposed converter, the output power can be automatically adjusted according to different load conditions, and the output power can be switched sensitively and smoothly while maintaining the target output voltage value.

Fig.10 shows the gate voltage of the MOSFETs of the full switching network of the proposed converter. The rise time of the gate voltage is 1.7us, which can ideally meet the demand of frequency modulation.

In addition, Fig.11 shows the output voltage, the gate voltage of the switching network and output current of the PFC module from interface port when the load changes abruptly. This is the waveform when the output of the prototype is given to a lower load and then suddenly shifted to a heavier load. This shows that the dynamic performance of the laboratory prototype is satisfactory and that the control strategy adapts smoothly and swiftly to various load conditions and output parameters.

Fig.12 shows the gate voltage and the resonant current of the resonant tank of the proposed prototype for the switching network at full load. It can be shown obviously from Fig. 12 that the proposed LLC converter operates as analyzed in the previous sections, with the resonant tank current presenting a fairly optimum sinusoid. Additionally, the disturbance to the resonant tank current during the gate voltage switching is relatively slight, which is attributed to the advantageous layout design.

Figure 13 shows the output accuracy of the proposed converter for different input voltage conditions. The prototype of the proposed digital power module is subjected
to a series of accuracy tests according to NB/T 33008.1-2013 (Inspection and test specifications for electric vehicle charging equipment Part 1: off-board charger). Firstly, according to the requirements of NB/T 33008.1-2013 voltage regulation accuracy test, the AC input voltage of the module varies in the range of 85% to 120% of its rated value and the output current varies in the range of 0 to 100% in the regulated state. The output voltage of the proposed LLC converter can be automatically regulated at any value within its regulated range, and the accuracy of voltage regulation does not exceed ±0.5% (as shown in the table). Moreover, the experiment was conducted not only at room temperature, but also at high temperature (45°C) and low temperature (-30°C). For the proposed prototype of the digital power module, the deviation increases slightly when increasing the output power. Nonetheless, its voltage regulation accuracy does not exceed ±0.25% for each different condition.

The operating temperature of the laboratory prototype is shown in Fig. 14. This line graph's shows how the temperature of the different components of the laboratory prototype during regular operation at different output conditions. In this case, the different parts of the laboratory prototype are represented by different crease lines. All test data are measured at an average room temperature of 36°C. It can be visualized from this graph that the operating temperatures of the switching network devices were all around 50°C and did not exceed 55°C even at maximum power output then, the operating temperature of the resonant inductor core did not exceed 70°C at all output powers.

The operating temperature of the transformer increases more significantly when the output power reaches a maximum power of 20kW and reaches a maximum temperature of 95°C. But the tester's operating temperature of its transformer basically stays around the average of 72°C when it is not brought to full load. Moreover, the largest source of power consumption in the prototype is the transformer, and the subsequent rectifier diode, which is why they also have the greatest operating temperature. In this regard, the operating temperature range of the rectifier diodes did not exceed 82°C in any of the cases of maximum output power. However, it is noteworthy that the operating temperature of the voltage device does not exceed 90°C in any case, except when the maximum power output of the test machine reaches a maximum of 101.2°C. The test data shows that the operating temperature of all parts of the laboratory prototype inside the normal output range can be controlled within the satisfactory range due to the excellent heat dissipation design.

The efficiency of the complete on-board charger is 93.21%, 95.20% and 94.30% at 20%, 50% and 100% load, respectively, while the efficiency of the converter proposed in this paper is 97.2%, 97.8% and 97.8%.

The proposed LLC converter and the PFC-based AC-DC converter are integrated into a digital power supply module, for which a series of functional and performance tests are undertaken according to NB/T 33008.1-2013. According to NB/T 33008.1-2013, the functional parameters of the module, such as the given range of output voltage, the given range of output current and the given range of input start-up voltage,
are all up to the standard and can operate normally under the specified working environment.

According to the requirements of the startup output voltage overshoot test of NB/T 33008.1-2013, the startup overshoot should be no more than ±1% under the rated output conditions. For the prototype of the proposed digital power module, the start-up overshoot is only 0.35%, which optimally satisfies the performance requirements of this standard.

Collectively, the stability and accuracy of the prototype of the proposed digital power module can excellently satisfies the requirements of NB/T 33008.1-2013.

VI. CONCLUSION

The proposed LLC converter which is used as a DC/DC converter for digital off-board chargers was introduced in this paper. The LLC converter has an interleaved parallel topology with a hybrid control strategy of pulse frequency modulation (PFM) and pulse width modulation (PWM). This control strategy dramatically expands the adjustable output voltage range and can smoothly output the target voltage. To satisfy the high output power requirements of modern digital off-board chargers, and the proposed LLC converter has been analyzed and parameterized critically. To verify the design parameters of the proposed LLC converter, a laboratory prototype with an output voltage range of 40-110 V and a maximum output power of 20 kW was fabricated. The prototype passed a series of tests with amazing robustness and stability to the stringent industrial specifications, achieving outstanding accuracy of control within the specified output range. It also enables sensitively automatic adjustment as load conditions are varied, while maintaining a stable target output voltage value.

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