A SiC-Based 60kW LLC Converter with Novel Transformer Design for Improving Voltage Balance and Wide Output Voltage Range

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Abstract

This paper introduces a novel transformer design to address the voltage imbalance issue for an LLC converter with multiple transformers in series to support a wide output voltage range. The proposed transformer design is implemented on a digital controlled SiC-based 60kW prototype with a switching frequency of 125kHz-250kHz. Identical voltage balance is demonstrated in a three phase LLC converter with 200Vdc-1000Vdc wide output voltage range and exceeding 98.5% in peak efficiency for EV fast charger.

1 Introduction

With continuously improving batteries and consumers demanding quicker turnaround on charging, the required power rating of a single charging pile is increased from 100kW to 500kW or even higher. The design trend of the DC fast charging module is towards high power rating, high efficiency, wide output voltage range and wide constant power operation range. The typical output voltage range is from 200Vdc to 1000Vdc to cover different EVs.

In each of the EV charging power module, there is a PFC stage followed by an isolated DC/DC stage. LLC converter is very attractive for the isolated DC/DC stage due to its ZVS operation and high efficiency [1]-[2]. However, as the power rating increases, the current ripple on the output and input capacitors is so large. The size and cost of the input and output capacitors become impractical. With the natural current sharing and the input and output ripple current cancellation, the three-phase resonant LLC converter was proposed and studied in [3]-[5]. It is the best fit for high power DC/DC converter. On the other hand, the output voltage range of LLC converter is limited. 2 level DC/DC solution was studied for wide output voltage range in EV chargers [6]. The constant current operation is achieved for a wide output voltage range with the flexible control scheme. But it is not able to support the constant power in a wide output voltage range. To support the constant power operation with wide voltage range, the outputs of two independent LLC converters can be connected by three switches. The outputs of the converters can be connected in series for high output voltage or in parallel to support the larger output current with lower output voltage. Compared to a single converter, the number of the required PWM outputs, the gate drivers, the resonant tanks and the current sensors have to be doubled. The cost is higher.

To simplify the control and reduce the cost, based on 1200V rated SiC MOSFETs, single converter solution with two transformers was studied in [7]. The current sharing is good with primary-series–secondary-parallel for the converter. However, the voltage difference can be large with the conventional transformer design in the primary-series–secondary-series mode. This has a significant impact on the selection of the output rectifiers, output filtering capacitors and the design of the power transformers.

This work will systematically investigate factors affecting the voltage balance. A SiC MOSFET-based digital controlled 60kW 2 level three-phase interleaved LLC resonant converter is designed. A novel transformer design is proposed and studied to achieve wide output voltage range. The experimental results for the converter manifest both high efficiency, high power density and good voltage balance at wide output voltage range.

2 The Specifications and Architecture of the DC/DC

2.1 Specifications

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The specifications are listed in Table 1. A resonant frequency of 180kHz was selected as a trade-off between efficiency and power density. The output voltage range is from 200V to 1000V while the DC link voltage range is from 650V to 870V. The converter supports wide voltage range from 300V to 1000V in constant power mode. The maximum output power is 60kW. The max output current rating is 200A. The target peak DCDC efficiency is above 98%. And the target efficiency is above 97% for full load. Forced air cooling is applied to the design.

DC Input Voltage	650Vdc-870Vdc
Battery side Voltage	200Vdc-1000Vdc
Rated Power	60kW Vout>=300Vdc; I_out_Max=200A
Peak Efficiency	> 98% at half load and > 97% at full load @300Vdc

Table 1: Specifications of the 60kW DC/DC converter

2.2 Topology

Figure.1 shows the block diagram of the 60kW three-phase interleaved LLC DC/DC converter. The input is isolated from the output through three high frequency transformers. Each transformer has one primary winding and two secondary windings. At primary side, there are three half-bridges based on 1200V SiC MOSFETs and three sets of resonant tanks. At secondary side, there are full-bridge rectifiers connected to the secondary windings of the transformers. The two outputs can be connected in series or in parallel through the configuration of S1~S3.

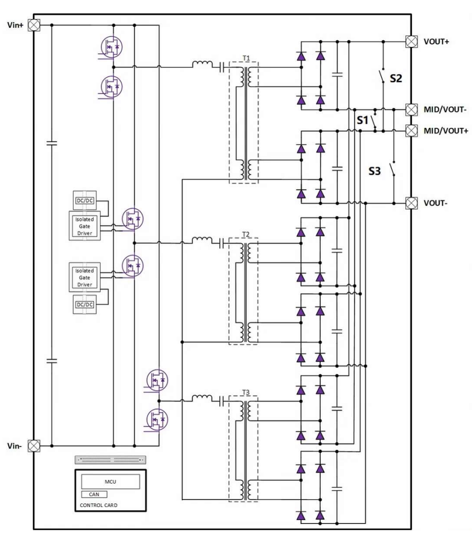

Fig. 1: Block diagrams of the 60kW DC/DC converter

2.3 Power Semiconductors and Resonant Frequency Selection

The maximum DC-link voltage is 870Vdc. The battery voltage is up to 1000Vdc. SiC MOSFET C3M0040120K 1200V 40mohm in TO-247-4L package is selected for the half-bridges at the primary side. SiC Schottky Diodes C6D20065D 650V 20A is selected for full-bridge rectifiers at the secondary side. The total usage is 12pcs for C3M0040120K. And it is 24pcs for C6D20065D in the design.

To get high efficiency and high power density, it is a trade-off to select the resonant frequency. 180kHz is selected for the resonant frequency.

Key design parameters are shown in Table 2.

Resonant frequency	180 kHz	Resonant choke primary	7 uH
Minimum switching frequency	125 kHz	Resonant cap primary	108 nF
Maximum switching frequency	250 kHz	Magnetizing inductance	30 uH

Table 2: Key design parameters.

3 The Output Voltage Balance Issue, the Factors Affecting the Voltage Balance and the Impact

3.1 The Output Voltage Balance

For the 60kW three-phase LLC converter, as shown in Figure 1, the primary windings are connected in series and then connected to the resonant tank. In this way, when the secondary side is connected in parallel, the secondary windings can naturally achieve current sharing. However, when the secondary side is connected in series, these two transformers may encounter a voltage imbalance issue. At primary side, the two outputs share the same primary power switches and the resonant tank. There is no difference. At output, the voltage drop on the output rectifiers can be different due to the device to device difference. But the voltage drop difference about ±0.3V. It is very small compared to the output voltage. The parasitic inductance of the output commutation loop is also part of the equivalent resonant circuit. It can also impact the voltage gain and output voltage. But with proper PCB design, the parasitic inductance can be managed very well. So the

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voltage balance mainly depends on the symmetry of the relevant parameters of the two transformers for each phase, including the coupling of the windings and the magnetizing inductance.

3.2 The Simulation Results and the Test Results of the Conventional Design

Considering the yield rate and the cost of the power transformers based on litz wire windings, the allowed coupling between primary and secondary windings can vary from 0.97 to 0.99. Refer to the simulation result in Fig. 2. With the coupling of 0.99 for the high side and 0.97 for the low side, the voltage difference between the two outputs is about 34V at 800V output.

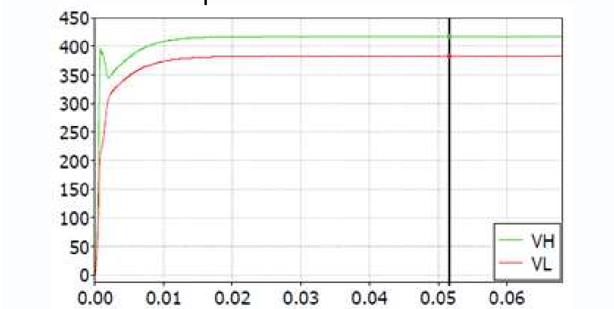

Fig. 2: Simulation results of the output voltage difference for the coupling mismatch.

Considering the yield rate and the cost of the power transformers, the achievable tolerance of the magnetizing inductance is about ±7%. Refer to the simulation result in Fig. 3, set the 15uH magnetizing inductance at upper limit for the high side and at the lower limit for the low side, the voltage difference between the two outputs is about 50V at 800V output.

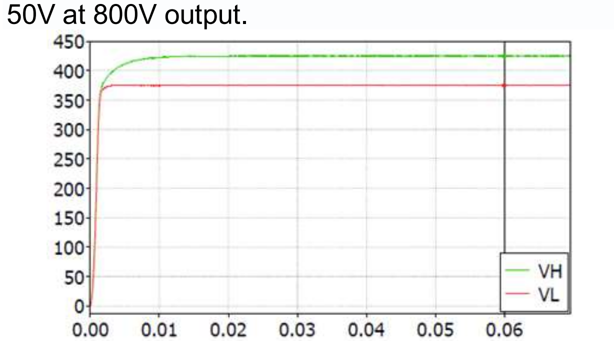

Fig. 3: Simulation results of the output voltage difference for the magnetizing inductance mismatch

Combine the coupling and magnetizing inductance mismatch in the simulation, the voltage difference between the high side and low side is about 78V at full load as shown in Fig. 4.

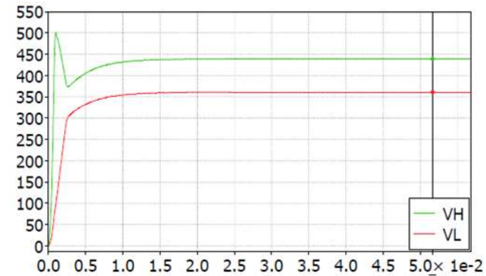

Fig. 4: Simulation results of the output voltage difference with the coupling and magnetizing inductance mismatch.

3.3 The Test Results and the Impact

As shown in Fig. 5, a digital controlled 60kW DC/DC prototype including the DC/DC power board, the control board, and the auxiliary power board is built to verify the simulation.

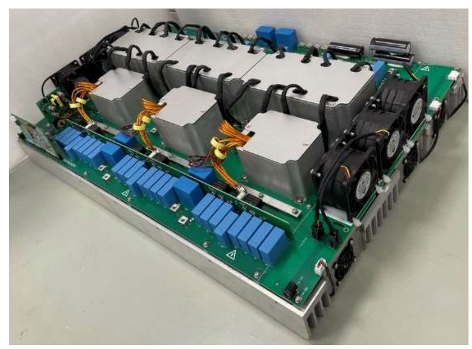

Fig. 5: Photo of the 60kW DC/DC prototype

As shown in Table. 3, the measured voltage difference between high and low side outputs is up to 71 V for 800V output in series mode.

Test result			
Output	Load	VH	VL
500V	20%	240V	262V
	50%	228.6V	271.9V
	100%	222.3V	278.6V
800V	20%	383.6V	416.9V
	50%	377V	422.7V
	100%	364.7V	435.3V

Table. 3: Test results of output voltage difference with the coupling and magnetizing inductance mismatch.

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We didn't perform the test at 1000V output. Because the output voltage of each output is up to 500V while the 650V output rectifiers were selected in the design. It is ok on the voltage stress but without too much margin if the voltage sharing between the two outputs is good. With the voltage difference, they can be over voltage stress. If we change the output rectifiers to 1200V devices, the system level performance will be impacted since the voltage drop of the 1200V rectifiers is higher and the parasitic capacitor is larger. It will also impact the overall cost. In addition, with the voltage difference, the power loss on the transformers are different. It will impact the thermal of the transformer and the efficiency of the converter.

4 The Proposed Solution and the Results

4.1 The Proposal and the Simulation Results

To get a better coupling between the two secondary windings of each transformer, as shown in Fig.6, a special winding coupling method is proposed to reduce the impact of the parameter tolerances of the two transformers on the voltage balance. First, for each transformer, the output winding can be split into two windings with good coupling. Two wires in parallel for the two windings. Then for each phase, the two transformers have the output windings cross coupled with each other. In this way, even with the tolerance on the transformer, with the coupling of 0.99 for the high side and 0.97 for the low side, magnetizing inductance 15uH at upper limit for the high side and at the lower limit for the low side, refer to the simulation results as shown in Fig.7, the two outputs match with each other very well.

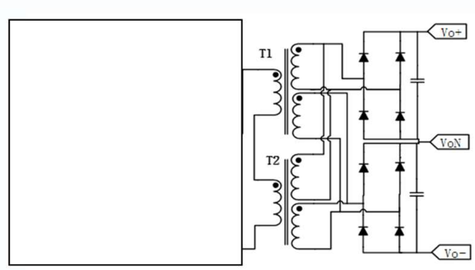

Fig. 6: The proposed solution for one of the three phases.

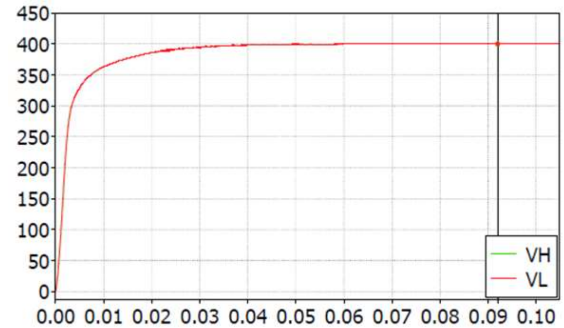

Fig. 7: Simulation results of the proposed solution with the coupling and magnetizing inductance mismatch.

4.2 Test Results

With the proposed transformer design, the testing waveform for 500Vdc output, 800Vdc output and 1000Vdc output are shown in Fig. 8, Fig. 9 and Fig. 10. The two outputs match with each other very well.

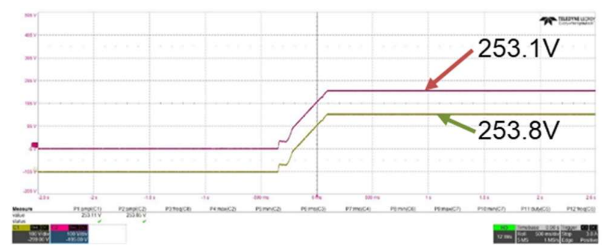

Fig. 8: Output waveforms of the high low side during start-up 500V output.

Fig. 9: Output waveforms of the high low side during start-up 800V output.

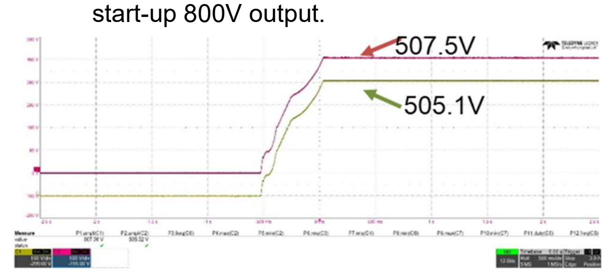

Fig. 10: Output waveforms of the high low side during start-up 1000V output.

As shown in Table. 4, the measured output voltage of the high and low side outputs also match with each other very well.

Test result			
Output	Load	VH	VL
500V	20%	250V	249.8V
	50%	250V	250V
	100%	253.1V	253.8V
800V	20%	401.7V	400.4V
	50%	403.2V	402.1V
	100%	404.5V	406.1V
1000V	20%	506.8V	505.7V
	50%	506.3V	505.5V
	100%	507.5V	505.1V

Table. 4: Test results of output voltage with the proposed transformer design.

The testing waveform for 300Vdc output voltage and 720Vdc input is shown in Fig.11. ZVS is achieved for all three half-bridges.

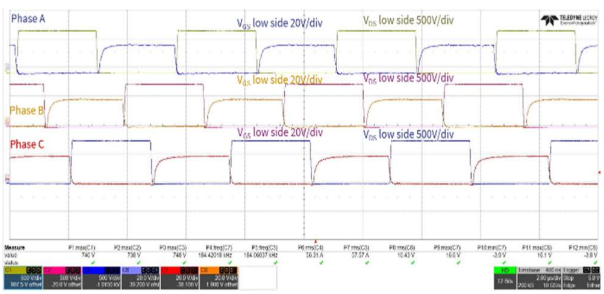

Fig. 11: Vgs and Vds waveforms

As shown in Fig.12, The current sharing can be achieved among the three resonant tanks.

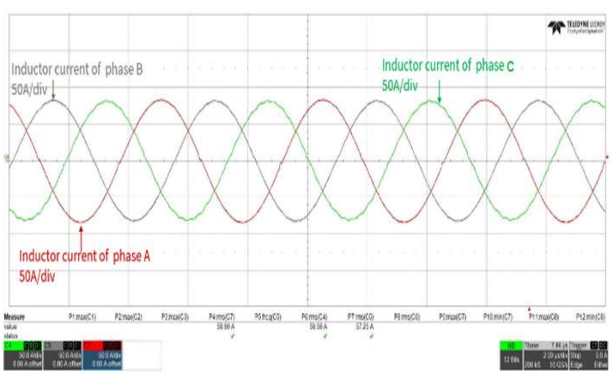

Fig. 12: Current waveform of resonant tanks

4.3 Efficiency Test Result

The efficiency of the 60kW DC/DC converter at different test conditions is shown in Fig.13. Input voltage and output voltage are marked in the curve. With the proposed flexible control scheme, for 300V output and above, above 98% peak efficiency and above 97% full load efficiency is demonstrated by the prototype with a switching frequency range 125-250kHz.

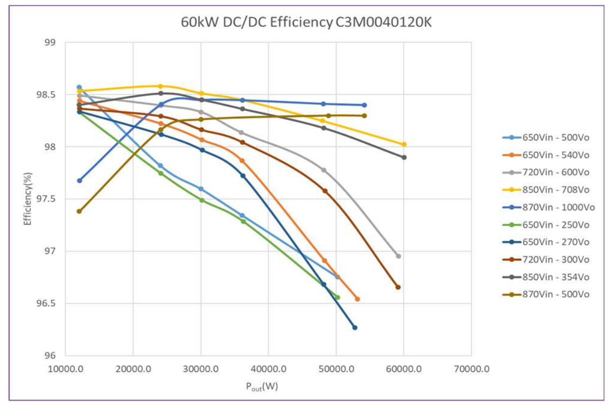

Fig. 13: Efficiency Curve of the 60KW DC/DC Converter

4.4 Thermal Test Result

In the thermal test of the prototype, forced air cooling was applied to the board using the attached heatsinks. T-type thermal couplers and KEYSIGHT 34972A acquisition unit are used to measure the case temperature of components.

Description	Rth j-c (c/w)	Calculated Power loss(watts)	Measured Case Temp. (°C)	Calculated Junction Temp. (°C)
Input: 730Vdc, Output: 300Vdc 60KW 200A				
MOSFET	0.46	33.2	96.6	111.9
Input: 650Vdc, Output: 200Vdc 130A				
MOSFET	0.46	47.5	101.6	123.4
Input: 870Vdc, Output: 500Vdc 60KW				
MOSFET	0.46	31	95.8	110.1

Table 5: Thermal Test Results.

The thermal test results are shown in Table 5. The junction temperature is calculated based on the measured case temperature, thermal resistance of the MOSFET and calculated component power loss. The maximum junction temperature of C3M0040120K is 175°C in the datasheet.

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Referring to the test result, the max junction temperature of the SiC MOSFET is 123.4°C in the application. We conclude that the SiC MOSFETs meet the thermal de-rating requirement in the design.

5 Summary

In this paper, A novel transformer design is proposed and verified on a digital controlled SiC-based 60kW prototype to address the voltage imbalance issue for LLC converter with multiple transformers. Identical voltage balance is achieved. And the SiC-based prototype with a switching frequency of 125kHz-250kHz is demonstrated with 200Vdc-1000Vdc output voltage range and exceeding 98.5% in peak efficiency. It is very useful for the high-power LLC converter with wide voltage range such as EV charger applications.

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