A SiC Based 30kW Three-Phase Interleaved LLC Resonant Converter for EV Fast Charger

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Abstract

This paper presents a SiC MOSFET-based 30kW three-phase interleaved LLC resonant converter for Electric Vehicle (EV) fast charger, with high efficiency, high power density and wide output voltage range. A flexible gain control scheme of the three-phase LLC resonant converter is studied. A digital controlled prototype with a switching frequency range of 135kHz-250kHz is demonstrated with 200Vdc-1000Vdc output voltage range, 6.5kW/L power density and exceeding 98% in peak efficiency.

1 Introduction

DC fast chargers bypass the on-board charger installed on the electric vehicle and provide a fast DC charging to the battery directly. The sales of electric vehicles (EV) are set to accelerate rapidly over the coming decades. This brings huge demand and opportunity on fast charging.

The AC-bus type power distribution architecture which is the mainstream for the fleet charging station now. In a charging station, AC power is distributed to several charging piles. In each of the charging pile, several charging power modules operate in parallel to provide high power output. In the charging module, there is an AC/DC stage followed by a DC/DC stage. We focus on the DC/DC stage in this study.

With continuously improving batteries and consumers demanding quicker turnaround on charging. The required power rating of a single charging file is increased from 100kW to 350kW or even 500kW. 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. The output power rating of a single power unit is towards to 30~60kW.

LLC converter is very attractive for the isolated DC/DC stage due to its ZVS operation and high efficiency [1]-[2]. To support 800V DC-link voltage, based on 600V Si MOSFET, the cascode full bridge LLC converter was adopted for the fast chargers with power rating less than 20kW for years. In recent years. With the price reduction and capacity increase of SiC, 2 level full bridge LLC converter became a good candidate. Based on 1200V rated SiC MOSFETs, 2 level DC/DC solution is suitable for high power EV chargers for 800V DC-link voltage[3]. Compared to the cascode solution, it only has half the number of the primary switches. The conduction loss on primary MOSFETs is also reduced significantly. In addition, one of the resonant tanks can be saved. It helps to improve the efficiency and power density of the charging power module.

However, as the power levels increase, there are some drawbacks on full bridge LLC converter. The current ripple on the output and input filtering capacitors is large. As a result, the size and cost of the required filtering capacitors become impractical at higher power levels. 2 phases interleaved LLC solution was studied [4]-[5]. However, the current sharing control between the two phases is complex. A three-phase resonant converter was proposed and studied in [6]-[9]. In this topology, three transformers are star connected in the primary with a floating star point. The current sharing between the phases is automatically improved compared to the two phases interleaved LLC. The ripple current is also much lower than full bridge LLC converter. The other notable improvement comparing to a full bridge LLC is that the current stress of the primary side MOSFET is also reduced.

In this paper, a SiC MOSFET-based digital controlled 30kW 2 level three-phase interleaved LLC resonant converter is designed. 6 pcs 1200V mohm SiC MOSFETs support 30kW output power rating. A flexible control scheme is studied to achieve wide output voltage range. The experimental results for the converter manifest both high efficiency and high power density at wide output voltage range.

2 The Specifications and Architecture of the DC/DC

2.1 Specifications

Table 1 provides the major design specifications of a 30kW DC/DC converter for EV fast charger. The output voltage range is from 200V to 1000V while the DC link voltage range is from 650V to 850V. The converter supports wide voltage range from 300V to 1000V in constant power mode. The maximum output power is 30kW. The max output current rating is 100A. The target peak DCDC eff 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-850Vdc
Battery side Voltage	200Vdc-1000Vdc
Rated Power	30kW Vout>=300Vdc; I_out_Max=100A for Vout<300V
Peak Efficiency	> 98% at half load and > 97% at full load @300Vdc

Table 1: Specifications of the 30kW DC/DC converter

2.2 Topology

Figure.1 shows the block diagram of the 30KW 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. With 3 windings in group one, the rectifiers provide output A. The other 3 windings provide output B. The two outputs can be configured in parallel mode or in series mode based on the system level requirements.

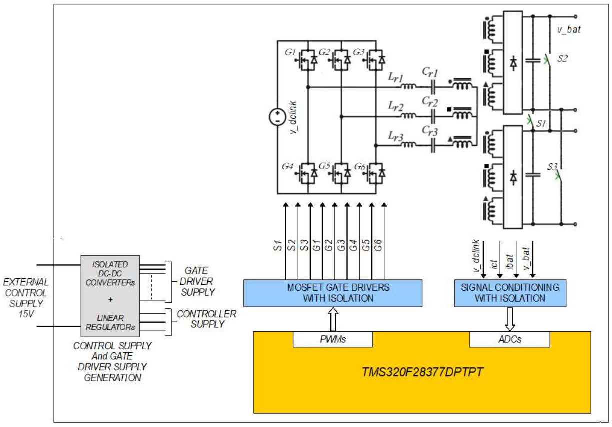

Fig. 1: Block diagrams of the 30kW DC/DC converter

2.3 Power Semiconductors and Resonant Frequency Selection

A smaller output capacitance (Coss) is critical for achieving achieve zero voltage switching (ZVS) with a lower magnetizing current for the LLC resonant converter. With reduced magnetizing current, the conduction loss and turn-off switching loss of the MOSFET can be minimized. Even it is ZVS for LLC converter, it is zero voltage turn-on only. It is still hard switching for turn-off. So fast switching speed is also very important for the efficiency. The maximum DC-link voltage is 850Vdc. 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 10A*2 in TO-247-3L package and C6D10065A 650V 10A in TO-220 package are selected for full-bridge rectifiers at the secondary side. The total usage is 6pcs for C3M0040120K. And it is 6pcs for C6D20065D and 12pcs for C6D10065A in the design.

To get high efficiency and high power density, it is a trade-off to select the resonant frequency. Higher resonant frequency helps to reduce the size of magnetics. But it also impacts the efficiency and thermal performance of the converter. To achieve above 98% efficiency at half load and above 97% efficiency at full load, based on the simulation and calculation. 180kHz is selected for the resonant frequency.

2.4 Digital Control

Digital controller TMS320F28377D was chosen to implement the flexible control. It achieves all the sensing of input voltage, output voltage, output current and the currents of three branch resonant tanks, and it provides 6 independent PWMs G1-G6 to MOSFETs Q1-Q6 of the LLC converter. The controller also handles the real-time CAN communication, start-up sequence and protections.

2.5 Magnetics and Key Parameters

The main transformer of the LLC converter is designed to meet the requirements of both 1000V/30A and 300V/100A output. The max flux density and core loss are designed and verified at 850V DC-link and 1000V/30A output. The winding wire size is designed for maximum current conditions with 650V DC-link and 300V/100A output. With a bobbin-less design, the window area of the core can be fully utilized. Next, a PQ6562 core using 3C97 material is selected. Three transformers are used for the 30kW LLC converter. To meet the gain range requirements for 200V-1000V, a 12:11:11 turns ratio is selected.

Key design parameters are shown in Table 2.

Resonant frequency	180 kHz	Resonant choke primary	11.8 uH
Minimum switching frequency	135 kHz	Resonant cap primary	66 nF
Maximum switching frequency	250 kHz	Magnetizing inductance	40 uH

Table 2: Key design parameters.

3 The Proposed Flexible Voltage Gain Control Scheme

A flexible control of three-phase interleaved LLC resonant converter is studied in the paper. It operates in the conventional Pulsed Frequency Modulation (PFM) combined with phase shedding and phase shift control.

3 switches are used to re-configure the output stage.

As shown in Fig. 2, to achieve the required voltage range and high efficiency, the DC-link voltage is variable between 650V and 850V. In this design, 3 switches are applied to configure the outputs flexibly. when the required output voltage is higher than 500V, the outputs A and B are connected in serials. When the battery voltage is less than 500V, the outputs A and B are connected in parallel to provide high current.

In this way the output voltage range is reduced to 200V to 500V. A flexible control is implemented to cover this range.

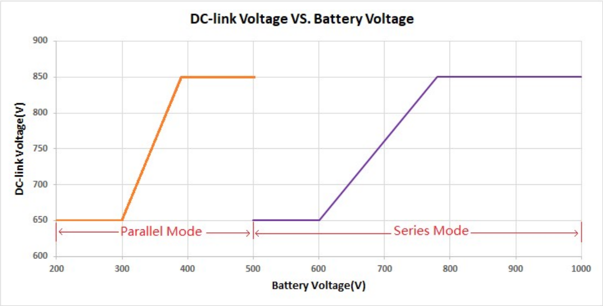

Fig. 2: DC-link vs. battery voltage.

As shown in Fig. 3, in series mode, in the output voltage range 600V-780V, the DC-link voltage setting of the AC/DC converter follows the output voltage by the turns-ratio 12:11 of the power transformer. The DC/DC converter operates around the resonant frequency with best efficiency. In the output voltage range 780V-1000V, the DC-link voltage is fixed at 850V. the DCDC converter operates in boost mode. In the output voltage range 500V-600V, the DC-link voltage is fixed at 650V. The converter operates in step-down mode. With higher turn-off current and higher switching frequency, the efficiency of the converter is compromised due to higher switching loss.

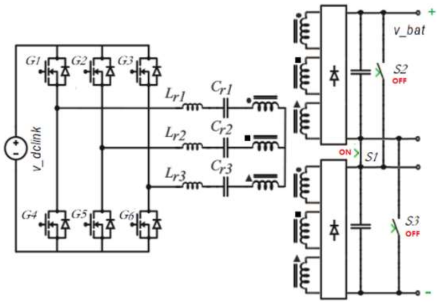

Fig. 3: Three-phase interleaved LLC converter with secondary side in series mode.

As shown in Fig. 4, in parallel mode, in the output voltage range 300V-390V, the DC-link voltage follows the output voltage by the turns-ratio 12:11 of the power transformer. The DCDC converter operates around the resonant frequency with best efficiency. In the output voltage range 390V-500V, the DC-link voltage is fixed at 850V. the DCDC converter operates in boost mode. In the output voltage range 250V-300V, the DC-link voltage is fixed at 650V. The converter operates in step-down mode.

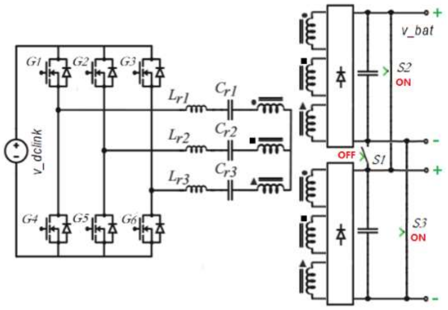

Fig. 4: Three-phase interleaved LLC converter with secondary side in parallel mode.

When the output voltage is lower than 250V, to reduce the switching loss, the duty cycle of G3 and G6 is set at zero, Then the LLC converter can operate as full-bridge LLC as shown in Figure 5. the full-bridge LLC converter operates in the conventional Pulsed Frequency Modulation (PFM) combined with phase shift control, to optimize the efficiency.

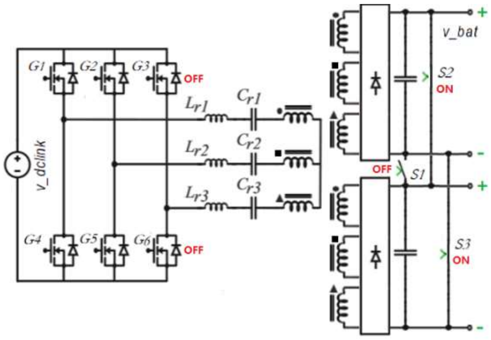

Fig. 5: Full bridge LLC converter by turn off G3 and G6.

4 Hardware Implementation and Results

4.1 Prototype

As shown in Fig. 6, a digital controlled 30kW DC/DC prototype is built to verify the design. The PCBA dimensions are 255mmx275mmx65mm, including the DC/DC power board, the control board, and the auxiliary power board. Forced air cooling is applied for the thermal management of the power semiconductors and magnetics.

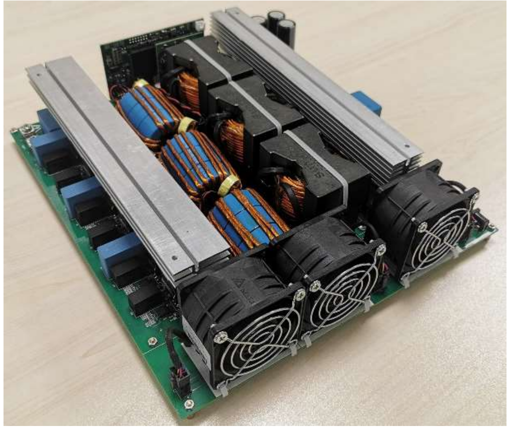

Fig. 6: Photo of the 30kW DC/DC prototype

4.2 Key Waveforms

The testing waveform for 300Vdc output voltage and 650Vdc input is shown in Fig.7. ZVS is achieved for all three half-bridges.

As shown in Fig.8, The current sharing can be achieved among the three resonant tanks.

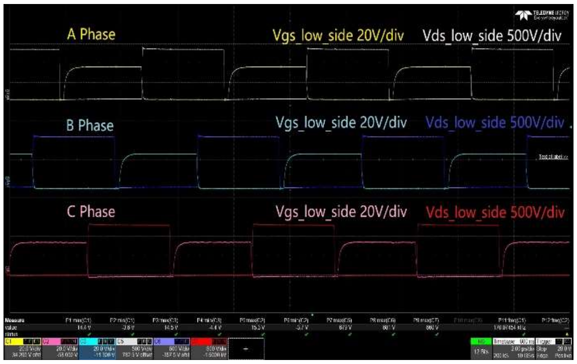

Fig. 7: Vgs and Vds waveforms in 3 phase interleaved LLC mode

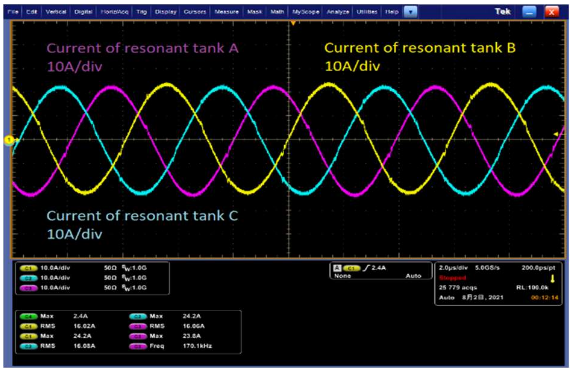

Fig. 8: Current waveform of resonant tanks

Figure 9 shows the testing waveforms of the converter in full bridge LLC mode. With light load especially for low voltage output, phase C is disabled. Refer to the waveform, There is no gate signals and tank current for phase C. ZVS is achieved for phase AB. The converter is reconfigured to a full bridge LLC. With phase shift control, we can reduce the required maximum switching frequency the converter. The burst mode operation region can be minimized especially for low voltage output. The efficiency of the converter is also improved.

Fig. 9: Vgs and Vds waveform of MOSFETs in full bridge LLC mode

4.3 Efficiency Test Result

The efficiency of the 30kW DC/DC converter at different test conditions is shown in Fig.10. 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 135-250kHz.

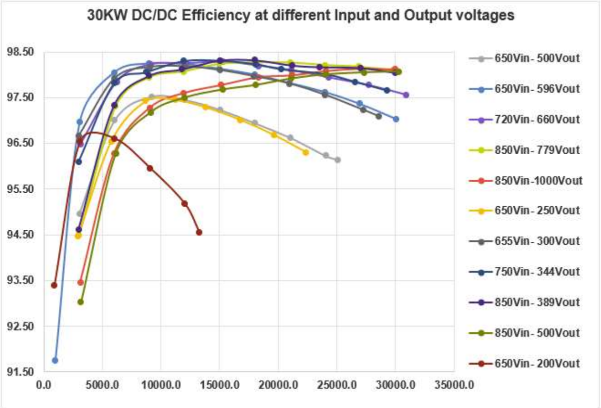

Fig. 10: Efficiency Curve of the 30KW DC/DC Converter

4.4 Thermal Test Result

In the thermal test of the prototype, forced air cooling was applied to the board using the attached heatsinks at an ambient temperature 30 ℃ condition. 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: 660Vdc, Output: 300Vdc 30KW 100A				
MOSFET Q1	0.46	41	77	95.6
Input: 650Vdc, Output: 200Vdc 20KW 100A				
MOSFET Q1	0.46	53.4	86.5	111
Input: 850Vdc, Output: 500Vdc 30KW 60A				
MOSFET Q1	0.46	27.7	51.7	64.4

Table 3: Thermal Test Results.

The thermal test results are shown in Table 3. 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. Referring to the test result, the max junction temperature of the SiC MOSFET is 111°C in the application. We conclude that the MOSFETs meet the thermal de-rating requirement in the design.

5 Summary

In this paper, a flexible voltage gain control scheme is studied on a SiC based 30kW three-phase interleaved LLC resonant converter. High efficiency and wide gain range is achieved to support 200V~1000V battery. 6.5kW/L power density and above 98% peak efficiency are demonstrated. Compared to a conventional cascode Si solution, this solution has lower part counts, higher power density, lower system cost. And it is easy for control. It is very useful for high power applications with wide output voltage range and wide constant power operation range such as EV charger application.

6 References:

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