

DEVELOPMENT OF COMPACT VARIABLE-VOLTAGE, BI-DIRECTIONAL 100KW DC-DC CONVERTER

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Abstract

This paper reports the status and recent progress in development of a 100kW variable bi-directional DC-DC converter with input voltage ranging from 200 to 300Vdc, output voltage ranging from 300 to 600Vdc, a total efficiency > 95%, a power density > 4kW/liter, and a specific power density > 4kW/kg with a high coolant temperature of > 90°C. Multiple approaches are being studied to reduce power losses, increase operation frequency, decrease converter weight and size, including (i) a novel yet simple approach developed to achieve zero-voltage soft-switching with synchronous mode operation for high efficiency without adding any extra switch or other major components, which has led to reduce the Si IGBT switching loss by near 50% and making it possible for the converter to operate at 25KHz, (ii) an interleaving 3-phase design and implementation leading to the elimination of the ripple current going into the sensitive voltage source, (iii) designing and building compact nano-inductor with discontinuous conduction mode operation and compact bus capacitor size with ripple cancellation, and (iv) packaging and implementation of SiC Schottky diode-Si IGBT power modules with minimized thermal resistance. Experimental results of the bi-directional DC-DC converter achieving a total efficiency of 97% operating at 100kW with a coolant temperature of 90°C and a power density better than 4 kW/liter will be presented.

INTRODUCTION

High power density is a key requirement on power management systems on an AECV. Multi-phase DC/DC converters have been recognized as an attractive option in managing power between different DC buses [1, 2]. In this paper, operation, implementation and characterization of a high efficiency, high power density, 3-phase interleaved bi-directional 100kW DC/DC converter is reported.

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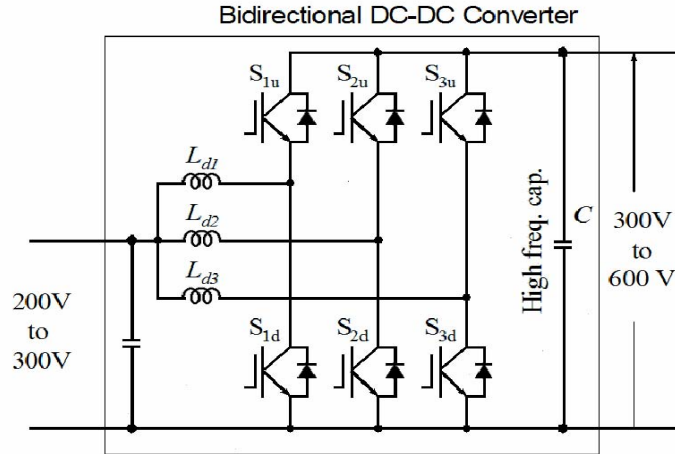


Fig. 1 The 100kW, bi-directional three-phase interleaved DC/DC converter

DC/DC CONVERTER CIRCUIT

The proposed 100kW, bi-directional three-phase interleaved DC/DC converter circuit is plotted in Fig. 1. This converter buffers between two DC buses with the lower bus voltage ranging from 200V to 300V and the higher one from 300V to 600V. When the three lower switches are actively switching, power is converted from the low-voltage side to the high-voltage side in a boost mode operation. On the other hand, if the three top IGBTs are actively switching, the circuit works in a buck mode operation by converting power from the high-voltage to the low-voltage side.

Interleaved Switching Scheme

In either the buck mode or the boost mode, switching timings of the three phases are controlled in a phase-shifted manner so that the current ripples of the three inductors largely cancels out each other. Fig. 2 shows the current waveform of the three inductors in the circuit when operating in a 21kW boost mode. The ripple cancellation is evident from the much-lower current ripple of the total current. This helps greatly reducing the requirement on the sizes of the decoupling capacitors at both sides of the converter, which in turn increases the overall power density of the whole circuit.

Soft-Switching Without Extra Components

Zero-voltage turn-on is achieved for all IGBTs by operating the circuit in the so-called synchronous mode [3]. Take a boost mode as an example, after the active switch S_{1d} in Fig. 1 is turned off, the inductor current goes through the anti-parallel diode of switch S_{1u} , discharging its energy to the output. During the same period of time, switch S_{1u} is also turned on, allowing the inductor current to reverse after its energy is completely discharged. This reverse inductor current ensures that switch S_{1d} turns on under a zero-voltage condition, eliminating turn-on switching losses. This is evident from Fig. 3

where the gate voltage and the drain voltage of S_{1d} and the inductor current are plotted in a 100kW operating condition. It can be seen that when the switch turns on, its drain voltage is zero and the corresponding inductor current is around $-50A$ that goes through the anti-parallel diode of S_{1d} . Gradual increase of the inductor current turns the switch on under a minimal stress condition and the device turn-on loss is much eliminated.

It is worth mentioning that such zero-voltage switching condition is achieved by simply utilizing the usually-idling S_{1u} and no extra component is added. Turn-off of the IGBTs still experiences hard-switching conditions.

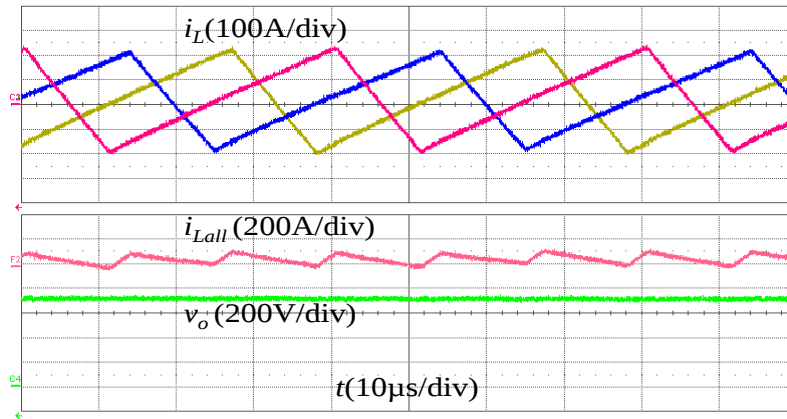


Fig. 2 Currents of the three inductors in the interleaved DC/DC converter. Current ripples of the three inductors cancels each other, leading to a much lower overall current ripple.

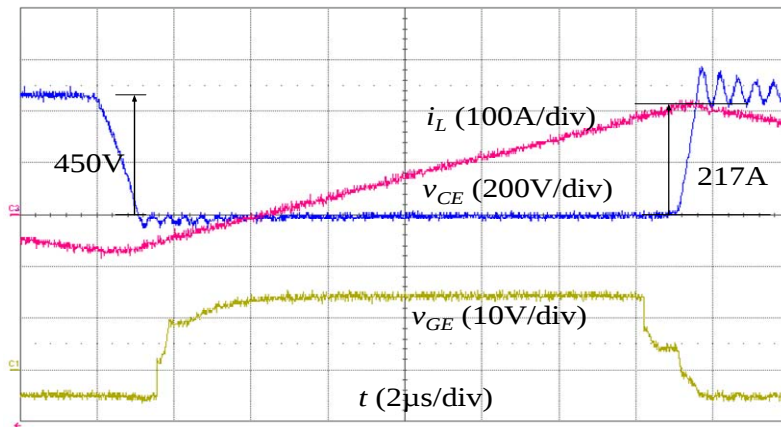


Fig. 3 Zero-voltage turn-on of the IGBT under the synchronous mode of operation at 100kW by utilizing the usually-idling IGBT.

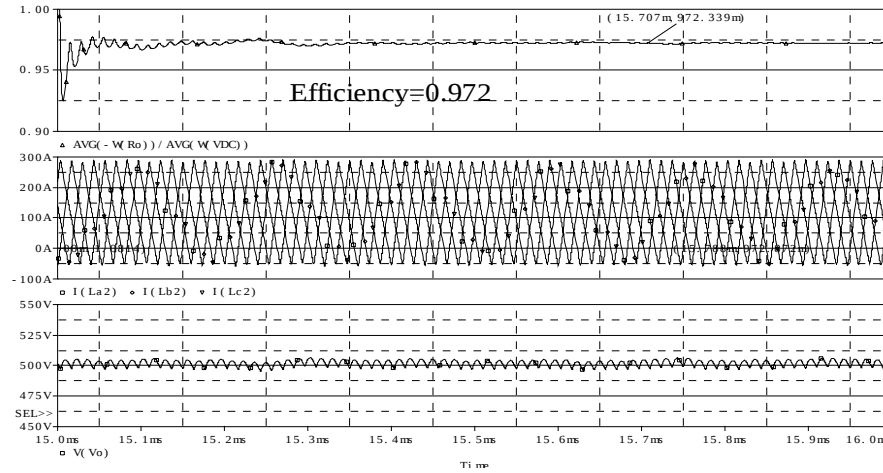


Fig. 4 Simulation results for boost mode with input 300V and output 500V.

SIMULATION RESULTS

The 100kW DC/DC converter is designed to be able to output 300V-700V when the input is varying between 200V-300V in the boost mode. In the buck mode, it can take inputs in the range of 400V-700V and provides an output in the range of 200V-300V. Simulation of the whole converter is carried out based on compact circuit models of the IGBT as well as the anti-parallel diode. As an example, simulated results at 25kHz with an input voltage of 300V and an output voltage of 500V are included in Fig. 4 where the output voltage, inductor currents and the overall circuit efficiency are plotted. The results show well-balanced 3-phase currents, an output voltage with a ripple of around 1% and an efficiency of 97.2%. The high converter efficiency is a result of low switching losses and good inductor design that minimized its ESR as well as core loss.

Extensive simulations have been carried out to investigate system efficiency with various input and output voltages. Figure 5 shows system efficiency at full 100kW loading condition for the boost and buck modes of operation. Fig. 5(a) shows the boost mode efficiency at different output voltages for input voltages of 200V and 300V, respectively. It can be seen that the maximum boost mode efficiency of 97.2% occurs when the input voltage is 300V and the output voltage is 500V. The worst-case boost mode efficiency occurs at an input voltage of 200V and an output voltage of 700V. Under this worst-case condition, the efficiency still reaches 94%. Fig. 5(b) shows the buck mode efficiency for the output voltages of 200V and 300V with the input voltage changing from 400V to 700V. The maximum buck mode efficiency of 97.2% occurs at an input voltage of 400V and an output voltage of 300V. The worst-case boost mode efficiency of 94.8% occurs when the input voltage is 700V and the output voltage is 200V. Efficiencies at light load condition are usually somewhat lower.

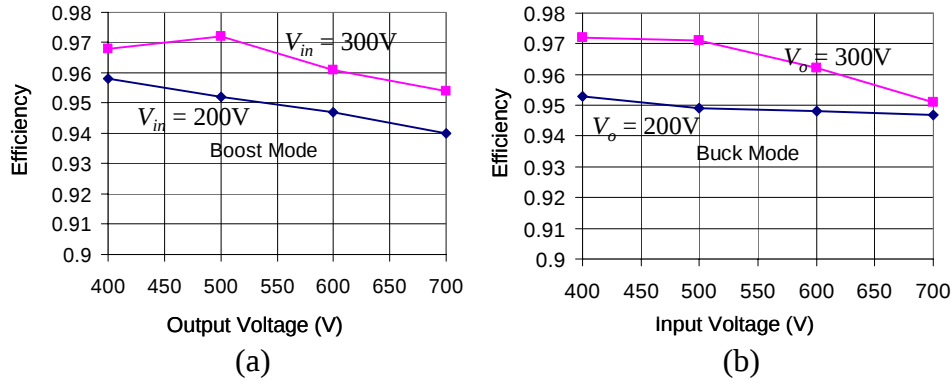


Fig. 5 Simulation results for the system efficiency in (a), boost mode and (b), buck mode

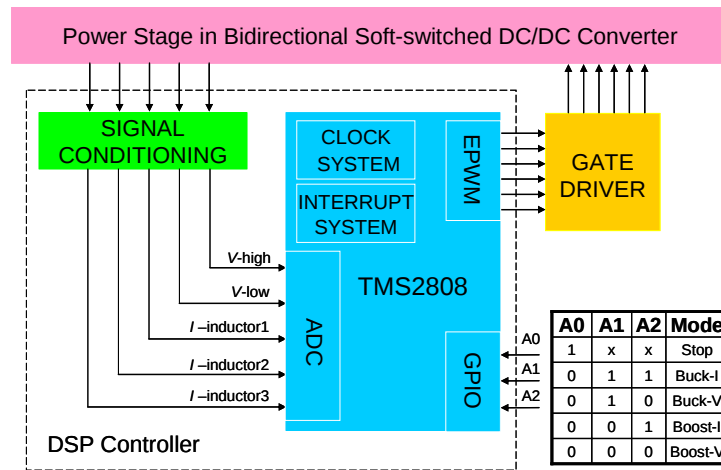


Fig. 6 Overall hardware system structure which comprises the power stage, the gate driver and the DSP controller.

EXPERIMENTAL DEMONSTRATION

System Construction

The hardware prototype converter has been designed and fabricated. An overview of the hardware system is shown in Fig. 6. The whole system comprises three major functional blocks, namely, the power stage, the gate driver and the DSP controller. All power components including the heat sink, the power device, the inductor, the high-frequency capacitors, and the gate driver board are mounted and tested individually. Figure 7 shows the complete power stage assembly of the three-phase 100-kW bi-directional DC-DC converter. Visible items in the figure include three-phase IGBT modules, IGBT driver board with six isolated IGBT drivers, three inductors and power



Fig. 7 A photo of the constructed 100kW DC/DC converter. The converter is housed within a metal case with a size less than 25 liters.

buses. The physical dimension of the enclosure is within the target of 25 liters. The heat sink sits underneath the IGBT modules with copper pipe extending out of the box for coolant loop hook-up. The power bus bar is capable of handling 500A and the heat sink allows a coolant temperature of 90°C. The circuit is enclosed in an aluminum box with 3/8" thick walls, designed to withstand major impact.

A liquid-cooled heatsink with a surface-to-coolant thermal resistance of 0.01K/W at a liquid flow rate of 1.5GPM is used to cool the power modules. It is estimated that the combined thermal junction-to-case (R_{jc}) and case-to-heatsink thermal resistances (R_{ch}) for a pair of IGBT and diode chips are 0.04K/W and 0.02K/W, respectively. Combining all six pairs of IGBT/diode chips in the whole converter, the overall power stage junction-to-coolant thermal resistance is estimated to be 0.02K/W. This allows a maximum total power module loss of 1.75kW while still keeping the junction below 125°C with a 90°C coolant. This maximum total power module loss should be kept somewhat lower than 1.75kW because heat generation among the 12 semiconductor chips is non-uniform.

It is worth noting that current sensors and IGBT heatsink temperature sensors are installed. Their output signals are fed back to an interface circuit that communicates with a DSP controller board. Signal communication between the power circuits and the interface/controller circuits are implemented via optical links for maximum electrical isolation and good electric noise immunity.

Efficiency Evaluation

With the fully-assembled unit, power testing is conducted in a 100kW test-bed for efficiency as well as other more detailed operating parameters. Both the buck mode and the boost mode operations are evaluated. Input voltages and the load are varied to

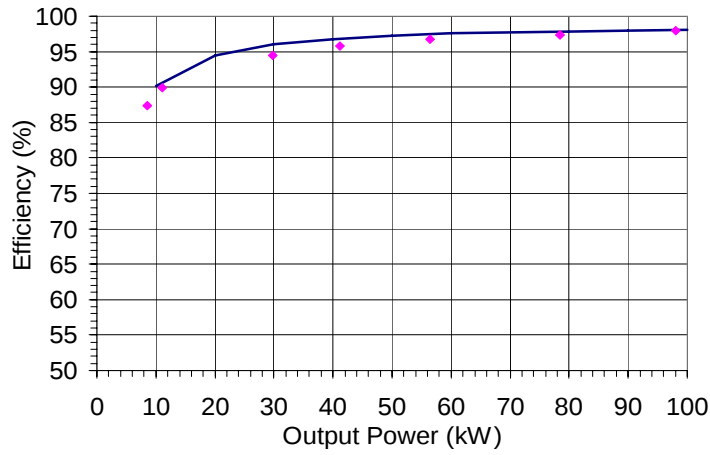


Fig. 8 Efficiency curve of the tested 100kW DC/DC converter at various power levels. $V_{in}=280V$, $V_{out}=450V$. Simulated and experimentally measured efficiencies are compared in the figure (line: simulation, dot: experiment) with very good agreement.

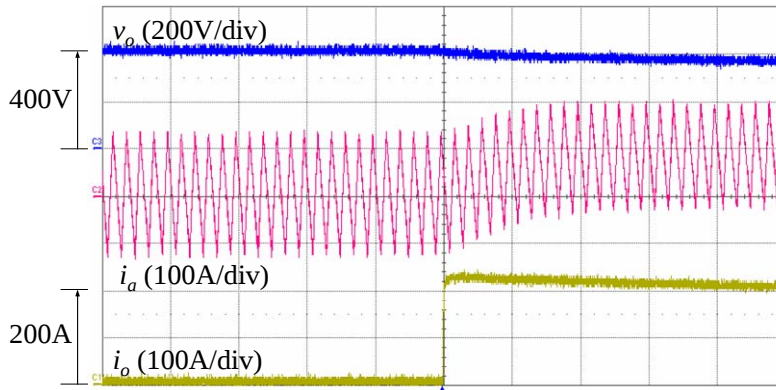


Fig. 9 Transient response of the converter under boost mode operation with a step load change from no load to 80-kW.

obtain different levels of output voltage and output power. The efficiency curve for a boost mode operation with an input voltage of 280V and an output voltage of 450V are plotted in Fig. 8. Output power is varied from a low level to the 100kW full power. More than 95% efficiencies are achieved at >30% full load. Under the full load condition, the system efficiency reaches 98%.

Dynamic Responses

Since the inductor current flows continuously under all loading condition, the transient response of this type of converter operation is smooth. The converter can operate from no load to full load or vice versa without significant output voltage fluctuation. Figure

9 shows the experimental output voltage and current and inductor current waveforms under boost mode operation when the load has been changed from no-load condition to an 80 kW load by closing a contactor. The output current rises rapidly and the average current through one of the three inductors also increases quickly from zero (same for the other two inductors). It is noted that under both conditions, the inductor current always decreases down to a negative level to ensure a zero-voltage turn-on of the IGBT, as explained in earlier section of the paper.

The DC-DC converter effort is on-going. SiC rectifiers have been fabricated. Packaging of SiC diodes and Si IGBTs with better heat rejection capability is being carried out, aiming at further reducing the power loss of the converter and enabling robust converter operations with coolant temperature $\geq 90^{\circ}\text{C}$. Multi-phase interleaved design is being further improved to reduce stress on the inductors so that inductor loss will remain low even under high output-to-input voltage ratio conditions. Experimental results will be reported in the near future.

CONCLUSION

In summary, a 100kW three-phase interleaved bi-directional DC/DC converter has been designed and implemented for 90°C operating heatsink temperature. The demonstrated circuit includes novel features such as ZVS without extra components, multi-phase current ripple cancellation, compact inductor and capacitor design. Experimental measurements show that full-load efficiencies of 97% and 98% were achieved at buck mode with a 450V input and at boost mode with a 240V input, respectively. The power module loss is found to be less than 40% of the total converter loss under the full-load condition, making it possible for the converter to be operated at a high coolant temperature. The proposed switching scheme and design approach for the soft-switched bidirectional dc-dc converter has not only achieved a power density $> 4\text{kW/liter}$ (a specific power density $> 4\text{kW/kg}$), but also allowed significant reduction on switching loss and noise. Work is on-going to implement SiC/Si based power modules with a substantially better package heat rejection so as to allow a more robust converter operation under the full power range.

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