A 3.3-kV All Silicon Carbide Module based Ultra-High-Density Building Block Concept for Multi-Megawatt Traction Applications

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***Abstract*—In the megawatt (MW) scale high-power traction applications, such as the large mining trucks and rail transport systems, silicon based IGBTs have been the pronounced solution for many years. With the increasing demand for higher power ratings and power density with enhanced system performance, the movement towards utilizing faster and more efficient silicon carbide (SiC) MOSFETs is only growing stronger. In this work, a 3.3-kV high-current SiC module-based building block concept with ultra-high power density for the MW traction applications is presented. To fully exploit the benefits of the 3.3-kV SiC modules in the 140 mm × 100 mm industrial package, a low inductance and ultra-compact system design is presented, including the laminated bussing structure, low inductance capacitor bank and a double-sided cold plate to hold 4× power modules. The presented building block can be used to develop a 3-phase traction inverter to drive one, two, or four MW-class traction motors, enabling a versatile modular solution. It is also feasible to use it as a building block to enable direct connection to medium-voltage grid. Detailed analysis are presented for these use cases and preliminary testing results are presented to validate the feasibility.**

Keywords— High density, medium voltage, silicon carbide, traction system

I. Introduction

While IGBTs have been the dominant solutions in the multi-megawatt (MW) heavy-duty off-road vehicles and locomotive sectors due to their high breakdown voltage and high current carrying capabilities, their silicon carbide (SiC) counterparts are mature enough to be utilized for the next generation multi-MW traction drives. Due to their faster switching speed, higher breakdown voltages, and operating temperatures, the SiC based power electronics can lead to downsized passive components, simplified cooling solutions, and can be integrated into more compact system packages. Major manufacturers have rolled out several 3.3 kV high current SiC power modules that features significantly low parasitic inductance and are optimized to enhance capabilities of the SiC MOSFETs, such as the 3.3 kV modules in LV100 package from Mitsubishi Electric [1], XHP-2 package from Infineon [2], the LM3 package from Wolfspeed [3] and etc.

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As the MW-class electric drivetrains may have different configurations in terms of the number of traction motors and the power levels, a modular building block design approach will be able to provide flexibility to accommodate for needs in different applications and lower the development cost, while enabling rapid system integration and implementation. In this work, a 3.3-kV all SiC based modular building block concept for the MW traction applications was proposed and demonstrated utilizing the state-of-the-art high current SiC half-bridge modules with custom designed low-inductance laminated busbar, high density dc link capacitor and a double sided cold plate. The power building block can be used to form a 3-phase traction inverter to drive one or multiple traction motors in the multi-MW power range, providing a versatile modular solution. Additionally, the building block can be utilized in solid-state-transformer (SST) based solutions to enable direct connection to MV grid without using the bulky 60-Hz transformers.

II. Modular Building Block System Design

A. Proposed Design Concept

The laminated bussing of the building block is developed for the industrial standard 140 mm × 100 mm module package, which has been adopted by many manufactures for the 1.7-kV and 3.3-kV class IGBTs and SiC MOSFETs. Though the layout of the auxiliary terminals can be different, DC power terminals are generally the same. Therefore, the proposed laminated DC bussing structure can be utilized for 3.3-kV modules from different suppliers. A double-sided cold plate is sandwiched between the 4× modules to enable a high density assembly. The modules are connected by the laminated busbar to a high density 2400V 670 µF capacitor bank with ultra-low stray inductance.

A custom designed half-bridge MV gate driver with fiber optical connections, shielding, and DESAT protection was designed to guarantee signal integrity and immunity. A diagram showing the main components can be seen in Fig. 1, while the assembly can is presented in Fig. 2.

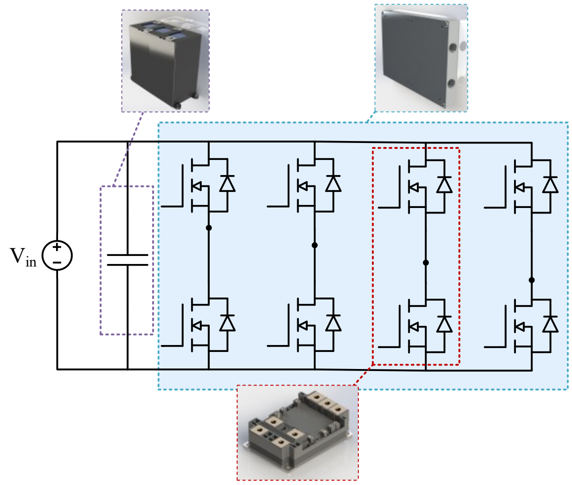
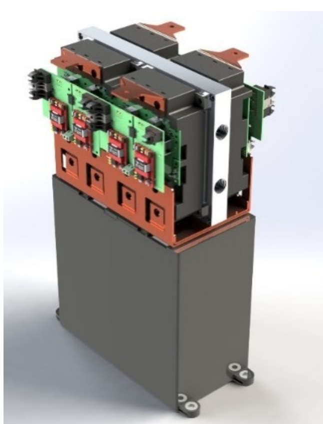


Fig. 1. Diagram showing the main components of the building block



(a)

(b)

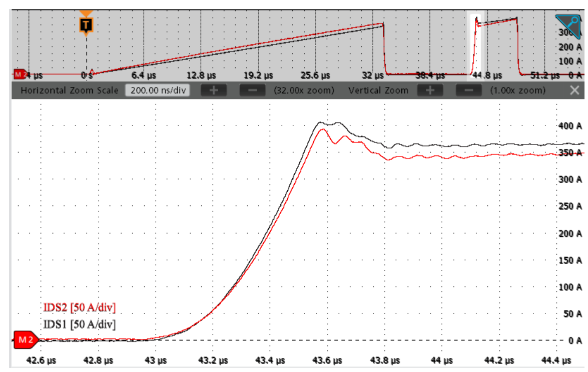
Fig. 2. The assembled building block (a) 3D render of the designed building block; (b) a picture of the assembled building block showing its dimensions

B. *Gate Driver Design*

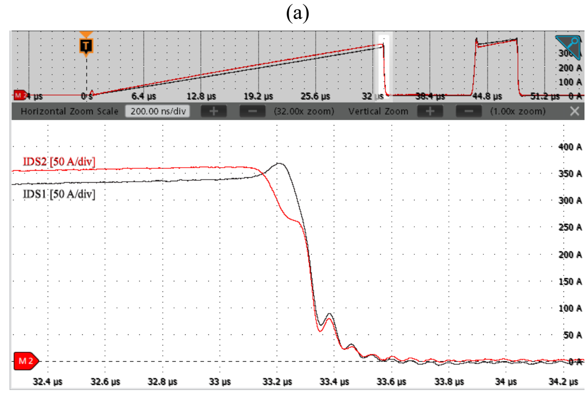
The gate driver design is a critical component in the building block. The gate driver must be able to drive the SiC modules at high speed, and with high charge and discharge rates, since high power modules often have many dies in parallel which will significantly increase capacitance. A IXDD630YI driver IC was used to guarantee enough switching bandwidth, while a 30 A current buffer was used to supply the high current demanded, with a functional under-voltage lockout protection. Using steering Schottky diodes and gate resistors for each path enable independent turn-on and turn-off, while parallel connections of 2512 package resistors achieve driving power requirements and enhance the thermal management of the resistor network. This also increases the reliability of the system during high temperature operation. PWM, data, and other functional signals are sent over fiber optics to guarantee best signal integrity and isolation. A DESAT circuit is used to protect the system in over-current protection situations. In addition, A soft turn-off function is used to protect against large high di/dt that can cause high voltage overshoot and damage the MOSFET in the case of a fault.

C. *Module Paralleling Performance*

Other than the fact that the 140 × 100 mm package has been widely adopted by the industry, the low parasitic inductance and the good paralleling capabilities are also important reasons to select this module package for the proposed modular building block design. Especially, the ease for module paralleling, which leads to better current sharing among the paralleled modules, are essential to enable the modular design. The performance of paralleling two 3.3-kV LM3 SiC modules CAB600M33LM3 from Wolfspeed was presented in [5], which shows satisfactory current sharing over a wide operating temperature range, even at 175 °C junction temperature. In this work, the performance of two Mitsubishi 3.3-kV SiC modules FMF375DC-66A in parallel were evaluated using the double pulse tests with the typical waveforms with 1800-V DC bus voltage shown in Fig. 3. The waveforms demonstrate an acceptable current sharing performance even at hard-paralleling conditions and indicate a low commutation loop inductance.



(a)



(b)

Fig. 3. DPT current waveforms of 2× Mistubishi 3.3kV SiC modules in parallel: (a) Turn-on waveforms. (b) Turn-off waveforms.

III. Application Concept and Discussions

A. *Potential Configurations*

The proposed multi-module building block (MMBB) can be configured for a wide variety of applications. The possible configurations of one MMBB is summarized in Fig. 4. Each MMBB consists of 4× half-bridge modules, which can operate independently, as shown in Fig. 4(a). The proposed MMBB can also work as a full-bridge or an H-bridge, when 2× half bridge modules are in parallel, as shown in Fig. 4(b). Similarly, when all the 4 half-bridge modules operated in parallel, the MMBB becomes a half-bridge circuit with massive current capability. In addition, as shown in Fig. 4(d), the MMBB can be configured as 3-phase inverter with a DC chopper.

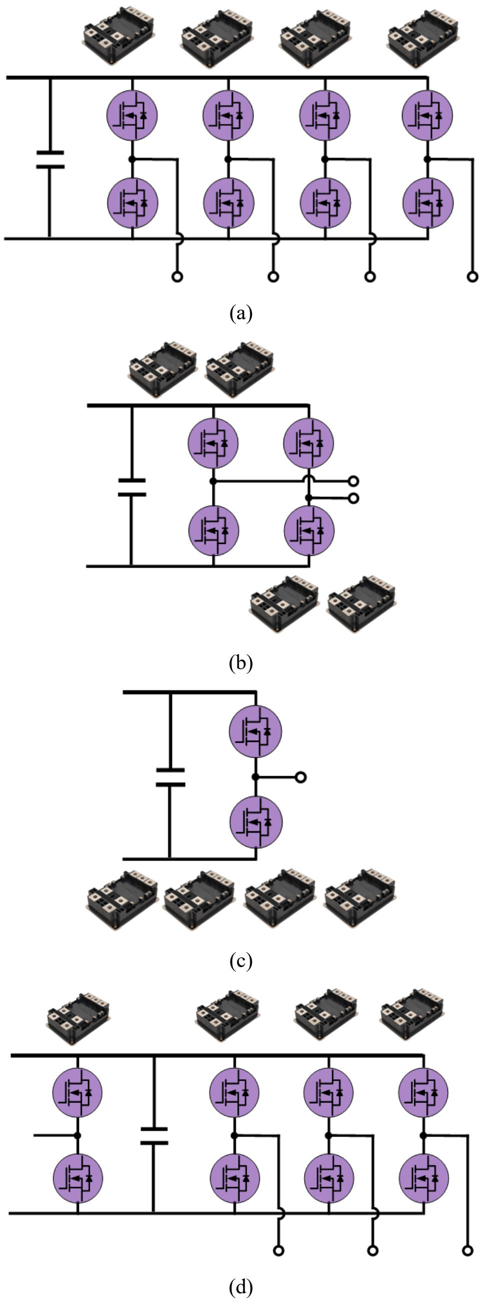
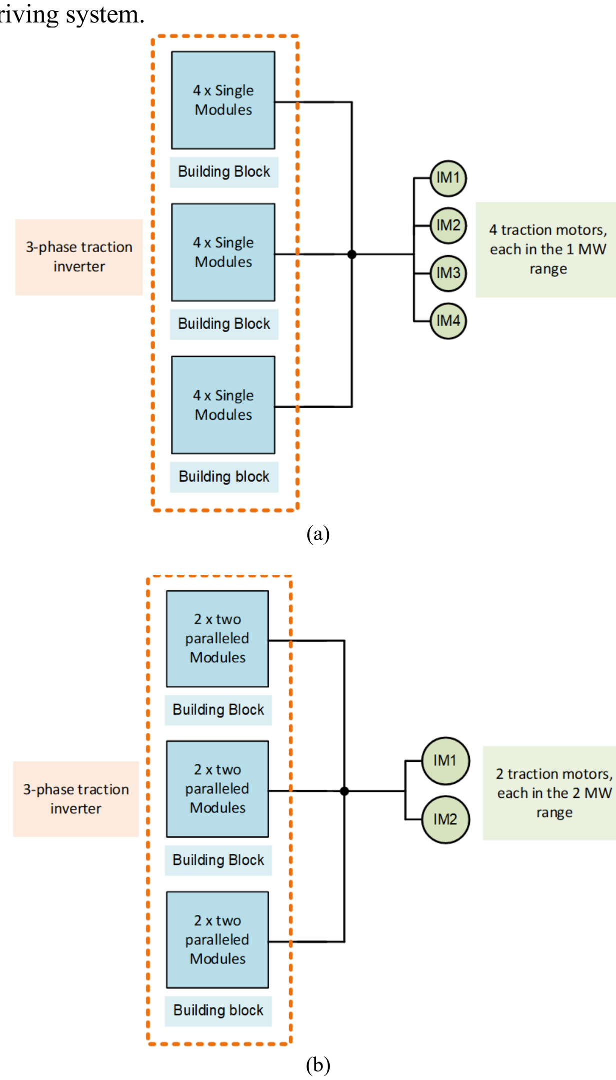


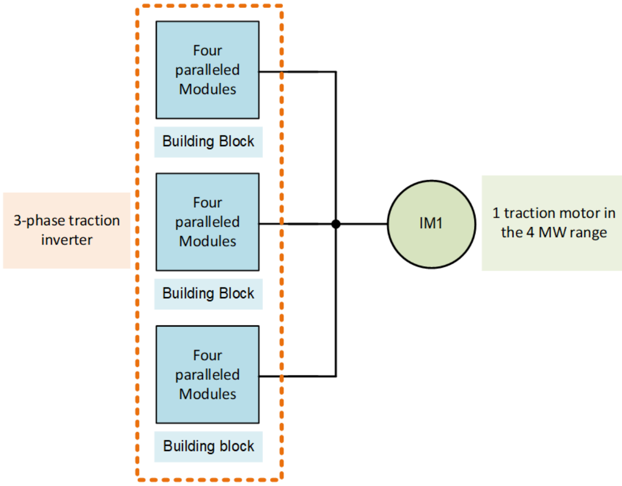
Fig. 4. Possible configuration of one MMBB: (a) 4× independently operated half bridge, (b) a full-bridge circuit with each half-bridge formed two paralleled modules, (c) a half-bridge circuit with four modules in parallel and (d) typical three-phase inverter with one chopper.

B. *Multi-MW Electric Drivetrains*

The building block is intended to be a modular solution for a multi-MW electric drivetrains [4] which may consist of one, two, or four traction motors. By using 3× MMBB to form a 3-phase 2-level inverter, different number of parallel modules per building block can be reconfigured to drive different number of motors. In addition, with the same package, the vendors usually offer modules with different current ratings, such that the power levels can be adjusted by selecting the proper power modules. Fig. 5 visually illustrate the concept.

The building block components and condensed design allow for a high power density expected to exceed 120 kW/L, and while similarly rated IGBTs are available in the same package, the building block will be superior on the system level. First, while IGBTs may have similar current ratings, their current carrying capability will fall dramatically with the increase of frequency, unlike SiC MOSFETs which have very minimal current derating [5]. Thus, the system can be operated at much higher frequency, and therefore minimizing the size and weight of passive components, and allow for a considerably smaller system volume and weight, a crucial requirement for mobile applications. Moreover, the SiC based building block is capable of achieving high efficiency and operate at higher junction temperature, which allows for a smaller thermal management system, and a higher reliability. This will allow for use with vehicles running in extreme conditions and requiring robust driving system.





(c)

Fig. 4. Diagrams illustrating the modular concept of the building block in a traction inverter application at system level using the configurations in Fig. 4(a), (b) and (c), respectively.

C. Solid-State Transformer (SST) based Applications

SST is an attractive concept to connect low voltage to MV grid using power electronics. Grid integration of renewables, DC fast chargers are all good applications for the SST system. Traditionally, charging stations are powered from a low voltage (LV) network through the use of bulky 50/60Hz line frequency transformers (LFT) which converts medium voltage (MV) from the distribution grid to LV. As more vehicles are on the road, reducing the size and complexity of the system, while increasing the efficiency and cost will be of great importance. A potential solution for this is the use of ultra-fast charging stations (UFCS) having direct connection to the MV distribution grid. The SSTs have shown to be a good candidate to be used as a modular building block for use in UFCSs with added merits over the traditional LFT, including better isolation and protection against disturbances, while providing the potential to be interfaced with different energy storage and renewable energy sources [6], [7].

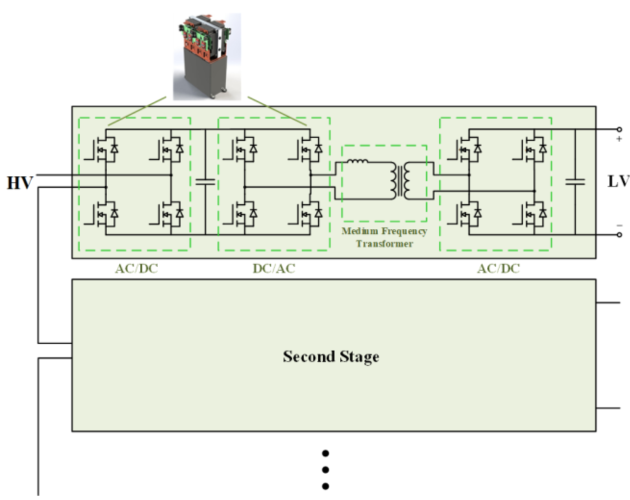


Fig. 5. Illustration of the building block application in SSTs, showing how multiple stages can be stacked to interface higher voltage.

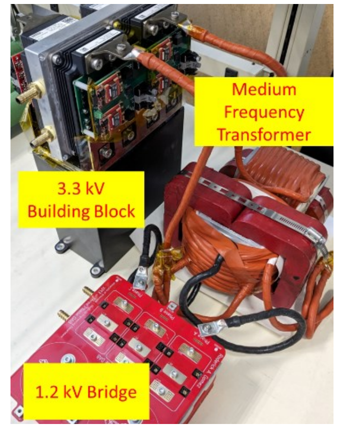
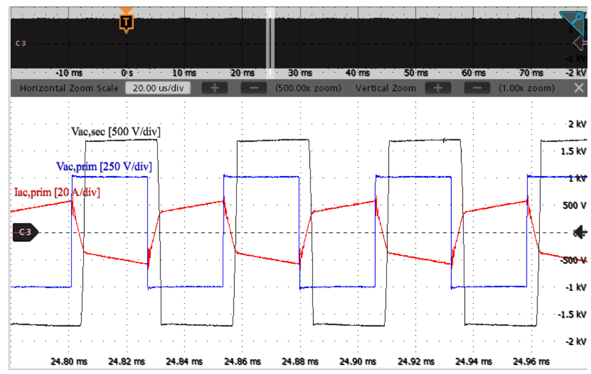
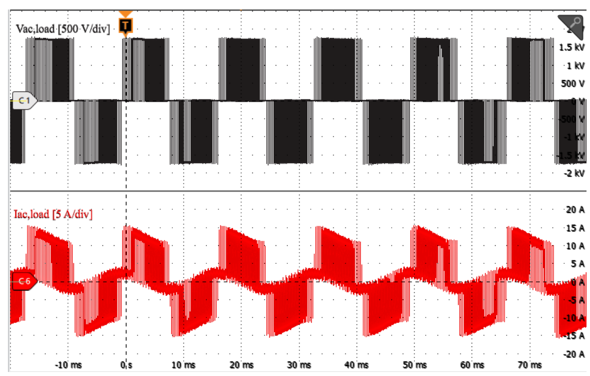


Fig. 6. Test setup showing the three main components.



(a)



(b)

Fig. 7. DAB waveforms. (a) Primary and secondary voltage, and primary current. (b) AC load side waveforms.

The MMBB concept proposed in this work can be used as the high voltage side of a MV connected SST-based charger. This is illustrated in Fig. 5. The ability to stack the modules up to interface with different levels of voltage will give high flexibility and the potential to optimize the cost of single modules vs the cost of the entire system, by varying the voltage ratings of single modules vs the number of stages added.

To verify the proposed concept, one stage of the MV SST discussed in the previous section was built and tested up to 12 kW. Since the system is bi-directional, the prototype was supplied with 800 V DC from the LV side through a full bridge inverter using 1.2 kV SiC modules. The 20 kHz AC output was then fed into a 1:3 medium frequency transformer, and then into the first 2 half-bridge 3.3 kV SiC modules in the building block, forming a dual active bridge converter (DAB). The output DC voltage of 1800 V is then inverted into a 1260 V_{rms} by the second 3.3 kV modules on the building block. The test setup can be seen in Fig. 6, while the waveforms of the DAB can be seen in Fig. 7(a), and the AC output waveforms can be seen in Fig. 7(b).

IV. CONLUSION

In this work, a high-density modular SiC building block concept for high power traction applications is propose. A protype using the standard 140 mm × 100 mm module package was developed with the maximum power density 120 kW/L. The concept has been proposed to be a modular building block for traction inverter applications and MV SST-based charging stations. Primary testing results were presented to demonstrate the feasibility of the proposed concept.

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