

# The half-bridge SiC-MOSFET switching cell : implementation in a three phase motor drive

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# The Half-Bridge SiC-MOSFET Switching Cell

## Implementation in a Three-phase Induction Motor Drive

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**Abstract**—In this paper, the concept of the Half-Bridge SiC-MOSFET Switching Cell (HB-SC), and its design and test procedures are explained. The HB-SC serves as the basic switching element of scalable power electronic converter. The HB-SC combines the power semiconductor switch, optimized power layout, gate driver, and management circuitry (measurement, protection, and interface blocks).

**Keywords**—SiC-MOSFET; integrated switch; half-bridge inverter leg; power layout for high switching speed applications; three-phase inverter

### I. INTRODUCTION

Electrical machines and variable frequency drives (electric drive systems) are widely used in the industry and they occupy a big and constantly growing market [1,2]. Due to the improvements in renewable energy systems and automotive industry, application areas and power levels of electric drive systems are even increasing [3,4]. In addition, integration of drive systems brings efficiency requirement regulations both for electrical machines and variable frequency drives [5].

The mentioned aspects lead to increasing of the importance of testing environments for electromechanical systems. Because several different types of electrical machines exist and they require different control approaches, the electric drive systems differ for each electrical machine type as well. The commercially available test benches usually have interfaces dedicated to fixed types of electrical machines, and they have restrictions on applicable control algorithms and switching frequencies [6,7].

The PDEng project “*Rapid Prototyping and Testing Environment for Electromechanical Systems*” is conducted to satisfy the need for a test environment with high flexibility concerning the types of the powered machines as well as the control hardware and software. The main focus of the project is designing, manufacturing, and testing of a generic power electronic drive that can be used for a broad range of electrical machines and power electronic systems while reducing the effort required for system reconfiguration. In [8], the topology and semiconductor switch studies resulted that the use of half-bridge SiC-MOSFET inverter legs provide the highest flexibility and scalability in the proposed generic power electronics drive.

In this work, first, the concept of the Half-Bridge Switching Cell (HB-SC) is explained, its internal structure is given, and possible application areas are mentioned. Second, the design steps for the HB-SC are explained, which includes the selection of SiC-MOSFET power switch, design of power circuitry layout, and design of management circuitry. Last, the assembly of the designed HB-SC is shown and three cells are connected in parallel to construct a three-phase inverter to drive an induction motor. Relevant parameters regarding the power layout and measurement circuitry are measured and presented.

### II. HALF-BRIDGE SWITCHING CELL CONCEPT

The main purpose of the “*Rapid Prototyping and Testing Environment for Electromechanical Systems*” project was creating a flexible and scalable power electronic drive that can power different types of electrical machines (induction machine and switched-reluctance motor), while requiring low effort for reconfiguration. Besides that, this generic power electronic drive could be used to implement complex control algorithms. The use of half-bridge inverter leg modules provides the highest flexibility in aspect of topology requirements and repairability of the power electronic drive [8]. Table I gives the required specifications for the generic power electronic drive.

TABLE I  
GENERIC POWER ELECTRONICS DRIVE REQUIREMENTS

Parameter	Explanation	Value
$V_{DC}$	DC bus voltage	up to 800V
$I_{max}$	Maximum phase current	100A
$P_{max}$	Maximum output power	30kW
$f_{sw}$	Switching frequency	8kHz – 50kHz

The given specifications lead to use of two possible semiconductor switches: (1) Si-IGBTs and (2) SiC-MOSFETs. Si-IGBTs are widely accepted in high power industrial systems due to their proved reliability, low conduction losses, and low costs. However, their maximum switching frequency is a limiting factor on the flexibility. The intention of complex control algorithms requires switching frequencies up to 50kHz. For this reason, SiC-MOSFETs provide a better solution than Si-IGBTs. Their ratings can reach up to 1.7kV and 300A, while allowing switching frequencies more than 50kHz.

The following solution is, a half-bridge SiC-MOSFET inverter leg that is equipped with its power layout, gate driver, and management circuitry. This integrated power switching unit is called Half-Bridge SiC-MOSFET Switching Cell (HB-SC) and it forms the basic scalable switching element for high power and high speed power electronic applications.

Following facilities are provided by the HB-SC (Fig. 1.):

- a low-inductive power circuitry including the PCB layout, half-bridge SiC-MOSFET, DC link capacitors, and power connectors,
- a low-noise management circuitry including gate drive & interface, measurement, protection, and power management parts,
- galvanic-isolation between the power and management circuitries.

The HB-SC provides an integrated and scalable power electronic solution for various power electronic converters. There are commercially available integrated switching systems in the market [9]. However, these integrated systems are mainly aiming three-phase electric drive applications and have restrictions on control algorithms. The key improvement of the HB-SC is to provide more flexibility respect to the present switching systems.

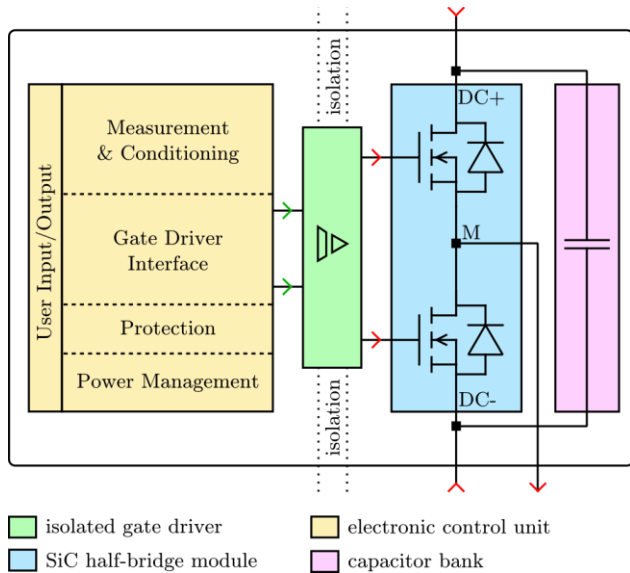


Fig. 1. Internal structure of the Half-Bridge Switching Cell.

### III. DESIGN STEPS OF THE HALF-BRIDGE SWITCHING CELL

In this chapter, the design steps of the HB-SC and the decisions given are explained in detail. First, two commercially available SiC-MOSFETs are compared based on their switching performances and one of them is chosen for the final design. Second, the power layout design is explained and last, the management circuitry is presented.

#### A. SiC-MOSFET Switch Selection

Two SiC-MOSFETs from two different manufacturers are compared based on their switching performances: (1) *CREE CAS120M12BM2* (2) *ROHM BSM120D12P2C005*. Both of the SiC-MOSFETs are rated at 1200V and 120A. The comparison is conducted based on the Double Pulse Test (DPT), which is a widely accepted technique to evaluate the switching performance of the semiconductor switches. In DPT, the device under test is subject to a hard switching under test voltage and test current, and the turn-on and turn-off losses are measured during the switching transitions.

The circuit schematic of the DPT is shown in Fig. 2, where the test voltage is set by the DC supply voltage and the inductor is used to build-up the switch current linearly, until the test current is reached. The gate signal, and the resulting switch voltage and current waveforms of the semiconductor switch are shown in Fig. 3.

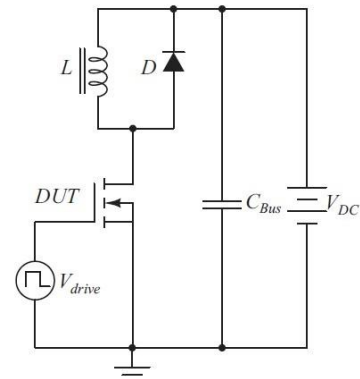


Fig. 2. Double Pulse Test schematic [10].

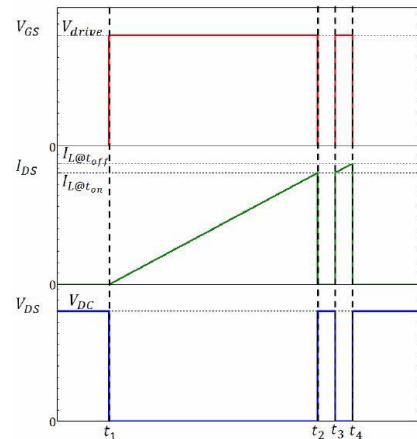


Fig. 3. Double Pulse Test waveforms: gate signal (top), switch current (middle), and switch voltage (bottom) [10].

The test starts when there is no current flowing through the switch. At instant  $t_1$ , the switch is turned on until the switch current reaches test current at  $t_2$ . Then the switch is turned off and the inductor current freewheels through the diode  $D$ . The switch is turned on again at  $t_3$ , shortly after  $t_2$ . Since the turn-off and turn-on losses are observable at instants  $t_2$  and  $t_3$ , test period is terminated at  $t_4$ , shortly after  $t_3$ . This test period is repeated once per second in order to avoid heating of the switch.

A DPT setup was created for both of the SiC-MOSFETs and they were tested under 800V test voltage and different test currents. The switching losses were obtained for every condition and the comparison is shown in Fig. 4. In all of the test conditions, *CREE* module resulted around 10% more total switching losses in comparison to *ROHM* module.

Another important aspect is the oscillations during the switching instants. As shown in Fig. 5, oscillations of the current waveform during turn-off were measured two times higher in amplitude for *ROHM* in comparison to *CREE*. Additionally, the turn-off oscillation duration was also observed longer for *ROHM*. This difference was caused by the module layout differences.

Besides the test results, the tested modules have differences in practical aspects as well. One of the differences is that *ROHM* module is 50% more expensive than *CREE* module. The second difference is, a dedicated gate driver is commercially available for *CREE* module. Taking the test results and practical aspects into account, *CREE* module is chosen as the semiconductor switch for the HB-SC.

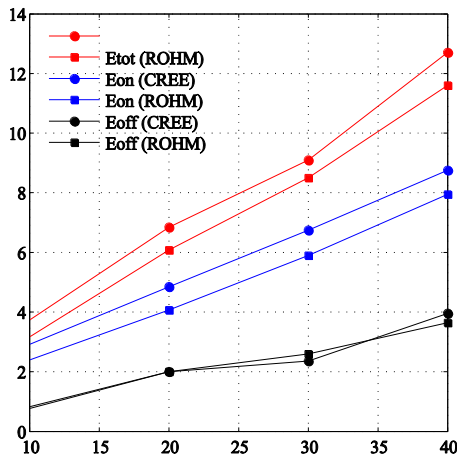


Fig. 4. Comparison of the switching losses of the tested SiC-MOSFETs: total switching losses (top two), turn-on losses (middle two), and turn-off losses (bottom two).

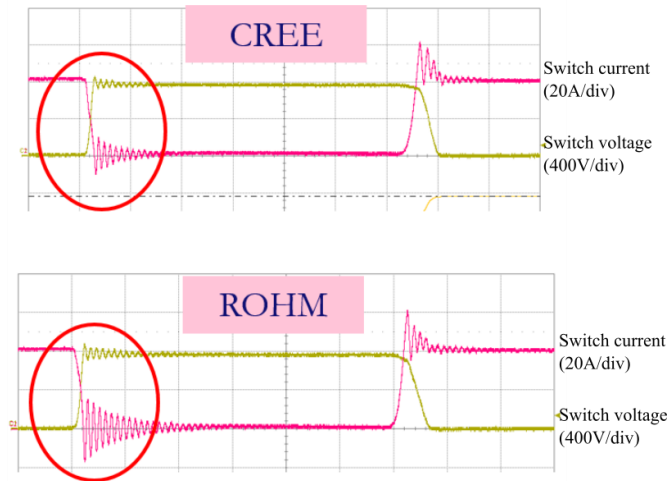


Fig. 5. Switching transition comparison of the tested SiC-MOSFETs.

### B. Power Layout Design

The HB-SC utilizes SiC-MOSFETs, which is capable of switching at high speeds under high voltage and current ratings. This requires an extra attention to the parasitic elements, specifically stray inductances and capacitances what is typically incurred for Si-IGBT modules [11]. The HB-SC printed circuit board (PCB) layout should provide a low inductive power plane in order to minimize the consequences of the parasitic elements. This can be achieved by careful consideration of power plane design and good selection of the DC link capacitors.

The following aspects are taken into account during the PCB design;

- PCB involves both high and low power circuitries. Number of layers is important in aspect of current density for high power circuitry, and in aspects of noise and magnetic compatibility for low power circuitry. A 4-layer PCB design is chosen in order to increase the current carrying capacity, obtain low inductive power traces, and reduce the stray capacitances. Taking these aspects into account, three different PCB sections are defined with different layer stack-up planning (Fig. 6).
- The PCB layout for the HB-SC is designed to demonstrate proper insulation up to 1000V. The required clearance and creepage values are calculated referring to IEC 60950 [12].

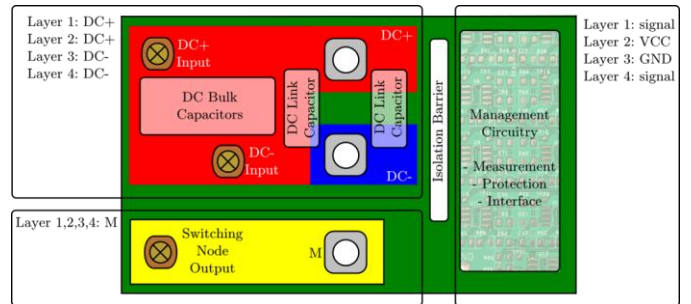


Fig. 6. Printed Circuit Board layout and stack-up planning for HB-SC.

A low inductive power plane is highly crucial for high speed and high power applications. Minimizing the inductance is best achieved by canceling out stray magnetic fields as much as possible [13]. Therefore, power planes for DC+ and DC- are placed on the top left side of the PCB, providing the shortest current path for the SiC-MOSFET (Fig. 6).

Besides that, the selection of the DC link capacitors is also a factor for decreasing the inductance of the power plane. Polypropylene film capacitors are the best candidates for DC link capacitors with their low parasitic inductive structure. To minimize the equivalent series inductance value, three film capacitors (2.2nF, 100nF, and 3μF) are connected in parallel and located directly on top of the SiC-MOSFET pins. The lowest value capacitor shows fastest response to the current transient, therefore it is located as close as possible to the switch pins.

Last, relatively slow changes in the supply voltage are smoothed with the use of DC bulk capacitors. Aluminum electrolytic capacitors offer a good solution for this purpose by

their high capacitance/size ratio. Two parallel branches of two series aluminum electrolytic capacitors are used to decrease the equivalent series resistance. Due to series connection, balancing resistors are used to equalize the voltages on the capacitors.

### C. Management Circuitry Design

The *Management Circuitry* of the HB-SC includes four different blocks: (1) measurement & conditioning, (2) protection, (3) gate driver interface, and (4) power management. These blocks and their relations with the power circuitry are shown in Fig.7.

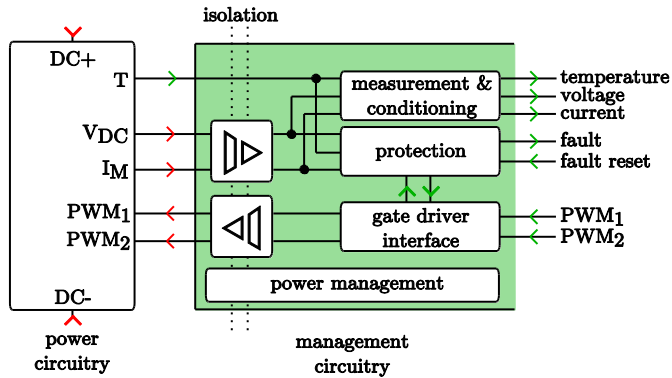


Fig. 7. Internal structure and blocks of the management circuitry.

1) *Measurement and conditioning block*: This block provides the following measurement information isolated from the power circuitry:

a) *DC bus voltage measurement*: The HB-SC senses the DC bus voltage by a resistor divider network on the power circuitry side and transfers the signal to the management circuitry through an isolation amplifier. After that, it conditions the signal and provides it with a gain of 3.3mV/V. Input to output delay of the voltage measurement is around 3.3μs.

b) *Switching node current (phase current) measurement*: The HB-SC equips a magneto-resistive current sensor to sense the switching node current and provides it to the management circuitry through galvanic isolation. After conditioning and filtering, the current sensor output signal is provided with a gain of 90mV/A. High bandwidth (400kHz) and low input to output delay (0.5μs) make this current sensor suitable for complex control algorithms, which requires fast and accurate current measurement.

c) *Temperature measurement*: The temperature of the SiC-MOSFET module is measured by an integrated-circuit CMOS temperature sensor with a gain of -8,2mV/C.

2) *Protection block*: Because SiC-MOSFETs are fast switching devices and not robust as Si-IGBTs, the protection of the SiC-MOSFETs gains importance. Therefore, the reliability of the system can be ensured with a fast and accurately reacting protection approach. For this purpose, the protection block is constructed with fast logic circuits. The following conditions define the thresholds for faults:

- Over-voltage fault : 900V
- Over-current fault : 70A

- Over-temperature fault : 90°C
- Gate-driver fault : shoot-through, missing signal

In case of one of these faults, the protection block takes the following actions: (1) generating a “fault” signal, (2) informing other HB-SCs and the controller/user, (3) disabling all PWM signals, and (4) keeping the fault state until it is reset.

3) *Gate driver and interface block*: Gate drivers are used to isolate and amplify the gating signals between the signal circuitry and gate pins. Besides that, they provide protection against over-current and shoot-through faults. The *PT62SCMD12* gate driver is used in this work because of its compatibility with the chosen SiC-MOSFET module. The HB-SC modules accept single-ended PWM signals from the control platform, while the chosen gate driver accepts differential input signals. Besides that, the gate driver does not provide an enable/disable circuitry for the gate signals. Therefore, an interface circuitry block is added between the PWM input and gate driver input. This block is responsible for converting the single-ended PWM signals to differential voltage levels and disabling the PWM signals during a faulty condition.



Fig. 8. Gate driver (*PT62SCMD12*) and the chosen SiC-MOSFET (*CASI20M12BM2*).

4) *Power management block*: The management circuitry consists of sensors, operational amplifiers, logic circuits, and gate driver. These blocks require different voltage and power levels. Additionally, an isolated voltage is required for DC bus voltage measurement. In HB-SC, management circuitry is powered with 24V and other circuitries are powered through 24V to 5V (nonisolated) and 5V to 5V (isolated) power supplies.

## IV. IMPLEMENTATION OF THE HALF-BRIDGE SWITCHING CELL IN A THREE-PHASE INDUCTION MOTOR DRIVE

Following the design rules and decisions in Chapter III, the HB-SC printed circuit board layout is designed and assembled as shown in Fig. 9 and 10. The numbered areas in Fig. 9 indicates the following functions:

- Area 1 includes the input power connections, DC bulk capacitors, and balancing resistors. As seen in Fig. 9, the power planes are designed as wide as possible to decrease the parasitic inductance of the power traces. DC bulk capacitors are located at the bottom side of the PCB.

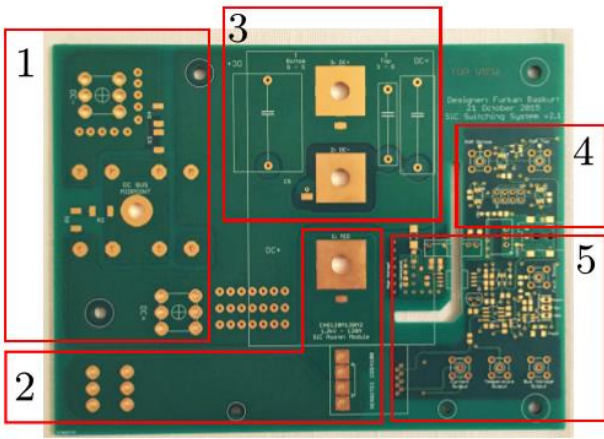


Fig. 9. The designed Printed Circuit Board of the HB-SC.



Fig. 10. Assembled HB-SC (without the gate driver).

- Area 2 includes the switching node of the SiC-MOSFET module and the output connector of the HB-SC.
- The DC link capacitors and gate-driver connections are located in area 3. Capacitors are placed directly on the top of the SiC-MOSFET to provide a low-inductive current path.
- The high-frequency part of the management circuitry occupies area 4. This area includes the PWM signals and gate-driver interface circuitry.
- Area 5, includes low-noise part of the management circuitry.

The HB-SC is implemented in a three-phase induction motor drive. For this purpose, three HB-SCs are connected in parallel and a test setup is constructed. The block diagram of the test and the experimental test setup are shown in Fig. 11 and 12.

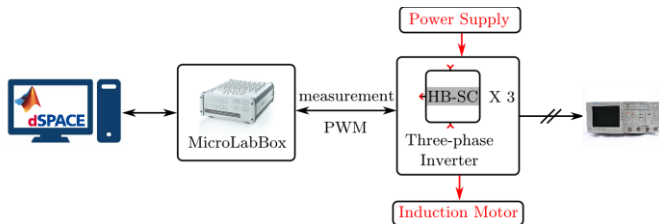


Fig. 11. Block diagram of the test setup.

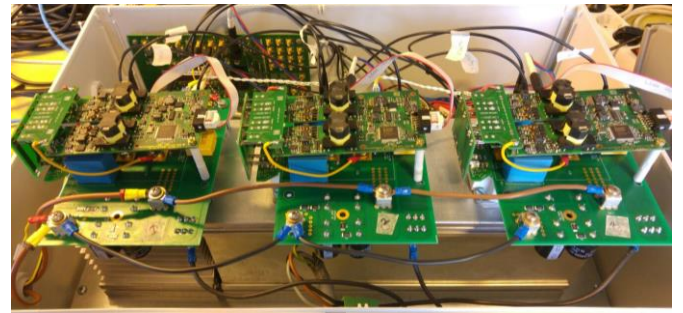


Fig. 12. Three-phase inverter circuit consisting of three HB-SCs in parallel.

First, the induction motor is operated around 2.5kW under two different DC bus voltages: (1) 440V and (2) 700V. During this test, one SiC-MOSFET's drain-source voltage and the switching node current from the same module are measured. As shown in Figs. 13 and 14, the drain-source voltages do not have over-shoot during turn-off transition for both of the conditions. This shows that the power plane design and choice of DC link capacitors ensure a low inductive path for the switches. In Fig. 14, the current ripple is more than the one in Fig. 13. This difference comes from the different  $dV/dt$  and changing MOSFET output capacitor values under different DC bus voltages.

Second, a phase current is measured with a current probe and it is compared with the HB-SC current sensor output. As shown in Fig. 15, the HB-SC current sensor output is identical to the current probe measurement in terms of amplitude and it includes only  $0.5\mu s$  phase shift. This verification indicates that the HB-SC current sensor output provides a fast and accurate current measurement for using in the control algorithms.

Third, the DC bus voltage is measured with a voltage probe and with the voltage sensor of the HB-SC, during a power-up and power-down cycle of the main power supply. The comparison of the two measurements are given in Fig. 16. As shown in the figure, both of the measurements are almost identical. Although the HB-SC voltage sensor output has  $3.3\mu s$  delay, the delay becomes unimportant when it is considered that a fast voltage measurement is not crucial for the drive applications.

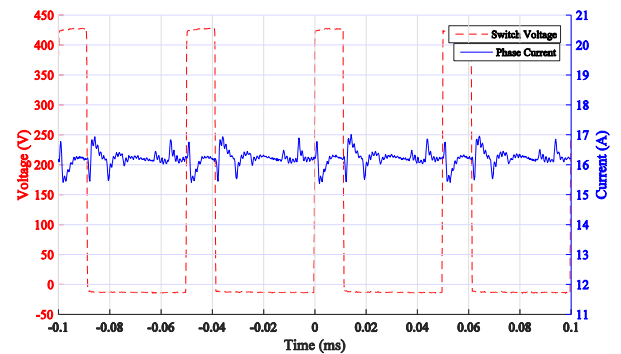


Fig. 13. Drain-source voltage of an upper SiC-MOSFET and the switching node current of the same module under 440V DC bus voltage.

## V. CONCLUSION

In order to create a flexible and scalable generic power electronic drive, half-bridge inverter legs are chosen as power semiconductor candidates. The specifications of the power electronic drive proposes the use of SiC-MOSFETs due to their low losses in high power and high switching frequency applications.

During the implementation of the HB-SC in a three-phase induction motor drive, the switching transition of the SiC-MOSFET demonstrated almost zero voltage overshoot under 440V/16A and 700V/13A switching conditions. This is a result of low-inductive power plane design and it ensures the safe operation of the SiC-MOSFETs in high power high switching frequency applications.

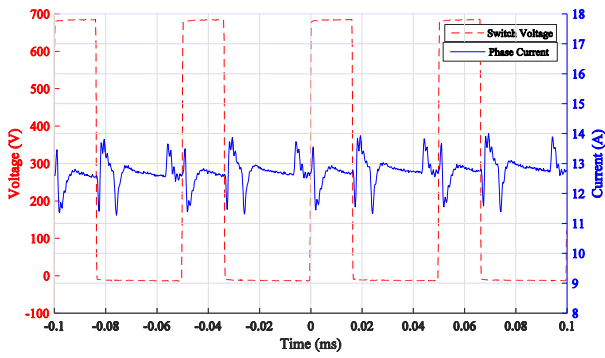
Besides the power switching function, current and voltage measurement facilities of the Half-Bridge Switching Cell are also verified. Current and voltage sensor output signals are consistent with the probe measurements, demonstrating 0.5 $\mu$ s delay for the current and 3.3 $\mu$ s delay for the voltage measurement. The accuracy and speed of the measurement facilities enable the use of measurements in complex control algorithms. With these features and further improvements on the Half-Bridge Switching Cell design (heatsink, integrated gate driver) will even decrease the reconfiguration effort for high power and high switching frequency applications.

## VI. ACKNOWLEDGEMENT

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(b)

Fig. 14. Drain-source voltage of an upper SiC-MOSFET and the switching node current of the same module under 700V DC bus voltage.

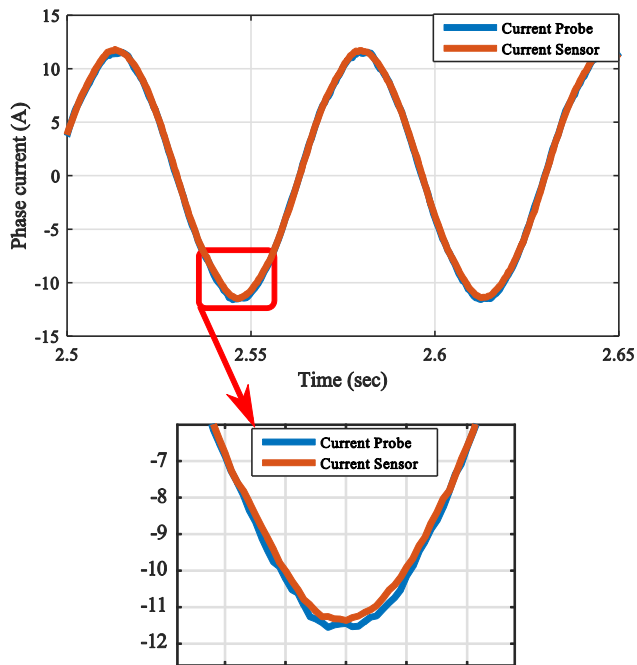


Fig. 15. Comparison of the switching node current measurements between the current probe and the HB-SC current sensor output.

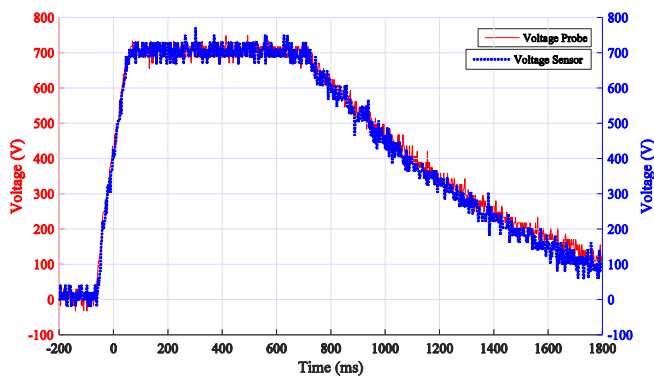


Fig. 16. Comparison of the DC bus voltage measurements between the voltage probe and the HB-SC voltage sensor output.

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