A Smart Silicon Carbide Power Module with Pulse Width Modulation Over Wi-Fi and Wireless Power Transfer-Enabled Gate Driver, Featuring Onboard State of Health Estimator and High-Voltage Scaling Capabilities

Preprint

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National Renewable Energy Laboratory

Presented at the 2023 IEEE Applied Power Electronics Conference (APEC)
Orlando, Florida
March 19-23, 2023

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5400-83691
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Suggested Citation
Khan, Faisal, Sarwar Islam, Joshua Major, Adil Usman, Gilbert Moreno, and Sreekant Narumanchi. 2023. *A Smart Silicon Carbide Power Module with Pulse Width Modulation Over Wi-Fi and Wireless Power Transfer-Enabled Gate Driver, Featuring Onboard State of Health Estimator and High-Voltage Scaling Capabilities: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5400-83691. https://www.nrel.gov/docs/fy23osti/83691.pdf.

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A Smart Silicon Carbide Power Module With Pulse Width Modulation Over Wi-Fi and Wireless Power Transfer-Enabled Gate Driver, Featuring Onboard State of Health Estimator and High-Voltage Scaling Capabilities

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***Abstract*— A wide range of utility applications require controllable switches with features such as high-voltage blocking and high-current carrying capacity, especially at high pulse width modulation (PWM) frequency. Low- and medium-voltage utility applications such as motor drives and flexible AC transmission systems as well as solid state transformers could also benefit from a low-cost high-voltage switching module. Wide-bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) metal oxide semiconductor field effect transistors (MOSFETs) are considered to be the present and next-generation device choices, although they have limitations. For relatively high-voltage applications with demanding thermal management, SiC is still the only choice, and GaN dominates the low-voltage regime. This manuscript proposes a new half-bridge power MOSFET module that is suitable for conventional H-bridge of multilevel configurations used in high-voltage applications. Constructed from bare SiC dies, this half-bridge module takes advantage of (1) optimized MOSFET placement inside the module, (2) customized heat exchanger, manifold, and cooling, (3) integrated gate driver module with pulse width modulation (PWM) over wi-fi to eliminate the need for low-voltage signals, (4) wireless power transfer (WPT)-enabled gate driver and other ancillary circuits, (5) and the option to incorporate an onboard state-of-health (SOH) estimator module. The entire architecture has been designed and built at the National Renewable Energy Laboratory (NREL) in Golden, CO.**

Keywords — Power module, WBG devices, SiC, GaN, PWM over wi-fi, wireless power transfer, Ga_2O_3 devices, State of health estimator module.

I. INTRODUCTION

A half-bridge power module is an integral part of any high-power energy conversion system. In the modular multilevel converter, the power flow is mostly controlled by sub-modules consisting of the half- and/or full-bridge circuits [1]. This medium-voltage power devices or sub-modules can withstand a very high blocking voltage, up to 15kV for Silicon Carbide (SiC) MOSFETs and 27kV for SiC insulated gate bipolar transistors (IGBTs) at high pulse width modulation (PWM) frequency [2]. The safe operation of these modules is ensured through isolated power supplies feeding the driver circuits, either through galvanic isolation or wireless power transfer (WPT) systems [3-5]. In addition, high-voltage isolation is also needed to separate the high-voltage bus from the low-voltage signal bus intended for PWM and other control signals. Multiple approaches and design considerations have been reported in literature for the development of an innovative gate driver circuit for SiC-based medium-voltage power modules [6-8] operated wirelessly. For instance, Nguyen et al. [6] developed a high-frequency WPT system with a nonoverlapped winding arrangement to offer small coupling capacitance, whereas the optimal design proposed in Anurag et al. [7] utilizes ferrite core and windings embedded in a polyamide material to maintain the required insulation and reduce the coupling capacitances in a WPT operated module. Similarly, Wei et al. [8] developed a WPT system using repeater coils for powering the multiple gate drivers in modular multilevel converter efficiently.

While it is been shown that the commercially available gate drivers for SiC-based power devices possess the blocking voltage of 650–1700 V, there exist a very few commercially available gate drivers for 10 kV SiC MOSFETs; however, commercialization of these modules is not feasible as of now due to disproportionate manufacturing costs and design complexities. This project therefore aims to design, fabricate, and characterize a universal architecture for the medium-voltage power modules that could be used with both SiC and

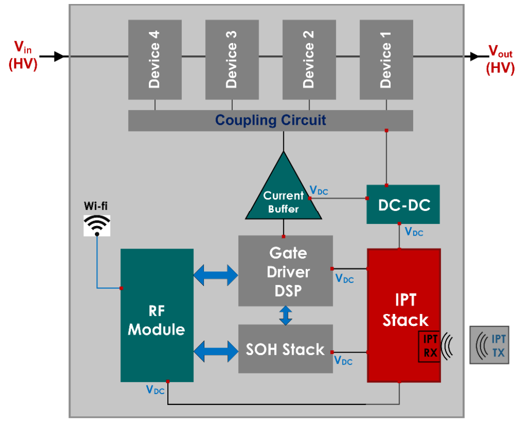


Fig. 1. Proposed all-in-one architecture: The internal components of a module.

GaN devices for high-voltage applications and can be stretched to accommodate future Ga_2O_3 MOSFETs. At the preliminary stage, this project targets the exploitation of SiC-based power devices to eventually replace them with Ga_2O_3 MOSFETs in the later stages. The outcome of this project is a wi-fi enabled smart module, which exploits WPT to eliminate gate driver ancillary power supply issues at extremely high voltage levels, such as 20 kV or higher and eliminates any need to isolate the PWM signal. The PWM signal for each module is transmitted over wi-fi, and it provides the flexibility to completely isolate the power module from the low-voltage bus, thus necessarily making it a two-terminal device. The proposed architecture is shown in Fig. 1. Using the PWM over wi-fi, the WPT powered gate driver, and an onboard state-of-health (SOH) block would make it the first "smart module," which is in turn very close to a two-terminal device, i.e., an ideal switch.

II Architecture of the Module

A high-performance power module consists of several mechanical parts such as baseplate to accommodate the devices, a thermally conductive layer that provides voltage isolation, heat exchanger unit, liquid cooling arrangement and so on. Multiple ancillary circuits are also needed to operate the power module such as gate driver/buffer, isolated dc-dc converters, and finally a protection circuit to safeguard the MOSFET. The NREL designed half-bridge module as shown in Fig. 2 has four MOSFETs - two parallel MOSFETs in each switch position. These are ROHM SiC devices rated at 650V, 118A; therefore, this half-bridge module is rated at 650V, 236A. The authors of this manuscript have designed and fabricated the various electrical and mechanical parts of this module using the NREL facilities, and the following paragraphs demonstrated the step-by-step fabrication details.

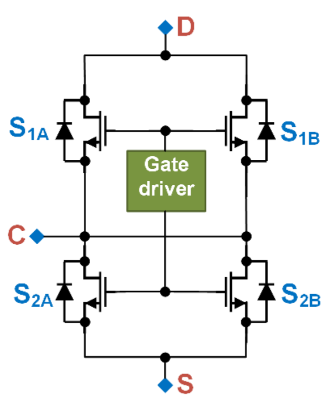


Fig. 2. The internal structure of the half-bridge module.

A. Baseplate design and thermal management:

A water-ethylene glycol jet impingement thermal management system was designed to cool the half-bridge module. Four slot jets impinged on copper finned structures that are fabricated on the module's baseplate directly below each device (see Fig. 3). ANSYS response surface optimization was used to optimize the device placement, baseplate thickness, and fluid channel sizes to minimize device temperatures (lower junction-to-fluid thermal resistance), minimize temperature variation between devices, and minimize pumping power requirements. The cooling system was designed to comply with typical automotive guidelines by using channel sizes that are >1 mm and limiting the fluid velocities to prevent erosion-corrosion effects. The optimized design provided a maximum junction temperature of 137°C at a 433 W/cm^2 device heat flux (Fig. 3), maintained device temperature variation to 1.4°C, and provided a pressure drop of 0.85 psi (at 3.3 L/min total flow rate). More information on the cooling system and packaging design can be found in [12].

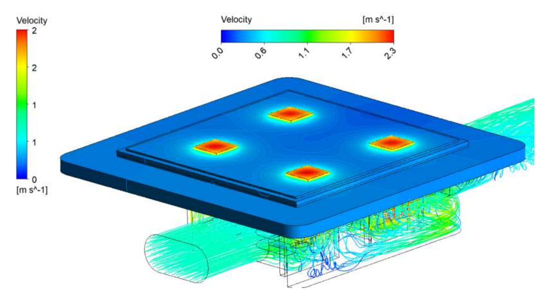
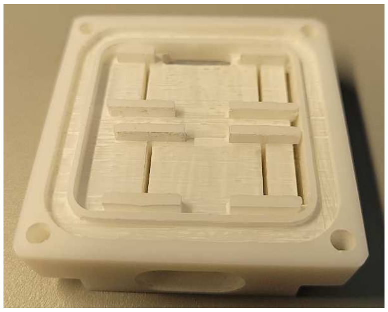


Fig. 3. CFD-computed module temperatures and velocity streamlines for the optimized design.

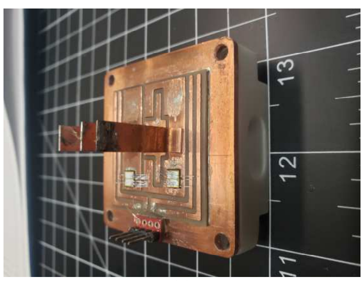
B. Casing and heat exchanger design:

A 3D printed casing has been designed and fabricated along with the coolant manifold to house the baseplate of the module. The baseplate is attached to a custom heat exchanger to implement jet impingement cooling. These parts are shown in Figs. 4(a) and 4(b). The direct-bond-copper (DBC) baseplate with the soldered devices are shown in Figure 4(c), and the completed prototype is shown in Fig. 4(d). 100-micron bond wires have been primarily used to connect the source terminals to the external connector.



(a)

(b)



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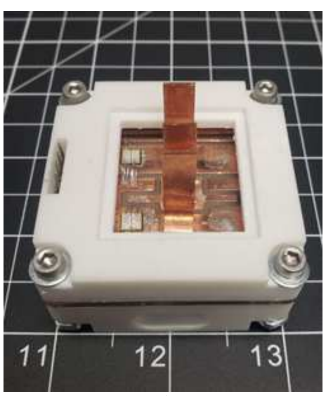
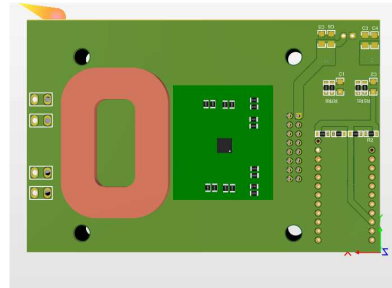


(d)

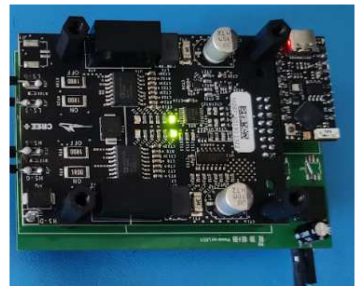
Fig. 4. (a) 3D printed casing, (b) milled heatsink for jet impingement cooling, (c) DBC baseplate with bus bar and devices, (d) partially completed half-bridge module.

C. *Motherboard design:*

A custom motherboard has been designed and populated to accommodate the wi-fi microcontroller board, a commercial half-bridge gate driver and a WPT receiver module. These parts are shown in Fig. 5. The motherboard has been designed in Altium, and a commercially available gate driver has been used for proof-of-concept purpose, although the final design will use a custom gate driver. A WPT receiver with adequate power rating has been used to power the gate driver and the wi-fi microcontroller. This microcontroller board consumed extremely low power, although it can generate PWM for both top and bottom switches using a wireless signal obtained from the transmitter laptop.



(a)



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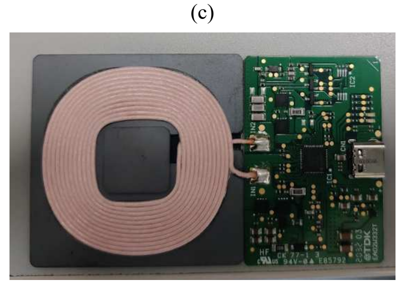


(d)

Fig. 5. (a) Motherboard PCB layout, (b) integrating the gate driver and wi-fi microcontroller board, (c) WPT receiver integrated motherboard, (4) WPT transmitter coil.

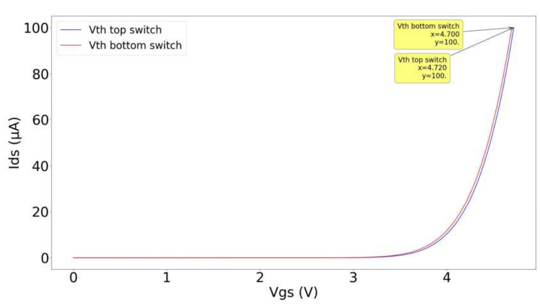
III. Experimental Results

A. Half-bridge module characterization:

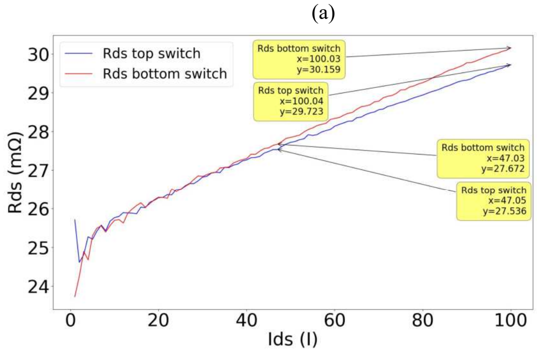
Due to worldwide device supply constraints, the initial tests were performed with only one device per switch position and limiting the current to 100A. After fabrication the module was tested using the Keysight B1505A power device analyzer to ensure proper device functionality. The first test performed was the gate threshold voltage (V_{TH}) measurements using the $V_{GS} = V_{DS}$ settings on the Keysight. The MOSFET datasheet showed a V_{TH} of between 2.7V and 5.6V, and the test results showed a V_{TH} of 4.7V and 4.72V at 100µA for the upper and lower switch, respectively (Fig. 6(a)). The second test performed was the $R_{DS(ON)}$ measurements where V_{GS} was maintained at 18V. The datasheet values for $R_{DS(ON)}$ showed between 17mΩ and 21.3mΩ at 25°C and $I_D = 47A$. The results from the Keysight showed an $R_{DS(ON)}$ of 27.54mΩ and 27.72mΩ for the upper and lower switch, respectively. Due to our desire for higher amperage, the test was performed up to $I_D = 100A$. The results came out to be 29.72mΩ and 30. 16mΩ for the upper and lower switch, respectively, as shown in Fig. 6(b). Fig. 7(a) shows the power consumption of the gate driver, and Fig. 7(b) shows the gate driver output while powered by the WPT. We have transmitted a 50-kHz sample signal having a duty ratio of 80%, and the gate driver generates this signal without any noise or error.

B. Building a Synchronous Buck converter using this Module:

To evaluate the module's dynamic and steady state performance, a synchronous buck converter has been built and tested at NREL power electronics lab. Although the module is rated at 650V, 236A, it has been tested at a maximum current of 30A during this initial phase. The input voltage was 27.63 V, and a constant 30A load was connected at the output of the buck converter. The switching frequency was 50 kHz, and the duty ratio was 30%. The components were chosen to operate the converter in continuous conduction mode. The experimental setup is shown in Fig. 8, and the test results are shown in Fig. 9. This initial setup suffered from significant parasitics caused by non-optimized package layout, and these large inductances induced by long current carrying paths have introduced high dv/dt across the drain and source of the MOSFET especially once switched at 50 kHz and 30A load current.



(a)



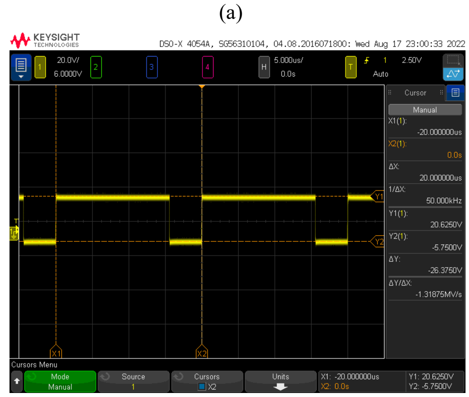
(b)

Fig. 6. (a) Characterizing V_{GS}, (b) $R_{DS(ON)}$ measurement

IV. Conclusions and Future Work

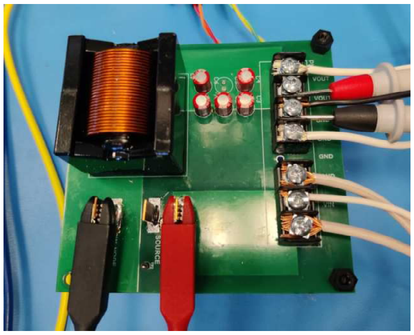
A new half-bridge power module architecture with PWM over wi-fi and wirelessly powered gate driver has been presented in this paper. The proposed architecture has not been fully tested for performance yet, and once completed, this "all-in-one module" will find applications where compactness is critical but the availability of ancillary power supply is an issue. This power module will have only two electrically accessible terminals (Fig. 1), and the PWM (incoming) and state-of-health information (outgoing) will be communicated wirelessly. This architecture can enable a complete weather-proof solution with adequate electromagnetic interference suppression ability. Using the remote monitoring and control,

(a)

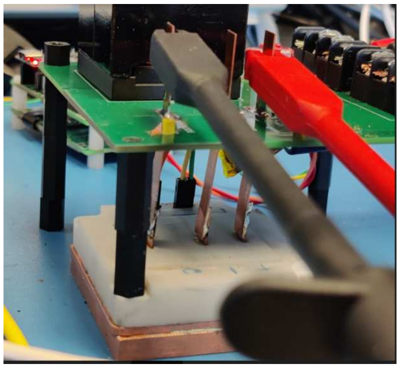


(b)

Fig. 7. (a) Power consumed by the gate driver, (b) The output of the wi-fi circuit while powered by WPT. The transmitted voltage had a frequency of 50 kHz and a duty ratio of 80%.



(a)



(b)

Fig. 8. (a) Completed buck converter, (b) connections between the converter board and the power module.

this module could be used in an artificial intelligence-enabled system, and with converters used in extreme weather condition such as geothermal, aerospace, and mining applications. This smart power module will have a wide application in power distribution system and can function as a major building block in solid state transformers and flexible AC transmission systems as well. During the next level of research, we will attempt to include the preliminary SOH module to complete the proposed architecture. In addition, a detail electromagnetic model of the module will be created to minimize the parasitics so that dv/dt could be minimized.

ACKNOWLEDGEMENTS

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the NREL Laboratory Directed Research and Development Program. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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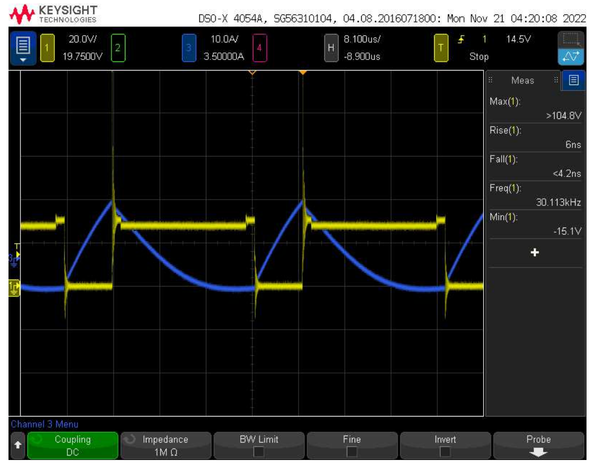

(a)

(b)

(c)

Fig. 9. (a) Voltage across the top MOSFET and the current through the inductor, (b) input voltage and current data obtained from the power supply, (c) output voltage and current obtained from the programmable load.

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