

# Gate Driver Design and Continuous Operation of an Improved 1200V/200A FREEDM-Pair Half-Bridge Power Module

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**Abstract**— FREEDM-Pair is an innovative power semiconductor switch which reduces the loss and cost through the hybrid integration of a Si IGBT and a SiC MOSFET. During the turn-off of the FREEDM-Pair, the Si IGBT is turned off first under ZVS condition and after a carefully selected delay time, the SiC MOSFET is turn-off. In this way, the turn-off loss of the Si IGBT is significantly reduced due to the ZVS turn-off condition. During the delay time, the current will be carried by the SiC MOSFET only. During the turn-on, the SiC MOSFET and the IGBT can be turned on at the same time. Due to faster turn-on speed of the MOSFET, the IGBT is also turned on under the ZVS condition. FREEDM-Pair also has better conduction characteristics compared to the Si IGBT by the combined current conduction capability of the unipolar and bipolar devices. Therefore the FREEDM-Pair provides an ideal option to realize the tradeoff between the cost and performance, and can be applied to main stream applications which currently use IGBT. Previously, the 1200V/200A FREEDM-Pair with individual gate terminals for IGBT and MOSFET have been designed and published. In this paper, a three terminal 1200V/200A FREEDM-Pair is presented and analyzed for the first time. In the three terminal FREEDM-Pair, a passive delay circuit is designed and integrated into the power module, so only one gate driver signal is needed. The designed delay circuit will generate the desired delay gate signal for the MOSFET automatically. To verify the designed gate driver function and the FREEDM-Pair performance in continuous operation, a half-bridge (HB) power module consisting of two FREEDM-Pair switches is developed. The continuous operation of the 1200V/200A FREEDM-Pair in a buck converter topology is reported for the first time.

**Keywords**—Si IGBT; SiC MOSFET; hybrid switch; gate delay circuit

## I. INTRODUCTION

SiC MOSFETs demonstrate ultrafast switching speed and low switching losses over Si IGBT due to their majority carrier conduction mechanism [1]. However, the much higher cost, primarily due to more expensive SiC wafers and fabrication process, impedes its wide adoption in power electronics applications. Therefore, the Si IGBTs are still the workhorse for important high volume applications such as motor drives, electric vehicles, PV inverters, etc. Si IGBTs have the advantages of simple MOS gate control, low forward voltage

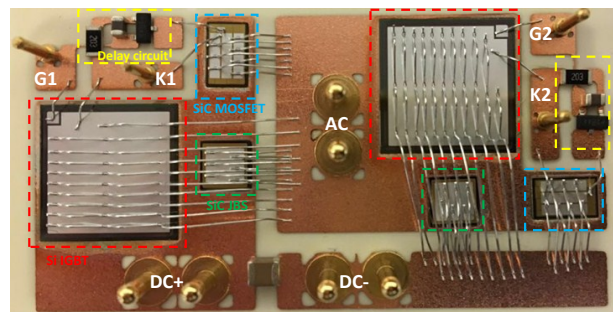
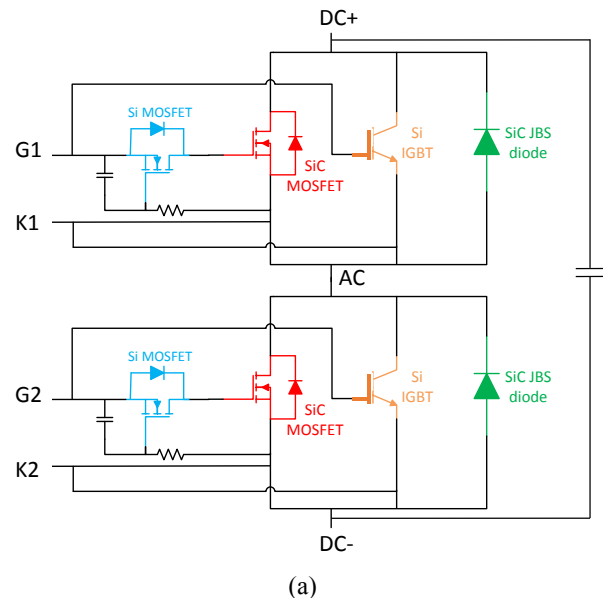
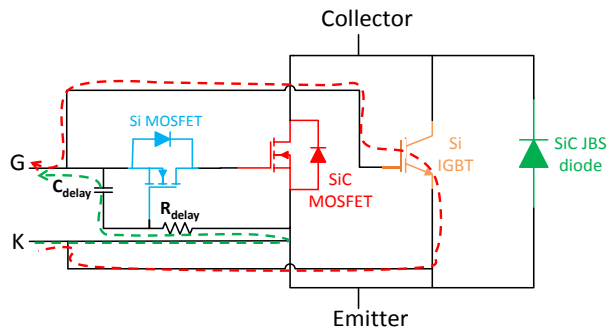
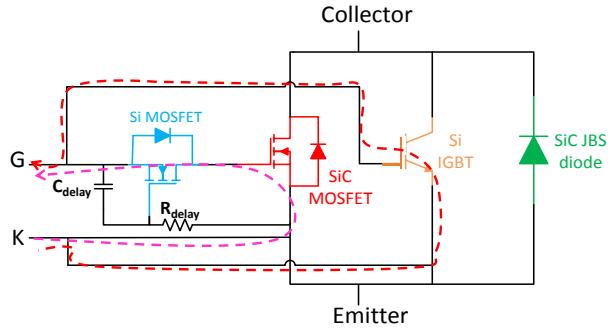


Fig. 1: (a) Circuit schematic of the 1200V/200A FREEDM-Pair HB module; (b) Packaged 1200V/200A FREEDM-Pair HB module.





(a)



(b)

Fig. 4: Turn-off gate current path.

During the turn-off process as shown in Fig.4, the delay capacitor of the gate delay circuit in the power module is discharged gradually by the discharging capacitor on the PCB gate driver board, shown as the green gate current path in Fig.4(a). Once the voltage on the delay capacitor reaches the threshold voltage of the LV Si MOSFET, the LV Si MOSFET is turned on, this period is the delay time  $T_d$ . After the LV Si MOSFET is turned on, the channel of the LV Si MOSFET can conduct current, thus the  $C_{iss}$  of the SiC MOSFET is being discharged by the discharging capacitor on the PCB gate driver board, shown as the purple gate current path in Fig.4(b). Different delay times can be chosen by adjusting the R-C circuit parameter in the gate delay circuit.

### B. Optimal delay time selection

The gate-to-emitter voltage ( $V_{ge}$ ) of the Si IGBT and the gate-to-source voltage ( $V_{gs}$ ) of the SiC MOSFET are measured when  $T_d=0.995\mu s$  as an example, and the result is shown in Fig.5. The  $V_{gs}$  of the SiC MOSFET is measured by inserting the probe tip into the silicone gel and touch onto the copper pads. It clearly shows a successful achievement of the desired delay. The total turn-off loss of the FREEDM-Pair consists of the partial turn-off loss of the Si IGBT (period 1 or period 1&2 in Fig.6 depending on the delay time), and the conduction loss of the SiC MOSFET (period 1 in Fig.6), together with the turn-off loss of the SiC MOSFET (period 2 in Fig.6).

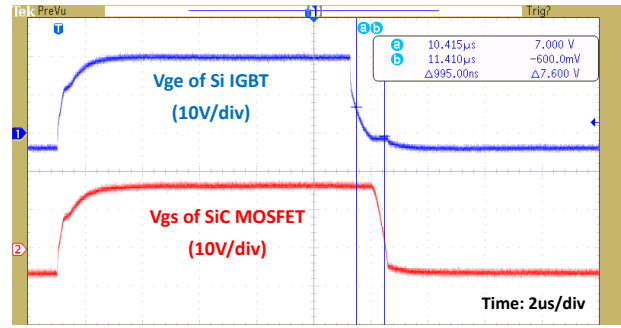


Fig. 5: Experimental waveforms of  $V_{ge}$  of Si IGBT and  $V_{gs}$  of SiC MOSFET with  $V_{ge} = 20V/-5V$ ,  $R_g = 20\Omega$ , and  $T_d=0.995\mu s$ .

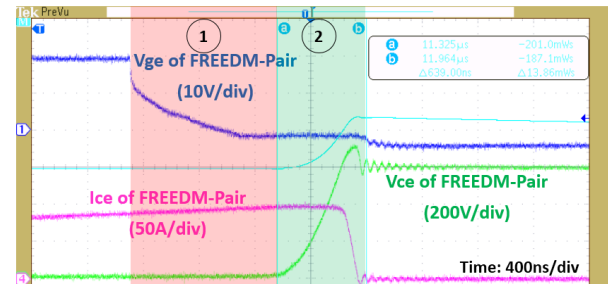


Fig. 6: Experimental turn-off waveform of FREEDM-Pair under 600V/100A, with  $V_{ge} = 20V/-5V$ ,  $R_g = 20\Omega$ , and  $T_d=0.995\mu s$ .

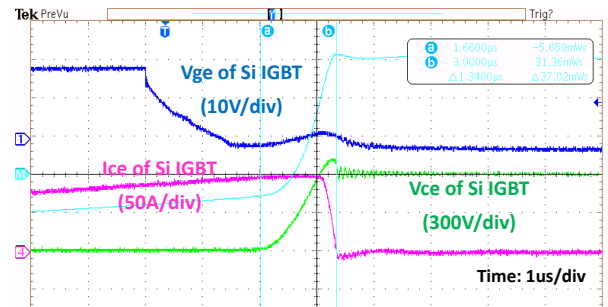


Fig. 7: Experimental turn-off waveform of Si IGBT under 600V/100A with  $V_{ge} = 20V/-5V$ ,  $R_g = 20\Omega$

As a comparison, Si IGBT is also tested under the same condition, shown in Fig.7. The turn-off loss is 37.02mJ, much higher than FREEDM-Pair. Fig. 8 shows the total turn-off loss of the FREEDM-Pair under different delay times for 600V/100A turn-off condition. It can be observed that with smaller delay time, the partial turn-off loss of the Si IGBT becomes dominant, and with larger delay time, the on-state loss during delay time of the SiC MOSFET and the turn-off loss of the SiC MOSFET become dominant. So there is a trade-off considering all these three losses. It can be seen that the optimal delay time is around 1us, resulting in the lowest total turn-off loss of the FREEDM-Pair. It shows a maximum of 66% loss reduction compared with Si IGBT under same switching conditions.

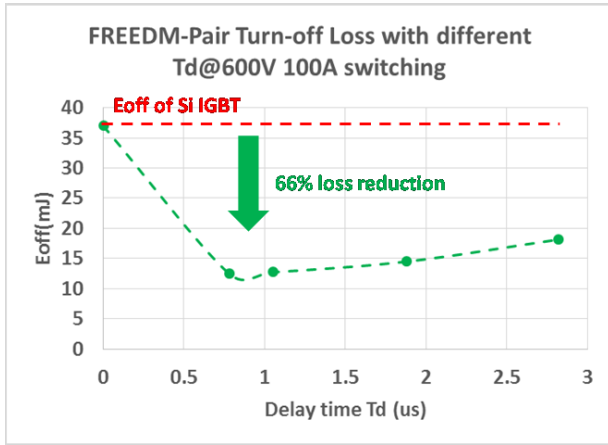


Fig. 8: Measured turn-off loss of FREEDM-Pair under different delay time  $T_d$ , and turn-off loss of Si IGBT

#### IV. CONTINUOUS OPERATION OF 1200V/200A FREEDM-PAIR

To verify the reliable functionality of the FREEDM-Pair HB power module, a buck converter is built and tested, shown in Fig.9. Experimental setup parameters are listed in Table I. Low-side FREEDM-Pair is used with gate-to-source voltage equals zero therefore it can be regarded as a rectifier formed by the body diode of MOSFET and the JBS diode. Gate-to-emitter voltage ( $V_{ge}$ ) and collector-to-emitter current ( $I_{ce}$ ) of the high-side FREEDM-Pair are measured and shown in Fig.10. it can be seen that the FREEDM-Pair HB module operates normally under 22.5kHz switching at 600V input voltage. Due to the hard switching turn-on of the high-side FREEDM-Pair, power level reported here is not at full rating. Results of continuous operation of the FREEDM-Pair HB power module at higher ratings will be reported in future publications.

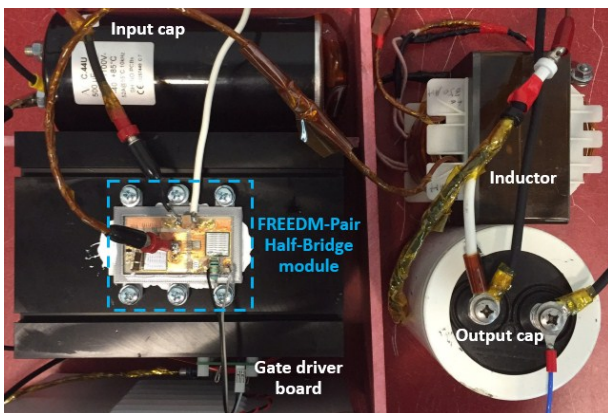


Fig. 9: Buck converter setup based on 1200V/200A FREEDM-Pair half-bridge module.

TABLE I. EXPERIMENTAL SETUP PARAMETERS

Parameters	Values	Units
Input voltage	600	V
Duty cycle	0.25	-
Switching frequency	22.5	kHz
Input capacitor	1100	$\mu$ F
Input inductor	16.8	mH
Output capacitor	500	$\mu$ F

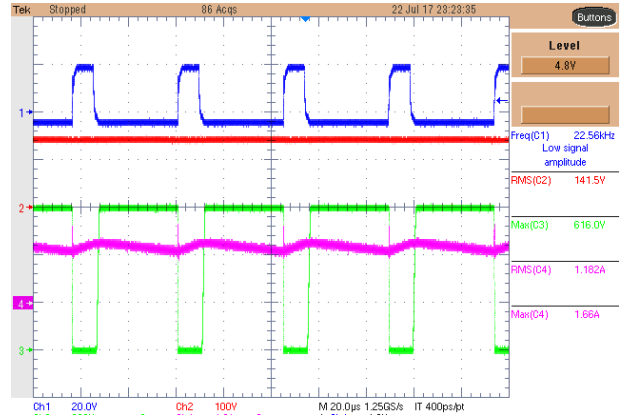


Fig. 10: Experimental waveforms of FREEDM-Pair half-bridge module based buck converter. (Blue:  $V_{ge}$  of high-side FREEDM-Pair; Green:  $V_{ce}$  of high-side FREEDM-Pair; Purple: Inductor current; Red: Output voltage)

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