Si IGBT+FRED+SiC MOSFET Hybrid Power Switches

Introduction

Hybrid power switches (HPS) combine the advantages of SiC unipolar and Si bipolar devices, effectively bridging the gap between these technologies. A hybrid power switch that integrates a Si IGBT with a SiC MOSFET merges the low conduction losses of Si IGBTs with the high switching efficiency of SiC MOSFETs, resulting in enhanced overall performance. This hybrid approach minimizes switching losses, allows for higher operating frequencies, and improves thermal management by reducing heat generation. Moreover, it offers a cost-effective alternative to full-SiC solutions while still achieving high efficiency and reliability. It also decreases electromagnetic interference (EMI) and dv/dt stress, making it particularly suitable for applications such as electric vehicle (EV) traction inverters, renewable energy systems, and industrial motor drives. Overall, this combination strikes an excellent balance between cost, efficiency, and performance for high-power applications [1-9].

Industry relevance

The hybrid power switch combining Si IGBT and SiC MOSFET technology is highly relevant in industries that demand high efficiency, robust power handling, and cost-effective solutions for power conversion. This hybrid approach is commonly used in electric vehicles (EVs) and renewable energy systems, where it enhances inverter efficiency, reduces thermal losses, and improves power density. In industrial motor drives, this technology enables faster switching with lower energy consumption, thereby increasing system reliability. Additionally, in railway traction and aerospace applications, the hybrid switch offers improved efficiency at high voltages while requiring less cooling. Compared to full-SiC solutions, this hybrid option provides a balanced trade-off between performance and cost, making it an appealing choice for industries transitioning to next-generation power electronics. (Figure 1)

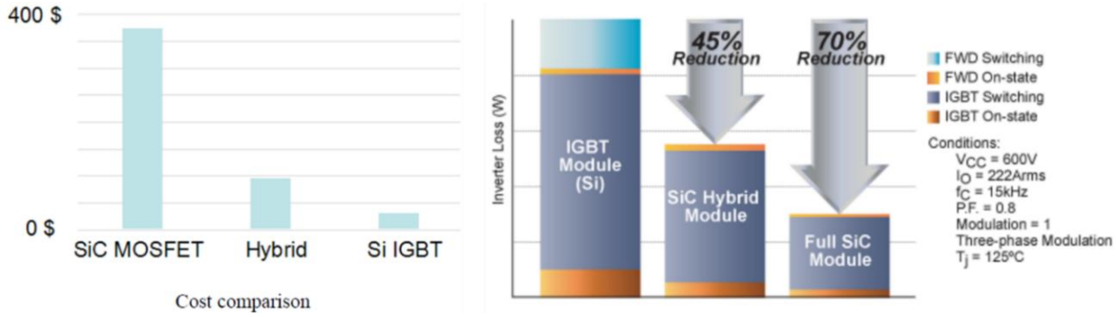
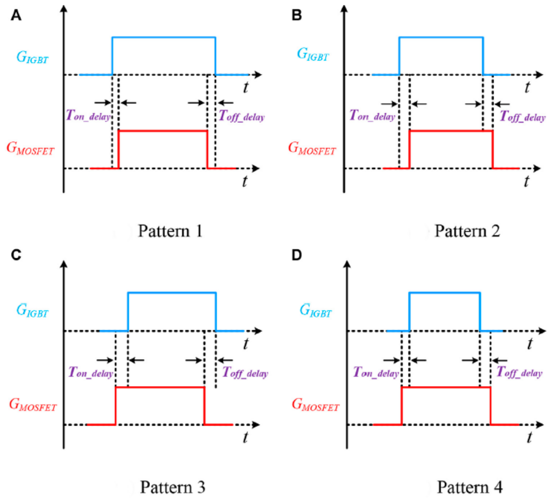


Figure 1: Cost and inverter loss comparison of SiC MOSFET, Hybrid and Si IGBT [1, 2]

Switching in Si IGBT+SiC MOSFET hybrid switch



Pattern 1

Pattern 2

Pattern 3

Pattern 4

Figure 2: Switching patterns of the Si/SiC hybrid switch [10]

Si/SiC hybrid switching can achieve four distinct switching patterns (Figure 2), allowing you to adjust the switch according to your application and requirements.

In Pattern 1, the turn-off characteristics of the Si/SiC hybrid switch consistently mirror those of the Si IGBT, regardless of any changes made to the Toff_delay. This indicates that the impact of Toff_delay on switching speed is minimal and can be overlooked. Therefore, we should focus solely on Ton_delay.

In Pattern 2, the switching speed of the Si/SiC hybrid switch is influenced by the delays in the turn-on (Ton_delay) and turn-off (Toff_delay) processes. As both Ton_delay and Toff_delay increase, the turn-on speed of the Si/SiC hybrid switch decreases gradually, while its turn-off speed increases gradually.

In Pattern 3, the switching characteristics remain consistent regardless of changes to the Ton_delay and Toff_delay. Specifically, the turn-on behavior of the Si/SiC hybrid switch always mirrors that of the SiC MOSFET, while its turn-off behavior aligns with that of the Si IGBT.

In this switching pattern, the effect of Ton_delay on the turn-on characteristics of the Si/SiC hybrid switch remains unchanged. Therefore, only Toff_delay should be considered.

Example for the analysis of Si/SiC hybrid switch loss reduction

To assess the improvement in turn-off losses of the hybrid switch, someone used a single pulse tester [11]. This tester includes a high-voltage DC power supply, DC capacitors, and a clamped inductive load. The results obtained as follows,

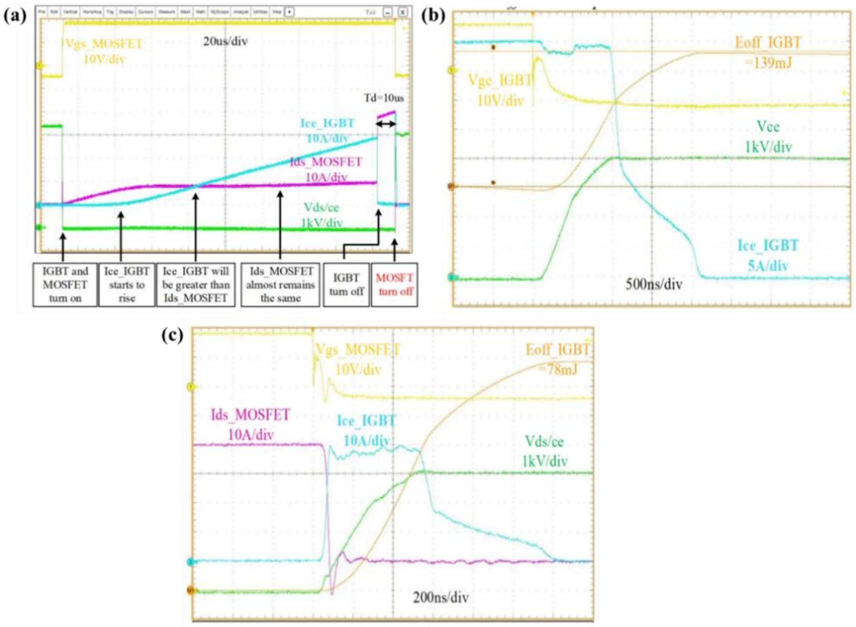


Figure 3: a) Hybrid switch single pulse test waveform at 4kV 40A with Td=10us at RT (Vgs_MOSFET=+18V/-5V, Vge_IGBT= +15V/-12V) b) Si IGBT turn off the waveform at 4kV 40A at RT (Vge=+15V/-12V) c) Hybrid switch turn off waveforms at 4kV with Td=10us at RT (Vgs_MOSFET=+18V/-5V, Vge_IGBT=+15V/-12V) [11].

Figure 3a depicts the single pulse test waveform of the hybrid switch. Initially, both the SiC MOSFET and Si IGBT are turned on simultaneously. Due to its lower voltage drop at low currents, the SiC MOSFET conducts nearly all the current. As the total current increases, a greater portion is transferred to the Si IGBT. At higher current levels, the Si IGBT carries the majority of the current, while the current through the SiC MOSFET (Ids) remains nearly constant. During turn-off, the SiC MOSFET is deactivated 10 microseconds after the Si IGBT.

Figure 3b displays the standard turn-off waveform for silicon IGBT. The turn-off loss for the silicon IGBT at 4 kV and 40 A is approximately 139 mJ, and it takes about 2 μs for the current to drop to zero. In contrast, the turn-off loss for the silicon carbide (SiC) MOSFET at the same voltage and current (4 kV, 40 A) measured with the same tester is only 20 mJ.

Figure 3c illustrates the turn-off waveform of the hybrid switch at time t_2. The total turn-off loss is made up of the Si IGBT turn-off loss (78 mJ) and the SiC MOSFET turn-off loss (1 mJ), resulting in a combined total of approximately 79 mJ. This total is about 44% lower than that of a standard IGBT. During the rapid voltage rise phase, the residual charge in the Si IGBT significantly reduces the turn-off loss, although it is still considerable. The turn-off loss can be further minimized by extending the delay time (Td).

At high temperatures, the switching loss of the Si IGBT is approximately three times higher than at room temperature, even though its forward characteristics remain stable. In contrast, the on-resistance (Ron) of the SiC MOSFET doubles at elevated temperatures, but its switching loss remains nearly unchanged. This indicates that Si/SiC hybrid switches have the potential to achieve an even greater loss reduction at higher temperatures.

Improving Costs and Efficiency with Hybrid Switches

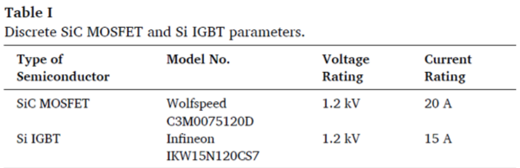


Table I
Discrete SiC MOSFET and Si IGBT parameters.

Type of Semiconductor	Model No.	Voltage Rating	Current Rating
SiC MOSFET	Wolfspeed C3M0075120D	1.2 kV	20 A
Si IGBT	Infineon IKW15N120CS7	1.2 kV	15 A

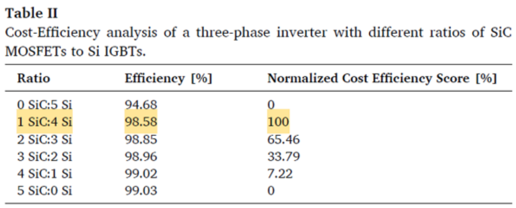


Table II
Cost-Efficiency analysis of a three-phase inverter with different ratios of SiC MOSFETs to Si IGBTs.

Ratio	Efficiency [%]	Normalized Cost Efficiency Score [%]
0 SiC:5 Si	94.68	0
1 SiC:4 Si	98.58	100
2 SiC:3 Si	98.85	65.46
3 SiC:2 Si	98.96	33.79
4 SiC:1 Si	99.02	7.22
5 SiC:0 Si	99.03	0

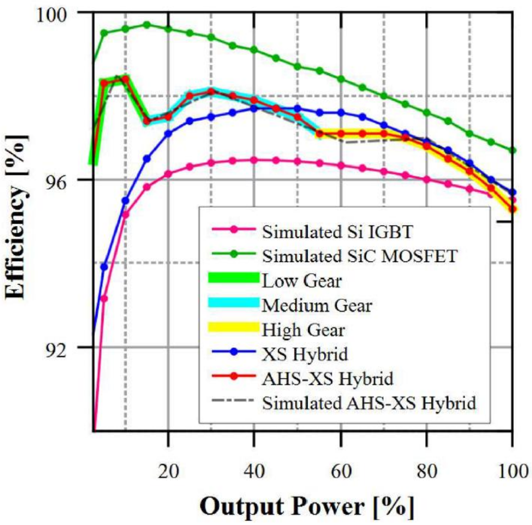


Figure 4: Efficiency curves of simulated Si IGBT simulated SiC MOSFET, non-AHS XS Hybrid, AHS XS Hybrid and simulated HS-XS Hybrid inverter over percentage of output power [12].

A report published outlines the selection of five devices to construct a 22 kVA rated three-phase, two-level voltage source inverter, as detailed in Table 1. The choice of these devices and their parallel configuration was primarily influenced by the availability and cost-effectiveness of 1.2 kV components with comparable current ratings in TO-247 packages. This setup enables different SiC-to-Si ratios, including 1:4, 2:3, 3:2, and 4:1.

Table II presents the simulation and CES analysis results, demonstrating that the highest Cost Effectiveness Score (CES) for the 10 kHz EV inverter is achieved with a 1:4 SiC MOSFET to Si IGBT ratio. This ratio is identified as the optimal trade-off between minimizing losses and maintaining cost efficiency.

Figure 4 illustrates that the full Si IGBT converter has the lowest efficiency, while the classic XS hybrid converter (1:4 SiC MOSFET to Si IGBT) performs better. The focus is on the XS hybrid converter using the AHS concept, which demonstrates notable efficiency improvements over the full Si IGBT converter across all load conditions. At low loads, its performance approaches that of a full SiC MOSFET solution, making it well-suited for EV applications where sub-load operation is common. Efficiency variations in the AHS hybrid converter are linked to gear level shifts, causing sudden drops at 20% and 60% output power as the inverter's maximum power rating increases. Overall, this design significantly enhances efficiency across the entire driving profile. Our product, CMSG120N013MDG, also adheres to the highly efficient 1:4 ratio of SiC:Si.

Application of Hybrid Switches

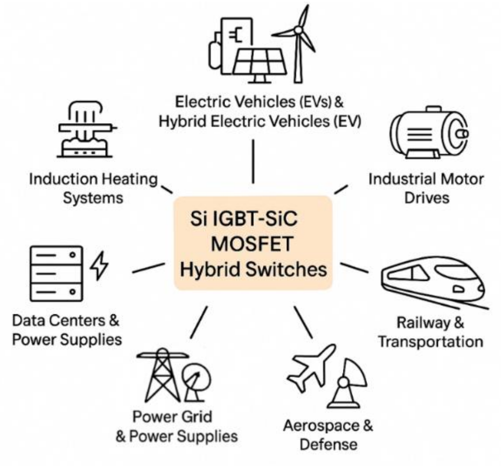


Figure 5: Applications of Si IGBT-SiC MOSFET hybrid switches

Figure 5 provides a summary of various high-end applications for hybrid switches that utilize Si IGBT and SiC MOSFET technologies. Si IGBT-SiC MOSFET hybrid switches are commonly used in high-power applications due to their efficiency, fast switching speeds, and reduced losses. They play a vital role in electric vehicles (EVs) and hybrid electric vehicles (HEVs), serving functions such as traction inverters, onboard chargers, and DC-DC converters, all of which contribute to improved battery life and power conversion. In renewable energy systems, these hybrid switches enhance the efficiency of solar inverters, wind energy converters, and battery storage systems. Their applications also extend to industrial settings, where they are used in motor drives, variable frequency drives (VFDs), and railway traction converters, ensuring better performance and reliability. Moreover, they are essential in aerospace, defense, data centers, uninterruptible power supply (UPS) systems, and high-frequency induction heating, where power efficiency and thermal management are critical concerns. Their ability to handle high voltage and current while minimizing energy losses makes Si IGBT-SiC MOSFET hybrid switches indispensable in modern power electronics. Some of the specific examples are discussed below.

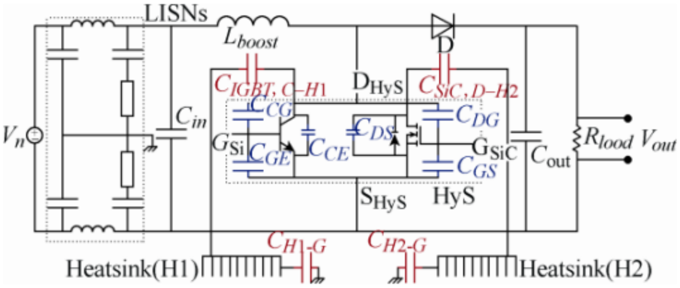


Figure 6: DC-DC boost converter with hybrid switch [13]

The initial implementation of a hard-switched DC-DC converter was a boost converter using a discrete HyS, as shown in Figure 6. A 650 V Si IGBT and SiC MOSFET-based HyS with a 1:5 SiC/Si current ratio was successfully demonstrated. However, due to thermal limitations, the converter operated at only 20 kHz, and the power output was not reported.

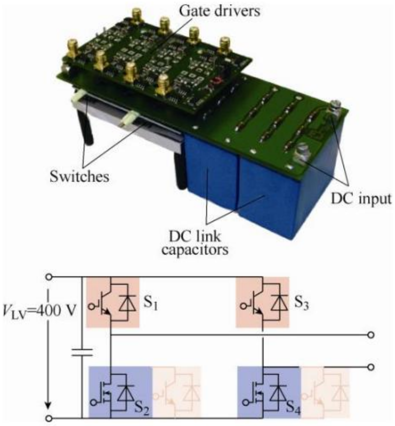


Figure 7: DC-DC converter with Si module plus SiC discrete[13]

In another case, a hybrid switch was utilized as a core component of a DC-DC converter within a solid-state transformer. This design incorporated a silicon (Si) module along with a silicon carbide (SiC) discrete version, as illustrated in Figure 7. The use of the hybrid switch achieved a loss reduction of over 50%.

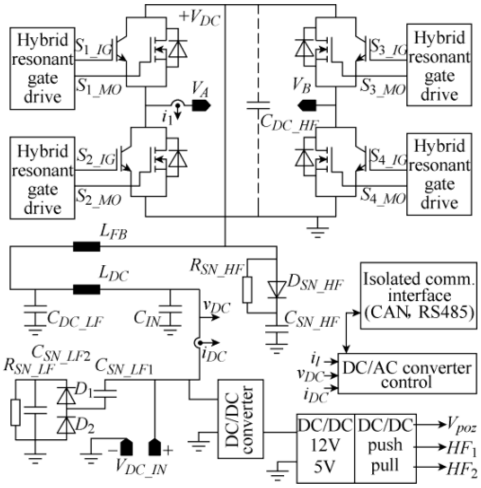


Figure 8: Dynamic wireless charging system with hybrid switch[13]

As shown in Figure 8, a resonant converter was also utilized in a high-performance dynamic wireless power transfer system for electric vehicles. Using a discrete-version HyS, the system achieved 98% efficiency at 5 kW at certain test points. According to the paper, the tests demonstrated a switching frequency close to 90 kHz.

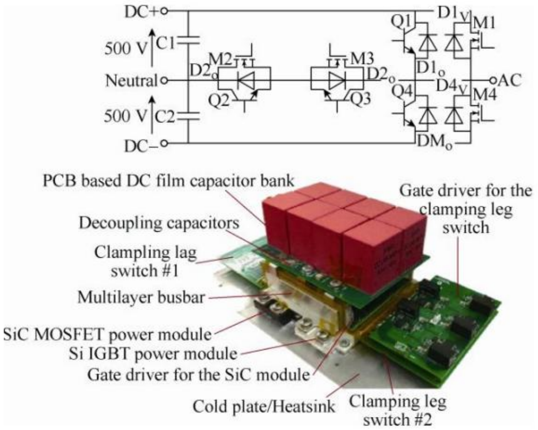


Figure 9: Three-level T-Type power electronics building block[13]

Figure 9 presents another T-Type power electronics building block that incorporates HyS, which has been shown to operate at a frequency of 28 kHz and a power rating of 17.5 kVA. This development utilizes commercial silicon carbide (SiC) MOSFET and silicon (Si) IGBT modules.

Product Overview

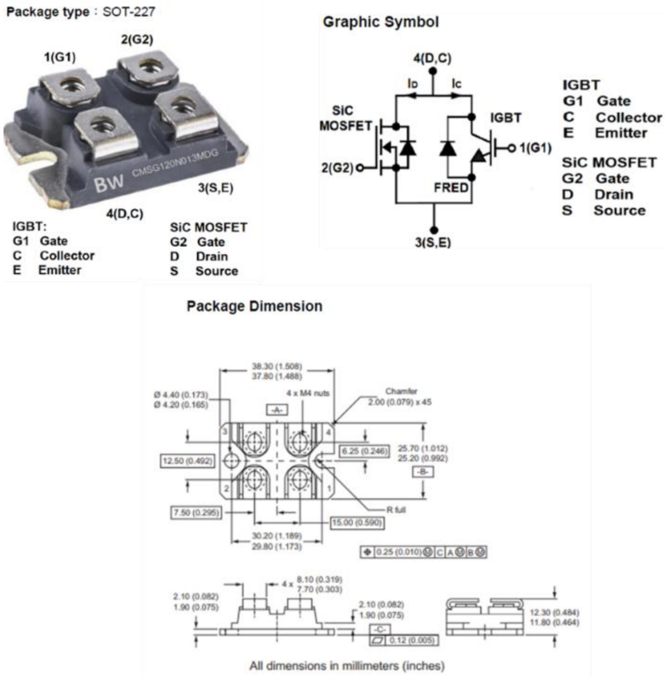


Figure 10: Si IGBT+FRED+Si IGBT hybrid module package type, graphical symbol, and package dimension.

The Hybrid IGBT with built-in SiC MOSFET and FRED in SOT-227 package offers high efficiency in both hard switching and resonant topologies, making it ideal for advanced power applications (Figure 10). Its dual gate pad design allows for optimized circuit performance, while its positive temperature coefficient in $V_{CE(on)}$ ensures easy paralleling for scalable power solutions. The device also features Pb-free lead plating for environmental compliance and low EMI, reducing noise and improving system reliability. These characteristics make it a robust and efficient choice for next-generation power electronics. The device offers low EMI, low gate charge (Q_G), and low switching loss, enabling soft switching for improved efficiency. With a high switching frequency of up to 150 kHz, it supports faster operation while minimizing power dissipation, making it ideal for high-performance power electronics applications.

The device is ideal for industrial UPS, chargers, energy storage, and high-power converters, as well as three-level solar string inverters and soft-switching applications. It is also well-suited for welding, inductive cooking, and inverterized microwave ovens, offering high efficiency and reliability in advanced power electronics systems.

Implementation

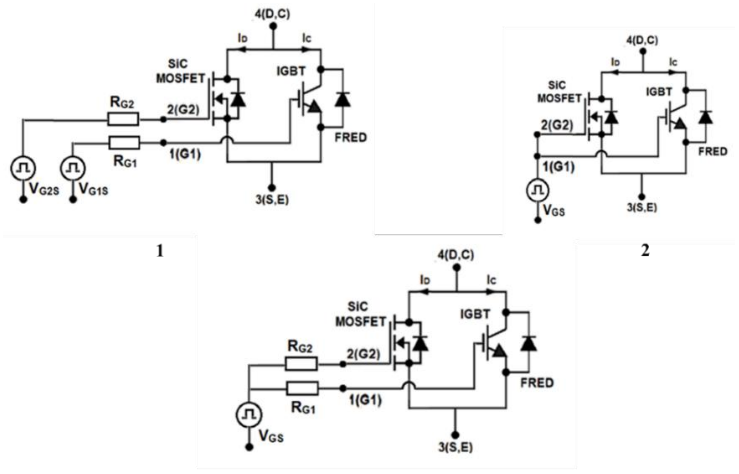


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Figure 11: Si IGBT + FRED + SiC MOSFET (Hybrid) power switch three different configurations [3].

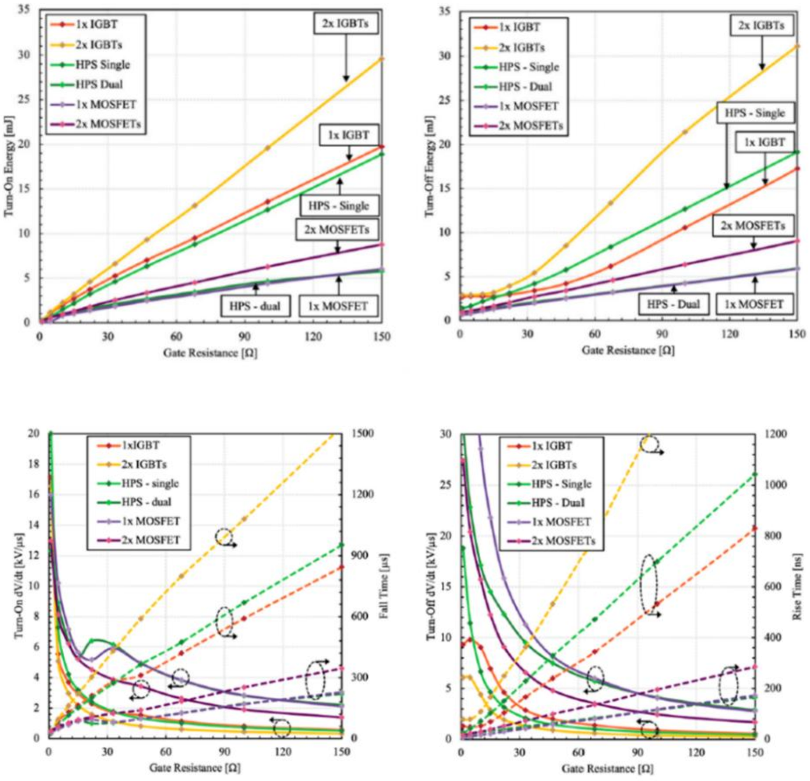


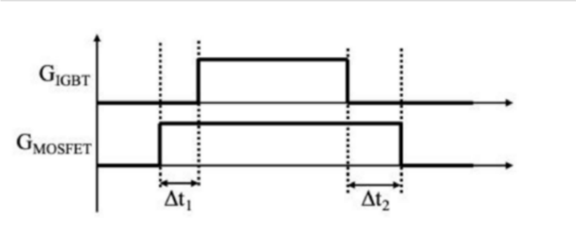
Figure 13: Measured turn-on and turn-off switching energy losses as a function of gate resistance and measured turn-on dV/dt and fall time and turn-off dV/dt and rise times as a function of different gate resistance [3].

The Si IGBT + FRED + SiC MOSFET power switch can be implemented in three different configurations (Figure 11). The high-performance switch (HPS) can be set up as a four-terminal device, where the gates are separated, or as a three-terminal device with two different configurations, where the gates are connected.

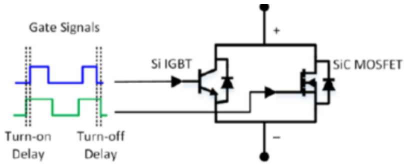
In Type 1, a dual gate configuration is used, with resistances (R_{G1} and R_{G2}) connected to both the Si IGBT and the SiC MOSFET. Type 2 features a single gate configuration without gate resistance, while Type 3 involves a single gate configuration with separate resistance for controlling both the IGBT and the MOSFET.

Currently, we are using the Type 1 and Type 2 configurations for our measurements. According to the report, the single gate configuration exhibits higher losses compared to the dual gate configuration. In the single gate configuration, losses increase with a rise in Rg, whereas the dual gate configuration shows lower and more stable losses. (Figure 12)

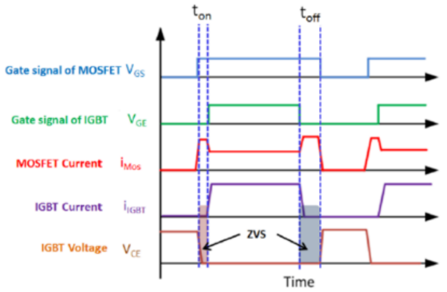
In the dual gate HPS setup, the gate resistance of the IGBT (R_{G1}) is fixed at 47 Ω for turn-on and 15 Ω for turn-off. It is essential to optimize both R_{G1} and R_{G2} in Type 1 and Type 3 configurations, as they are critical to the module's performance [3]. Additionally, we need to test all three configurations under both DC and pulse current conditions to optimize their output.



The staggered gate signals for the constituent Si-IGBT and the SiC-MOSFET of the hybrid switch.



The proposed ZVS switching pattern for Si/SiC hybrid switches.



Graphic illustration of the turn-on and turn-off signals of the Si/SiC hybrid switches based on the ZVS switching pattern.

Figure 13: Switching performance of Si IGBT+FRED+SiC MOSFET module [4, 5].

The improved switching performance is made possible with optimized staggered gate signal pulses to respective devices in the hybrid switch. The MOSFET turns on earlier but switches off later than the IGBT. As a result, the IGBT achieves quasi-zero voltage switching (ZVS) at both turn-on and turn-off due to its very low on-state voltage. However, when implementing this switching pattern in hybrid switches, the safe operating area (SOA) of SiC devices must be carefully considered. Otherwise, the large current spikes occurring before turn-on and after turn-off in the SiC MOSFET could lead to device failure due to overcurrent. (Figure 13)

To ensure the superior performance of HPS, we must measure the switching characteristics such as turn-on delay time (td(on)), rise Time (tr), turn-off delay time (td(off)), fall time (t_f), turn-on switching energy (Eon), and turn-off switching energy (Eoff).

Performance Data

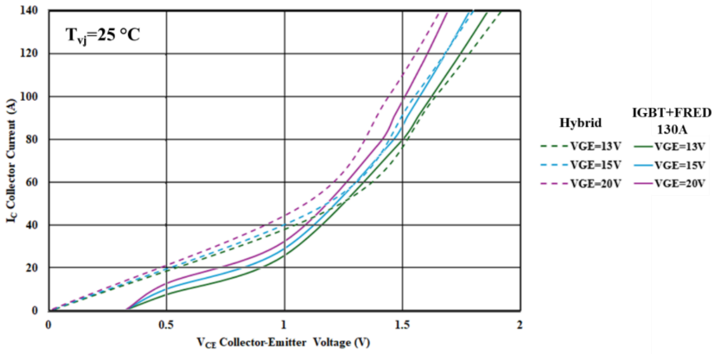


Figure 14: I_C *vs* V_{CE} characteristics of hybrid module.

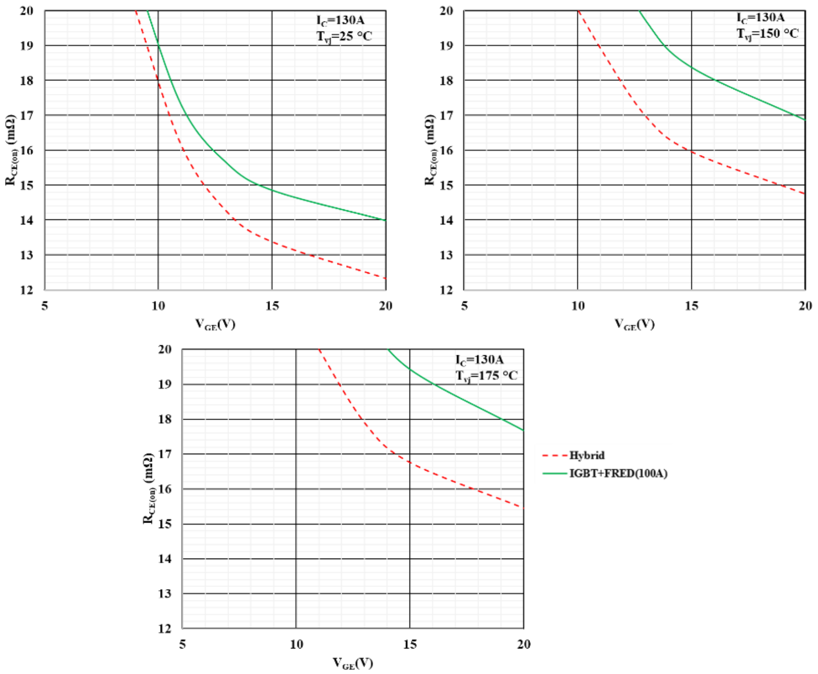


Figure 15: V_{GE} *vs* $R_{CE(on)}$ characteristics of hybrid module.

The developed hybrid module, CMSG120N013MDG, demonstrated a typical $V_{CE(on)}$ of 1.73V and a typical $R_{CE(on)}$ of 13.3mΩ at V_{G1E} = V_{G2S} = 15V and I_C = 130A. The equivalent MOSFET parameters include a typical $R_{DS(on)}$ of 13.3mΩ at V_{GS} = 15 V and I_D = 130 A. Compared to competitors' SiC MOSFETs and Si IGBT parts with the same current rating, our components exhibited lower resistance levels.

The V_{CE} vs. I_C and $R_{CE(on)}$ vs. V_{GE} plots (Figure 14 and Figure 15) demonstrate that the hybrid module consistently exhibits a lower $R_{CE(on)}$ compared to the IGBT+FRED (130 A) module at higher V_{GE}, indicating improved charge carrier dynamics and better gate control characteristics. This enhanced performance implies reduced conduction losses, improved thermal efficiency, and potentially lower cooling requirements, making the hybrid module a more efficient and reliable choice for high-power applications. The collector-emitter breakdown voltage is 1200 V, and the DC collector and drain currents are 260 A at 25 °C and 130 A at 100 °C. The hybrid module can merge the low conduction losses of Si IGBTs with the high switching efficiency of SiC MOSFETs, resulting in enhanced overall performance.

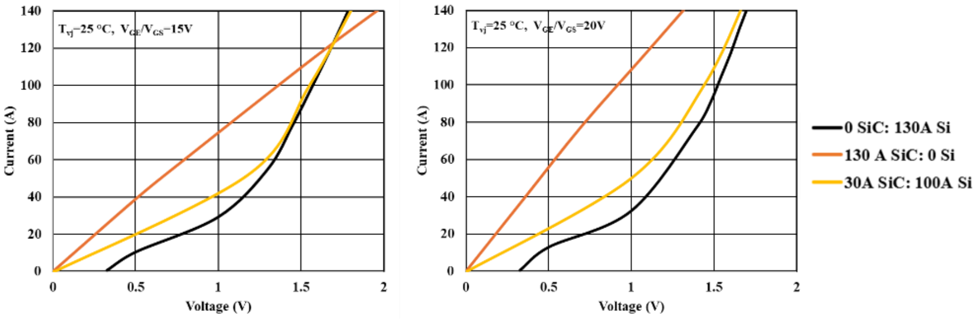


Figure 16: Comparison of current *vs* voltage curves of 0 SiC:130A Si, 130A SiC:0 Si, and 30A SiC:100A Si.

Figure 16 compares the current versus voltage curves for three configurations: 0 SiC:130A Si, 130A SiC:0 Si, and 30A SiC:100A Si.

At higher gate-source voltages (V_{gs}) and higher currents, the Si-SiC hybrid module (30A SiC MOSFET: 100A Si) exhibits lower conduction losses than the 130A Si IGBT. Although the 130A SiC MOSFET demonstrates even lower conduction losses compared to both the 130A Si IGBT and the hybrid module, the hybrid module is a more feasible option due to its tunable switching capabilities and lower cost.

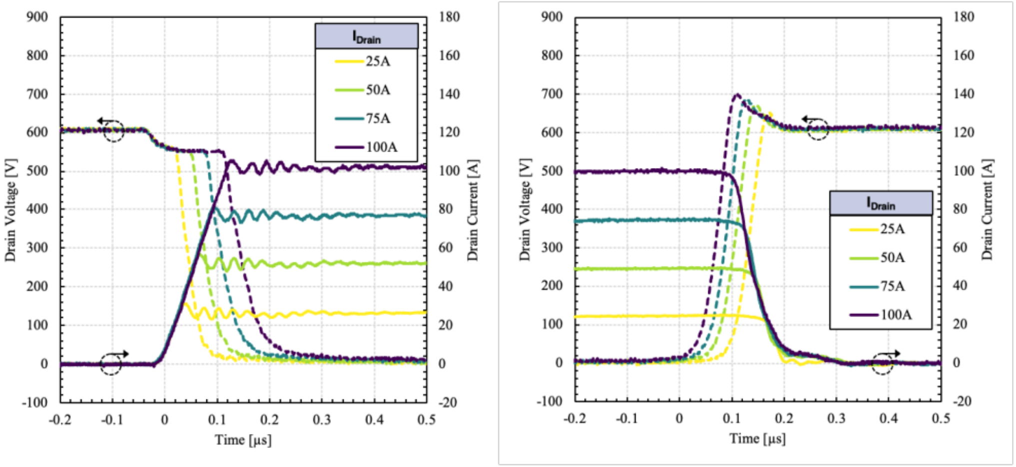


Figure 17: measured switching waveforms of hybrid module a) turn-on and b) turn off

Test condition: $R_{G\text{-}MOS}$=33 Ω, $R_{G\text{-}IGBT}$=47 Ω, $V_{GS(on)}$=18V, $V_{GS(off)}$=0V, t_{delay}=0s, T_{amb}=25°C

The measured switching patterns are shown above (Figure 17). The slew rate remains consistent regardless of the load current, and no oscillation or ringing is observed during the switching transitions.

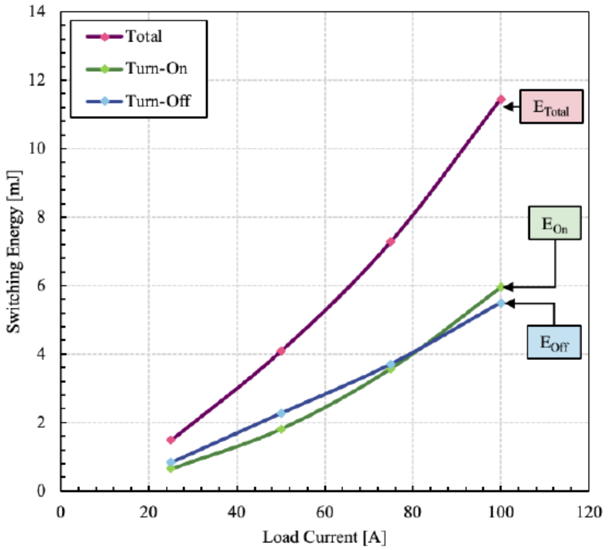


Figure 18: Measured switching energy losses at different load currents.

Test condition: R_G = 33Ω, $V_{G(ON)}$ = 18V, $V_{G(OFF)}$=0V,$t_{delay\text{-}off}$ = 1µs, T_{amb}=25˚C.

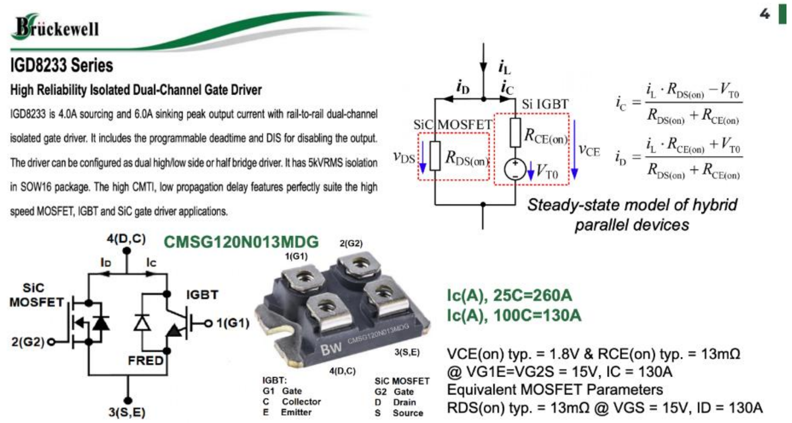
Figure 18 presents the measured switching energy losses at various load currents. As the load current increases, the switching losses also rise. However, the losses remain significantly lower compared to IGBT-only solutions.

Gate driver for hybrid switching

One key advantage of this hybrid device lies in its ability to operate under zero-voltage switching (ZVS) conditions, thanks to the independent control of gate signals for each device. By synchronizing the turn-on moments of both components, significant reductions in turn-on losses are achieved – up to 70% compared to using solely Si IGBT and 50% compared to relying solely on SiC MOSFET.

Moreover, the strategic sequencing of turn-off events further refines the efficiency of the system. Optimal performance is attained when the Si IGBT initiates its turn-off process before the SiC MOSFET, resulting in a notable 61.4% reduction in turn-off losses. This meticulous optimization approach finds practical application in devices like the Buck converter, showcasing tangible benefits in real-world scenarios.

Introducing the IGD8233, our high-reliability Isolated dual-channel gate driver. This advanced component plays a pivotal role in controlling the precise turn on/off operations of power modules, ensuring seamless and efficient functionality in power conversion systems.



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IGD8233 Series

High Reliability Isolated Dual-Channel Gate Driver

IGD8233 is 4.0A sourcing and 6.0A sinking peak output current with rail-to-rail dual-channel isolated gate driver. It includes the programmable deadtime and DIS for disabling the output. The driver can be configured as dual high/low side or half bridge driver. It has 5kVRMS isolation in SOW16 package. The high CMTI, low propagation delay features perfectly suite the high speed MOSFET, IGBT and SiC gate driver applications.

$$i_C = \frac{i_L \cdot R_{DS(on)} - V_{T0}}{R_{DS(on)} + R_{CE(on)}}$$

$$i_D = \frac{i_L \cdot R_{CE(on)} + V_{T0}}{R_{DS(on)} + R_{CE(on)}}$$

Steady-state model of hybrid parallel devices

CMSG120N013MDG

Ic(A), 25C=260A
Ic(A), 100C=130A

VCE(on) typ. = 1.8V & RCE(on) typ. = 13mΩ
@ VG1E=VG2S = 15V, IC = 130A
Equivalent MOSFET Parameters
RDS(on) typ. = 13mΩ @ VGS = 15V, ID = 130A

IGBT:
G1 Gate
C Collector
E Emitter

SiC MOSFET
G2 Gate
D Drain
S Source

Demo board information

The figure below (Figure 19) shows the Gerber file demo board used for testing our hybrid module.

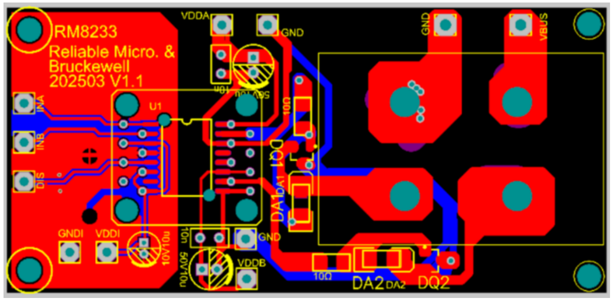

Figure 19: Image of the Gerber file for the demo board utilized in testing hybrid module.

Conclusions

In conclusion, the Si IGBT + SiC MOSFET hybrid power switch effectively combines the advantages of silicon carbide (SiC) unipolar and silicon (Si) bipolar devices. This combination results in high efficiency, reduced switching losses, and improved thermal management. The switch supports high switching frequencies, minimizes electromagnetic interference (EMI), and allows for easy paralleling, making it suitable for various industrial and high-power applications, such as electric vehicle (EV) traction inverters, renewable energy systems, industrial motor drives, and power converters.

The CMSG120N013MDG hybrid module has demonstrated excellent performance, featuring lower conduction resistance and a high breakdown voltage, making it a cost-effective and efficient alternative to full-SiC solutions. As industries transition to next-generation power electronics, this hybrid technology offers a balanced trade-off between performance, cost, and reliability, ensuring its continued relevance in modern power conversion systems.

We also introduced the IGD8233, our high-reliability isolated dual-channel gate driver. This advanced component plays a crucial role in precisely controlling the turn-on and turn-off operations of power modules, ensuring seamless and efficient functionality in power conversion systems.

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