The Characterization of a Silicon-Carbide Gen2 based Inverter on a Motor Testbench

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Abstract

Wide bandgap materials, such as silicon carbide (SiC), offer significant advantages over conventional silicon (Si) technologies for automotive applications. Indeed SiC-based automotive power modules provide higher system efficiency compared to their Si-based counterparts since they generate lower power losses, i.e., switching and conduction losses. This paper provides a comparative evaluation between Si-IGBT and SiC-MOSFET based automotive power modules in terms of efficiency. The main objective is to highlight the performance of Infineon's second generation SiC-MOSFET based HybridPACK™ Drive (HPD G2) power module in terms of generating low power losses and achieving high system efficiency. For this purpose, a laboratory inverter system was built based on different automotive power modules and several experimental tests were carried-out. The drive was characterized on a motor test bench with two mechanically coupled permanent magnet synchronous motors (IPMSM) operating in both motor and generator modes. Four-quadrant efficiency maps were generated by operating the system in torque and speed-controlled modes. The obtained results prove the high performance of Infineon's SiC-MOSFET based HPD G2 power modules with a system efficiency that exceeds 99%. Moreover, Numerical simulations under real driving cycle were performed and the obtained results further prove the aptitude of SiC-based automotive power modules in generating high system efficiency.

I. Introduction

Global awareness of climate change and increasing energy prices have led to massive research in the area of sustainability, electrification and decarbonization. In this regard, during the last decades, the electrified vehicle (EV) market has been rapidly growing. It is anticipated that EVs will take over 35% of the entire car market by 2040. Semiconductor power modules are core components of power electronics in EVs. The current trends, and main considerations, when designing a power electronics conversion system is to achieve high system efficiency and power density and to ensure reduced system size and cost. It is also important to ensure high switching frequency operation capability.

To meet these targets, high-performance automotive-qualified power semiconductor devices are required. Generally, the overall performance of the automotive module is determined by the semiconductor properties. It is commonly known that SiC-based power devices are the best choice in applications where high-power densities, high efficiency and high reliability are required. Indeed, SiC material allows realization of power devices with improved characteristics compared to Si-based devices with the same blocking voltage capability. For instance, SiC MOSFETs feature low on-state resistance, high switching speed, high voltage-blocking capability and high working temperature. Moreover, these devices have low body-diode reverse recovery current, low parasitic capacitances, and no tail recovery current. This leads to improved system performance in terms of power losses. These advantages, and many others, make SiC MOSFETs an increasingly interesting technology in high frequency, high voltage, automotive power modules.

With the strong growth of EV markets worldwide, MOSFET technologies are also evolving at break-neck speeds. Recently, several academic and industrial research works were elaborated to investigate SiC technologies in depth and take full advantage of their strong capabilities, particularly, in automotive applications. Currently, two main SiC MOSFET Technologies dominate the market. The Planar SiC MOSFET, which was commercialized in 2011 and is still the dominant MOSFET structure up today. It has the same cross-sectional structure as the structure of vertical double-diffused MOSFET in Si technology. And, the Trench MOSFET, which is an alternative structure with advantages of smaller cell pitch resulting in higher packing density and low ON-resistance.

Infineon Technologies is one of the lead manufacturers of semiconductor power devices and it has continuously taken part in the investigations of SiC MOSFET technologies. Recently, Infineon has also introduced its CoolSiC™ MOSFET trench concept, based on which several discrete devices and automotive power modules were developed. Amongst these modules we distinguish the second generation CoolSiC™ HybridPACK™ Drive (HPD Gen2), which is a pioneering power module in the automotive industry. By incorporating Infineon's latest CoolSiC™ G2 technology, the latter offers higher power with a better power to cost ratio and benchmark power cycling capability compared to its first generation. Moreover, it offers several package enhancements such as Rivet, Heat stake Domes, PinFin Baseplate, phase current sensors modules, and much more.

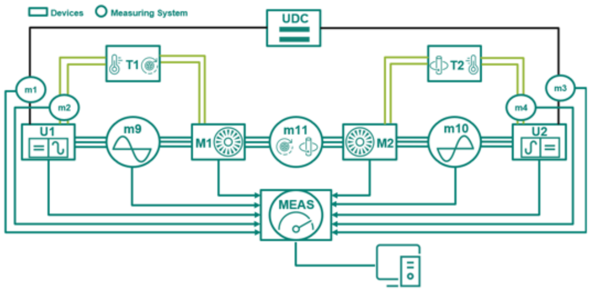
This paper presents an experimental comparative evaluation of different Si-based and SiC-based automotive power modules in terms of efficiency. For this purpose, a laboratory inverter system was set up and integrated into an electric motor test bench. The latter consists of two mechanically coupled permanent magnet synchronous motors (IPMSM) with independent control loops for speed and torque. The set-up can be operated in both motor and generator operation modes. The main objective is to highlight the high performance of Infineon's HPD G2 SiC-MOSFET based power modules in terms of efficiency. In the following section II, we will thoroughly present the test bench and the test conditions and provide the experimental results for three different types of automotive power modules. The investigated modules are the FS01MR08A8MA2LBC (SiC-MOSFET based HPD G2), FS03MR12A6MA1B (Si-IGBT based HPD G1), both from Infineon, and another commercially available Si-IGBT automotive power module. A comparative evaluation of these power modules in terms of efficiency, under the same operating conditions, is also provided. In section III, we will present numerical simulation results of three different vehicle models under real driving cycle profiles to further empathize the capability of CoolSiC™ G2 based automotive power modules in terms of achieving high system efficiency. Finally, we finish with some concluding remarks.

II. Efficiency Estimation of Automotive Power Modules

II. 1. Experimental Set-up

This paper presents an experimental evaluation of Infineon's SiC-MOSFET based HPD Gen1 and Gen2, with a commercially available Si-IGBT based power module, for automotive applications in terms of efficiency. For this purpose, a laboratory traction inverter system was set up and integrated into an electric motor test bench. The latter consists of two mechanically coupled 85kW (114hp) IPMSM with independent control loops for speed and torque. Each IPMSM is able to operate in the range of 12,000rpm with a maximum torque of 270Nm.

The system can be operated in both motor and generator operation modes. A full schematic of the adopted test bench is illustrated in Figure 1.a. The definition of all components is also provided in Figure



UDC	DC-Link	m1/m3	Measurement of DC currents / voltages Inverter 1 / Inverter 2
U1	Inverter 1 (speed controlled)	m2/m4	Measurement of speed and temperature of motor M1 / M2
U2	Inverter 2 (torque / current controlled)	m9/m10	Measurement of AC currents / voltages of motor M1 / M2
M1	Motor 1 (speed controlled)	m11	Measurement (speed / torque) of motor M1/M2)
M2	Motor 2 (torque / current controlled)	MEAS	Measuring system
T1/T2	Measurement (speed / temperature of motor M1 / M2)		

(a) (b)

Figure 1. Electric Motor Test Bench (a) structure and (b) different elements

1.b. The intermediate circuit (UDC), you see in this picture, represents the central element in both systems. The latter acts as the DC-voltage source and allows electrical energy to be exchanged between the different components of the set-up.

This set-up offers a variety of application-specific measurement options with high accuracy, including measurements with real driving profiles, efficiency measurements of the drive, motor and overall system, 4-quadrant control measurements and analysis of the thermal behavior of the module. These measurement options provide a precise and realistic investigation for power module evaluation.

In the following sub-sections, we will use this experimental set-up to evaluate the efficiency of the FS01MR08A8MA2LBC, i.e., SiC-MOSFET based HPD G2 from Infineon, in comparison with a commercially available Si-IGBT based automotive power module. We will also compare the performance of these modules to the performance of the FS03MR12A6MA1B, i.e., Si-IGBT HPD G1 from Infineon. This is done by operating the system in torque and speed-controlled modes and generating 4-quadrant efficiency maps.

II. 2. Evaluation of the 750V SiC-MOSFET based HPD G2 FS01MR08A8MA2LBC

Initially, we tested the performance of the 750V CoolSiC™ HPD G2 FS01MR08A8MA2LBC from Infineon in terms of efficiency. The system was first operated in motor mode and then in generator mode. At a DC voltage of 325VDC, the speeds were characterized in the range of 6000 rpm and the torques in the range of +/-250 Nm as shown in Figure 2 below. These operating points are typical for a battery electric vehicle (EV) application, i.e., constant torque range and field weakening range of the motor.

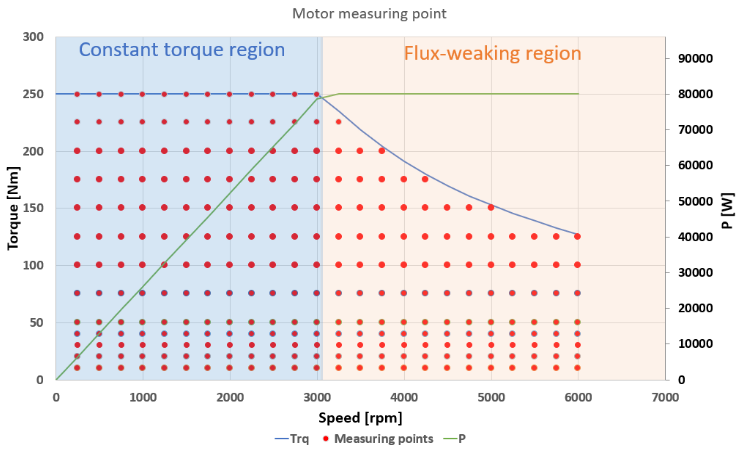


Figure 2. Values of the generated torque and speed, and the corresponding power, at 325VDC

Based on these specifications, we have created an efficiency map of the inverter as can be seen from Figure 3, where the upper section represents the resulting curves for motor mode operation, and the lower section represents the resulting curves for generator mode operation. For accurate recording, the specific measurement points from Figure 2, were approached, held, and recorded with the measurement system. The software used allowed currents, voltages, power, and frequencies to be recorded from both the energy source and the inverter. The speed, torque, power, and frequency of the motor were also recorded. The efficiency of both the inverter and the motor was then approximated using the following calculation formula:

$$\eta = \frac{P_{out}}{P_{in}}$$

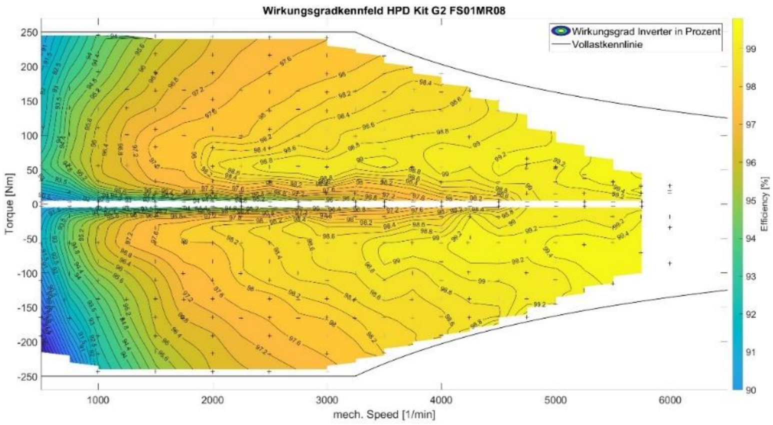


Figure 3. Efficiency map of the FS01MR08A8MA2LBC based traction inverter

The exact efficiency of the inverter could be measured both in the constant torque range and in the field, weakening range from a speed of about 3000rpm. The color gradient in Figure 3 clearly shows that the efficiency of the inverter increases at higher speeds. These results also empathize the high performance of the FS01MR08A8MA2LBC based inverter system in terms of increased system efficiency across a wide range of operating points. They also show the capability of the Infineon's SiC-MOSFET based HPD G2 in providing high system efficiency that exceeds 99%.

For better understanding of Figure 3, simplified curves were created as depicted in Figure 4. The red color represents the motor curve, and the grey color represents the generator curve. The two curves run parallel at most points and show comparable behavior. In motor operation, the inverter exhibits high efficiency, starting from 96% at lower speeds and progressively improving to 98.8% at speeds up to 3000 rpm. This upward efficiency trend continues in the field weakening range, where efficiency starts from

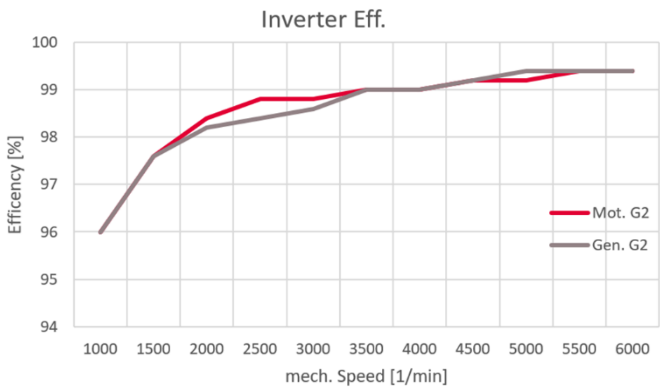


Figure 4. Efficiency measurement of the FS01MR08A8MA2LBC in both motor and generator operation modes

99% and peaks to 99.4%. The same conclusion can be drawn for the generator mode. The efficiency of the inverter at generator mode starts from 96% for speeds in the rage of 0 … 3000rpm and continues to improve to reach 98.6% 3000rpm. In the field weakening range, the efficiency continues to increase to reach 99.4%. The highest observed efficiency point is 99.57%, occurring at 5750rpm with a torque of 65Nm. It is also worth noting that, in the constant torque range, motor operation tends to be more efficient than generator operation. Conversely, as the field weakens, generator operation becomes more efficient than motor operation. However, the difference is generally negligible, i.e., only a few percentage points.

II. 3. Evaluation of a 750V Si-IGBT based commercially available automotive power module

To gain a deeper insight into the advantages of Infineon's SiC-MOSFET based HPD G2 automotive power modules compared to the conventional, widely used, Si-IGBT based power modules we have conducted a second set of experimental tests. These tests were elaborated on a 750V commercially available Si-IGBT based power module. For fair comparison purposes, this test was conducted under the same operating conditions as the previous test. The obtained results are illustrated in Figure 5 for both motor and generator operating modes.

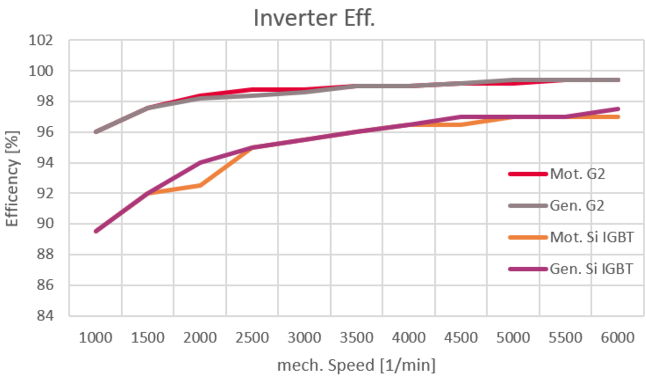


Figure 5. Efficiency comparison between the 750V SiC-Mosfet based HPD Gen2 FS01MR08A8MA2LBC and a commercially available 750V Si-IGBT based power module

The orange and purple lines show the behavior in motor and generator modes, respectively, for the Si-IGBT based inverter. We can clearly see that in the constant torque range, the inverter efficiency with the Si-IGBT module varies between 89.5% and 95.5%. In contrast, the SiC-based inverter achieved an impressive 97% efficiency in motor mode and 97.5% in generator mode. These results further prove the superiority of the SiC-MOSFET based HPD Gen2 power module compared to the Si-IGBT based power module. In the field weakening range, which extends the motor speed beyond its base speed up to 6000rpm, the SiC-MOSFET based inverter maintained high efficiency, particularly in generator operation. This consistent high performance underlines the benefits of SiC technology, and the superiority of the Infineon’s HPD G2, in terms of reduced losses and improved thermal management.

II. 4. Evaluation of the 1200V SiC-MOSFET based HPD G1 FS03MR12A6MA1B

Not only the type of material, i.e. Si or SiC, but also the progressive development of different SiC technologies has significantly improved the performance of automotive power modules. To illustrate the impact on efficiency, we made a third comparison with the FS03MR12A6MA1B, the SiC MOSFET-based HPD G1 (planar structure) from Infineon Technologies. Efficiency measurements were performed on the module and the results analyzed [1]. The results of this module were included and compared with previous measurements of SiC-based HPD G2 and Si-based IGBT power modules, as shown in Figure 6.

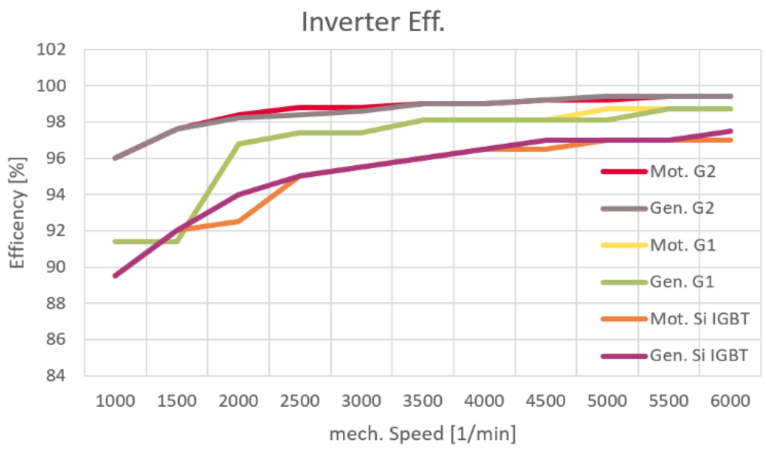


Figure 6. Efficiency comparison between the 750V FS01MR08A8MA2LBC, 750V Si-IGBT based power module, and 1200V SiC-Mosfet FS03MR12A6MA1B

The yellow line in the graph of Figure 6 represents the efficiency curve of the FS03MR12A6MA1B, i.e., SiC-MOSFET based HPD G1, in motor mode, while the green line represents its efficiency in generator mode. We can see that in motor mode the G2 technology shows an improvement compared to the G1 technology especially in the low-speed range, i.e., up to 1000rpm, where an efficiency difference of almost 4.6% is observed. At higher speed ranges the difference is slightly lower but the best performance in terms of efficiency is still obtained with the G2 technology, i.e., for 3000rpm we see an efficiency difference of 1.4% and for 6000rpm it is round about 0.7%. The efficiency values, for all technologies, in motor mode are summarized in the following Table 1. The same conclusions can be drawn for generator mode where the best performance is also observed with the G2 technology. The efficiency results for this operation mode are summarized in Table 2.

Table 1. Maximum inverter efficiency in motor mode

Motorized: Rpm/Eff.	**Power Module with Si IGBT**	**HPD Gen1 with SiC MOSFET**	**HPD Gen2 with SiC MOSFET**
>1000 rpm	89,5 %	91,4%	96%
>3000 rpm	95,5 %	97,4%	98,8%
>6000 rpm	97 %	98,7%	99,4%

Table 2. Maximum inverter efficiency in generator mode

Generative: Rpm/Eff.	**Power Module with Si IGBT**	**HPD Gen1 with SiC MOSFET**	**HPD Gen 2 with SiC MOSFET**
>1000 rpm	89,5 %	91,4%	96%
>3000 rpm	95,5 %	97,4%	98,6%
>6000 rpm	97,5 %	98,7%	99,4%

To resume, based on the obtained experimental results over a wide range of speed and torque values, inverters based on Infineon's SiC-MOSFET HPD G2 power modules feature exceptionally high levels of efficiency. In particular, they outperform inverters based on traditional Si-IGBTs. This remarkable superiority is due to the clear advantages of Infineon's G2 CoolSiC™ technology over conventional Si technologies. In addition, the further development of Infineon's trench SiC MOSFET technology has resulted in a significant increase in efficiency of up to 4.6% compared to the first generation HPD G1. In summary, the use of SiC technology in automotive inverters represents a major step forward in achieving higher efficiencies, smaller system sizes and improved thermal management in electric vehicles. The ability of SiC-based inverters to maintain high efficiency under varying operating conditions positions them as a superior alternative to traditional silicon technologies.

III. Simulation under real WLTP driving cycle and Efficiency Estimation

The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) is one of the most commonly known and used driving cycles, for characterizing power modules, in the automotive industry. The latter consists of various acceleration, deceleration and power phases lasting 1800 seconds over 23.3 km. Despite the different opinions and criticisms on whether the WLTP accurately reflects real driving behavior, given the different driving styles, it remains a suitable basis for assessing a vehicle's efficiency. The WLTP driving profile allows manufacturers to calculate the required engine power for a given vehicle and its key parameters such as weight, drag, power, acceleration and recuperation [2].

In this work we use the WLTP Class 3 cycle as shown in Figure 7. This driving cycle is specifically designed for vehicles with a power-to-weight ratio of more than 34 W/kg, and has been the basis for the official type of approval of new vehicle models in the EU since 2017. To simulate WLTP fuel consumption, Simulink uses a method that accurately reproduces real-world driving resistance. Three different vehicle models were used for the simulation, i.e.., Testla 3 model, VolksWagen (VW) ID.3, and VW ID.7. Their characteristics are summarized in Table 3. These parameters are used in the simulation to calculate the driving resistances. The study focuses on comparing the performance of silicon carbide (SiC) and silicon (Si). The reference model for the simulation is the Tesla Model 3. The model was adapted for VW vehicles by considering specific data on power electronics, vehicle mass and aerodynamics. To analyze the influence of mass and size on efficiency, comparisons were made between the smaller and lighter ID.3 and the larger ID.7 in separate simulations. When comparing the vehicles, it's essential to exercise caution, as the results can be influenced by various factors.

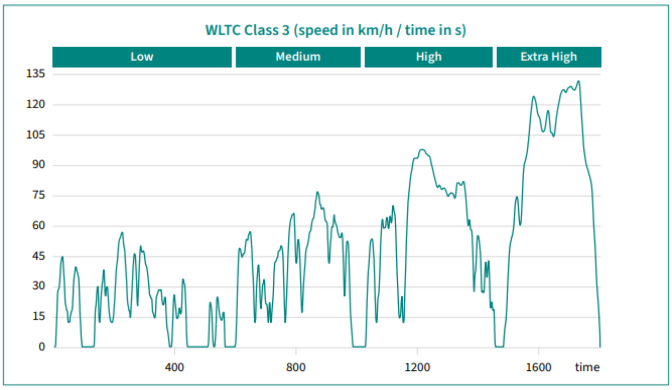


Figure 7. WLTP driving profile

Table 3. Vehicle characteristics

Car	Tesla Model 3	VW ID.3	VW ID.7
Cw	0,23	0,27	0,23
Frontal Area [m²]	2,22	2.3	2,46
Weight [kg]	1836	1815	2172
Consumption by manufacturer [kWh/100km]	13,2	15	14,1 – 16,3

The obtained numerical results are provided in Table 4. We can see that, the Tesla Model 3 has a smaller advantage in terms of fuel consumption compared to the VW ID.3 and VW ID.7, despite similar Cw values, frontal areas and weights. The main reason for this lies in the fact that the Tesla Model 3 is equipped with a SiC power module, which was specifically designed for this purpose. In contrast, the VW ID.3 and VW ID.7 use Si IGBTs in their inverters. The higher efficiency of SiC power modules compared to Si IGBTs already provides an advantage in terms of consumption. Therefore, it's crucial to consider the specific components and technologies used in each vehicle when making comparisons.

A closer look at the simulation results clearly shows that SiC technology has a significant impact on efficiency. The Tesla Model 3 shows a 7.1% improvement in efficiency compared to Si technology. The Volkswagen models also show a very similar increase in energy efficiency. In both VW vehicles, an efficiency improvement of 7.3% was observed with SiC technology.

There are many reasons for the consumption savings. Of course, the increase in efficiency described above plays a major role. Compared to Si devices, SiC devices have a higher rated voltage, better switching behavior and lower on-resistance Rds(on). This results in lower conduction losses and higher efficiency, especially at high temperatures. This can be seen in the application, especially at higher speeds or over longer distances, exactly where WLTP simulation is used.

Based on extensive Simulink simulations and test bench results, SiC technology consistently outperforms traditional Si technologies. It offers significant improvements in efficiency, lower power dissipation and longer range, making it an excellent choice for modern electric mobility applications. It is in the higher power range that SiC technology really comes into its own and shows its best performance.

Table 4. Comparison of efficiency according to the WLTP simulation

Car	Tesla Model 3	VW ID.3	VW ID.7
Efficiency SiC [%]	95,7	96,3	96,4
Efficiency Si [%]	88,6	89,0	89,1
Consumption savings [%]	7,1	7,3	7,3

IV. Conclusions

In this paper we have investigated the performance of a traction inverter using three different types of automotive power modules. For this purpose, we have carried-out several experimental tests on a traction inverter system with Si-IGBT and SiC-MOSFET based power modules. The obtained results prove the high performance and the superiority of Infineon’s second generation SiC-MOSFET based HPD G2 power module in terms of generating low power losses and achieving high system efficiency that exceeds 99%. These results also show that the HPD G2 outperforms inverters based on traditional Si-IGBTs and G1 MOSFETs. This remarkable superiority is due to the clear advantages of Infineon's CoolSiC™ G2 technology over conventional Si and SiC G1 technologies. As the industry continues to prioritize efficiency and performance, SiC technology will play a critical role in shaping the next generation of automotive inverters. Further research and development in this area is likely to focus on optimizing SiC technology for even greater efficiency gains, cost effectiveness and integration into a wider range of EVs, thereby accelerating the transition to more efficient and sustainable automotive solutions.

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