International Research Journal in Global Engineering and Sciences. (IRJGES)
ISSN : 2456-172X | Vol. 6, No. 3, September 2021 – November 2021 | Pages 1-10

Simulating Power Electronics Based on Silicon Carbide for Electric Vehicles

Jyothsna Nakka[1], Ramya Gullapelly[2], A.Thirumala[3], P.Sadanandam[4], P.Shankar Babu[5]
1, 2, 3 Assistant Professor, Department of Electrical and Electronics Engineering, Vaagdevi College of Engineering, Warangal, Telangana-506005, India.
4, 5 Associate Professor, Department of Electrical and Electronics Engineering, Vaagdevi College of Engineering, Warangal, Telangana-506005, India.

Abstract:
Assault Systems and Rohm Semiconductor demonstrate the utilization of silicon carbide (SiC) as a fundamental material in power electronics to enhance the energy efficiency of electric vehicles. Application examples include electric drive and electric vehicle simulation models.
Keywords: Electrified Powertrains Library, silicon carbide semiconductor, power electronics, inverters, electric cars, Dymola

1 Introduction

As electric vehicles advance, battery-powered electric motors integrated into electric powertrains are increasingly incorporated into vehicles, along with onboard power supply systems. Renewable energy sources must be adapted to integrate into current power networks due to their diverse specifications in the industry market.

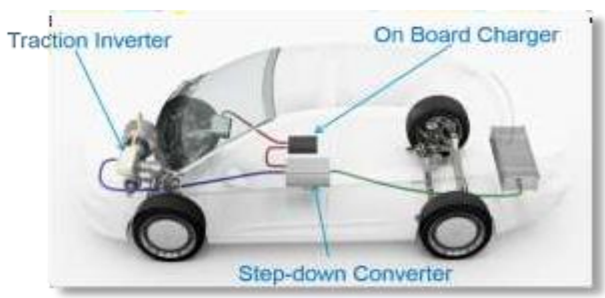


Figure 1: Concept drawing illustrating the interconnection of power electronics components, including the plug-in charger (red), the DC battery circuit (green), and the electric motor (blue).

In the aforementioned applications, circuits that utilize both direct current (DC) and alternating current (AC), or circuits with different voltage levels, must be interconnected via an electric system. This connection is facilitated by transformers or power electronics. Power electronics find wide applications in scenarios where size and weight are critical factors, such as in electric vehicles (EVs). For instance, as depicted in Figure 1, power electronics are necessary to link the electric machine, the plug-in cable chargers, and the battery pack.
Assault Systems and Rohm Semiconductor collaborate to investigate these scenarios through system simulation, employing semiconductor devices in a simulation environment like Dipolar.

Following the background on power electronics and the advantages of SiC provided in Chapter 2, Chapter 3 introduces inverter models from the power electronics package in the Electrified Powertrains Library (EPTL). Chapter 4 covers the thermal-electric modeling and calibration of inverter modules.

In Chapter 5, an inverter model within an electric drive system model is utilized to analyze the effects of the new power electronics material on the system's electric efficiency and cooling requirements.

An electric car simulation demonstrates how energy efficiency and range increase when the electric drive system model is transformed into a multi-dimensional table model to expedite the simulation process.

2 Background

2.1 Silicon Carbide (SiC)

Like most semiconductors, silicon serves as the foundation for power electronics. Two other types of materials in this category are germanium and gallium nitride. SiC, or silicon carbide, is a relatively recent addition to this list. It is among the best materials for use in power electronics due to its mechanical strength and tolerance to temperatures as high as 200°C. Its resilience to carbon diamonds is another noteworthy characteristic. It can dissipate electrical loss power more efficiently due to its five-fold improvement in specific thermal conductivity over silicon. Finally, it exhibits lower specific electric resistance compared to traditional semiconductor materials. SiC, a semiconductor made of compounds, combines silicon (Si) with carbon (C). With a breakdown electric field of 10 and a band gap three times larger.

2.2 SiC Characteristics in Power Electronics Devices

It is feasible to construct high-voltage devices with a maximum operating voltage ranging from 600 V to a few thousand V that have a thin drift layer and high doping density because SiC has a breakdown electric field that is an order of magnitude stronger than Si. SiC is capable of realizing a high breakdown voltage device with very low on-resistance per unit area because the drift layer contains the majority of a high-voltage power device's resistance. For the same breakdown voltage, it is theoretically possible to reduce the drift layer resistance per area by a factor of 300 compared to Si (Nagano, 2018).

Bipolar devices, like IGBTs, are minority carrier devices that are primarily utilized for Si due to their ability to amplify the increase in on-resistance that accompanies high breakdown voltage. Larger switching losses pose a problem, even though the switching frequency is limited by the dissipated heat generated by the electric loss power.

SiC enables the production of majority carrier devices with high breakdown voltage, including Schottky Barrier Diodes (SBD) and high-speed MOSFETs. The device simultaneously achieves low on-resistance, high speed, and high breakdown voltage of power transistors. Furthermore, the larger band gap compared to Si enables power devices to operate at extremely high temperatures (Tanaka, 2018; Ogawauchi, 2018). In the past, Rohm funded the development of SiC devices and established an integrated production process that included testing, packaging, and wafer ingot pulling. Rohm is now capable of providing SiC devices, SBDs, and modules of superior quality.

Onboard chargers for electric vehicles and industrial high-voltage power supplies have begun to be adopted (Nakamura, 2015). Rohm works with the government as a technological partner and supplier of SiC components for motor drive inverters for the Venture Formula E team. SiC is a crucial modern tool for enhancing the efficiency of global electric power networks in this manner.

3 Electrified Powertrains Library

3.1 Overview

Models representing the essential elements of an electric drive system at various levels of complexity, such as physical, switching, averaged, and energy-based, are available in the Electrified Powertrains Library (EPTL). Electric machines and inverters with their corresponding controls are integral parts.

3.2 Power Electronics Package

The power electronics package includes models for switching electronic devices required, for example, in electric drive modeling. It encompasses semiconductor switches, which are critical components of power electronics equipment, including converters and inverters.

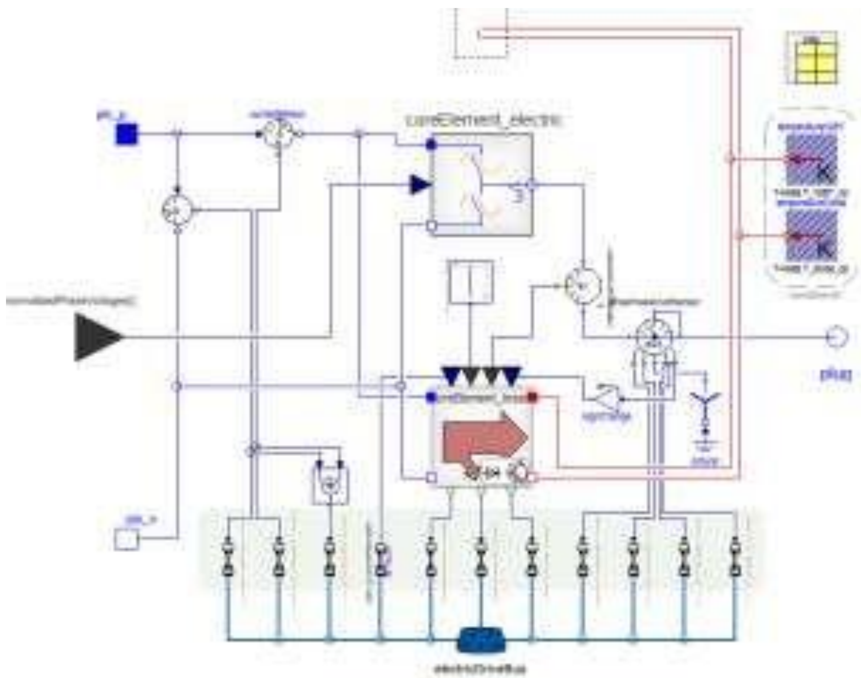


Figure 2: Electrical and loss model of an inverter

Inverters are particularly interesting in this context because they can bridge DC and AC electric circuits. Various levels of detail are available for inverter models:

- Idealized switching electrical models
- Idealized averaged electric models
- Idealized averaged electric models with losses
- Idealized switching electrical models with losses

3.2.1 Electrical Model To improve simulation speed in large-scale system models later on, the averaged model with constant efficiency is used to model the electrical behavior among the model alternatives available in the EPTL.

The intended three-phase voltage serves as the input load signal.

Phase currents and phase shift are recorded to determine the active current that must be drawn from the battery. The three-phase currents for the active current are then subjected to the Clarke transformation, which transforms the AC currents into a space vector with real and imaginary parts.

The following equation represents the relationship between the current on the AC and DC sides of the inverter, assuming a constant efficiency of α, to be entered as a parameter table as specified in the datasheet provided in the Appendix: $IDC=IAC\cdot\eta 1$

The power losses are converted into heat flow and can be connected to the thermal model to predict the device temperature.

3.2.3 Thermal Model

Along with the model describing the electrical behavior and loss generation, a thermal representation of the respective inverter is included. The diode and the MOSFET are modeled as major differences between the averaged and the switching electrical models include that the averaged model is an approximation of a switched inverter and does not describe the harmonics of the AC electric signal apart from the fundamental wave. Hence, the behavior differs from a model of a switched inverter as soon as the load is not 100% sinusoidal anymore. For example, switched inverter models coupled with detailed loss models can be used to find a trade-off between current ripple and inverter losses.

A detailed description of the electric behavior models for MOSFET, IGBT, and switches can be found in (Denz, 2014). The mentioned publication also includes a validation of the EPTL models using electric measurement data.

3.2.2 Losses Model

- The following effects' power losses are calculated by the loss model:
  - Conduction losses of the diode with regard to forward voltage Vf taken from the datasheet: $1Pcond,diode=(1-m\cdot\cos(\phi))\cdot Vf\cdot 2\cdot I$

4 Modeling and Calibration of a Silicon Carbide-Based Inverter Module

4.1 Topology The inverter model is based on the half-bridge module BSM120D12P2C005 by Rohm Semiconductor (Rohm, 2016) with the characteristics listed in Table 1.

Category	**Device**	**Benchmark**
Technology	Sic	Si
Type	MOSFET	IGBT
Maximum Voltage	1200V	1700V
Voltage Drain - Source	600V	900V
Maximum Current	120A	150A
Operating Temperature	150 °C	80°C
Number of switches	6	6
Voltage coefficient Kv	1.35	1.35

Table 1. Characteristics of the used device (Sic) and a Silicon (Si) based benchmark device.

Conduction losses of the switching element with regards to drain-source $0Vds0$, drain current, and device temperature:

$Pcond,switch=(1-m\cdot\cos(\phi))\cdot Vds0\cdot 2\cdot I$

Reverse recovery of the diode with regards to forward voltage, forward current, device temperature, and forward voltage:

$Ploss,RR=ns\cdot Err\cdot 2\cdot (Kv\pi)\cdot Vref$

Loss energy per switching operation with regards to current, device temperature, and voltage to switch:

$Pswitching=ns\cdot (Eon+Eoff)\cdot \pi\cdot (Vref)2\cdot Vref$

The module is modeled using an averaged electric model with losses and a thermal model. In this context, *m* is the modulation index, *I* is the load current, *ns* is the number of switches, *Vref* is the reference voltage for the datasheet parameters, *Kv* is a coefficient for accounting for the nonlinear influence of the normalized voltage on the losses.

4.2 Calibration of the power module

Additionally to the scalar parameters as shown in Table 1, the electric model of the diode includes the multi-dimensional relationship of source current and source-drain voltage with regard to the operating temperature of the device.

Furthermore, in order to calculate the dissipated heat losses, it is necessary to input the loss energy for each switching operation in addition to the recovered loss energies in relation to the operation temperature and drain current.

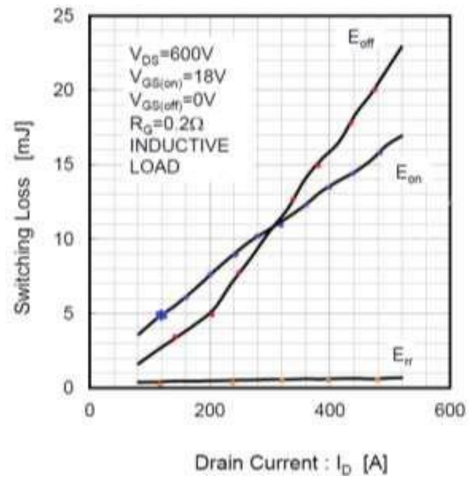


Figure 3. Sampling the characteristic curve of the used SiC device for switching losses when operating at 25°C.

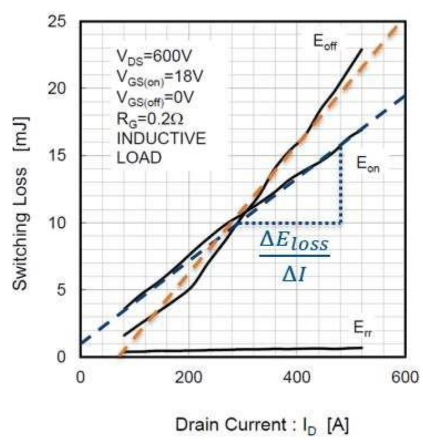


Figure 4. Linearizing the characteristic curve of the used SiC device for switching losses when operating at 25°C.

The SiC device in the EPTL can be calibrated in one of two ways:

1. Table-Based: Utilizing characteristic curves provided for the relevant device or sampling them, as shown in Figure 3. The ND Table class interfaces the Modelica model with the recorded dataset, performing multi-dimensional interpolation to provide output for specified operating loads and circumstances.
2. Linear Equation: If the device's properties exhibit sufficiently linear dependencies, the curve can be captured by linear equations within a confined area of operation, as depicted in Figure 4.

With the switch-off loss energy curve exhibiting discontinuities, particularly at 200 amperes, the table-based method is chosen for modeling the losses.
The ND Table class is implemented as described by (Schmitt et al., 2015), providing an example for the forward characteristic of a Si-based diode.

4.3 Test Bench Simulation

To assess the impact of increased efficiency, the inverter is sim

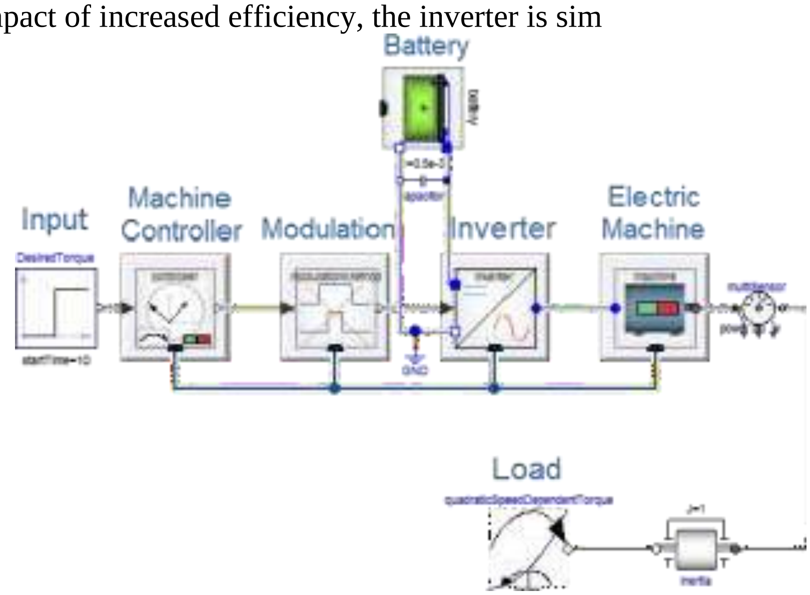


Figure 5: Simulation Setup - Electric drive system including electric and loss model of the inverter comprising the power electronics.

The electric drive consists of five components: the electric machine with its machine controller, the inverter with modulation, and the battery pack. The impedance effects of the cables of the high-voltage circuit, as well as additional electric consumer or auxiliary devices, are neglected in this setup.

Table 2: Simulation Starting Values and Boundary Conditions for the Simulation.

Variable	Unit	Value
Operating Temperature	°C	80
Switching frequency	kHz	25
Modulation harmonic	type	sinus
Electric machine type	type	PSM
Nominal machine frequency	Hz	195
Nominal torque	Nm	122

Nominal phase RMS voltage	V	114
Nominal RMS current per phase	A	170
Electric machine power	kW	50
Desired Torque as input	Nm	+10
Load Torque	Nm	-10

A 50 kW three-phase permanent magnet synchronous machine (PSM) with three pairs of poles powers the electric device. The associated machine controller offers maximum torque per ampere control, field-weakening control, and the goal torque as input.
A rather high switching frequency of 25 kHz has been used to highlight the differences in dissipated loss power.
Table 2 provides the general boundary conditions for the simulation.
Figure 6 illustrates that reduced switching energies lead to reduced heat loss power, consequently resulting in reduced DC power side power consumption.

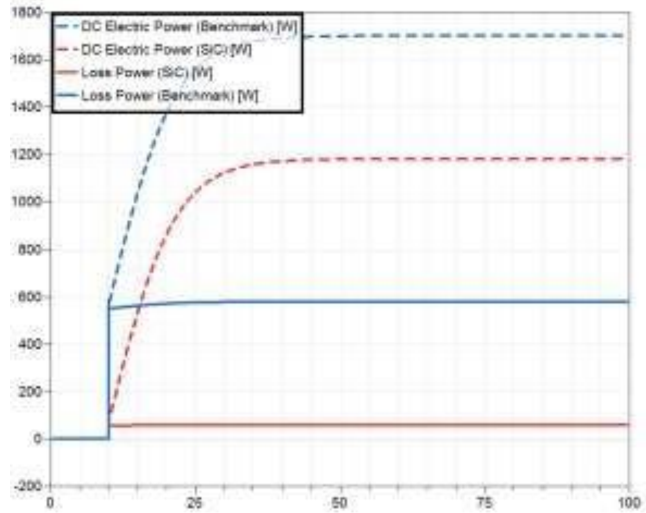
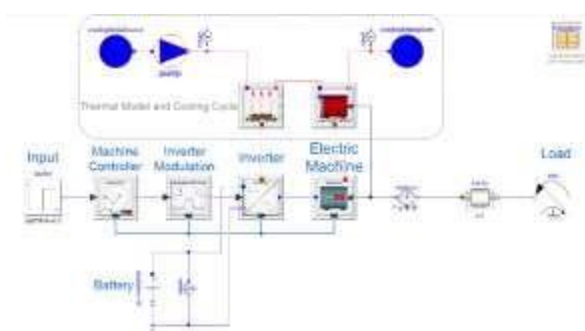


Figure 6 compares the DC load power and loss power for the first 100 simulation seconds between the SiC-based device (red) and the Si-based benchmark device (blue).
When the DC power load is significantly reduced while maintaining a comparable amount of AC output, the battery drains less. As a result, the state-of-charge (SOC) of the battery remains higher.
As the modeling complexity increased significantly with the liquid cooling cycle, the battery was replaced by a voltage source.



International Research Journal in Global Engineering and Sciences. (IRJGES)
ISSN : 2456-172X | Vol. 6, No. 3, September 2021 – November 2021 | Pages 1-10

Figure 7 depicts the simulation setup for the water-cooled electric drive system, including the thermal-electric models of the inverter and electric machine.
The assessment of the resulting reduction of the load for the cooling cycle is conducted through a simulation with the configuration specified in Table 3.

Table 3 outlines the simulation starting values and boundary conditions for the simulation.

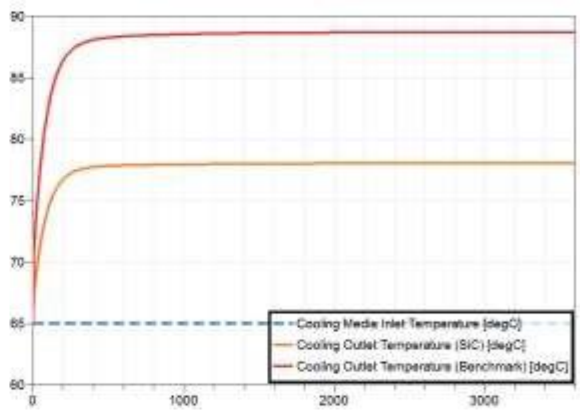
Variable	**Unit**	**Value**
Inlet temperature coolant	°C	65
Volume flow	l/min	6.0
Operating Temperature	°C	transient
Switching frequency	kHz	25
Modulation harmonic	type	sinus
Electric machine type	type	PSM
Electric machine power	kW	50
Desired Torque (Input)	Nm	+122
Load Torque	Nm	-122
Nominal machine speed	rpm	3000

Figure 8 presents the results of the test bench simulation.

5. Simulation and discussion

5.1 Water-cooled electric drive system

The corresponding thermal representation is added to the electric test bench component models in order to evaluate the implications of the lower loss power as determined in chapter 4.3. The use case, as shown in Figure 7, involves a permanent magnet synchronous machine that is water-cooled. According to the Fluid Heat Flow package in the Thermal library of the Modelica Standard Library 3.2.2, the liquid cooling media type employed in this application is water/ethylene-glycol (50:50). It depicts a standard automotive configuration where a volume flow is initiated through the inverter and then the machine by use of an external pump. The class Sources models the cooling cycle's input and output surroundings. As the heat losses produced are decreased, significantly less temperature rise occurs in the coolant.
The temperature of the cooling medium serves as the preferred indicator when utilizing a cooling cycle with liquid cooling. The dissipated heat loss power raises the temperature of the coolant. Foster circuit characteristics offer the interface thermal conductance model.



5.2 Electric vehicle simulation

The vehicle simulation package offers an expandable and adaptable infrastructure together with all necessary components, from operational control models to the environment, to enable the development of example use cases for electric drives in various configurations. As a result, characteristic maps are made for particular temperatures and supply voltages. Prior to initiating the map generation process, these values need to be specified. For this purpose, the cooling cycle stated in chapter 5.1 is used to operate the inverter in thermal equilibrium, and the boundary conditions as outlined in chapter 4.3 are selected accordingly.

Figure 9: Simulation Test bench for Electric Vehicles

Based on the electric power train depicted in **Figure 10** and the battery serving as the main energy source, **Figure 11**'s simulation indicates a significant increase in driving range.

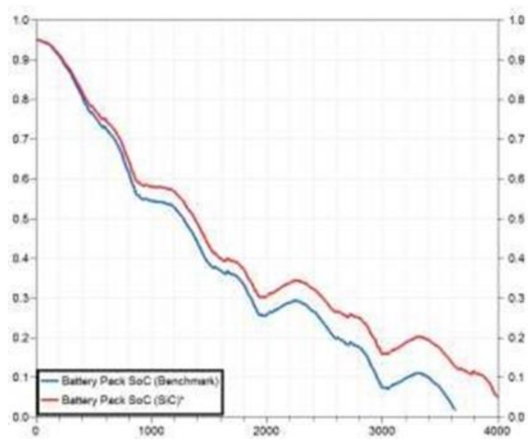


Figure 10 Charging state (SOC) of the EV traction battery when adopting the driving profile “Artemis Motor way”.

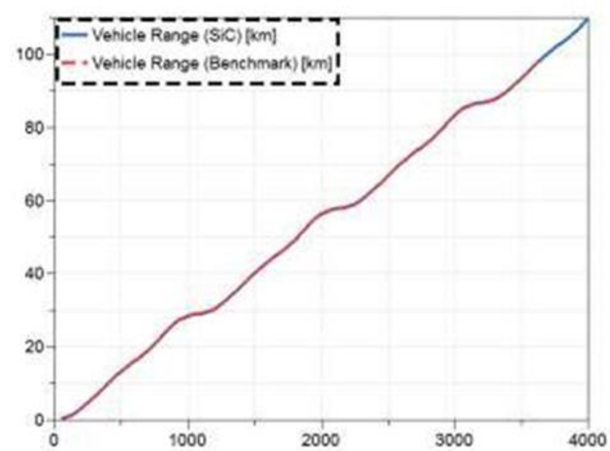


Figure 11: Maximum EV driving range when adopting the driving profile "Artemis Motorway".

6 Outlook

Even with high-level simulation, the improvement brought about by device replacement could already be seen. Of course, tuning and improved accuracy in the simulation environment are still required. The use of silicon carbide (SiC) in DC/DC converters is growing at the moment, and the authors are optimistic that this trend will continue as the ratio between cost and performance improves.

Conclusion

In conclusion, this study has demonstrated the significant potential of utilizing silicon carbide (SiC) in power electronics for electric vehicles (EVs) and other applications. Through comprehensive simulation and analysis, the benefits of SiC devices, such as improved energy efficiency and reduced heat loss, have been highlighted.

The investigation included modeling and calibration of SiC-based inverter modules, evaluating their performance in electric drive systems, and assessing the impact on cooling systems. The results indicated notable enhancements in energy efficiency and driving range, showcasing the advantages of employing SiC technology in electric vehicles.

Furthermore, the study emphasizes the importance of ongoing research and development to optimize SiC-based systems further. As the technology matures and becomes more cost-effective, its widespread adoption in DC/DC converters and other power electronics applications is expected to increase, leading to significant advancements in electric vehicle technology and energy efficiency.

Overall, the findings of this study underscore the promising future of silicon carbide in revolutionizing power electronics for electric vehicles and beyond, paving the way for more sustainable and efficient transportation solutions.

REFERENCES

1. Semiconductors. In Lund, Sweden, in 2014, the 10th International Modelica Conference Proceedings were published. DOI: 10.3384/ECP14096343.
2. SiC Power Module BSM120D12P2C005, Rohm Co., Ltd. Data sheet. 2016.09 – Rev C. 2016.
3. Markus Andres, Thomas Schmitt, Stephan Ziegler, and Stephan Diehl. An Innovative Approach to Parameterizing Models in Dymola with External Files in View of a Later Model Export via the Functional Mock-Up Interface. The 11th International Modelica Conference Proceedings, Nice, France, 2015. DOI: 10.1328/ecp1511823.
4. T. Hamada, Y. Nakano, and T. Nakamura. Innovative SiC Power Modules and Their Future Prospects. IEE-Japan Industry Applications Society Conference, Tokyo, 2015; 4_S10_5, VOL. 3.
5. S. Kyogoku, R.Iijima, S. Tanaka, and S. Harada. Effect of the trench bottom shielding zone on SiC double-trench MOSFET switching properties. 4-010 IEEJ Annual Meeting in 2018.
6. A. Toba, H. Takubo, K. Matsubara, T. Nagano. Active Gate Driving for SiC-MOSFETs: Suppression of Surge Voltage. 4-017, IEEJ 2018 Annual Meeting.
7. K. Nakahara and Y. Ogawauchi "High-speed Gate Drive Circuit Study Utilizing SiC-MOSFET Hybrid Current/Voltage Source" 4-018 IEEJ 2018 Annual Meeting.