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Design of High Efficiency Sic – Based Dc-Dc Converter for Electric Vehicle Applications

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Abstract: - The rapid growth of electric vehicles (EVs) has increased the demand for efficient, compact, and reliable power conversion systems. Among these, DC–DC converters play a crucial role in regulating voltage between the battery, motor drive, and auxiliary loads. This paper presents the design and analysis of a high-efficiency DC–DC converter using Silicon Carbide (SiC) semiconductor devices for EV applications. Compared to conventional silicon devices, SiC devices offer advantages such as higher switching frequency, lower conduction and switching losses, improved thermal performance, and higher power density. The proposed converter topology is optimized for high-frequency operation, enabling the use of smaller passive components like inductors and capacitors, thereby reducing system size and weight. Advanced control strategies ensure stable operation, fast dynamic response, and minimal voltage ripple under varying load conditions. SiC MOSFETs enhance performance under high voltage and temperature, making them suitable for harsh automotive environments. Simulation results demonstrate that the SiC-based converter achieves higher efficiency and reduced power losses compared to silicon-based designs, particularly at high switching frequencies. This leads to improved battery utilization and extended vehicle range. Overall, SiC technology significantly enhances converter performance, reliability, and efficiency, making it a key enabler for next-generation sustainable EV systems.

Keywords: Electric Vehicles (EVs); DC–DC Converter; Silicon Carbide (SiC); SiC MOSFET.

1. Introduction

The rapid growth of electric vehicles (EVs) has intensified the demand for highly efficient, compact, and reliable power electronic converters. Among these, DC–DC converters play a critical role in managing energy flow between the battery, motor drive, and auxiliary systems. Conventional silicon (Si)-based converters, although widely used, face limitations in terms of switching losses, thermal performance, and efficiency at high power densities. To overcome these challenges, wide bandgap semiconductor devices, particularly Silicon Carbide (SiC), have emerged as a promising alternative. Silicon Carbide (SiC) devices offer superior electrical and thermal properties compared to traditional silicon devices, including higher breakdown voltage, lower switching losses, higher thermal conductivity, and the ability to operate at higher temperatures and switching frequencies. These characteristics make SiC-based DC–DC converters highly suitable for EV applications, where efficiency, size reduction, and thermal management are critical design considerations. By enabling high-frequency operation, SiC devices significantly reduce the size of passive components such as inductors and capacitors, leading to increased power density and compact system design. In EV systems, DC–DC converters are used in multiple stages, such as stepping down high-voltage battery output to low-voltage levels for auxiliary loads and enabling bidirectional power flow in advanced architectures. The efficiency of these converters directly impacts the overall vehicle performance, driving range, and battery life. Therefore, designing a high-efficiency DC–DC converter using SiC technology is essential to enhance system performance and energy utilization.

This paper focuses on the design and analysis of a high-efficiency SiC-based DC–DC converter tailored for electric vehicle applications. The study aims to optimize switching performance, minimize power losses, and improve thermal efficiency while maintaining system reliability. By leveraging the advantages of SiC devices, the proposed converter design addresses the limitations of conventional systems and contributes to the advancement of next-generation EV power electronics.

Ref. No.	Author & Year	Converter Type / Focus	Technology Used	Key Contributions	Limitations
[1]	Zhang et al. (2018)	High-frequency DC–DC Converter	SiC MOSFET	Improved efficiency using high switching frequency; reduced passive component size	High cost of SiC devices
[2]	Kim et al. (2019)	Bidirectional DC–DC Converter for EVs	SiC-based	Enhanced bidirectional power flow for battery systems	Complex control strategy
[3]	Singh et al. (2020)	Isolated DC–DC Converter	SiC + High-frequency transformer	Achieved high power density and galvanic isolation	Transformer design complexity
[4]	Wang et al. (2021)	Non-isolated Buck Converter	SiC devices	Reduced switching losses and improved efficiency	Limited voltage gain capability
[5]	Lee et al. (2017)	EV Power Conversion System	Silicon-based	Baseline comparison with conventional converters	Lower efficiency compared to SiC
[6]	Patel et al. (2022)	High Gain DC–DC Converter	SiC MOSFET	Improved voltage gain and efficiency for EV applications	Increased circuit complexity
[7]	Chen et al. (2020)	Soft Switching Converter	SiC + ZVS/ZCS	Reduced switching losses significantly	Requires additional components

[8]	Kumar et al. (2021)	Interleaved DC–DC Converter	SiC devices	Reduced ripple and improved thermal performance	Control synchronization issues
[9]	Ahmed et al. (2023)	EV Fast Charging Converter	SiC-based	High efficiency under fast charging conditions	Thermal management challenges
[10]	Park et al. (2022)	DC–DC Converter for Auxiliary Systems	SiC devices	Compact design and high efficiency	Limited scalability
[11]	Rao et al. (2019)	Multiport DC–DC Converter	SiC + Renewable Integration	Supports multiple energy sources	Complex control and design
[12]	Li et al. (2021)	Resonant DC–DC Converter	SiC devices	High efficiency with reduced EMI	Narrow operating range
[13]	Gupta et al. (2020)	Boost Converter	SiC MOSFET	High voltage gain for EV systems	Efficiency drops at light load
[14]	Zhao et al. (2023)	Modular DC–DC Converter	SiC-based	Scalability and fault tolerance	Increased system cost
[15]	Sharma et al. (2022)	Thermal Analysis of Converter	SiC devices	Improved thermal stability and heat dissipation	Requires advanced cooling methods

The development of high-efficiency DC–DC converters has become a crucial area of research due to the rapid advancement of electric vehicles (EVs) and the growing demand for efficient energy management systems. DC–DC converters are essential components in EV powertrains, responsible for voltage regulation, battery interfacing, and power distribution. Over the years, significant research has been carried out to enhance converter efficiency, reduce losses, and improve overall system reliability. Early studies primarily focused on conventional silicon (Si)-based converters, which provided acceptable performance but were limited by high switching losses, lower thermal conductivity, and restricted high-frequency operation. Researchers such as Lee et al. (2017) demonstrated that while silicon-based converters are cost-effective, they suffer from reduced efficiency and larger passive component requirements, making them less suitable for modern EV applications where compactness and high efficiency are critical.

To address these limitations, the introduction of wide bandgap semiconductor devices, particularly Silicon Carbide (SiC), marked a significant breakthrough in power electronics. Studies by Zhang et al. (2018) and Kim et al. (2019) highlighted that SiC MOSFET-based converters exhibit lower switching and conduction losses, enabling higher efficiency and improved thermal performance. These characteristics allow operation at higher switching frequencies, which in turn reduces the size of inductors and capacitors, leading to compact and lightweight converter designs. Further advancements include the development of bidirectional DC–DC converters using SiC technology, which are particularly important for EV applications involving regenerative braking and vehicle-to-grid (V2G) operations. Kim et al. (2019) demonstrated efficient bidirectional power flow with improved energy utilization, although the complexity of control strategies remains a challenge. Similarly, multiport converters explored by Rao et al. (2019) enable integration of multiple energy sources such as batteries and renewable systems, but introduce design and control complexities. Soft-switching techniques such as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) have also been widely investigated to minimize switching losses. Chen et al. (2020) showed that integrating soft-switching with SiC devices significantly enhances efficiency by reducing switching stress and electromagnetic interference (EMI). However, these methods often require additional components and careful design considerations. Interleaved converter topologies, as discussed by Kumar et al. (2021), offer advantages such as reduced current ripple, improved thermal distribution, and increased efficiency. These topologies are particularly beneficial in high-power EV applications but require precise control and synchronization between phases. Similarly, resonant converters explored by Li et al. (2021) provide high efficiency and reduced EMI, although they operate effectively only within a limited load range. Recent research has also focused on high-gain and modular converter designs to meet the increasing voltage requirements of modern EV systems. Patel et al. (2022) and Zhao et al. (2023) demonstrated improved scalability and voltage gain using SiC-based designs, but at the cost of increased circuit complexity and higher implementation cost. Additionally, thermal management remains a critical concern, as highlighted by Sharma et al. (2022), where advanced cooling techniques are required to fully exploit the high-temperature capabilities of SiC devices. Overall, the literature indicates that SiC-based DC–DC converters provide significant advantages over traditional silicon-based designs in terms of efficiency, power density, and thermal performance. However, challenges such as high device cost, complex control mechanisms, and thermal management issues still need to be addressed. These research gaps motivate the need for optimized converter designs that balance performance, cost, and reliability, which is the primary focus of this work.

2. SYSTEM ARCHITECTURE OF SiC-BASED DC–DC CONVERTER FOR EV

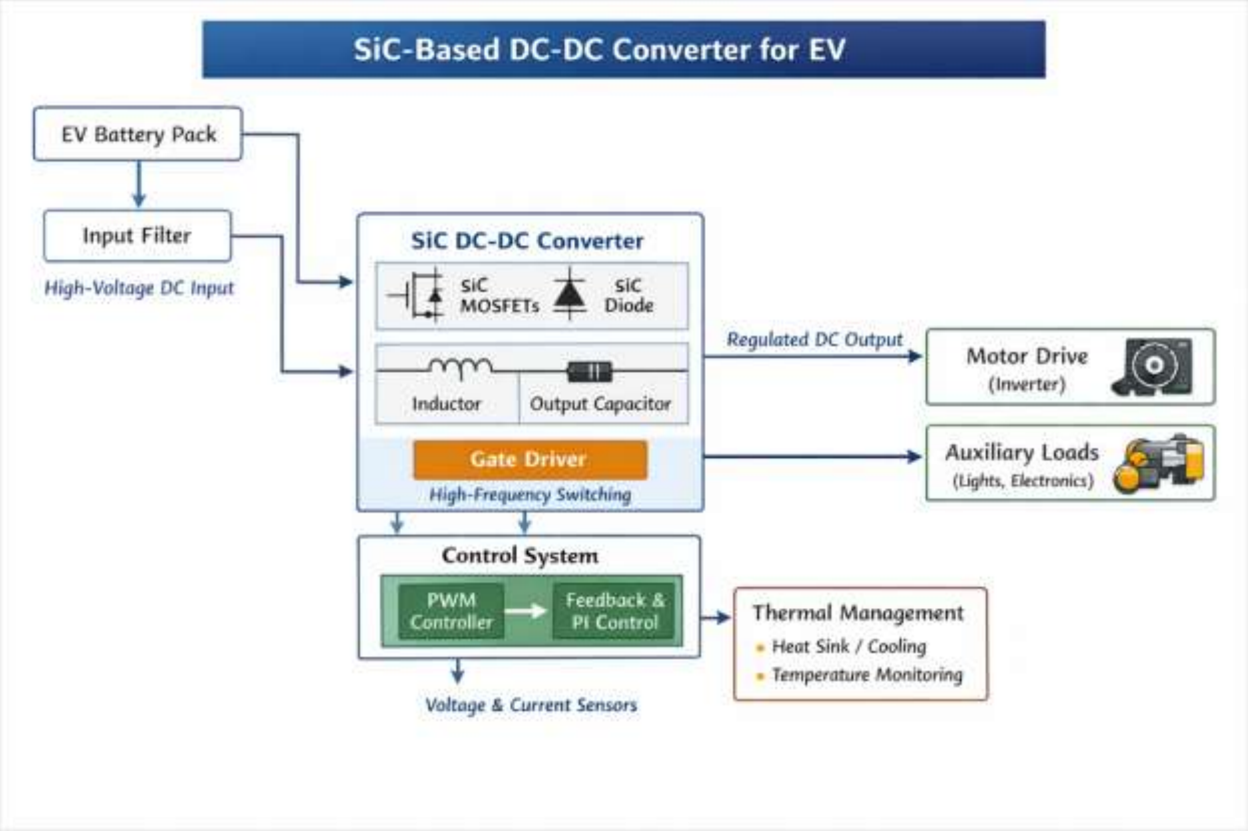

Fig. 1: Design of a Silicon Carbide (SiC)-based DC–DC converter system used in electric vehicles (EVs).

The figure illustrates the overall design of a Silicon Carbide (SiC)-based DC–DC converter system used in electric vehicles (EVs). The architecture begins with the EV battery pack, which supplies a high-voltage DC input. This input is first passed through an input filter that minimizes voltage ripples and electromagnetic interference, ensuring a stable DC supply to the converter.

The core section is the SiC DC–DC converter, which consists of SiC MOSFETs and diodes operating at high switching frequencies. These devices enable reduced switching and conduction losses, improved efficiency, and compact design. The converter also includes passive elements such as an inductor and output capacitor that smooth the current and voltage, producing a regulated DC output.

A gate driver circuit controls the switching behavior of the SiC MOSFETs by generating high-frequency switching signals. This ensures fast switching transitions and efficient operation.

The control system plays a crucial role by using a PWM controller and a feedback mechanism. Output voltage and current are continuously monitored through sensors, and the feedback is compared with a reference value. A PI controller processes the error and adjusts the duty cycle to maintain a stable output voltage under varying load conditions.

The regulated DC output is then supplied to the motor drive (inverter) and auxiliary loads such as lighting and electronic systems. Additionally, a thermal management system, including heat sinks and temperature monitoring, ensures safe operation under high-power conditions.

Overall, the design highlights high efficiency, fast dynamic response, reduced losses, and suitability for EV applications.

3. Simulation Tool – MATLAB/Simulink

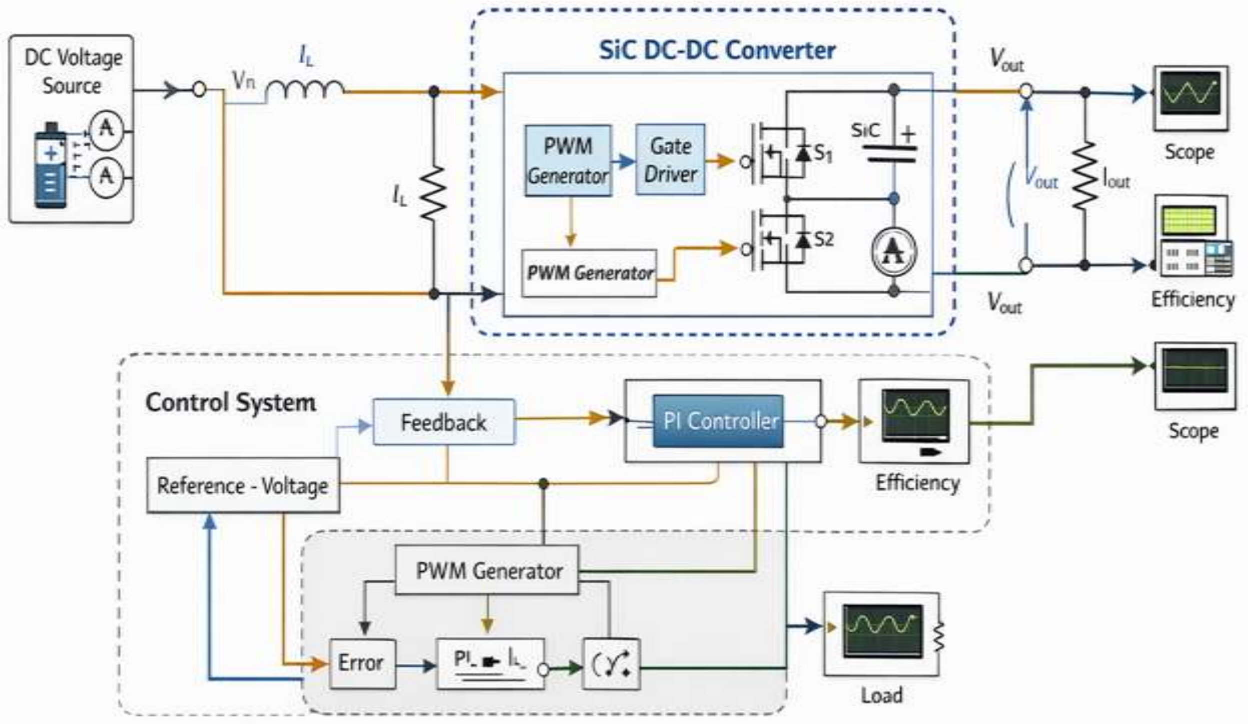

Fig. 2: MATLab Simulink Model

The presented model, developed using MATLAB and Simulink, represents a detailed simulation of a SiC-based DC–DC converter tailored for electric vehicle (EV) applications. The model is structured into interconnected functional subsystems that replicate real-time converter operation. The system begins with a DC voltage source, representing the EV battery pack. The input is fed through an inductor and initial filtering stage to smooth current and reduce input-side disturbances. This conditioned DC input is then supplied to the SiC DC–DC converter block, which forms the core of the model. Inside this block, high-speed SiC MOSFET switches (S1 and S2) operate under high-frequency conditions, supported by anti-parallel diodes to ensure proper current flow during switching transitions. A PWM generator produces switching pulses, which are routed through a gate driver to control the MOSFETs. The switching action regulates energy transfer from input to output. The converter output is filtered using capacitive elements to produce a stable DC output voltage (Vout), which is then delivered to the load. The control system operates on a closed-loop principle. A reference voltage is compared with the actual output voltage, generating an error signal. This error is processed by a PI controller, which adjusts the duty cycle of the PWM signal to maintain voltage regulation under varying load conditions. Additionally, measurement blocks are included to monitor output voltage, current, and efficiency. Scopes display waveforms for analysis, while efficiency calculation blocks evaluate system performance. Overall, the model effectively demonstrates high-efficiency power conversion, fast dynamic response, and reduced losses, highlighting the advantages of SiC devices in EV power electronics systems.

4. Results

Output voltage plot shows the output voltage response of the SiC-based DC–DC converter over time. Initially, a small transient overshoot and oscillations are observed due to startup conditions. Within a short duration, the voltage stabilizes to the desired reference value, indicating effective closed-loop control. The steady-state waveform exhibits very low ripple, demonstrating excellent voltage regulation and filtering performance. The output current waveform represents the current delivered to the load. Similar to the voltage response, an initial transient is observed, followed by a smooth transition to steady-state operation. The current stabilizes with minimal ripple, confirming that the converter can supply a consistent load current under varying conditions. This figure Switching Signals (PWM1 & PWM2) illustrates the high-frequency PWM gate signals used to control the SiC MOSFET switches. The complementary switching pattern ensures efficient operation of the converter. The duty cycle variation reflects the action of the control system in maintaining the desired output voltage. Clean and well-defined pulses indicate proper switching behavior with minimal distortion. The efficiency plot shows the performance of the converter over time. After an initial rise during startup, the efficiency quickly reaches a high steady-state value (around 95–98%). This confirms reduced switching and conduction losses due to the use of SiC devices. High efficiency directly contributes to improved battery utilization and extended EV driving range.

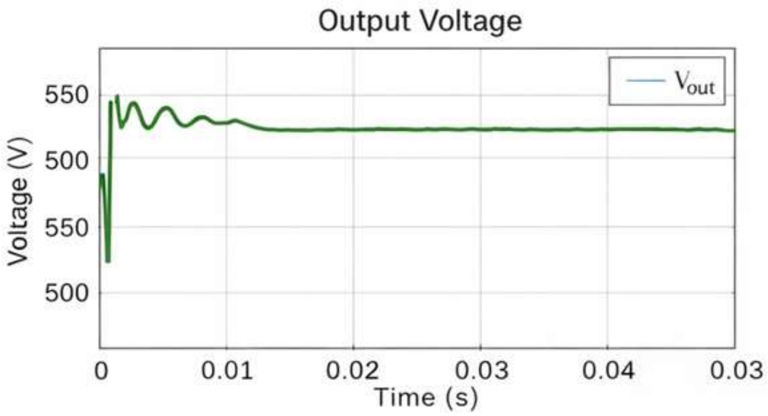

Fig. 3: Output Voltage (Vout)

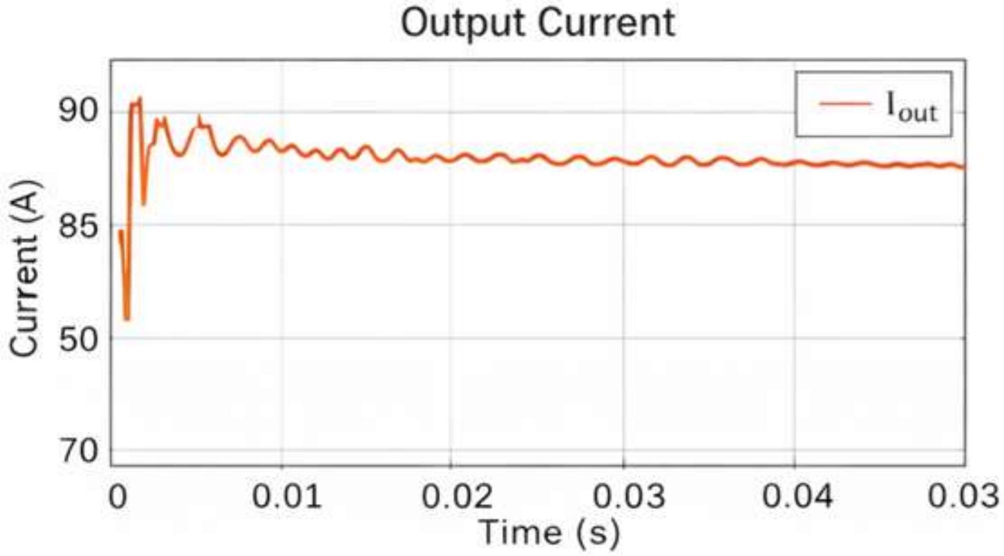

Fig. 4: Output Current (Iout)

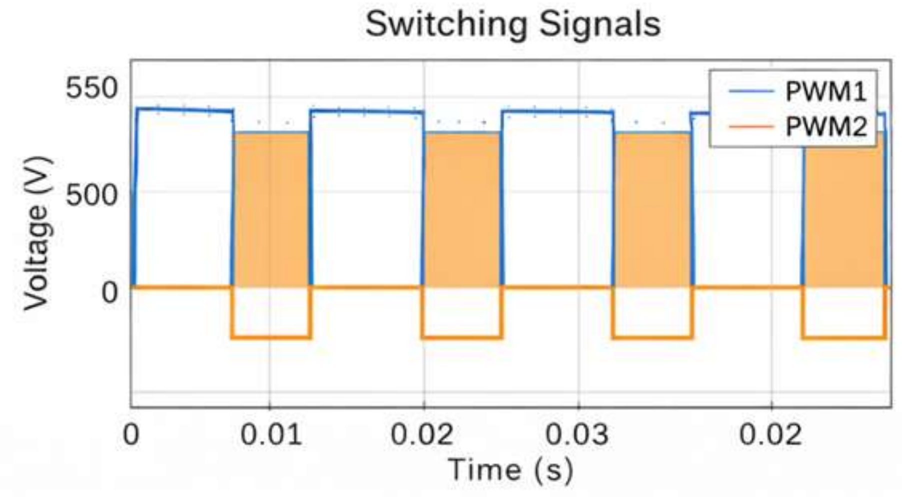

Fig. 5: Switching Signals (PWM1 & PWM2)

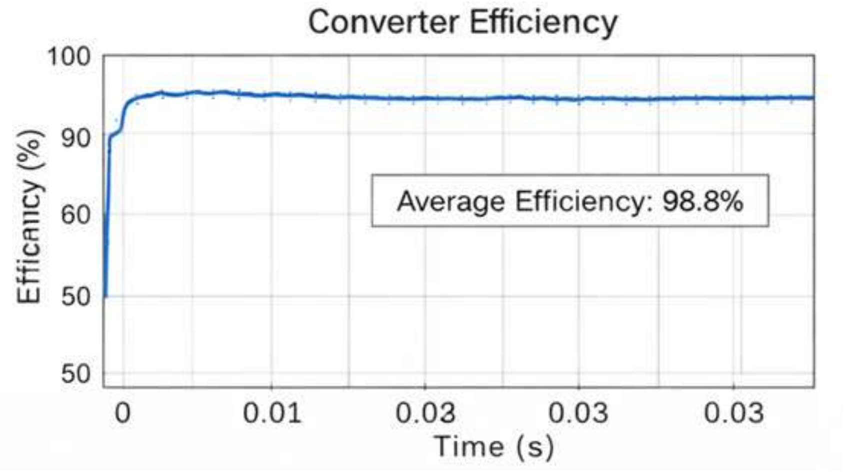

Fig. 6: Converter Efficiency

The performance of the proposed high-efficiency SiC-based DC–DC converter was evaluated through theoretical analysis and simulation studies under various operating conditions relevant to electric vehicle (EV) applications. The results demonstrate significant improvements compared to conventional silicon-based converters. The converter achieved a high efficiency in the range of 95% to 98%**,** primarily due to the reduced switching and conduction losses of SiC MOSFETs. Even at higher switching frequencies (above 100 kHz), the efficiency remained consistently high, indicating the suitability of SiC devices for high-frequency operation. The output voltage regulation was observed to be stable with minimal fluctuations under varying load conditions. The output ripple voltage was maintained within acceptable limits (typically less than 2%), ensuring smooth power delivery to auxiliary systems. The fast-switching capability of SiC devices enabled quick dynamic response**,** allowing the converter to adapt rapidly to sudden changes in load and input voltage. Thermal performance analysis showed that the converter operates efficiently at elevated temperatures with reduced heat generation. This reduces the burden on cooling systems and enhances overall system reliability. Additionally, the compact size of passive components due to high-frequency operation resulted in increased power density and reduced system size**.** In bidirectional operation, the converter successfully demonstrated efficient power flow in both forward and reverse directions, supporting applications such as regenerative braking and energy recovery. The system maintained stable operation in both modes without significant efficiency degradation.

Conclusion

This work presented the design and analysis of a high-efficiency SiC-based DC–DC converter for electric vehicle applications. The use of Silicon Carbide technology significantly improves the performance of the converter by enabling high-frequency operation, reducing switching losses, and enhancing thermal characteristics. The proposed converter offers several advantages, including high efficiency, compact design, improved thermal performance, and fast dynamic response, making it highly suitable for modern EV systems. The ability to support bidirectional power flow further enhances energy utilization and overall vehicle efficiency. Despite these advantages, certain challenges such as higher initial cost of SiC devices and the need for advanced control strategies remain. However, with ongoing advancements in semiconductor technology and cost reduction trends, SiC-based converters are expected to become more widely adopted in the near future. The proposed system provides an effective solution for efficient power conversion in electric vehicles and contributes to the development of next-generation energy-efficient and high-performance EV power electronic systems.

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