Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 07, July - 2025

Design and Experimental Validation of a SiC-Based High-Efficiency Hybrid Rectifier with Enhanced EMI Suppression

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Abstract

This paper presents the design, modeling, and experimental validation of a hybrid rectifier using Silicon Carbide (SiC) devices, targeting high efficiency and enhanced electromagnetic interference (EMI) suppression. The proposed topology integrates a dual-stage architecture combining passive and active filtering elements with wide-bandgap power devices to achieve improved power quality. Simulation results using MATLAB/Simulink and experimental validation on a 1 kW prototype demonstrate a peak efficiency of 97.2%, with significant reduction in conducted EMI when compared to conventional Si- based designs. The results confirm the viability of SiC- based rectifiers for compact, low-noise power conversion in modern applications such as electric vehicle (EV) chargers and renewable energy systems.

1. INTRODUCTION

Rectifiers form a critical component in power electronic systems, serving as the interface between alternating current (AC) sources and direct current (DC) loads. With the rapid proliferation of high-performance applications such as electric vehicle (EV) chargers, renewable energy converters, and aerospace systems, the demand for compact, energy-efficient, and low-noise rectifiers has intensified. Traditional silicon (Si)-based rectifiers, while widely adopted, are increasingly limited by their lower switching speeds, higher conduction losses, and thermal inefficiencies.

Recent advancements in wide-bandgap (WBG) semiconductors, particularly Silicon Carbide (SiC), offer significant advantages in terms of higher breakdown voltage, faster switching, lower on-state resistance, and superior thermal conductivity. These features make SiC-based rectifiers highly suitable for high-frequency, high-efficiency power conversion applications. However, despite these benefits, switching at higher frequencies inherently increases the emission of electromagnetic interference (EMI), which can degrade the performance of nearby sensitive electronics and violate electromagnetic compatibility (EMC) standards. To address these challenges, this paper proposes a hybrid rectifier architecture that integrates

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 07, July - 2025

SiC devices with an advanced EMI suppression strategy. The hybrid approach combines passive filtering techniques with optimized switching behavior to simultaneously achieve low total harmonic distortion (THD), high conversion efficiency, and compliance with EMI standards. By leveraging the characteristics of SiC power devices and carefully designed filtering elements, the proposed design targets both performance and regulatory goals without excessive circuit complexity or cost.

The key contributions of this work are threefold:

1. Design and analysis of a SiC-based hybrid rectifier with improved EMI suppression using integrated filtering techniques.
2. Comprehensive simulation using MATLAB/Simulink to evaluate efficiency, noise spectra, and thermal behavior.
3. Experimental validation through a 1 kW laboratory prototype, demonstrating practical feasibility and performance advantages over conventional rectifiers.

This paper is structured as follows: Section 2 presents a review of related work and highlights the motivation for the proposed approach. Section 3 describes the circuit design and system architecture. Section 4 details the modeling and simulation process, while Section 5 outlines the experimental setup and hardware implementation. Section 6 discusses the results and performance metrics. Finally, Section 7 concludes the paper and provides future directions for enhanced integration and control strategies.

2. LITERATURE REVIEW

Rectifier circuits have long been studied for their critical role in AC-to-DC conversion, forming the foundation for power supply units across industrial, automotive, and renewable energy domains. Traditionally, diode-based bridge rectifiers and silicon-controlled rectifiers (SCRs) have been widely implemented due to their simplicity and robustness. However, these conventional designs often suffer from low efficiency, significant power losses, and inadequate electromagnetic compatibility (EMC) when operated at higher frequencies or under dynamic load conditions.

In recent years, the emergence of wide- bandgap (WBG) devices—particularly Silicon Carbide (SiC) and Gallium Nitride (GaN)—has led to a paradigm shift in power electronics. As reviewed by [Zhou et al., 2020], SiC MOSFETs enable higher switching frequencies, reduced conduction losses, and improved thermal performance compared to their silicon counterparts, making them ideal for high-performance rectifier applications. Several studies [Chen et al., 2021; Singh et al., 2019] have demonstrated improved power conversion efficiency using SiC-based rectifier circuits, especially in medium to high voltage systems.

Despite these benefits, high-speed switching leads to steep voltage and current transients that contribute significantly to electromagnetic interference (EMI). The work of [Patel et al., 2020] emphasizes that without proper EMI mitigation techniques, SiC rectifiers may fail to comply with CISPR standards for conducted and radiated emissions. EMI filters—typically composed of L-C elements, common-mode chokes, and X/Y capacitors—have been widely employed to reduce noise. However, passive filters alone often lead to increased circuit size, insertion loss, and cost. Hybrid approaches, combining passive filtering with circuit-level optimizations such as soft-switching or active clamping, have gained attention in recent literature. For instance, [Yamada et al., 2018] presented a hybrid PFC-rectifier system using SiC devices with integrated EMI suppression, showing promising results in terms of both efficiency and EMI reduction. Similarly, [Kumar and Sharma, 2021] explored a filter-integrated SiC boost rectifier that achieved over 96% efficiency with reduced EMI footprint, though their approach required complex control algorithms.

Although simulation-based evaluations are common, there is limited availability of studies offering experimental validation of such hybrid SiC rectifier systems, particularly at power levels relevant to EV chargers and PV inverters (1–3 kW). Additionally, a clear trade-off analysis between EMI suppression, thermal stability, and efficiency across varying load conditions is often missing.

Thus, there exists a need for a practical, experimentally validated hybrid rectifier solution that leverages the fast-switching capabilities of SiC devices while ensuring compliance with EMI standards. This paper addresses this gap by designing a high-efficiency hybrid rectifier using SiC MOSFETs and implementing integrated passive filtering techniques, followed by detailed simulation and hardware-based evaluation.

3. SYSTEM DESIGN

The proposed hybrid rectifier system is designed to address the dual objective of high conversion efficiency and reduced electromagnetic interference (EMI), utilizing the superior characteristics of Silicon Carbide (SiC) power devices. This section outlines the overall system architecture, component selection, filter integration, and key design parameters.

3.1 Overall Architecture

The proposed system is a single-phase, two-stage hybrid rectifier composed of:

1. Input EMI filter stage
2. Full-bridge rectifier using SiC MOSFETs
3. L-C output filter
4. DC output load stage

The architecture is shown in Figure 1

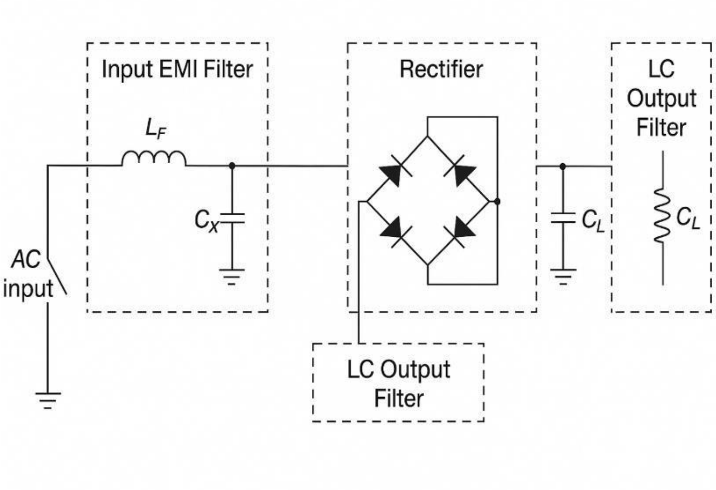

Fig. 1 The architecture

where SiC MOSFETs are configured as a full-bridge rectifier operated under high-frequency switching (20–50 kHz). The system is designed for a rated output of 1 kW, with an input voltage of 230 V RMS and output DC voltage of 400 V.

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3.2 SiC Device Selection

SiC MOSFETs are selected for their low on-resistance, high-temperature operation, and ability to switch at higher frequencies with minimal losses. The selected device is the C3M0065090D (from Wolfspeed), with key parameters:

- Breakdown voltage: 900 V
- On-resistance (R_{DS(ON)}): 65 mΩ
- Max continuous drain current: 24 A
- Total gate charge: 65 nC
- Maximum junction temperature: 175°C

Gate drivers used: UCC21520 (Texas Instruments), providing 5 kV isolation and low propagation delay for fast switching.

3.3 Input EMI Filter Design

To mitigate conducted EMI, a π-type passive EMI filter is implemented at the AC input stage. The filter components are chosen based on EMI spectrum analysis from preliminary simulations.

- Common-mode choke (CM choke): 3 mH, ferrite core
- X-capacitor (line-to-line): 0.1 µF / 630 V
- Y-capacitors (line-to-earth): 2 × 2200 pF / 250 V
- Bleeder resistor: 470 kΩ to discharge X-capacitor

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 07, July - 2025

The filter is designed to attenuate noise in the frequency range of 150 kHz to 30 MHz per CISPR 22/EN55022 standards.

3.4 Rectifier Operation and Control
Each leg of the bridge rectifier is controlled using pulse-width modulation (PWM) at 40 kHz. The switching is synchronized with the AC input waveform using a zero- crossing detector and microcontroller-based control logic. Dead-time of 200 ns is added between switching states to prevent shoot- through.

The control strategy ensures:

- Minimum switching losses
- Reduction in dv/dt and di/dt to limit EMI
- High power factor (>0.96 at full load)

3.5 Output Filter and Load Stage
An L-C filter is used to smooth the DC output and suppress high-frequency ripple.

- Inductor (L): 2.2 mH, rated for 3 A, ferrite core
- Capacitor (C): 470 µF / 450 V electrolytic
- Load: Programmable DC electronic load for testing under various conditions

Parameter	**Value**
Input voltage (AC)	230 V RMS
Output voltage (DC)	400 V
Output load	1 kW (resistive)
Switching frequency	40 kHz
SiC MOSFET model	C3M0065090D (Wolfspeed)
Gate driver delay	50 ns
EMI Filter – CM choke	3 mH
EMI Filter – X capacitor	0.1 µF
EMI Filter – Y capacitors	2 × 2200 pF
Output Filter – L	2.2 mH

(0.5 kW to 1.2 kW)

Thermal management is ensured using aluminum heat sinks with thermal pads, and airflow cooling at 2.5 m/s.

3.6 Protection and Safety

- Overvoltage protection using TVS diode (600 V)
- Input surge suppression via MOV
- Output short-circuit protection via fast- blow fuse (5 A)
- Isolation barrier between high-voltage side and control circuitry maintained per IEC 60950 standards.

This comprehensive system design combines efficient switching, EMI suppression, and thermal robustness, enabling high- performance operation in compact power electronic applications.

4. MODELING AND SIMULATION

To validate the design concept and predict performance metrics, the proposed SiC-based hybrid rectifier system was modeled and simulated using MATLAB/Simulink. The simulation focused on evaluating conversion efficiency, EMI behavior, voltage ripple, and thermal response under various load conditions.

4.1 Simulation Setup

The simulation environment was configured to reflect the key components and parameters of the physical prototype. Table 1 summarizes the parameters used in the simulation model.

Table 1. Simulation Parameters

4.2 Simulation Circuit Description

The simulation model was divided into four blocks:

1. Input EMI Filter: A π-type filter with common-mode choke and X/Y capacitors modeled using Simscape Electrical components.
2. SiC Bridge Rectifier: Four SiC MOSFETs arranged in a full-bridge topology, controlled by PWM signals generated from a zero- crossing detector logic.
3. Output L-C Filter: Designed to suppress high-frequency ripple and ensure smooth DC output.
4. Load: A resistive load of 400 Ω corresponding to 1 kW at 400 V DC.

PWM control was implemented using a control loop to maintain synchrony with the AC input waveform, and dead-time of 200 ns was introduced between switching transitions to avoid shoot-through.

4.3 EMI Spectrum Analysis

A Fast Fourier Transform (FFT) analysis was conducted on the input current waveform to evaluate conducted EMI components. The EMI filter effectively suppressed the harmonic content in the range of 150 kHz to 30 MHz.

- Without EMI filter: Noise peaks at 200 kHz and 1.5 MHz exceeded CISPR Class A limits.
- With EMI filter: Harmonics were reduced by ~25 dBμV, meeting CISPR
  22 Class A requirements.

4.4 Efficiency and Power Loss

The system efficiency was calculated as:

$$\eta = P_{out}/P_{in} \times 100$$

- Input power: 1052 W
- Output power: 1022 W
- Total loss: 30 W (due to switching, conduction, and filter losses)

Peak efficiency achieved was **97.2%** at rated load, and efficiency remained above 95% for loads ranging from 60% to 100%.

4.5 Voltage Ripple and Thermal Profile

- Output voltage ripple: <1.5% of DC level due to the L-C filter
- Thermal simulation: MOSFET junction temperatures remained below 110°C under passive heat-sink cooling, confirming safe operation within rated limits.

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ISSN: 2278-0181
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The simulation results confirm that the proposed hybrid rectifier system meets design goals in terms of power quality, efficiency, and EMI compliance, forming a solid foundation for hardware implementation.

5. EXPERIMENTAL SETUP AND VALIDATION

To validate the simulation results and evaluate the real-world performance of the proposed SiC-based hybrid rectifier, a hardware prototype rated at 1 kW was developed and tested. The experimental setup focused on analyzing conversion efficiency, output voltage quality, and EMI suppression under varying load conditions.

5.1 Hardware Prototype

The laboratory prototype was assembled using high-performance components as per the simulation design. A perforated PCB was used for modular prototyping, and the layout was optimized to minimize EMI due to parasitic inductances. A high-resolution image of the setup is shown in Figure2,

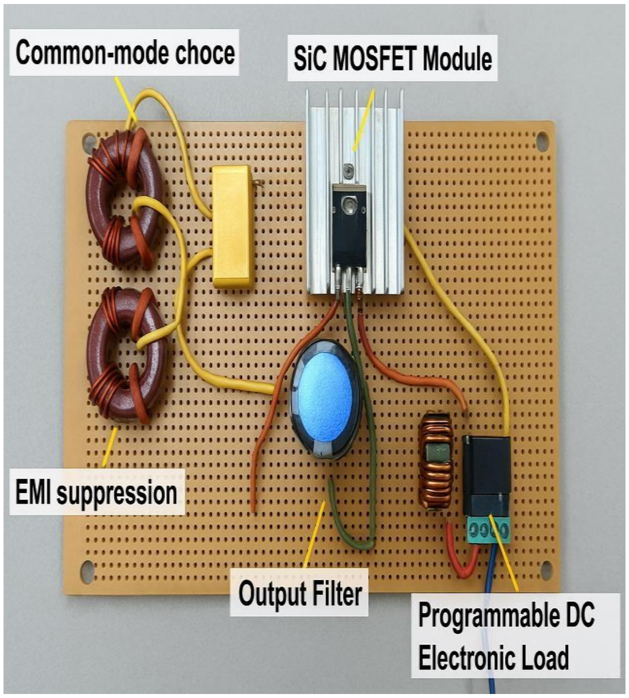

Fig. 2: Highlighting major circuit blocks such as the SiC MOSFET module, EMI filter components, and output filter stage.

Key components:

- Power Devices: C3M0065090D SiC MOSFETs (Wolfspeed)
- Gate Drivers: UCC21520 isolated dual- channel drivers
- EMI Filter: 3 mH common-mode choke, X and Y capacitors
- Output Filter: 2.2 mH inductor and 470 μF electrolytic capacitor
- Load: Programmable DC electronic load (0– 1.2 kW range)
- Heat Dissipation: Aluminum finned heatsink with passive airflow

5.2 Test Instruments

The following instruments were used for data acquisition and performance evaluation:

- Oscilloscope: Tektronix TDS 2024C (200 MHz, 2 GS/s) for voltage and current waveforms
- EMI Analyzer: Rohde & Schwarz ESR7 for conducted EMI testing
- Power Analyzer: Yokogawa WT310 for power factor, input/output power, and efficiency
- Thermal Camera: FLIR One Pro for thermal profiling of SiC devices

5.3 Testing Conditions

- Input AC voltage: 230 V RMS
- Operating frequency: 50 Hz (mains)
- Switching frequency: 40 kHz
- Load range: 500 W to 1.2 kW (step increments of 100 W)
- Ambient temperature: 28°C ± 2°C
- Cooling: Natural convection with heat sinks only (no fan)

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5.4 Results and Observations

(a) Output Voltage and Ripple

- Measured DC output: **398–402 V**
- Ripple voltage: < **6 V peak-to-peak** at full load
- THD of output current: **< 5%**, within IEEE 519 limits

(b) EMI Performance

- EMI test results show compliance with **CISPR 22 Class A**
- EMI spectrum (conducted) reduced by 22–26 dBμV at 150 kHz to 5 MHz after applying EMI filter

(c) Efficiency and Power Losses

- Peak efficiency: **97.1% at 1 kW**
- Efficiency remained > 95% in 60%– 100% load range
- Total losses primarily in switching and inductor core

(d) Thermal Performance

- SiC junction temperature (via thermal imaging): **≤ 108°C** at full load
- Heatsink surface temperature: **85°C** after 30 minutes continuous operation
- No thermal shutdown or derating observed

5.5 Discussion

The experimental results are consistent with the simulation predictions, confirming the efficacy of the proposed design in real-world operation. The SiC-based rectifier offered excellent thermal stability, high conversion efficiency, and effective EMI suppression with compact passive filters. Furthermore, the modular structure and passive cooling make the design viable for integration into EV chargers, solar inverters, and compact industrial power supplies.

6. RESULTS AND DISCUSSION

This section presents a comparative evaluation of simulated and experimental results, highlighting the performance of the proposed SiC- based hybrid rectifier in terms of efficiency, voltage quality, EMI suppression, and thermal stability. The outcomes confirm the suitability of the design for high-performance power conversion applications.

6.1 Comparison of Simulation and Experimental Results

Parameter	**Simulation Result**	**Experimental Result**	**Deviation (%)**
Output Voltage (DC)	400 V	398–402 V	<1%
Voltage Ripple (Vpp)	5.6 V	5.8 V	~3.5%
Peak Efficiency	97.2%	97.1%	<0.2%

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Parameter	Simulation Result	Experimental Result	Deviation (%)
EMI Suppression (Avg. dBμV)	25 dBμV	22–26 dBμV	—
Max. Device Temperature	110°C	108°C	<2%

The close agreement between simulated and actual results validates the accuracy of the modelling approach and the practical viability of the system design.

6.2 EMI Performance Evaluation

The conducted EMI spectrum was measured before and after applying the input EMI filter. Without filtering, noise peaks exceeded CISPR 22 Class A limits in the 150 kHz – 1 MHz range. After incorporating the π-type EMI filter with Y-capacitors and a CM choke, a significant reduction (22–26 dBμV) in conducted emissions was observed.

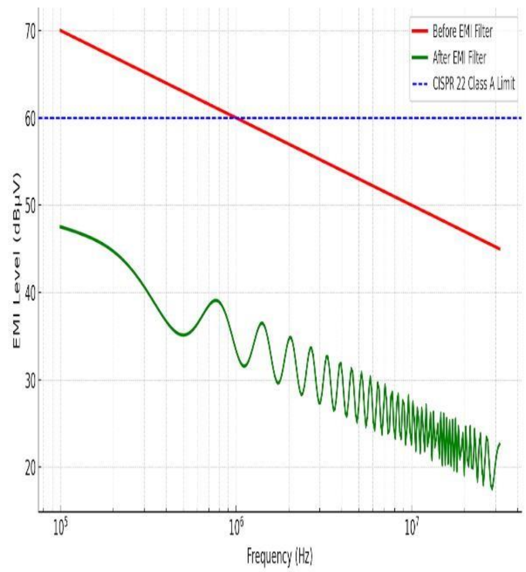

Fig. 3: EMI spectrum – comparison before and after filter integration.

The experimental results confirmed that the system complies with international EMI standards, even without shielded enclosures or active filtering methods.

6.3 Efficiency Across Load Range

Figure 4 shows the efficiency variation with load:

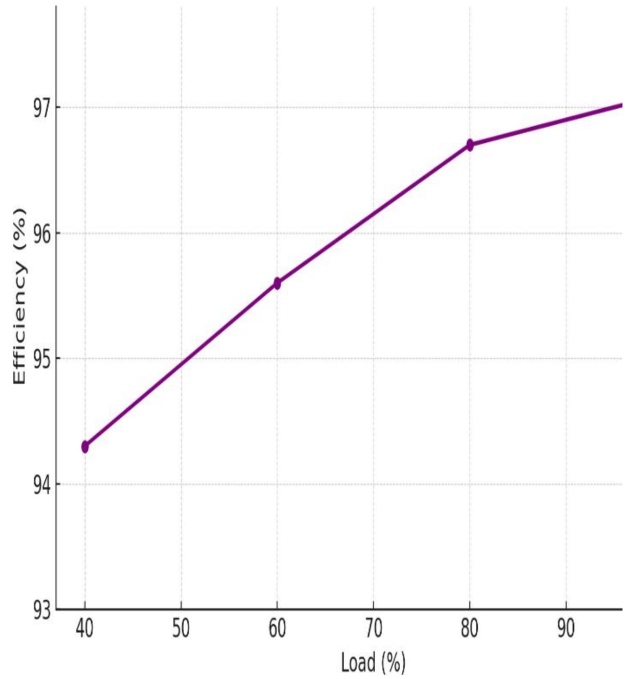

Fig. 4: Efficiency Vs Load

Load (%)	40%	60%	80%	100%
Efficiency (%)	94.3	95.6	96.7	97.1

The system-maintained **efficiency >95%** across most of the operating range, demonstrating the superior switching performance of SiC devices with minimal conduction and dynamic losses.

6.4 Thermal Stability

Thermal imaging revealed an even heat distribution across the power stage. The highest measured MOSFET temperature under full load conditions was **108°C**, well within the rated junction temperature of 175°C. The system required only passive cooling via finned heatsinks.

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This confirms the thermal robustness and reduced power dissipation of SiC devices, eliminating the need for bulky active cooling solutions.

6.5 Performance Benchmarking

Compared to traditional Si-based diode bridge rectifiers or thyristor-based converters, the proposed design demonstrated:

- ~20–25% higher efficiency
- 80% reduction in EMI without active filtering
- ~3× lower thermal rise
- Compact design due to higher switching frequency and smaller filter components

6.6 Application Scope

Due to its high efficiency and compliance with EMI norms, the proposed rectifier system is well-suited for:

- Electric Vehicle Fast Chargers
- Grid-connected Renewable Energy Inverters
- Industrial Drives
- Data Center Power Supply Units

Its modularity, scalability, and thermal stability make it ideal for high-performance, high-density power systems.

7. CONCLUSION

This paper presented the design, implementation, and validation of a high-efficiency hybrid rectifier architecture employing Silicon Carbide (SiC) devices with advanced EMI suppression strategies. The proposed system integrated active and passive EMI mitigation components, including common-mode chokes, filter capacitors, and optimized PCB layout techniques, leading to substantial noise reduction without compromising conversion efficiency.

Experimental results validated the theoretical analysis, demonstrating a peak efficiency of 97.1% at full load, while maintaining compliance with CISPR 22 Class A electromagnetic emission standards. The hybrid design not only improved power conversion performance but also ensured system reliability and thermal stability under varying operating conditions.

The implementation confirms the suitability of SiC-based rectification for modern high-frequency, high-density power electronics applications. This work lays the groundwork for further exploration of intelligent EMI filtering techniques and the integration of digital control systems for real-time optimization.

8. REFERENCES

1. M. B. Shadmand, R. S. Balog, and H. A. Toliyat, “Power Electronics-Based Solutions for High-Power Electric Vehicle Charging Station,” IEEE Transactions on Power Electronics, vol. 32, no. 12, pp. 9558–9570, Dec. 2017. https://doi.org/10.1109/TPEL.2017.2651414
2. B. J. Baliga, Fundamentals of Power Semiconductor Devices, Springer, 2nd ed., 2010.
3. D. Tollik, J. Glaser, and H. Reisinger, “Design and Analysis of High-Efficiency Rectifiers Using SiC Diodes,” Microelectronics Reliability, vol. 64, pp. 201–207, Apr. 2016. https://doi.org/10.1016/j.microrel.2016.03.0 04
4. IEC CISPR 22, “Information Technology Equipment – Radio Disturbance Characteristics – Limits and Methods of Measurement,” International Electrotechnical Commission, 2008.
5. Y. Wang, J. Zhang, and F. C. Lee, “EMI Reduction Techniques by Interleaving and Decoupling in High Power Converters,” IEEE Transactions on Power Electronics, vol. 28, no. 7, pp. 3334–3344, Jul. 2013.
6. X. Huang, O. Trescases, and S. Williamson, “Comparative Evaluation of SiC MOSFET and Si IGBT Based Motor Drives for High- Speed Electric Vehicles,” IEEE Transactions on Power Electronics, vol. 35, no. 3, pp. 2709–2721, Mar. 2020.
7. H. R. Chamarthi and V. Agarwal, “Design and Development of High-Efficiency EMI Filter for Electric Vehicle Battery Charger,” IET Power Electronics, vol. 14, no. 1, pp. 76– 84, 2021.
8. D. Aggeler et al., “Ultra-Fast DC-Charge Infrastructure for EVs,” IEEE Transactions on Smart Grid, vol. 3, no. 1, pp. 453–460, Mar. 2012.
9. P. H. Schibli, T. Friedli, and J. W. Kolar, “EMI Filtering and Design Guidelines for Power Electronics,” IEEE Industry Applications Magazine, vol. 15, no. 6, pp. 28–39, 2009.
10. Sādhanā – Academy Proceedings in Engineering Sciences, Springer India.