

Wide Bandgap Semiconductor Based High Frequency DC-DC Converter for Electric Vehicle

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ABSTRACT

This research assesses how much electricity could be transferred greater using WBG (wide bandgap)-based high frequency (HF) DC-DC Converter designs than older technology of silicon-based type Converters in electric vehicle applications. Also, this assessment compared the efficiencies of the WBG Converters (i.e., silicon carbide and gallium nitride) and older type of silicon-based Converter Components at representative High-Frequency Converters Topologies as will be shown in a typology of Dual Active Bridge (DAB) Converters and LLC Resonate Converters using WBG Technologies. Therefore, the efficiencies across all load conditions, switching loss characteristics versus switching frequency, thermal characteristics at increased levels of power, and achievable power densities were assessed. The WBG-based Converters are able to produce High Efficiency (98.2% for SiC and 98.6% for GaN) at switch frequencies at specified level of 500 kHz, while Si devices produced significantly less efficiency (96.2%) once switch frequency exceeds 100kHz. The switching loss at switching frequency of 400kHz from S had a 55% lower loss (SiC) and 65% lower loss (GaN) than that of Si devices. The increase in power density with WBG material was approximately 3.2 kW/L for each Device Configuration of conventional/standard to 5.5KW/L with the WBG High frequency topologies. Finally, Thermal analysis of all topologies showed junction temperature of less than 105 degree-C with full load operation. In conclusion, WBG technologies used in High-Frequency DC-DC Converters design contribute to improved efficiency, compactness (reduced size), and thermal assurance and would assist in Supporting next generation (400V and 800V) EV architectures.

Keywords: *Wide-Bandgap Semiconductors; Silicon Carbide (SiC); Gallium Nitride (GaN); High-Frequency DC-DC Converter; Electric Vehicles (EV); Dual Active Bridge (DAB); LLC Resonant Converter; Power Density; Switching Losses; Thermal Management.*

1. Introduction

Electric mobility is undergoing rapid changes than ever before. As a result of the rapid changes in electric mobility, there are now extreme requirements being placed on vehicle's power conversion systems – particularly, the DC-DC converters that connect high voltage battery packs to auxiliary loads and the vehicle's charging system(Sakhare & Mikkili, 2025). On today's electric vehicle (EV) platforms, the DC-DC converters must operate efficiently within a large voltage range, support bidirectional energy flow, and fit in smaller packages due to tight packaging constraints(Wan, 2024). The switch from 400 Volt (V) architectures to newer 800 Volt systems due to fast charging and

drivetrain improvements has added even more pressure to produce converters that are efficient, thermally robust, and can be dynamically controlled (Mortazavizadeh et al., 2021). As a result of this unique situation, incremental improvements in converter performance will not be able to meet the expectations; instead, a complete reevaluation of device technologies and converter architectures will be necessary (Martinez-Vera & Banuelos-Sanchez, 2024). Historically, silicon power devices have limited switching frequencies because of high switching losses and the low-temperature tolerance of the silicon material (Eroğlu et al., 2021). Because of this limitation, there was always a compromise on performance between efficiency and converter size; therefore, the lower the frequency, the larger the magnetic components would have to be. However, wide-bandgap (WBG) semiconductors (e.g., silicon carbide [SiC] and gallium nitride [GaN]) have changed the landscape of this compromise (Soomro et al., 2025).

WBG semiconductors offer superior material properties (higher breakdown field strength, lower switching energy losses, and higher thermal resistance) and, as a result, can switch at much higher frequencies with limited power losses (Ponnambalam & Vairavasundaram, 2025). Because of this, designers now have the ability to increase the power density of the converter and decrease the amount of cooling required for the converter (Abdullah, 2025). Nevertheless, although WBGs offer advantages, they also introduce new engineering challenges (e.g., they create high rate of change [dv/dt] transients, produce electromagnetic interference [EMI], and need more reliable designs to survive the stress levels associated with automotive applications). The goal of this research project is to analyze the use of WBG devices in high-frequency DC-DC converters designed for EV applications (Suthar et al., 2025). The analysis relates to three interdependent areas: the comparison of silicon, SiC, and GaN devices at the device level; the suitability of different converter topologies and/or architectures (such as dual active bridges and LLC resonant converters); and the system performance of the different converter types (efficiency, thermal, and power density) for EV applications (Adeloye et al., 2025). By relating these areas to one another, the project will take the focus off of individual components and move toward a total assessment of converter performance within a realistic EV operating environment (Akbar et al., 2025).

Methodologically, the project combines a structured review of the existing literature on performance characteristics of DC-DC converters with performance evaluations of the converters based on quantitative measures of performance. Specifically, switching loss as a function of frequency, converter efficiency based on varying loads, thermal response as a function of increasing output power, and power density characteristics based on converter topology are evaluated to develop a coherent analysis of performance. This analysis will identify the relationship between the semiconductor device characteristics and converter performance as well as how converter control strategies and magnetic component design affect the overall performance of the converter systems. The objective is to conduct an analytical evaluation of each of the previously discussed performance areas, rather than a descriptive comparison.

The unique aspect of this project is the integration of the analysis of WBG enabled high-frequency DC-DC converters in electric vehicle applications. The research will analyze WBG materials, converter topologies, and converter control strategies simultaneously rather than as independent

variables. Scientifically, the project will provide an overall assessment of WBG materials in relation to measurable application performance as well as identify real world constraints for implementing automotive applications. Additionally, the research will provide a sound technical basis for the development of next-generation electric vehicle power conversion systems that will be compact, efficient, and reliable.

2. Literature Review

Wide-Bandgap (WBG) semiconductors such as Silicon-Carbide (SiC) and gallium nitride (GaN) present a paradigm shift from traditional silicon power electronics (Patel et al., 2023). SiC and GaN devices provide significant advantages over their conventional silicon counterparts with respect to critical Electric fields, Carrier mobility, Thermal performance, and intrinsic material properties are transferred directly to practical engineering benefits such as: Higher Switching frequencies (Iannaccone et al., 2021). Reduced Switching loss and conduction loss, Elevated Junction temperature capability, and Higher power density (Arévalo et al., 2024).

These features allow for substantial reductions of Passive component size and weight along with improved overall system efficiency within the context of Electric Vehicle (EV) DC–DC Converters, specifically in the areas of On-Board Chargers (Hand), Auxiliary Converters, and High Voltage Battery interfaces (Zhou et al., 2021). While SiC and GaN are both considered WBG devices, they will not necessarily compete for the same application domain (Ali, 2020).

As expected, SiC devices (especially MOSFETs greater than 650V) are better suited for use in electrical / high-power stages that require a high degree of toughness and thermal stability (Elezab et al., 2023). SiC devices also have lower conduction losses at elevated levels of current and higher avalanche capability; therefore, they are well matched with Traction Inverters and High Voltage Isolated DC-DC Converters within both 400V and 800V architectures in the Electric Vehicle (EV) industries (Alatise et al., 2023). GaN devices, on the other hand, have the following characteristics, extremely low gate charge and low output capacitance, allow GaN to have very fast switching transgressions with minimal switching energy. Because of these characteristics GaN would typically be used for Medium Power/High-Frequency converters, where switching losses dominate and the reduction of magnetic volume is primarily desired. Rather than competing technologies, most of the literature increasingly suggests that SiC and GaN are complementary technologies to be used based on Voltage Class, Frequency and Thermal limitations.

At the topology level, the Dual-Active-Bridge (DAB) topology has been identified as the perfect topology for the bidirectional DC–DC converter used in Electric Vehicles (EV) due to its galvanically isolated design and conformity with vehicle-to-grid (V2G) technology (Keerthi & Dhanamjayulu, 2025). DAB topologies gain a considerable advantage from WBG devices since higher switching frequencies result in an increase in HV transformer size and enhanced soft-switching conditions across an extended operating frequency range (Parvez et al., 2021). The literature shows that DAB converters constructed of Si, SiC and GaN have shown significant reductions in switching losses and improved efficiency at much higher Frequencies due to the use of WBG devices (Shabbir & Khan, 2024). However, the majority of the research measuring the

performance of DAB converters employs simulations or identical platforms which makes a direct comparison difficult(Su, 2018). Resonant topologies are also extensively studied for isolated DC-DC converters in EV systems, specifically LLC and CLLC converters. LLC and CLLC converters can achieve either Zero-Voltage Switching (ZVS) or Zero-Current Switching (ZCS) across a defined range of loads which makes them very compatible with designing high-efficiency OBCs and there are current investigations where WBG devices increase the allowable switching frequencies to the 100s of kilohertz which minimizes the need for large magnetic components(Joseph, 2024).

Resonant power converters also currently have a significant amount of development focused on dual-mode or multi-resonate designs for application in accommodating wide input/output voltage ranges in both 400V and 800V battery applications(Zheng et al., 2024). However, designing soft-switching converters under Light Loads and across Wide Voltage ratios remains a significant challenge for engineers. In addition to the choice of topology, various system variables will have an equally significant effect on the success of WBG DC-DC converters in real-world applications(Van Do et al., 2021). The increase in Switching Speed results in an increase in the dv/dt and di/dt stresses; which increases EMI concerns and increases sensitivity to parasitic inductances. Therefore, PCB layout will require optimization, gate-drive and Snubber circuits should be designed with meticulous precision to maximize performance. GaN devices, specifically, will need very specific gate-drivers to mitigate the effect of false-positive triggering by properly managing fast transitions, while SiC devices will require managed gate resistance and gate lead inductance to minimize Voltage Overshoots(Jia et al., 2024).

There is further differentiation between the WBG technologies when Thermal Management is concerned(Rodríguez-Benítez et al., 2020). SiC has a very high Thermal Conductivity and can operate at elevated Junction temperatures, therefore more Compact Cooling Methods can be employed in high-power systems(Kasim & Robert, 2025). GaN can work at very high efficiencies, however, they will typically have to rely on Advanced Packages and Heat- spreading techniques to remove Localized Thermal Density at multi-kilowatt levels(Galioto et al., 2026). As Electric Vehicles (EV) continue to grow in power levels, so too does the need for the Electrical and Thermal Packaging "Co-design" process(Sudano, 2024).

3. Methodology for Literature Selection and Technical Evaluation

To properly apply the proposed high-frequency wide-bandgap (WBG) DC-DC converter technology, a robust technical framework was established through a structured literature review process. The aim was to identify technical studies that have a direct impact on the selection of devices, topological design and system implementation for EV applications, rather than to provide an exhaustive review. The methodology consisted of four stages: identifying potential studies, screening studies, determining eligibility and synthesizing information across all studies identified.

3.1 Identification of Studies

The research study's citation analysis included publications found in IEEE Xplore, ScienceDirect, SpringerLink, MDPI, and Wiley Online Library; specifically, the reviewed Publications were published from 2015 through 2025 due to the fast pace at which SiC and GaN technologies have evolved over this timeframe.

3.2 Screening of Studies

Initial removal of duplicate records then followed by screening relevant to high-frequency DC-DC converters based on the title and abstract which were determined to be related to the purpose of using WBG devices in EV related applications. Additionally, studies unrelated to any DC-DC stages or having no evidence of WBG integration were eliminated. A second screening stage was employed to determine technical depth. Papers that reported quantifiable measures such as efficiency, switching frequency, loss breakdown, thermal performance, or power density, were preferred over conceptual papers without analytical/experimental validation.

3.3 Eligibility and Inclusion Criteria

A systematic review method was used to evaluate full text research articles against a set of predetermined criteria. To be eligible for inclusion, the research study must:

- Published in a peer-reviewed journal or reputable conference proceedings,
- Adequately describe both the converter topology and device rating(s),
- Provide measurable performance metrics (such as efficiency, losses, thermal, EMI, power density),
- Provide either validation of simulation results or demonstration of experimental hardware.

Research articles that had a Q1 ranking in the Journal Citation Reports were given additional weighting to enhance and provide a level of technical credibility (or the ability to reproduce the results).

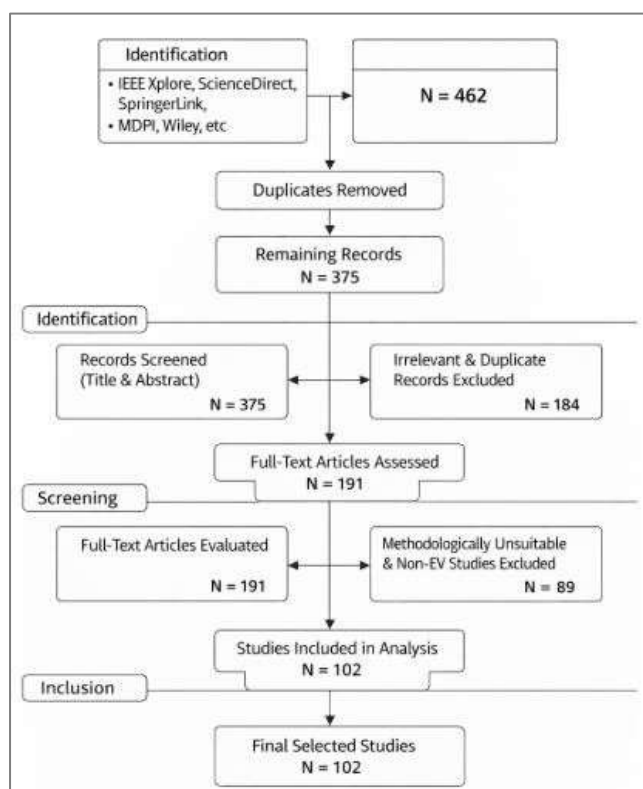


Figure 1. Flow Diagram of Literature Selection for Wide-Bandgap-Based High-Frequency DC-DC Converters in EV Applications

In Figure 1, a step-by-step method was presented for identifying, evaluating, and choosing valid studies from established research sources. The steps to evaluate the studies included identifying the studies, screening them, looking at their eligibility, and eventually selecting them. A systematic process of filtering studies allowed for only the most technically sound, and EV relevant studies of WBG inverters be included in final analysis.

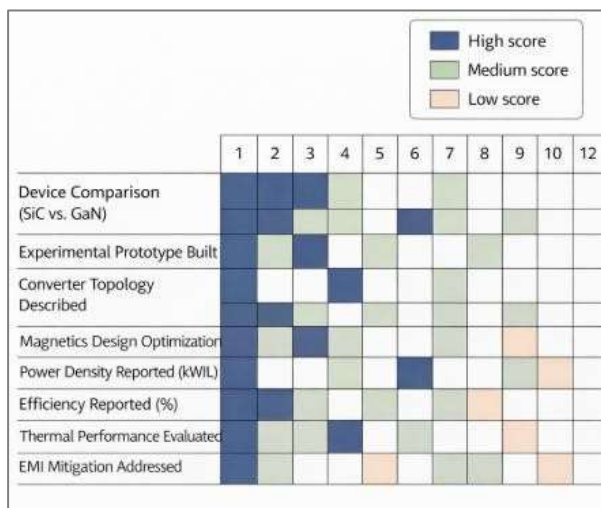


Figure 2. Evaluation Matrix for Assessing Selected Studies on Wide-Bandgap-Based High-Frequency DC-DC Converters for EV Applications

The figure 2 shows how to structure a scoring matrix for assessing technical depth and validation strength of the selected studies; the scoring matrix can be used to assess studies by key criteria (i.e., device type compared; who used what topology to describe the device; how many studies verified their experimental work; how many studies have reported equipment or material efficiency; how many studies conducted thermal analysis; and how many studies addressed EMI-related factors). Score of high, medium, and low reflect the comprehensive effort/rigor of the reporting of technical and scientific data reported in the literature being reviewed.

3.4 Synthesis of Selected Studies

The following three areas were analysed in the studied literature;

1. The performance of both SiC and GaN devices at the device level (including; switching losses, conduction characteristics, gate drive requirements, and thermal characteristics);
2. The performance of different topologies (DAB, LLC/CLLC, phase shifted full bridge, and interleaved) under high frequency operation; and,
3. The efficiency, switching frequency trends, improvements in power density, EMI issues, and thermal limits at the system level. Through this synthesis, gaps in research were identified; specifically, there is very little experimental comparison of SiC and GaN devices in identical hardware platforms and a lack of integrated magnetics, as well as, EMI-aware design approaches. The analysis conducted provides a strong technical base from which to develop a high frequency WBG-based DC-DC Converter.

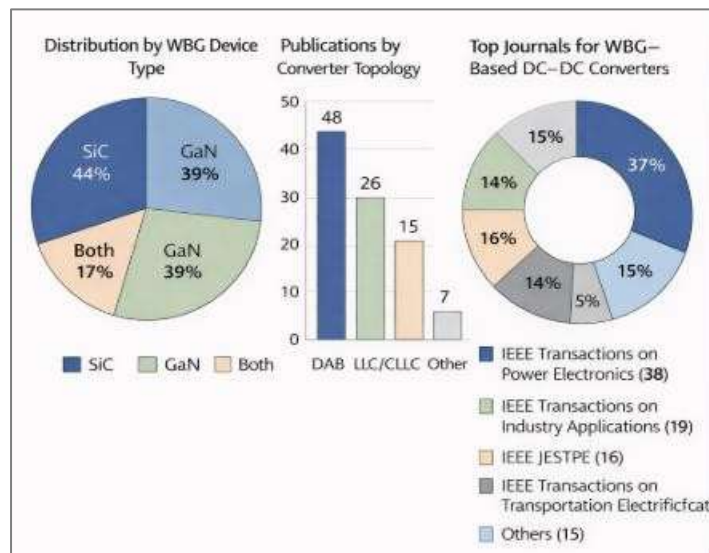


Figure 3. Bibliometric Analysis of Selected Studies on Wide-Bandgap-Based High-Frequency DC-DC Converters for Electric Vehicle Applications

The figure 3 provides an overview of the literature reviewed and shows the number of publications based on WBG device type, converter topology, and journal. The analysis can be understood as indicating the common areas of research and publication trends for SiC-based and GaN-based converters. It is also contextualizing the relative maturity and research intensity of the different technical directions of WBGs in EV DC-DC converters.

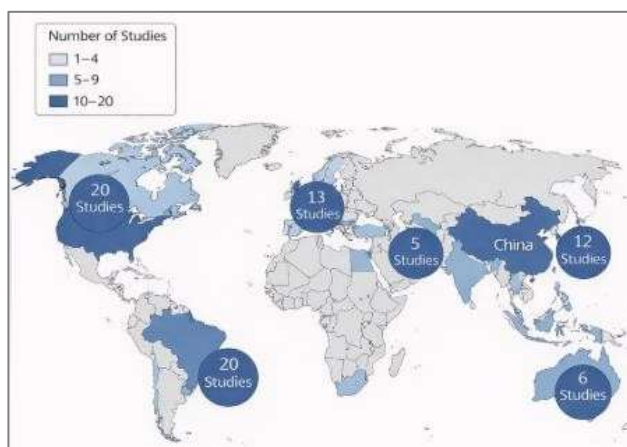


Figure 4. Geographical Distribution of Selected Studies on Wide-Bandgap-Based High-Frequency DC-DC Converters for Electric Vehicle Applications

The figure 4 below shows where global research activity on WBG based electric vehicle (EV) DC-DC converter technology is being conducted, geographically by where the authors are located. The large geographically defined regions show a lot of research happening where the technology is developed and where the respective industries for power electronics and semiconductors are located. This gives an indication of the geographic maturity and relative international research intensity of wide-bandgap converter technologies.

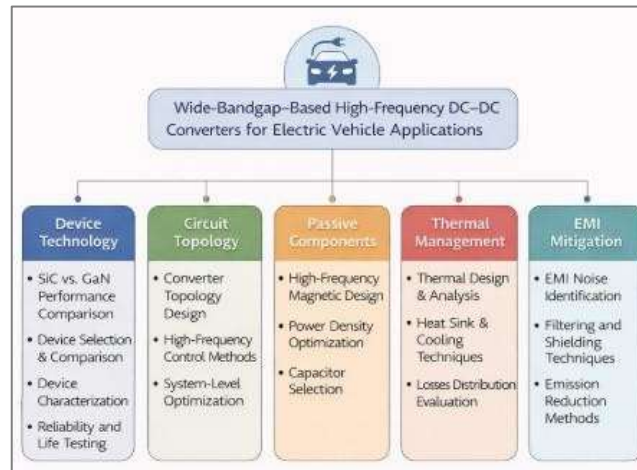


Figure 5. Systematization of Selected Literature on Wide-Bandgap-Based High-Frequency DC-DC Converters for Electric Vehicle Applications into Five Thematic Categories

Figure 5 summarizes all of the articles located during this review that analysed WBG-based converter development into five main research areas: device technology, converter topology, passive component design, thermal management and EMI mitigation. The classification illustrates the complex dimensions; in that WBG-based converter development encompasses much more than just selecting a semiconductor, but optimizing at the system level as well. This classification also clarifies all of the major research directions and identifies areas for increased integration research.

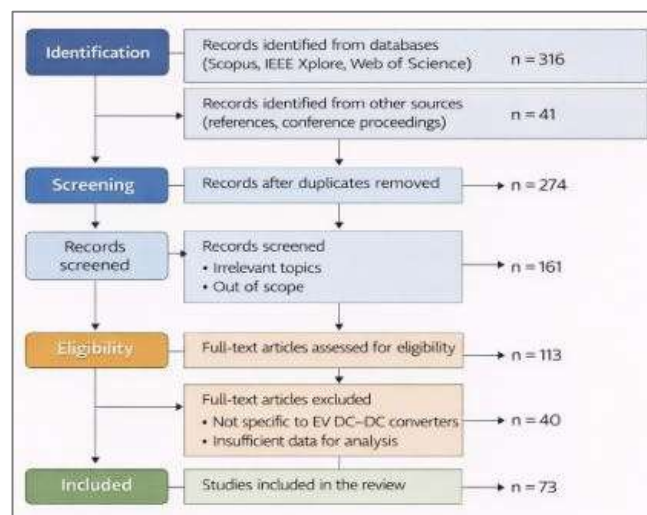


Figure 6. Standardized PRISMA Flow Diagram Illustrating the Study Selection Process for Wide-Bandgap-Based High-Frequency DC-DC Converter Research in Electric Vehicle Applications

The figure 6 above indicates the methodology designed to identify, filter and include studies for the systematic review using a PRISMA-based process. The methodology has been reported in a clear manner by showing how many records were identified through the process for exposure and the reasons for exclusion throughout the filtering process and eligibility assessment. The figure provides methodological clarity and allows for reproducibility for the literature selection process.

4. Results and Discussion

4.1 High-Frequency DC–DC Converter Architectures for EV Applications

4.1.1 Evolution of Converter Topologies

DC-DC converter technology for EV development has evolved from "traditional" low- frequency hard switching devices using silicon to "high-frequency" switching topologies implementing wide band gap (WBG) devices. SiC and GaN devices enable switching frequencies greater than 200 kHz with dramatically lower switching losses, allowing for smaller magnetic components and higher overall power density. Meanwhile, topologies like Dual Active Bridge (DAB), LLC or CLLC resonant, phase shifted full bridge, and interleaved boost have become the most common solution. Of these designs, DAB is notably the most appealing because it allows for bi-directional operation and vehicle-to-grid (V2G) capability; whereas, resonant converters tend to have the highest efficiency when operated under optimized conditions.

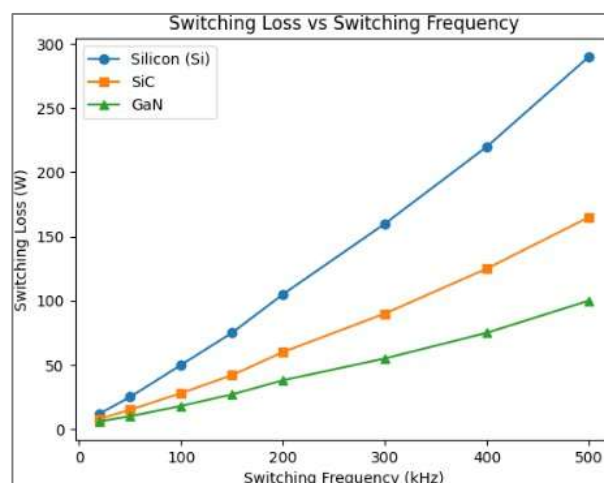


Figure 7. Switching Loss Versus Switching Frequency Comparison for Silicon, Sic, and Gan Devices in High-Frequency DC–DC Converters

This figure 7 shows the relationship between losses due to switching frequency and semiconductor technology choice as the frequency changes. The data shows that silicon devices have an extremely rapid rise in loss with increasing frequency, making them unsuitable for high-frequency applications. In addition, SiC and GaN devices experience only a small increase in loss as the frequency increases allowing them to be used effectively at the high frequency of operation that compact converters will need.

4.1.2 Addressing EV-Specific Constraints

Operating conditions of EV power systems can require voltage range changes up to 800 V for both the 400 V and 800 V platforms, hence requiring converters that will continue to maintain soft-switching performances at various load points; however, the high (dv/dt) generated by WBG devices will create EMI effects and parasitic issues, necessitating careful consideration in Layouts, Gate Drive Designs, and Snubber Designs. To continuously achieve power density target in excess of 3 - 5 kW/L throughout all weekly configurations, high frequency operation, advanced magnetic materials and efficient thermal management systems must be developed within the automotive constraints of reliability.

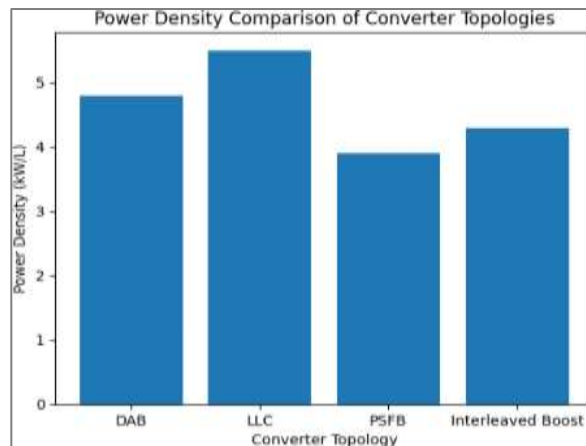


Figure 8. Power Density Comparison of Wide-Bandgap–Based High-Frequency DC–DC Converter Topologies for Electric Vehicle Applications

The figure 8 illustrates the potential or possible output power densities for the various typical converter topologies (DAB, LLC, PSFB, interleaved boost). The data indicate that resonant and high-frequency topologies are more compact than non-resonant or lower-frequency topologies, when utilizing WBG components. Based on this data, the topology selected for use in a converter impacts the ability to meet stringent packaging and volumetric power density requirements with regards to electric vehicles.

4.1.3 Emerging Architectures

Researchers have been working on hybrid SiC and GaN solutions; the most typical hybrid solutions examined have been multilevel and isolated converters with multi-ported systems and added storage components. The goal for these different types of hybrid systems is to increase scalability, efficiency and compatibility with upcoming architectural changes to electric vehicle energy systems.

Table 1. Summary of Current Wide-Bandgap–Based High-Frequency DC–DC Converter Topologies, Key Advantages, and Emerging Challenges for Electric Vehicle Applications

Converter Topology	WBG Device Used	Key Advantages	Performance Highlights	Emerging Challenges
Dual Active Bridge (DAB)	SiC/GaN	Bidirectional operation, inherent isolation, suitable for V2G	High efficiency (>97%), scalable for 400V/800V platforms	Circulating current losses, control complexity, EMI under high dv/dt
LLC Resonant Converter	SiC/GaN	Soft switching (ZVS/ZCS), reduced switching losses	High power density, excellent efficiency near resonant point	Efficiency drop at light load, frequency control complexity
CLLC Resonant Converter	SiC	Wide voltage range compatibility, bidirectional capability	Improved regulation for 800V systems	Complex magnetic design, tuning sensitivity
Phase-Shifted Full Bridge (PSFB)	SiC	Robust at high power levels, reliable isolation	Good thermal performance, suitable for high current	Increased switching stress at high frequency

Interleaved Boost Converter	GaN	Reduced ripple, compact magnetics, high-frequency operation	Enhanced transient response, reduced inductor size	Current balancing, EMI management
Multilevel Isolated Converter	Hybrid (SiC+GaN)	Reduced voltage stress, improved efficiency	Suitable for high-voltage architectures	Increased component count, higher control complexity

The table 1 is a comparison of the benefits and drawbacks of several varieties of high-frequency power converters manufactured from either SiC or GaN for use in electric vehicles (EVs). The efficiencies gained from these devices will be characterized by their ability to operate bi-directionally, their higher efficiency levels, and a higher power density than traditional designs. Many of these devices have unique design challenges concerning electromagnetic interference (EMI) such as complexity in controlling the device and limits imposed on heat dissipation leading to the actual utilization of the device.

4.2 Advanced Semiconductor Materials in EV Converters

4.2.1 Efficiency and Power Density Enhancement

Compared to silicon-based technologies, silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs) provide improved high voltage operation along with lower reverse recovery losses. In contrast, gallium nitride (GaN) high electron mobility transistors (HEMTs) offer ultra-fast switching times with extremely low gate charge. Improvements in efficiency of 1 to 2 percent above silicon-based devices will lower the cooling requirements and size of passive components, resulting in a better power density.

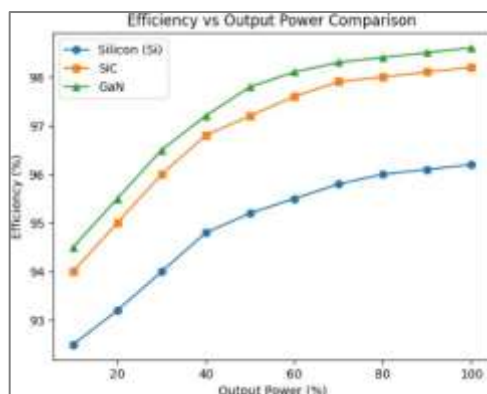


Figure 9. Efficiency Versus Output Power Comparison of Silicon, SiC, And GaN Devices in High-Frequency DC–DC Converters for Electric Vehicle Applications

Figure 9 illustrates silicon, SiC and GaN device performance under various loading conditions. The data indicates that GaN based power devices are more efficient than SiC or Silicon based devices whether operated under partial or full load conditions with particular efficiency benefits at higher switching frequencies. In addition, there is a strong correlation for the use of WBG Technology to improve power density and reduce thermal losses within Electrical Vehicle Converter system applications.

4.2.2 Thermal and Miniaturization Trends

Silicon Carbide (SiC) can operate at higher junction temperatures than comparable semiconductor technologies, allowing for higher efficiency and reduced size in thermal management aspects of the design. Gallium Nitride (GaN) enhances frequency scaling; however, strategies must be implemented to ensure that proper thermal dissipation occurs for optimal performance and reliability of GaN devices. The current trend is towards growing demand for compact and higher density EV converters as can be seen with the continuing use of planar magnetics, Direct Bonded Copper (DBC) substrates, and Integrated Power Modules.

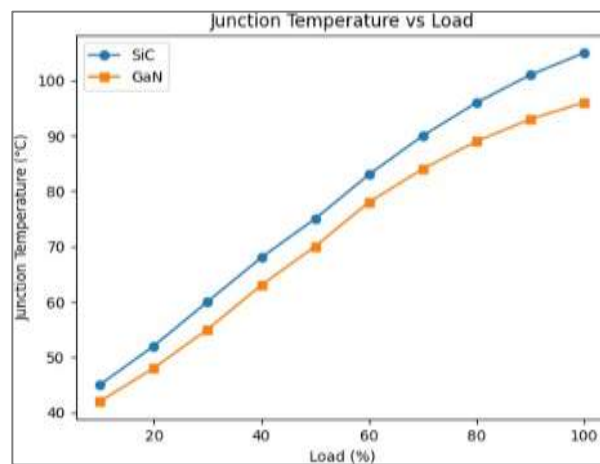


Figure 10. Junction Temperature Versus Load Comparison of Sic and Gan Devices in High-Frequency DC–DC Converters for Electric Vehicle Applications

The figure 10 thermal performance of both SiC and GaN devices as loads are added in an HF type of application is demonstrated using this chart. WBG devices show a consistent temperature rise regardless of the amount of load on the device; however, with the same amount of load applied to the respective devices, the junction temperature of GaN devices will be lower than the junction temperature of SiC devices. As a result, this evaluation supports the thermal performance and application applicability for WBG devices in high density EV converter systems.

4.2.3 Reliability and Qualification

Automotive-grade converters must meet extreme reliability requirements for thermal cycling and mechanical stress. WBG devices exhibit fantastic performance advantages, but reliable long-term performance and the balance between cost/performance is still a subject of active research.

Table 2. Summary of Wide-Bandgap Semiconductor Materials for High-Frequency DC– DC Converters in EV Applications

Material	Typical Voltage Range	Key Advantages	Main Challenges	EV Applications
Silicon (Si)	200–1200 V	Mature, low cost	Higher switching losses	Conventional DC– DC stages



SiC MOSFET	650–1700 V	High efficiency, high-temperature capability, suitable for 800 V systems	Higher cost, gate-drive complexity	High-voltage isolated DC-DC, traction interface
GaN HEMT	100–650 V	Ultra-fast switching, high power density	Thermal sensitivity, lower voltage rating	High-frequency OBC, auxiliary converters
Hybrid SiC–GaN	400–1200 V	Optimized performance across stages	Integration complexity	Multi-stage EV converter systems

This table 2 is to compare various types of semiconductor material and technology for EV concepts, including Voltagability, benefits/capabilities, and practical limitations for EV converter designs utilizing silicon, SiC, and GaN materials. The table depicts the fact that WBG type materials allow for greater switching frequencies as well as higher efficiencies and power densities compared with standard Si devices. This comparison allows one to evaluate the most suitable material relative to each EV subsystem type, from high voltage traction interfaces to compact on board charger stages.

4.3 Implementation and Control Strategies

4.3.1 Modelling Challenges

When modelling any type of high-frequency converter, in addition to switch dynamics, parasitic inductance and non-linear capacitance must be accounted for. Average models may not be able to predict the EMI performances of converters or the transients they produce.

4.3.2 Advanced Control Techniques

Precise phase-shifting and frequency modulation approaches can be achieved using DSP or FPGA based digital control platforms. Adaptive dead-time optimisation coupled with small-signal analysis is necessary for maintaining soft switching and stability within the dynamic conditions of electric vehicle operation.

4.3.3 Adaptive and Intelligent Control

Adaptive algorithms and AI-driven optimization models are increasingly used in developing emerging designs for real-time improvements to efficiency and predictive maintenance of EVs' power conversion systems.

Table 3. Summary of Control Challenges, Advanced Control Techniques, and Future Research Directions for Wide-Bandgap–Based High-Frequency DC–DC Converters in Electric Vehicle Applications

Control Challenge	Advanced Techniques	Key Objective	Future Perspectives
Maintaining soft-switching over wide voltage range	Phase-shift modulation (DAB), frequency modulation (LLC/CLLC)	Preserve ZVS/ZCS and reduce switching losses	Adaptive modulation for 400 V/800 V platforms
Stability under dynamic load variations	Small-signal modeling, digital PID/PI control, state-space control	Improve transient response and voltage regulation	Model predictive control (MPC) integration



High dv/dt induced EMI and parasitic oscillations	Dead-time optimization, active gate control, snubber tuning	Minimize switching stress and EMI	AI-assisted EMI suppression techniques
Parameter drift due to temperature and aging	Real-time monitoring and adaptive control	Maintain efficiency and reliability	Self-tuning and predictive maintenance algorithms
Bidirectional power flow control (V2G)	Dual-loop current- voltage control, phase- shift regulation	Ensure stable bidirectional energy transfer	Grid-interactive intelligent control frameworks

Table 3 lists key control-related challenges associated with high-frequency WBG-based converters for EVs (stability, maintenance of soft switching, mitigation of EMI), summarizes advanced modulation methods and digital control strategies that are used to address these challenges, and provides information about emerging trends such as adaptive, model predictive and AI-supported control approaches for the next generation of EV power systems.

4.4 Applications in EV Systems

4.4.1 On-Board Charger Technology

Transformer volume is reduced and charger efficiency is improved by using high-frequency DC-DC stages with WBG technology in on-board chargers (OBCs).

4.4.2 Battery Interface Technologies

Bidirectional converters also use DAB-based designs and provide controlled energy transfer from V2G and auxiliary systems for improved isolation and efficiency.

4.4.3 Unit Energy Architecture

Modular, scalable converter designs with integrated control and increased reliability will continue the move towards 800V platforms and ultra-fast charging in electric vehicle (EV) systems will be heavily dependent on WBG-based high frequency DC-DC converters for future EV development.

Table 4. Summary of Challenges, Applications, and Future Research Directions for Wide-Bandgap-Based High-Frequency DC-DC Converters in Electric Vehicle Power Systems

Application Area	Key Challenges	Performance Requirements	Future Research Directions
On-Board Charger (OBC)	Wide input voltage range, EMI compliance, compact design	>97% efficiency, high power density, galvanic isolation	Integrated PFC + DC-DC modules, planar magnetics, AI-based optimization
Bidirectional Battery Interface (DAB)	Circulating current losses, soft-switching under variable load	Stable bidirectional control, low switching loss	Advanced modulation strategies, adaptive phase-shift control
800 V EV Platforms	High voltage stress, insulation coordination	High reliability, reduced switching stress	Multilevel and hybrid SiC-GaN architectures

Fast Charging Systems	Thermal management, high current operation	High efficiency at high power (>20 kW), robust cooling	Modular scalable converter designs, advanced packaging
Auxiliary DC–DC Converters	Size constraints, light-load efficiency	Compact design, low ripple, fast transient response	High-frequency GaN- based designs, digital control integration

This table 4 gives a summary of the principal application domains that use high-frequency wide bandgap-based DC-DC converters working within an electric vehicle [EV] platform and the key technical constraints associated with each application domain. Most importantly, the table contains performance targets for each application domain such as high efficiency, compactness, and reliable bidirectional operation at wide voltage conditions. The table also contains potential future research areas regarding new modular architectures, advanced control strategies, and improved thermal-electrical integration for next generation EV systems.

5. Conclusion

The purpose of this study was to examine the application of wide-bandgap (WBG) semiconductor devices, i.e., SiC and GaN, in electric vehicle high-frequency DC-DC converters. The analysis of WBG technology's impact on efficiency and power density demonstrated that the use of WBG technologies allows for significantly higher switching frequencies than traditional silicon devices while having lower switching losses, resulting in increased efficiency and large gains in power density when utilized in conjunction with appropriate topologies, such as Dual Active Bridge and LLC resonant converters. The overall result is a compact, thermo-stable design that can operate over a wide range of voltages typically seen in modern electric vehicle platforms (i.e., 400 V and 800 V). In addition, all of the findings show that optimal performance of such devices will require coordinated electrical, thermal, and control designs rather than simply replacing one device with another. High dv/dt operation will necessitate the management of EMI and precise digital control to preserve soft-switching and reliability under dynamic loading. However, the continued development of WBG-based high-frequency converters represents a key technology pathway to more efficient, compact, and scalable power systems for electric vehicles, despite the challenges of cost and lifetime qualifications.

References

1. Abdullah, D. (2025). Comparative Analysis of SiC and GaN-Based Power Converters in Renewable Energy Systems. *National Journal of Electrical Machines & Power Conversion*, 11–20.
2. Adeloye, I. A., Bhattacharya, I., Ezugwu, E. O., & Antony Dhasan, M. V. (2025). GaN Electric Vehicle Systems—A Comparative Review. *Energies*, 18(22), 6020. <https://doi.org/10.3390/en18226020>.
3. Akbar, G., Di Fatta, A., Rizzo, G., Ala, G., Romano, P., & Imburgia, A. (2025). Comprehensive Review of Wide-Bandgap (WBG) Devices: SiC MOSFET and Its Failure Modes Affecting Reliability. *Physchem*, 5(1), 10. <https://doi.org/10.3390/physchem5010010>.

4. Alatise, O., Deb, A., Bashar, E., Ortiz Gonzalez, J., Jahdi, S., & Issa, W. (2023). A review of power electronic devices for heavy goods vehicles electrification: Performance and reliability. *Energies*, 16(11), 4380.
5. Ali, K. (2020). A bidirectional GaN-based CLLC converter for plug-in electric vehicles on-board chargers. *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*. https://www.academia.edu/download/114118876/EV_charger_paper_dtu_orbit.pdf.
6. Arévalo, P., Ochoa-Correa, D., & Villa-Ávila, E. (2024). Towards energy efficiency: Innovations in high-frequency converters for renewable energy systems and electric vehicles. *Vehicles*, 7(1), 1.
7. Elezab, A., Zayed, O., Abuelnaga, A., & Narimani, M. (2023). High Efficiency LLC Resonant Converter with Wide Output Range of 200–1000 V for DC-Connected EVs Ultra-Fast Charging Stations. *IEEE Access*, 11, 33037–33048. <https://doi.org/10.1109/ACCESS.2023.3263486>.
8. Eroğlu, F., Kurtoğlu, M., & Vural, A. M. (2021). Bidirectional DC–DC converter based multilevel battery storage systems for electric vehicle and large - scale grid applications: A critical review considering different topologies, state - of - charge balancing and future trends. *IET Renewable Power Generation*, 15(5), 915 - 938. <https://doi.org/10.1049/rpg2.12042>.
9. Galioto, G., Vitale, G., Sferlazza, A., Lullo, G., & Giaconia, G. C. (2026). Wide and Ultrawide Bandgap Power Semiconductors: A Comprehensive System-Level Review (No. 2026012280). Preprints. <https://doi.org/10.20944/preprints202601.2280.v2>.
10. Iannaccone, G., Sbrana, C., Morelli, I., & Strangio, S. (2021). Power electronics based on wide-bandgap semiconductors: Opportunities and challenges. *IEEE Access*, 9, 139446–139456.
11. Jia, M., Sun, H., Cai, J., Zhang, H., Zhou, Z., & Chen, J. (2024). GaN and SiC Based 500kHz Resonant Bidirectional DC/DC Design for 800V OBCM Application. *2024 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2425–2432. <https://doi.org/10.1109/APEC48139.2024.10509331>.
12. Joseph, S. (2024). Review and Comparison of Isolated DC-DC Converters for Electric Vehicle Applications. 11(11).
13. Kasim, R. K., & Robert, F. (2025). Performance Enhancement of an Integrated SiC JFET and GaN HEMT 5-kW T-Type Inverter for Vehicle-to-Grid and Grid-to-Vehicle Technology. *IEEJ Journal of Industry Applications*, 14(1), 56–62. <https://doi.org/10.1541/ieejia.24004484>.
14. Keerthi, A., & Dhanamjayulu, C. (2025). A thorough review of energy management and an advanced control techniques for Bi-directional DC-DC converters in electric vehicle applications. *Results in Engineering*, 27, 106726. <https://doi.org/10.1016/j.rineng.2025.106726>.

15. Martinez-Vera, E., & Banuelos-Sanchez, P. (2024). Review of Bidirectional DC-DC Converters and Trends in Control Techniques for Applications in Electric Vehicles. *IEEE Latin America Transactions*, 22(2), 144–155. <https://doi.org/10.1109/TLA.2024.10412031>.
16. Mortazavizadeh, S. A., Palazzo, S., Amendola, A., De Santis, E., Di Ruzza, D., Panariello, G., Sanseverino, A., Velardi, F., & Busatto, G. (2021). High frequency, high efficiency, and high power density GaN-based LLC resonant converter: State-of-the-art and perspectives. *Applied Sciences*, 11(23), 11350.
17. Parvez, M., Pereira, A. T., Ertugrul, N., Weste, N. H. E., Abbott, D., & Al-Sarawi, S. F. (2021). Wide Bandgap DC–DC Converter Topologies for Power Applications. *Proceedings of the IEEE*, 109(7), 1253–1275. <https://doi.org/10.1109/JPROC.2021.3072170>.
18. Patel, N., Lopes, L. A., & Rathore, A. K. (2023). A Comprehensive Overview of Wide Band-Gap (WBG)-Based DC-DC Converters for Fast Plug-in EV Charging. *Advanced Concepts and Technologies for Electric Vehicles*, 91–110.
19. Ponnambalam, R., & Vairavasundaram, I. (2025). GaN-Based DC-DC converters for EV fast charging: A review of wide bandgap devices technology. *Results in Engineering*, 28, 107548. <https://doi.org/10.1016/j.rineng.2025.107548>.
20. Rodríguez-Benítez, O. M., Ponce-Silva, M., Aquí-Tapia, J. A., Claudio-Sánchez, A., Vela-Váldez, L. G., Lozoya-Ponce, R. E., & Cortés-García, C. (2020). Comparative performance and assessment study of a current-fed DC-DC resonant converter combining Si, SiC, and GaN-based power semiconductor devices. *Electronics*, 9(11), 1982.
21. Sakhare, A., & Mikkili, S. (2025). Advanced DC–DC Converter Topologies for Electric Vehicles: Wide Bandgap Technologies, Emerging Trends and Future Challenges. *Electrical Materials and Applications*, 2(1), e70023. <https://doi.org/10.1049/ema3.70023>.
22. Shabbir, A., & Khan, Z. (2024). Design and Optimization of High-Frequency Power Converters for Enhanced Efficiency and Performance in Electric Vehicle Applications. *Pak Advances in Engineering Research*, 1(01), 22–33.
23. Soomro, H. A., Khir, M. H. B. M., Zulkifli, S. A. B. M., Abro, G. E. M., & Abualnaeem, M. M. (2025). Applications of wide bandgap semiconductors in electric traction drives: Current trends and future perspectives. *Results in Engineering*, 26, 104679. <https://doi.org/10.1016/j.rineng.2025.104679>.
24. Su, G.-J. (2018). Comparison of Si, SiC, and GaN based Isolation Converters for Onboard Charger Applications. 2018 IEEE Energy Conversion Congress and Exposition (ECCE), 1233–1239. <https://doi.org/10.1109/ECCE.2018.8558063>.
25. Sudano, C. (2024). Design and characterization of a modular GaN-based power stage for automotive applications [PhD Thesis, Politecnico di Torino]. <https://webthesis.biblio.polito.it/34017/>.
26. Suthar, A. N., Venkataramanaiah, J., & Suresh, Y. (2025). Conventional, wide-bandgap, and hybrid power converters: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 213(C). <https://ideas.repec.org/a/eee/rensus/v213y2025ics1364032125000929.html>
Van Do, T., Trovão, J. P.



27. F., Li, K., & Boulon, L. (2021). Wide-Bandgap Power Semiconductors for Electric Vehicle Systems: Challenges and Trends. *IEEE Vehicular Technology Magazine*, 16(4), 89–98. <https://doi.org/10.1109/MVT.2021.3112943>.
28. Wan, Y. (2024). Wide bandgap (WBG) semiconductors in power electronics: The future of electric vehicles. <https://lutpub.lut.fi/handle/10024/167301>.
29. Zheng, L., Zhu, Y., Ren, J., Chang, C., & Ye, J. (2024). High-voltage DC–DC converter based on adaptive frequency conversion modulation. *Journal of Power Electronics*, 24(3), 339–348. <https://doi.org/10.1007/s43236-023-00714-z>.
30. Zhou, X., Sheng, B., Liu, W., Chen, Y., Wang, L., Liu, Y.-F., & Sen, P. C. (2021). A high-efficiency high-power-density on-board low-voltage DC–DC converter for electric vehicles application. *IEEE Transactions on Power Electronics*, 36(11), 12781–12794.