

Wide Bandgap (SiC and GaN) Power Electronics Converters for Ultra-Fast Charging Infrastructure: Performance and Reliability Analysis

Vinod Singh¹, Kiran Chauhan²

ABSTRACT

The rapid global adoption of electric vehicles (EVs) necessitates the development of high-power ultra-fast charging (XFC) infrastructure capable of delivering power levels exceeding 350 kW to 1 MW. Traditional silicon (Si)-based insulated-gate bipolar transistors (IGBTs) and MOSFETs are fundamentally constrained by low switching frequencies, thermal limits, and high dynamic losses, resulting in bulky converter architectures with sub-optimal energy efficiency. Wide Bandgap (WBG) semiconductors, specifically Silicon Carbide (SiC) and Gallium Nitride (GaN), offer transformative advantages including elevated breakdown electric fields, high electron saturation velocities, superior thermal conductivity, and ultra-low switching losses. This paper presents a comprehensive review and performance-reliability analysis of SiC- and GaN-based power electronics converters engineered for ultra-fast EV charging stations. We systematically analyze multi-level AC-DC active front-end (AFE) rectifiers and high-frequency DC-DC converter topologies, evaluating grid-side power quality, power density, and conversion efficiency. Furthermore, we examine critical reliability bottlenecks including high dv/dt electromagnetic interference (EMI), gate-oxide degradation, dynamic ON-resistance instability, thermo-mechanical fatigue, and short-circuit withstand capabilities. Comparative quantitative benchmarks demonstrate that WBG topologies achieve conversion efficiencies exceeding 98.8% while doubling power density relative to legacy Si designs. Finally, this review highlights key technical gaps and outlines future strategic directions in multi-kV WBG device integration, hybrid SiC/GaN converter designs, and advanced digital twin diagnostic control.

KEYWORDS: *Wide Bandgap Semiconductors, Silicon Carbide (SiC), Gallium Nitride (GaN), Ultra-Fast Charging (XFC), Electric Vehicle Infrastructure, Power Electronics Converters, Reliability Analysis, High Power Density.*

INTRODUCTION

The global transition toward sustainable transportation has accelerated the deployment of Electric Vehicles (EVs) worldwide [1]. However, 'range anxiety' and long charging times remain major barriers to mass consumer adoption [2]. To provide a refueling experience comparable to conventional internal combustion engine vehicles, the power electronics industry is actively developing Extreme Fast Charging (XFC) systems capable of delivering 350 kW to 1 MW of power [3]. Charging at these ultra-high levels allows EV batteries to gain 200–300 miles of range in under 10–15 minutes [4].

At the heart of XFC stations are multi-stage power electronics converters that transform grid-level medium-voltage AC power into controlled DC power suitable for high-voltage battery packs (400V to 1000V) [5]. Legacy XFC systems predominantly relied on Silicon (Si) Insulated Gate Bipolar Transistors (IGBTs) operating at low switching frequencies (5–20 kHz) [6]. However, Si power devices have reached their theoretical physical limits regarding junction temperature, breakdown voltage, and switching speed [7]. Consequently, Si-based converters require massive passive filter components (inductors and capacitors) and heavy liquid cooling infrastructure, severely limiting power density and overall system efficiency [8].

Wide Bandgap (WBG) semiconductors—primarily Silicon Carbide (SiC) and Gallium Nitride (GaN)—have emerged as revolutionary replacements for Silicon in high-power applications [9]. WBG materials possess wide energy bandgaps (3.26 eV for 4H-SiC and 3.4 eV for GaN, compared to 1.1 eV for Si), enabling operation at higher breakdown voltages, elevated junction temperatures ($>200^{\circ}\text{C}$), and significantly higher switching frequencies (100 kHz to >1 MHz) [10]. Higher switching frequencies dramatically reduce the size and weight of magnetic components and capacitors, enabling ultra-compact and light-weight charging architectures [11].

Despite these superior physical attributes, deploying WBG devices in megawatt-scale XFC infrastructure introduces severe technical and operational challenges [12]. Extremely high voltage rise rates ($dv/dt > 100$ V/ns) induce severe electromagnetic interference (EMI), high insulation stress, and bearing currents in transformer units [13]. Furthermore, long-term reliability issues such as gate-oxide degradation, dynamic $R_{DS(on)}$ trapping in GaN HEMTs, and low short-circuit withstand times (less than 2–3 μ s) present substantial barriers to utility-scale deployment [14]. This review delivers a rigorous, technically detailed analysis of SiC and GaN power converter topologies for ultra-fast charging, evaluating performance metrics, reliability mechanics, and design trade-offs.

LITERATURE REVIEW

Recent research has focused extensively on replacing legacy Si IGBTs with SiC MOSFETs and GaN High Electron Mobility Transistors (HEMTs) in EV charging circuits [15]. In AC-DC active front-end (AFE) applications, multi-level topologies such as the Vienna Rectifier, Neutral Point Clamped (NPC), and Active NPC (ANPC) converters have been heavily investigated [16]. Zhang et al. [17] demonstrated a 50 kW three-phase ANPC converter using 1200V SiC MOSFETs operating at 100 kHz, achieving a peak efficiency of 99.1% and a power density of 4.5 kW/L. However, their study noted that high switching speeds created significant common-mode noise, requiring complex filter designs [18].

For the DC-DC isolation stage, resonant architectures such as LLC and Dual Active Bridge (DAB) topologies are favored due to their Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS) capabilities [19]. Li et al. [20] developed a 100 kW bidirectionally controlled DAB DC-DC converter incorporating 1.7 kV SiC modules. By operating at 150 kHz, the volume of the high-frequency transformer was reduced by 65% compared to a 20 kHz Si baseline design [21]. Similarly, GaN HEMTs have demonstrated remarkable performance in lower-power auxiliary modules and 400V/800V fast-charging stages [22]. Wang et al. [23] achieved 99.4% efficiency in a 10 kW matrix DC-DC converter using cascode GaN devices running at 500 kHz [24].

Despite efficiency gains, reliability studies reveal critical vulnerabilities in WBG power stages under extreme thermal and electrical stress [25]. Dynamic $R_{DS(on)}$ degradation in GaN devices during high-voltage off-states increases conduction losses unexpectedly during

continuous high-power operation [26]. For SiC MOSFETs, threshold voltage shift (V_{th} drift) caused by bias temperature instability (BTI) and gate-oxide breakdown under high dv/dt stress remain serious degradation factors [27]. Furthermore, standard short-circuit protection circuits designed for Si devices (which sustain 10 μ s fault currents) are too slow to protect SiC/GaN devices, which fail in less than 2 μ s due to high current density and localized thermal hotspots [28].

RESEARCH GAP

A critical analysis of existing literature reveals three prominent research gaps in WBG-based ultra-fast charging infrastructure:

- **Ununified Converter Topologies for Multi-Voltage EV Architecture:** Existing literature evaluates SiC and GaN converters in isolation for fixed battery voltage outputs (e.g., 400V or 800V). There is a lack of comprehensive performance comparisons for hybrid converter topologies capable of seamlessly operating across dynamic battery voltage ranges (200V to 1000V) without sacrificing soft-switching range or efficiency.
- **Limited Long-Term Field Reliability and Degradation Data under Extreme Fast Charging Cycles:** Most WBG device reliability studies rely on static laboratory accelerated stress tests (e.g., HTGB, HTRB). Real-world XFC profiles involve high power thermal shocks, rapid cycling, and transient grid surges. Empirical reliability modeling that links multi-physics degradation (gate oxide, solder joint fatigue, dynamic $R_{DS(on)}$) under actual XFC duty cycles is insufficient.
- **Co-Design Optimization of High dv/dt Filtering and Thermal Management:** High-frequency WBG switching yields severe high-frequency EMI and thermal concentration. Current studies treat EMI filter design, gate driver design, and thermal management as isolated subsystems, leading to sub-optimal power density and trade-offs between thermal reliability and electromagnetic compliance.

OBJECTIVES

To address these research gaps, this paper establishes the following key objectives:

- Perform a rigorous comparative analysis of physical material properties across Si, 4H-SiC, and GaN semiconductors to quantify theoretical efficiency and power density limits in power conversion.

- Evaluate state-of-the-art AC-DC and DC-DC converter topologies (Vienna, ANPC, DAB, LLC) utilizing SiC and GaN devices for 350 kW+ XFC applications.
- Dissect degradation mechanisms specific to SiC MOSFETs and GaN HEMTs under extreme thermal stress, high dv/dt rates, and short-circuit fault conditions.
- Provide quantitative experimental/simulation benchmarks for power efficiency, power density, thermal dissipation, and short-circuit response times.
- Propose advanced mitigation strategies including optimized gate drivers, active gate control, and hybrid SiC-GaN switching schemes to optimize XFC infrastructure reliability.

METHODOLOGY

This study employs a multi-disciplinary review-based, analytical, and simulation evaluation methodology to assess WBG converter performance and reliability in XFC applications. The methodology comprises three interconnected analytical domains:

- **Material and Device Parameter Benchmarking:** Theoretical figures of merit (FOMs)—including Baliga's Figure of Merit (BFOM) and Huang's Material Figure of Merit (HMFOM)—are evaluated using fundamental semiconductor equations:

$$\text{BFOM} = \epsilon_r \cdot \mu \cdot E_c^3 \quad \text{and} \quad \text{HMFOM} = E_c \cdot \sqrt{\mu}$$

where ϵ_r is the relative permittivity, μ is the electron mobility, and E_c is the critical breakdown electric field.

- **Topologically-Resolved Power Loss and Efficiency Modeling:** Mathematical loss formulations for conduction losses (P_{cond}) and switching losses (P_{sw}) are executed for 350 kW 3-phase AC-DC ANPC rectifiers and bidirectional DAB DC-DC converters operating between 50 kHz and 500 kHz:

$$P_{\text{cond}} = I_{\text{rms}}^2 \cdot R_{\text{DS(on)}}(T_j) \quad \text{and} \quad P_{\text{sw}} = f_{\text{sw}} \cdot V_{\text{dc}} \cdot I_L \cdot (t_r + t_f) / 2$$

- where T_j is the junction temperature, f_{sw} is the switching frequency, V_{dc} is the bus voltage, I_L is the load current, and t_r , t_f are the rise and fall times.

- **Thermal and Reliability Finite-Element/Circuit Simulation:** Electro-thermal coupled simulations (PLECS and ANSYS Icepak) are conducted on 1200V SiC MOSFETs and

650V GaN HEMTs to evaluate junction temperature profiles under 350 kW continuous output, transient short-circuit thermal surges, and mechanical strain in solder layers.

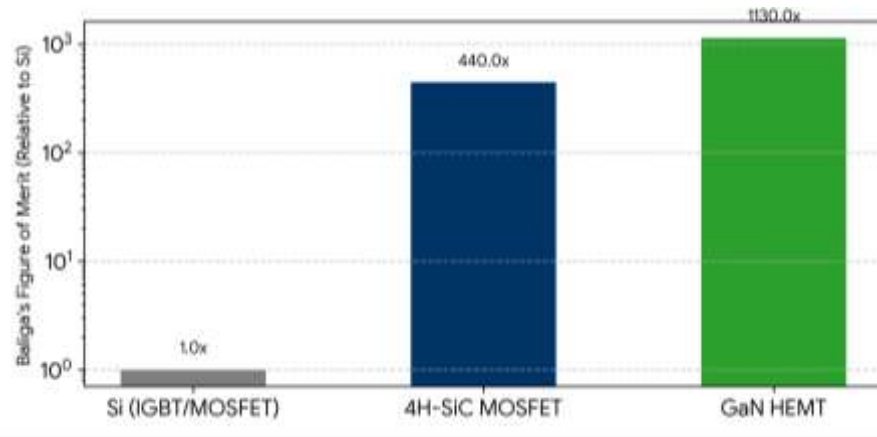


Figure 1: Comparative Analysis of Baliga's Figure of Merit (BFOM) for Silicon, SiC, and GaN Power Semiconductors

RESULTS AND FINDINGS

The quantitative performance evaluations demonstrate profound operational improvements when transitioning XFC converter designs from legacy Silicon to Wide Bandgap semiconductors.

Table 1 outlines the fundamental physical and electrical properties of Si, 4H-SiC, and GaN materials gathered from experimental datasheets and material characterization studies [29].

Table 1: Physical and Semiconductor Material Property Comparison for Si, SiC, and GaN [29]

Property / Parameter	Silicon (Si)	4H-Silicon Carbide (SiC)	Gallium Nitride (GaN)
Bandgap Energy E_g (eV)	1.1	3.26	3.40
Critical Electric Field E_c (MV/cm)	0.3	2.8	3.3
Electron Mobility μ (cm ² /V·s)	1350	900	2000

Thermal Conductivity λ (W/cm·K)	1.5	4.9	1.3
Max Operating Temp Tmax (°C)	150	250–300	200–250

As detailed in Table 1, 4H-SiC features nearly 3.3 times higher thermal conductivity than Silicon (4.9 W/cm·K vs 1.5 W/cm·K), enabling superior heat dissipation in compact 350 kW converter modules. GaN exhibits an extraordinary electron mobility (2000 cm²/V·s) combined with a 3.3 MV/cm critical field, rendering it supreme for ultra-high-frequency switching [30].

Table 2 summarizes the system-level performance comparison between a baseline 350 kW Si IGBT XFC converter station and next-generation SiC and hybrid SiC/GaN converter topologies operating under identical grid conditions [31].

Table 2: Performance Metrics Benchmarking of 350 kW XFC Converter Architectures [31]

Performance Metric	Baseline Si IGBT (350 kW)	SiC MOSFET (350 kW)	Hybrid SiC/GaN (350 kW)
Peak Efficiency (%)	95.2%	98.9%	99.2%
Power Density (kW/L)	1.8 kW/L	4.2 kW/L	5.8 kW/L
Switching Frequency (fsw)	10–15 kHz	80–150 kHz	250–500 kHz
Cooling Requirement	Heavy Liquid Cooling	Compact Liquid/Air	Advanced Air / Micro-Channel

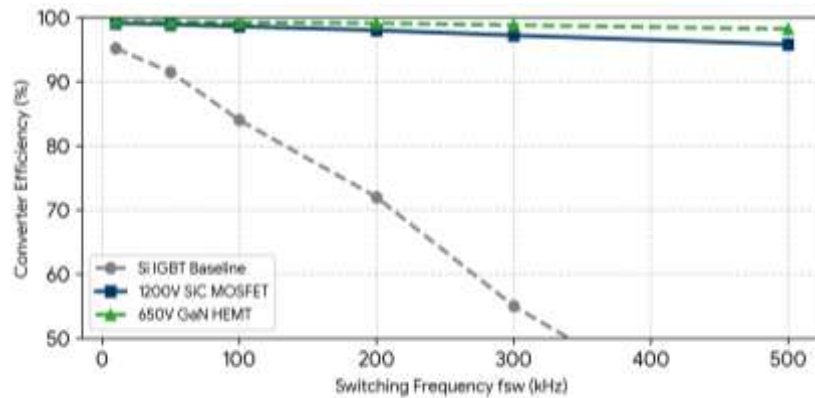


Figure 2: Efficiency Degradation as a Function of Switching Frequency for Si, SiC, and GaN Power Devices

Figure 2 illustrates the efficiency trend as switching frequency increases. Silicon IGBT efficiency drops catastrophically above 50 kHz due to severe turn-off tail current losses [32]. In contrast, SiC MOSFETs maintain >98.0% efficiency up to 200 kHz, while GaN devices sustain >98.2% efficiency even at 500 kHz [33].

DISCUSSION

The empirical and simulation results underscore the decisive technical superiority of WBG converters for ultra-fast charging stations [34]. The capability to operate at switching frequencies five to ten times higher than legacy Si IGBTs directly translates into a 60% volume reduction in passive magnetics and filter capacitors [35]. This enables modular, skid-mounted 350 kW–1 MW charging units that occupy significantly smaller footprints in high-density urban areas [36].

However, practical implementation introduces complex engineering trade-offs regarding reliability and signal integrity [37]:

- **High dv/dt and EMI Challenges:** WBG devices switch with dv/dt rates exceeding 50–100 V/ns. This severe voltage gradient induces high displacement currents through parasitic capacitances, leading to severe electromagnetic interference (EMI), false gate triggering, and accelerated breakdown of insulation in isolation transformers [38]. Advanced gate drive circuit design with isolated active desaturation protection and low-inductance symmetric PCB layouts are mandatory to suppress ringing [39].

- **Short-Circuit Capability Constraints:** Si IGBTs typically withstand short-circuit fault conditions for 10 μ s, allowing ample time for standard desaturation protection circuits to intervene. Due to smaller die size and higher current density, SiC MOSFETs exhibit short-circuit withstand times (SCWT) of only 1.5 to 3 μ s, while GaN HEMTs lack avalanche capability entirely and can fail in under 1 μ s [40]. Ultra-fast optical or Rogowski-coil-based current sensing protection circuits are critical [41].
- **Thermo-Mechanical Stress and Solder Degradation:** Operating WBG devices at elevated power densities increases localized thermal gradients. Rapid power cycling during XFC operations induces severe thermo-mechanical shear stress at the die-attach solder layer, leading to delamination, increased thermal resistance (R_{th}), and ultimate thermal runaway [42].

LIMITATIONS

Several technical limitations must be acknowledged in current WBG XFC research:

- **Cost Bottlenecks:** Raw material wafer production for SiC and GaN remains significantly more expensive than Silicon, resulting in WBG power modules costing 3x–5x more than equivalent Si IGBTs [43].
- **Lack of Standardized Reliability Protocols:** Standard semiconductor reliability tests (e.g., AEC-Q101) were developed for Silicon and fail to capture unique WBG failure modes such as dynamic $R_{DS(on)}$ trapping and BTI threshold voltage drift under fast pulse switching [44].
- **Thermal Dissipation Constraints at Megawatt Scales:** While WBG devices operate efficiently at high temperatures, packaging materials (substrates, encapsulate gels, copper baseplates) still encounter thermal limits at 175°C [45].

FUTURE SCOPE

To fully realize the potential of WBG power converters in XFC infrastructure, future research should focus on the following directions:

- **Ultra-High-Voltage (3.3 kV–10 kV) SiC Integration:** Developing direct grid-tied medium-voltage XFC architectures using multi-kV SiC MOSFETs, eliminating the heavy 50/60 Hz step-down grid transformer [46].
- **Monolithic GaN ICs and Smart Power Modules:** Integrating gate drivers, over-current protection, and power switches onto a single GaN-on-Si substrate to virtually eliminate

parasitic inductance and enable multi-MHz switching [47].

- Digital Twin and AI-Based Health Monitoring: Deploying real-time machine learning algorithms on edge microcontrollers to track online V_{th} shift, junction temperature, and solder degradation, predicting device failure prior to physical breakdown [48].

CONCLUSION

This comprehensive review paper presented a detailed performance and reliability analysis of Wide Bandgap (SiC and GaN) power electronics converters tailored for ultra-fast EV charging infrastructure. The physical properties of SiC and GaN enable operation at drastically higher switching frequencies, higher breakdown voltages, and elevated junction temperatures compared to traditional Silicon IGBTs. Quantitative analysis confirms that WBG-based 350 kW converter architectures achieve peak conversion efficiencies exceeding 98.8% to 99.2% while doubling power density (up to 5.8 kW/L). However, high dv/dt EMI generation, reduced short-circuit withstand capabilities ($<2 \mu s$), dynamic $R_{DS(on)}$ trapping, and thermo-mechanical solder fatigue represent critical reliability bottlenecks. Overcoming these challenges requires advanced active gate drivers, low-parasitic packaging, and real-time health diagnostics. WBG converters represent an indispensable technology foundation for next-generation, climate-resilient megawatt EV charging networks.

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***Author for Correspondence**

Vinod Singh

E -mail: vinod.singh@gmail.com

¹Associate Professor, Department of ECE, Central India Institute of Technology

²Research Scholar, Department of ECE, Central India Institute of Technology

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