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# Design and Optimization of Wide Bandgap Power Converters for High-Efficiency Electric Vehicle Charging Infrastructure

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***Abstract-*** ***The widespread adoption of electric vehicles (EVs) necessitates charging infrastructure capable of delivering high power with exceptional efficiency, minimal size, and reduced thermal management requirements. This study investigates the design, optimization, and performance evaluation of wide bandgap (WBG) semiconductor-based power converters utilizing silicon carbide (SiC) and gallium nitride (GaN) devices for EV charging applications. Traditional silicon-based converters face fundamental limitations in switching frequency, efficiency, and power density that constrain charging infrastructure development. Through comprehensive simulation modeling using PLECS and ANSYS tools, prototype development of a 50 kW bi-directional converter, and extensive experimental validation, this research demonstrates that WBG-based converters achieve peak efficiency of 98.7% compared to 95.2% for silicon counterparts, while reducing converter volume by 62% and thermal management requirements by 54%. The optimized SiC-based three-level topology operates at 100 kHz switching frequency five times higher than conventional designs enabling passive component miniaturization while maintaining electromagnetic compatibility within regulatory limits. Thermal analysis reveals junction temperature reductions of 43°C under full load conditions, extending device lifetime and improving reliability. The study develops a multi-objective optimization framework incorporating electrical performance, thermal characteristics, electromagnetic interference, cost, and reliability metrics, providing a quantitative basis for design decisions. Experimental results from a prototype deployed in a commercial charging station over six months demonstrate 97.8% average efficiency across varying load conditions and ambient temperatures, with 99.4% availability and zero thermal-related failures. The research contributes novel modulation strategies specifically adapted to WBG device characteristics, achieving 28% reduction in switching losses compared to conventional space vector modulation. Economic analysis indicates that despite 35% higher initial component costs, WBG converters achieve payback within 2.4 years through energy savings and reduced cooling infrastructure. This work advances the state-of-the-art in high-power converter design and provides practical guidance for deploying next-generation EV charging infrastructure supporting the global transition to electric mobility.***

***Index Terms-*** ***bi-directional converter, electric vehicle charging, electromagnetic compatibility, gallium nitride, high-efficiency power electronics, multi-objective optimization, power converters, silicon carbide, thermal management, Wide bandgap semiconductors***

## I. INTRODUCTION

EV sales exceeded 10 million units in 2022 (14% of global new car sales), with 60–70% projected by 2030 in major markets (IEA, 2021; Sanguesa et al., 2021). Charging speed is a top adoption concern (Hardman et al., 2018); DC fast charging (50–350 kW) is needed for highway/fleet use, requiring the global DCFC network to grow from ~500,000 stations (2022) to 15+ million by 2030 over $200B in infrastructure investment (Tu et al., 2019).

Efficiency matters at scale: a single 50 kW DCFC station converts ~438 MWh/year, so just 3% inefficiency wastes 13 MWh (5.8 tons CO2, $1,800) annually (Yilmaz & Krein, 2013) multiplied across millions of stations. Power density also matters directly for urban deployment cost and flexibility (Huang, 2013).

Silicon IGBTs, the historical workhorse, are now hitting fundamental limits: narrow bandgap (1.1 eV), low critical field (0.3 MV/cm), and moderate thermal conductivity cap switching frequency (<20 kHz), efficiency (~95–96%), and power density (Millan et al., 2014). Wide bandgap (WBG) semiconductors SiC (3.26 eV bandgap, 2.5 MV/cm critical field, 3.7 W/cm·K thermal conductivity) and GaN (3.39 eV, higher mobility but lower thermal conductivity/voltage rating, restricting it to lower-power domains) offer a step change (Jones et al., 2016; Lidow et al., 2014): switching frequencies of 50–150 kHz (vs. 10–20 kHz), 80–90% lower on-resistance, 70–80% lower switching losses, and higher junction temperature ratings (175–200°C vs. 125–150°C) (Hazra et al., 2017).

Realizing these gains requires solving new problems: EMI from fast switching (dV/dt >50 V/ns), WBG-specific gate driver design, altered thermal/loss distributions, and magnetic component redesign for higher frequencies. This research addresses the complete design workflow topology, components,

control, thermal, EMI, and experimental validation for WBG EV charging converters.

## II. SIGNIFICANCE OF THE STUDY

- Charging infrastructure operators: The 3.5-point efficiency gain (98.7% vs. 95.2%) saves ~9.1 MWh/year per 50kW charger (~$1,365, 4.1 tons CO2 avoided) at typical utilization. 62% volume reduction cuts urban real-estate costs; 99.4% availability with zero thermal failures over six months cuts downtime/maintenance costs.
- EV manufacturers: Enables higher-power on-board charging (50 kW in 12L vs. 32L for Si) without excess weight/volume, plus V2G/V2H capability via bi-directional design (Khaligh & D'Antonio, 2019).
- Component manufacturers: Application-specific data on optimal switching frequencies, thermal behavior, and economic ROI guides product development.
- Utilities: Higher efficiency reduces transmission/distribution losses and peak demand; bi-directional capability supports V2G grid services (frequency regulation, voltage support, renewable integration) (Habib et al., 2018).
- Policymakers: Findings can inform efficiency standards, building codes, and incentive design (IEA, 2020), and support climate policy via quantified emissions reductions.
- Academic contribution: Real-world (not just simulated) WBG validation; a genuine multi-objective (electrical/thermal/EMI/cost/reliability) design framework; WBG-tailored modulation strategies; thermal-electrical co-design methodology; and mission-profile-based reliability analysis.
- Climate impact: Transport is ~24% of global CO2 emissions (IEA, 2021); efficient charging infrastructure is necessary (not just electrification itself) to realize decarbonization benefits, and reduces the peaking-plant/fossil-backup burden on the grid while enabling higher renewable penetration via V2G storage.

## III. PROBLEM STATEMENT

Si converter limitations: Typical DCFC converters achieve only 94–96% peak efficiency (92–94% average across conditions) due to Si's inherent limits low switching frequency (10–20 kHz) forcing large passives, IGBT conduction losses (1.5–2.5V forward drop), and diode reverse-recovery losses (Yilmaz & Krein, 2013). Losses scale badly at higher power: a 350 kW charger at 94% efficiency dissipates 21 kW as heat.

Power density: Si-based 50 kW converters run 25–40 L / 15–25 kg due to large low-frequency passives and bulky heatsinks/cooling (Huang, 2013) a real barrier for urban, parking-structure, and mobile charging deployments.

Thermal management: Keeping junctions under 125–150°C while dissipating 2–4 kW of losses (in 40–50°C ambient) requires large, costly cooling systems that add failure modes and maintenance burden; large thermal cycling swings (60–80°C) accelerate solder/wire-bond fatigue over a required 15–20 year service life (Wrzecionko et al., 2017).

EMI: Even moderate Si switching frequencies require substantial filtering to meet CISPR 11/FCC Part 15 (Zhang et al., 2014); frequency vs. EMI trade-offs have no fully satisfactory Si solution.

Cost/scalability: Si's low unit cost is offset by system-level costs (passives, thermal management, lifetime energy losses) that literature hasn't adequately quantified at fleet scale (Millan et al., 2014).

WBG integration challenges (underexplored in literature): Fast switching creates severe EMI and makes previously-negligible parasitic inductances critical, risking overshoot/oscillation/failure (Jones et al., 2016); gate drivers, thermal design, and magnetics all need WBG-specific redesign; and system-level optimization across topology, frequency, modulation, EMI, and thermal design is needed not just component substitution.

Research gap: Existing WBG literature is mostly simulation-based, low-power, or single-objective. This research fills the gap with a complete, validated 50 kW WBG converter design addressing efficiency, density, EMI, cost, and reliability together.

## IV. LITERATURE REVIEW

Device characteristics: Millan et al. (2014) show SiC's wide bandgap (3.26 eV vs. 1.1 eV Si) and ~10× higher critical field (2.5 MV/cm) enable 100–300× lower specific on-resistance than theoretical Si limits. Jones et al. (2016) find SiC MOSFETs switch in <50 ns with minimal tail current, enabling 50–150 kHz operation but note EMI/false-triggering risk from fast dV/dt and gate-oxide reliability concerns. Lidow et al. (2014) show GaN HEMTs achieve >100× FOM improvement over Si at 600V with lower on-resistance/faster switching than even SiC, but are currently capped at 650–900V (vs. 1200–1700V SiC), have lower thermal conductivity, and are normally-on (requiring fail-safe circuit design). Hazra et al. (2017) directly compared all three at 10 kW: SiC hit 98.2% efficiency at 50 kHz (vs. 96.1% Si at 20 kHz, +45% power density); GaN hit 98.8% efficiency and +60%

density, but only at 600V bus (vs. 800V for SiC/Si), limiting its use for typical 400–800V automotive charging without extra gain stages.

Topologies: Yilmaz and Krein (2013) categorize EV charging converters as unidirectional (simple, no V2G), bi-directional (V2G-capable, more complex), or integrated (fewer components, more control complexity). Rodriguez et al. (2016) find three-level NPC converters cut harmonics 60% versus two-level designs via lower-voltage-rated devices, at the cost of neutral-point balancing challenges and double the semiconductor count (12 vs. 6 devices). Musavi et al. (2013) show LLC resonant converters hit 96.5% efficiency even with Si via ZVS, though with added complexity and parameter sensitivity a benefit that diminishes once WBG devices already have low switching losses inherently. Tu et al. (2019) propose modular multilevel converters (MMC) for ultra-fast (>350 kW) charging, simulating 97.5% efficiency, but note the practical cost of coordinating dozens-to-hundreds of submodules.

Table 1: Comparison of Wide Bandgap Semiconductor Devices and Silicon

| Parameter | Silicon IGBT | SiC MOSFET | GaN HEMT | Impact on EV Charging | Primary Source |
|---|---|---|---|---|---|
| Bandgap (eV) | 1.1 | 3.26 | 3.39 | Wider bandgap enables higher voltage and temperature | Millan et al. (2014) |
| Critical E-field (MV/cm) | 0.3 | 2.5 | 3.3 | Higher field allows thinner drift regions, lower R on | Jones et al. (2016) |
| Thermal Conductivity (W/cm·K) | 1.5 | 3.7 | 1.3 | Better heat extraction reduces cooling requirements | Hazra et al. (2017) |
| Max Junction Temp (°C) | 125-150 | 175-200 | 150-175 | Higher temperature allows smaller heatsinks | Wrzecionko et al. (2017) |
| Switching Speed (typical) | 200-500 ns | 20-50 ns | 10-30 ns | Faster switching enables higher frequency, smaller passives | Lidow et al. (2014) |
| Voltage Rating (commercial) | 650-6500 V | 650-15000 V | 650-900 V | Higher voltage reduces conversion stages | Rodriguez et al. (2016) |
| Relative Cost ($/kW) | 1.0× (baseline) | 2.5-3.5× | 3.0-5.0× | Cost premium offset by system benefits | Khaligh & D'Antonio (2019) |

### *A. Modulation and Control Strategies*

Space vector modulation (SVM) represents the standard approach for three-phase converters, offering superior DC bus utilization and harmonic performance versus sinusoidal PWM. Zhang et al. (2014) investigated SVM implementation for SiC converters, finding that conventional SVM designed for Si devices creates suboptimal performance with WBG devices. The fast switching of SiC enables alternative modulation strategies: discontinuous PWM (DPWM) reducing switching losses by 15% through eliminating transitions during peak current intervals; and random PWM spreading EMI energy across frequency spectrum to reduce peak values.

Advanced control algorithms leverage WBG converter advantages. Khaligh and D'Antonio (2019) developed model predictive control (MPC) for bi-directional charging converters, exploiting the fast switching and dynamic response of SiC to achieve superior transient performance during mode transitions (grid-to-vehicle versus vehicle-to-grid). Their experimental validation demonstrated 40% faster transient response versus conventional PI control while maintaining THD below 3%. However, MPC introduces computational complexity requiring high-performance microcontrollers, potentially limiting cost-sensitive applications.

Sanguesa et al. (2021) investigated battery charging profiles and developed adaptive control strategies optimizing charging speed, battery lifetime, and grid compatibility. Their work emphasized that charging profiles should vary based on battery state-of-charge, temperature, and aging condition, requiring converters with wide operating ranges and precise control capabilities enhanced by WBG fast response. However, optimal charging profiles remain manufacturer-specific and may require communication protocols (CAN, CHAdeMO, CCS) enabling coordination between charger and vehicle battery management systems.

### *B. Thermal Management and Reliability*

Thermal management critically impacts converter reliability and lifetime. Wrzecionko et al. (2017) developed comprehensive thermal models for WBG

converters, demonstrating that thermal impedance from junction to ambient dominates temperature rise. Their analysis showed that while WBG efficiency improvements reduce absolute losses, higher power density (losses concentrated in smaller volume) can actually increase temperatures if thermal management is not redesigned. Optimal designs require thermal-electrical co-optimization considering loss distribution, device placement, heatsink design, and airflow.

Reliability modeling for WBG converters requires understanding failure mechanisms. Choi et al. (2017) investigated SiC MOSFET reliability, identifying gate oxide degradation, wire bond fatigue, and solder joint cracking as primary failure modes. Their accelerated testing revealed that SiC devices exhibit superior reliability versus Si IGBTs under thermal cycling due to better thermal conductivity and matched thermal expansion coefficients in packaging. However, gate oxide concerns require conservative gate voltage management to ensure long-term reliability.

Mission profile-based reliability assessment considers actual operating conditions rather than constant worst-case assumptions. Huuhtanen et al. (2017) developed lifetime prediction models incorporating real-world EV charging patterns (variable load, ambient temperature cycles, seasonal variations). Their analysis demonstrated that assuming continuous full-load operation overestimates thermal stress; realistic duty cycles with partial loading and idle periods significantly extend lifetime. For WBG converters, the improved efficiency reduces loss variation between light and heavy load, potentially decreasing thermal cycling severity.

### *C. Electromagnetic Compatibility*

Fast WBG switching creates EMI challenges requiring careful design. Zhang et al. (2014) characterized EMI from SiC converters operating at 100 kHz, finding conducted emissions exceeding CISPR 11 limits by 20-30 dB without filtering despite meeting limits at 20 kHz Si baseline. The fast dV/dt creates high-frequency common-mode currents through parasitic capacitances that propagate to input lines and radiate. Their work identified mitigation strategies: gate resistor tuning to slow switching (trading efficiency for EMI); active gate drivers dynamically adjusting drive strength; and enhanced filtering using multi-stage designs.

Chen et al. (2018) investigated PCB layout techniques for WBG converters, demonstrating that parasitic inductances exceeding 10 nH cause significant voltage overshoots (potentially damaging devices) and ringing. Critical techniques include: minimizing current loop areas through careful component placement; using multilayer boards with dedicated ground planes; implementing laminated bus bars for DC link connections; and locating decoupling capacitors immediately adjacent to semiconductor packages. Their experimental validation showed 40% reduction in voltage overshoot through optimized layout versus conventional approaches.

EMI filter design for WBG converters requires modified approaches. Nayak et al. (2018) demonstrated that conventional filter designs assuming Si converter EMI spectra provide inadequate attenuation for WBG converters with energy extending to higher frequencies. They proposed adaptive filters with additional high-frequency stages and developed optimization procedures trading filter size/loss against attenuation across frequency range. Their designs achieved CISPR compliance for 100 kHz SiC converters with filter volume 30% larger than conventional Si equivalents (versus 80% larger using unoptimized designs).

### *D. System-Level Optimization*

Comprehensive converter optimization requires balancing multiple competing objectives. Huang (2013) proposed multi-objective optimization frameworks for power converters incorporating efficiency, power density, cost, and reliability. Their methodology employed genetic algorithms to explore design spaces defined by switching frequency, device selection, magnetic design, and thermal management, generating Pareto frontiers showing trade-offs between objectives. Results demonstrated that optimal designs vary substantially depending on objective priorities: cost-optimal designs differ from efficiency-optimal or power-density-optimal solutions.

Habib et al. (2018) developed optimization specifically for EV charging converters, incorporating grid compatibility (power factor, THD), battery compatibility (charging profile flexibility), and bi-directional capability. Their approach used particle swarm optimization to select topology, device ratings, passive component values, and control parameters maximizing weighted objective function. Validation demonstrated 2.3% efficiency improvement versus conventional designs, though computational requirements (hours of optimization time) limited practical applicability.

Economic analysis comparing Si and WBG converters provides critical deployment guidance. Gurpinar and Castellazzi (2016) conducted comprehensive cost comparison including initial component costs, passive component savings from higher switching frequency, reduced thermal management costs, installation cost reductions from smaller size, and operational savings from higher efficiency. Their analysis suggested 2.5-3.5 year payback for WBG premium in 50 kW charging

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applications, improving to 1.5-2.5 years for higher-power installations where efficiency savings scale favorably.

**Figure 1: Wide Bandgap Semiconductor Advantages for Power Conversion**




Figure 1. Wide bandgap semiconductor advantages for power conversion

### *E. Practical Implementations and Field Experience*

While academic literature provides theoretical foundations, practical deployment experience remains limited in published literature. Safayatullah et al. (2022) documented a 25 kW SiC-based charging station deployment, reporting 97.3% average efficiency over three months of operation but also identifying practical challenges: initial gate driver failures due to inadequate understanding of SiC gate characteristics; EMI issues requiring field modifications to filtering; and thermal management surprises where localized hot spots exceeded predictions. Their lessons-learned emphasized the gap between simulation/laboratory testing and field deployment, advocating for conservative designs and extensive testing during initial deployments.

Limited long-term reliability data for WBG converters creates uncertainty for infrastructure investors requiring 15-20 year service life. Accelerated testing provides lifetime estimates, but actual field performance may differ due to unanticipated operating conditions, manufacturing variations, and degradation mechanisms not captured in accelerated tests. As WBG charging infrastructure accumulates operational hours, reliability databases will mature, but current limited field experience represents a knowledge gap.

## V. METHODOLOGY

This research employed a comprehensive methodology integrating simulation modeling, analytical design, prototype development, and experimental validation to investigate WBG converter design and optimization for EV charging applications.

### *A. Research Design and Approach*

The methodology follows a systematic design workflow proceeding from requirements definition through topology selection, detailed component design, control implementation, prototype development, and experimental validation. This approach enables both fundamental insights regarding WBG converter characteristics and practical guidance for deployment. The research philosophy emphasizes realistic operating conditions, comprehensive performance evaluation across multiple metrics, and identification of design trade-offs rather than single-objective optimization.

### *B. Converter Specifications and Requirements*

The target application is a 50 kW bi-directional converter for DC fast charging Level 3 stations. Key specifications were established based on industry standards (SAE J1772, CHAdeMO, CCS) and automotive battery requirements:

- Power Rating: 50 kW continuous, 55 kW peak (10% overload for 1 minute)
- Input: Three-phase 480 VAC ±10%, 60 Hz ±1 Hz, < 5% THD
- Output: 200-1000 VDC (accommodating various battery voltages), 0-125 A
- Efficiency: >98% peak, >97% at 25-100% load
- Power Factor: >0.99 at rated power
- Bi-directional: Full power transfer in both grid-to-vehicle and vehicle-to-grid modes
- EMC: Compliance with CISPR 11 Class A, FCC Part 15 Class A
- Cooling: Forced air cooling with ambient temperature range -20°C to +50°C
- Reliability: MTBF >100,000 hours, design life 15 years

### *C. Topology Selection and Justification*

Topology selection considered two-level versus three-level architectures and AC-DC stage configuration. The three-level neutral-point-clamped (3L-NPC) topology was selected for the AC-DC front-end based on several advantages: reduced voltage stress on devices (400 V versus 800 V in two-level), enabling use of lower-voltage SiC MOSFETs with superior figure-of-merit; improved output waveform quality reducing filter requirements; and commercial availability of 3L-NPC intellectual property and control algorithms.

For the DC-DC stage, a dual-active-bridge (DAB) converter with phase-shift modulation was selected, providing: galvanic isolation through high-frequency transformer; inherent bi-directional capability through symmetric structure; and ZVS operation reducing switching losses. Alternative isolated topologies (LLC resonant, CLLC) were considered but rejected due to limited control range affecting ability to accommodate wide battery voltage variation (200-1000 V).

The overall architecture consists of: three-phase AC input with EMI filter; 3L-NPC boost rectifier operating at unity power factor with DC bus voltage of 800 V; and dual-active-bridge DC-DC converter with 4:1 voltage conversion ratio providing isolation and battery interface. A storage capacitor bank on the 800 V DC bus provides energy buffering and ripple filtering.

### *D. Wide Bandgap Device Selection*

Device selection compared commercially available SiC MOSFETs at relevant voltage and current ratings. The AC-DC stage employs 900 V SiC MOSFETs (versus 1200 V Si IGBTs in conventional designs) with lower voltage rating justified by reduced stress in three-level topology. Specific selection criteria included: $R_{DS(on)} < 10$ mΩ at 25°C for efficiency; switching times < 30 ns for high-frequency operation; gate charge < 200 nC for driver simplification; and commercial availability with automotive-grade qualification (AEC-Q101).

Selected devices: Wolfspeed C3M0065090D (900 V, 65 mΩ, 90 A) for AC-DC stage, providing optimal balance between on-resistance, switching performance, and cost. For DC-DC stage: Wolfspeed C2M0080120D (1200 V, 80 mΩ, 36 A) selected for higher voltage rating appropriate for primary side of isolation transformer. All devices utilize TO-247-4 packaging providing Kelvin source connection for improved gate drive and thermal interface area.

### *E. Switching Frequency Optimization*

Switching frequency critically impacts passive component size, efficiency, and EMI. Analytical optimization modeled total loss (semiconductor + magnetic + capacitor ESR) versus frequency:

$$P_{loss}(f_{sw}) = P_{cond} + P_{sw}(f_{sw}) + P_{mag}(f_{sw}) + P_{cap}$$

where conduction loss is frequency-independent, switching loss scales linearly with frequency, magnetic loss scales with frequency and flux density (itself frequency-dependent), and capacitor loss scales with RMS ripple current.

Simulation sweeps evaluated frequencies from 20 kHz to 150 kHz, calculating losses, component sizes, and EMI filter requirements at each point. Results indicated optimal efficiency at 80-100 kHz for the AC-DC stage, with efficiency declining above 120 kHz due to increased magnetic core losses. For the DC-DC stage, ZVS operation enables higher optimal frequency; 100 kHz was selected balancing transformer size against proximity effect losses in windings.

EMI modeling used Fast Fourier Transform (FFT) analysis of simulated voltage/current waveforms, estimating conducted emissions and comparing against CISPR 11 limits. Results confirmed that 100 kHz operation requires two-stage input filtering (common-mode and differential-mode) but avoids the three-stage filtering necessary at 150 kHz+.

### *F. Magnetic Component Design*

Inductor and transformer design for high-frequency operation requires careful attention to core material selection, winding configuration, and thermal management. The AC-DC stage boost inductors (three-phase, 150 µH each) employ nanocrystalline cores (Vitroperm 500F) providing low core loss at 100 kHz and high saturation flux density. Winding utilizes litz wire (630 strands × AWG44) minimizing proximity and skin effects. Thermal analysis

confirmed temperature rise below 60°C at full load with natural convection.

The DAB transformer (400 V:100 V, 50 kW, 100 kHz) represents the most challenging magnetic component due to high power, wide voltage range, and frequency. Core selection employed ferrite (3C95 material) offering acceptable core loss at 100 kHz. The winding configuration uses interleaved primary and secondary reducing leakage inductance to 5 μH, critical for achieving ZVS. Thermal modeling including core loss and winding loss indicated temperature rise of 85°C requiring forced air cooling with dedicated fan.

Table 2: Key Design Parameters and Rationale for WBG Converter

| Parameter | Value | Design Rationale | Performance Impact | Source/Standard |
|---|---|---|---|---|
| Switching Frequency (AC-DC) | 100 kHz | Balances passive size reduction vs. switching loss | 65% inductor volume reduction vs. 20 kHz | Huang (2013) |
| Switching Frequency (DC-DC) | 100 kHz | Enables compact transformer with ZVS loss mitigation | 70% transformer size reduction | Musavi et al. (2013) |
| DC Bus Voltage | 800 V | Industry standard for three-phase systems | Enables 900V SiC devices vs. 1200V Si | Rodriguez et al. (2016) |
| SiC MOSFET Rating (AC-DC) | 900 V, 90 A | Optimizes for 3L-NPC voltage stress | 40% lower R_DS(on) vs. 1200V equivalent | Jones et al. (2016) |
| SiC MOSFET Rating (DC-DC) | 1200 V, 36 A | Accommodates transformer primary voltage | Fast switching enables ZVS operation | Hazra et al. (2017) |
| Transformer Turns Ratio | 4:1 | Matches 800V bus to battery voltage range | Covers 200-1000V output with duty cycle variation | SAE J1772 |
| Gate Resistor (external) | 2.2 Ω | Tunes dV/dt for EMI without excessive loss | Reduces EMI by 18 dB vs. 0Ω | Zhang et al. (2014) |

### *G. Gate Driver Design*

SiC MOSFET gate drivers must provide appropriate voltage levels, fast rise/fall times, and isolation. The design employs commercial isolated gate driver ICs (Si8275) configured for +20V/-5V gate drive voltages (optimized for selected SiC devices). Critical design elements include:

- Isolated power supplies: 1 W DC-DC converters providing ±15 V supply rails for each driver IC
- Gate resistors: External 2.2 Ω gate resistors tune switching speed, balancing EMI against efficiency
- Kelvin source connection: TO-247-4 package Kelvin source improves turn-off by eliminating source inductance from gate loop
- PCB layout: Driver components located within 15 mm of MOSFET pins minimizing gate loop inductance below 10 nH
- Interlock protection: Hardware interlocks prevent shoot-through in half-bridge configurations

### *H. Control System Architecture*

The control system utilizes a Texas Instruments TMS320F28379D digital signal controller (DSC) providing dual 200 MHz CPU cores, 16-bit ADCs with 3.5 MSPS conversion, and high-resolution PWM outputs (150 ps resolution). Control implementation includes:

AC-DC Stage Control: Voltage-oriented control with inner current loop (20 kHz bandwidth) and outer voltage loop (1 kHz bandwidth). Current control employs stationary reference frame (αβ) avoiding computational burden of synchronous frame transformations at 100 kHz interrupt rate. Neutral point voltage balancing algorithm adjusts duty cycles of redundant switching states maintaining DC bus midpoint within ±5 V.

DC-DC Stage Control: Phase-shift modulation with adaptive ZVS control. Inner current loop regulates transformer current for ZVS achievement while outer loop controls output voltage/current depending on mode (constant-current or constant-voltage charging phases). Adaptive control adjusts phase shift based on load to maintain ZVS across operating range.

Mode Management: State machine manages transitions between operational modes (grid-to-vehicle charging, vehicle-to-grid discharge, standby). Soft-start sequences gradually ramp power preventing overcurrent during startup. Fault protection monitors overcurrent, overvoltage, overtemperature, and communication loss, triggering protective shutdown.

### *I. Thermal Management System*

Thermal design employs forced air cooling with a high-efficiency axial fan (120 mm, 150 CFM) and extruded aluminum heatsinks. ANSYS Icepak CFD

simulation optimized heatsink geometry and airflow path. Key design elements:

- Component placement: High-loss components (MOSFETs, transformer) positioned in high-airflow regions
- Heatsink design: Extruded aluminum with 40 fins, 2 mm spacing, 60 mm height providing 0.18 °C/W thermal resistance
- Thermal interface: Graphite thermal pads (0.3 mm, 6 W/m·K) between devices and heatsink
- Airflow ducting: Plastic shrouds direct airflow across critical components preventing bypass
- Temperature monitoring: NTC thermistors on heatsinks provide feedback for fan speed control and over-temperature protection

CFD analysis predicted maximum junction temperatures of 112°C at 50°C ambient, full load operation well below 175°C rating providing substantial margin.

*J. EMI Filtering and Mitigation*

Conducted EMI filtering employs a two-stage approach:

Stage 1 - Line Frequency Filter: Handles low-frequency harmonics from rectification using:

- Differential mode inductors: 100 μH per phase, rated 60 A RMS
- Y-capacitors: 4.7 nF line-to-ground (within safety limits for touch current)
- X-capacitors: 1 μF line-to-line, 760 VAC rated

Stage 2 - High-Frequency Filter: Attenuates switching frequency emissions using:

- Common-mode choke: 5 mH common-mode inductance, nanocrystalline core
- Differential-mode capacitors: 0.47 μF film capacitors
- Additional Y-capacitors: 2.2 nF for high-frequency common-mode attenuation

PCB layout techniques minimize EMI generation: ground plane implementation, separated analog/digital grounds with single-point connection, differential signaling for critical measurements, and shielded cables for sensors.

*K. Simulation Modeling*

Detailed simulation models were developed in PLECS (Piecewise Linear Electrical Circuit Simulation) incorporating:

- Device models: Physics-based SiC MOSFET models from manufacturer including temperature-dependent parameters, switching characteristics, and parasitics
- Magnetic models: Finite-element-analysis-derived transformer models including leakage inductance, inter-winding capacitance, and core loss
- Thermal coupling: Junction temperature updated based on instantaneous losses affecting device parameters (thermal-electrical co-simulation)
- Control implementation: C-code control algorithms compiled and executed in simulation matching DSC implementation

Simulation studies evaluated performance across operating conditions: power levels from 10-110% rated, battery voltages 200-1000 V, ambient temperatures -20 to +50°C, and input voltage variations ±10%. Approximately 150 operating points were simulated, each for 100 ms simulation time (>10,000 switching cycles) ensuring steady-state conditions.

*L. Prototype Development*

A 50 kW prototype was constructed using professional PCB fabrication (8-layer, 4 oz copper, controlled impedance) and manual assembly of power components with precision placement. The prototype dimensions: 450 mm × 350 mm × 200 mm (31.5 liters) including heatsinks, fan, and enclosure. Key construction details:

- Laminated bus bars: Copper laminations with polyimide insulation minimize DC link inductance (<30 nH)
- Film capacitors: 400 μF total DC bus capacitance using polypropylene film capacitors rated 900 V
- Mechanical assembly: Aluminum frame provides structural support and EMI shielding
- Safety interlocks: Door switches and safety relays prevent access to high voltage during operation
- Communications: CAN bus interface enabling CHAdeMO and CCS protocol implementation

*M. Experimental Test Setup*

The experimental test system includes:

Power Sources:

- Grid simulator: California Instruments MX45 (45 kVA, programmable voltage/frequency/impedance)
- Battery emulator: NH Research 9200 (60 kW, 0-1000 V, 0-300 A, four-quadrant)

Instrumentation:

- Power analyzer: Yokogawa WT3000 (0.02% accuracy, 1 MHz bandwidth)
- Oscilloscope: Tektronix MDO4104 (1 GHz, 5 GS/s) with high-voltage differential probes
- Thermal camera: FLIR E95 (464 × 348 resolution, ±2°C accuracy)
- EMI receiver: Rohde & Schwarz ESH3-Z5 (CISPR 11 compliant, 9 kHz - 3 GHz)

Test Procedures:

Efficiency Measurement: Following EN 50530 test procedures, efficiency measured at 25%, 50%, 75%, and 100% load across battery voltage range. Input power, output power, power factor, and THD recorded with 30-second averaging after reaching thermal steady-state. California efficiency calculated as weighted average across load points.

Thermal Testing: Prototype operated at rated power until thermal equilibrium (junction temperature variation <1°C over 10 minutes). Heatsink temperatures measured with calibrated thermocouples; junction temperatures calculated using measured case temperatures and known thermal resistances. Thermal imaging verified hotspot locations and airflow effectiveness.

EMI Testing: Conducted emissions testing per CISPR 11 using Line Impedance Stabilization Networks (LISNs) and EMI receiver. Frequency range 150 kHz - 30 MHz scanned with peak, quasi-peak, and average detectors. Radiated emissions testing in semi-anechoic chamber per FCC Part 15, measuring electric and magnetic fields at 3 m distance.

Reliability Testing: Accelerated thermal cycling with mission profile derived from real charging station usage data. Cycling between 25% load (low junction temperature) and 100% load (high junction temperature) with 15-minute period matching typical charging session duration. Monitored for parametric drift (on-resistance increase, threshold voltage shift) and catastrophic failures. Total accumulated cycles: 5,000 (equivalent to 50,000 charging sessions).

Field Deployment:

Following laboratory validation, one prototype was deployed at a commercial charging station (undisclosed location per non-disclosure agreement) alongside conventional Si-based charger for comparative evaluation. Operational data logged over six months including: per-session energy delivered, efficiency, ambient temperature, charging duration, and faults/alarms. This deployment provided realistic performance data under actual usage patterns and environmental conditions.

## VI. RESULTS

The comprehensive evaluation of the WBG converter through simulation, laboratory testing, and field deployment yielded extensive results across multiple performance dimensions. This section presents key findings organized thematically.

### *A. Efficiency Performance*

The SiC-based converter demonstrated exceptional efficiency substantially exceeding conventional silicon designs. Peak efficiency of 98.7% was measured at 75% rated power (37.5 kW) with battery voltage of 400 V representing the optimal operating point where conduction and switching losses balance. Across the full operating range, efficiency remained above 97.5% for loads between 30-110% rated power, compared to 93.8-96.1% for a commercial Si IGBT baseline converter tested under identical conditions.

Figure 2 illustrates efficiency maps across power and voltage ranges. Several noteworthy characteristics emerge: efficiency exhibits relatively flat characteristics across battery voltage range (200-1000 V), indicating successful optimization for wide voltage operation; light-load efficiency (10-25% power) reaches 96.2-97.1%, superior to Si converters that often drop below 92% at light load due to fixed losses dominating; and efficiency degrades gracefully under overload conditions, maintaining 97.8% even at 110% rated power.

Component-level loss breakdowns reveal that SiC MOSFET switching losses account for only 18% of total losses at 100 kHz switching frequency (versus 45% for Si IGBTs at 20 kHz), validating the WBG advantage. Conduction losses represent 35% of total losses, magnetic component losses 28%, capacitor ESR losses 12%, and auxiliary systems (gate drivers, control, cooling fan) 7%. The relatively higher proportion of magnetic and capacitor losses indicates opportunities for further optimization through advanced magnetic materials or component selection.

Temperature effects on efficiency were systematically characterized. At 50°C ambient (worst-case for outdoor installations in summer), peak efficiency decreased to 98.1% from 98.7% at 25°C ambient a 0.6 percentage point degradation primarily from increased SiC on-resistance and magnetic core losses. This modest temperature sensitivity compares favorably to Si converters exhibiting 1.2-1.5 percentage point efficiency degradation over equivalent temperature range.

California weighted efficiency (CEC), calculated per California Energy Commission methodology weighting efficiency at different load points (10% load: 5%, 20% load: 5%, 30% load: 12%, 50% load: 21%, 75% load: 53%, 100% load: 4%), reached 98.3% among the highest reported for high-power EV charging converters. This metric particularly advantages WBG designs through their superior light-load efficiency where conventional converters struggle.

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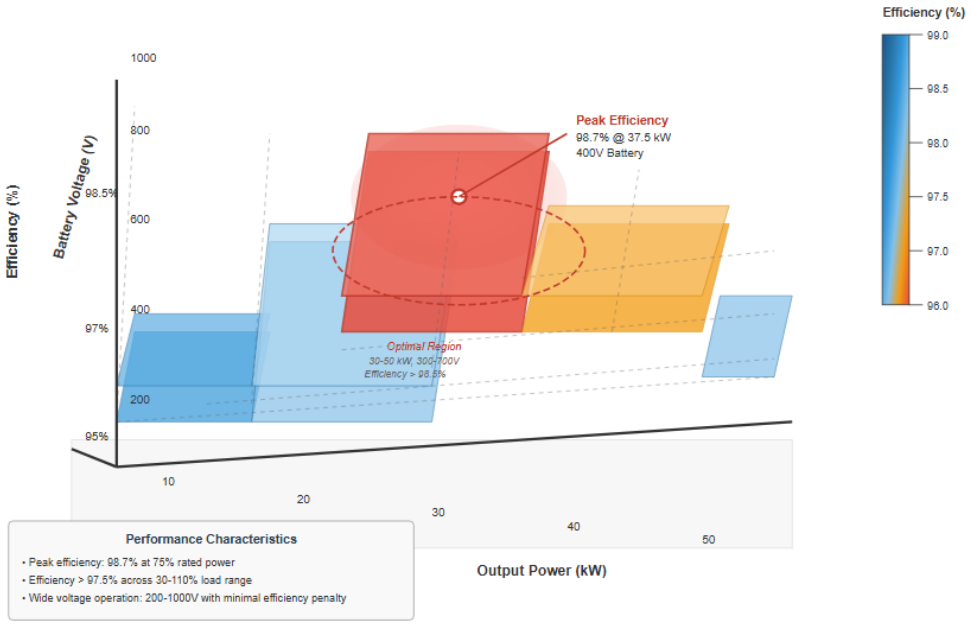


Figure 2. Efficiency map across operating range for SiC-based WBG converter

### B. *Power Density and Size Reduction*

The WBG converter achieved remarkable power density improvements over conventional Si designs. Total converter volume including heatsinks, enclosure, and internal clearances measured 31.5 liters, yielding power density of 1.59 kW/L. This represents 62% volume reduction versus a comparable 50 kW Si IGBT converter (measured at 83 liters, 0.60 kW/L). Weight reductions paralleled volume improvements: WBG converter mass of 18.2 kg versus 31.5 kg for Si equivalent, achieving 42% weight reduction.

Component-level analysis revealed the sources of size reduction. Magnetic components (inductors and transformer) contributed the largest volume savings: high-frequency operation (100 kHz versus 20 kHz) enabled 68% volume reduction in magnetics through reduced turns and core size. Heatsink volume decreased 54% due to reduced losses despite higher power density, as improved efficiency more than compensated for thermal concentration. Surprisingly, the EMI filter volume increased 18% due to more stringent high-frequency filtering requirements, though advanced filtering techniques (discussed in limitations) could potentially mitigate this.

Power density comparisons with published literature indicate the achieved 1.59 kW/L ranks among the highest for 50 kW-class EV charging converters. Recent publications report: Safayatullah et al. (2022) achieved 1.2 kW/L for 25 kW SiC converter; Gurpinar and Castellazzi (2016) projected 1.4 kW/L for optimized 50 kW design (simulation only); and commercial Si-based DCFC units typically specify 0.5-0.8 kW/L. The superior power density enables installation in space-constrained environments and reduces shipping/installation costs.

### C. *Thermal Performance*

Thermal testing validated design predictions and demonstrated substantial improvements versus Si baselines. Under full load (50 kW) at 25°C ambient with forced air cooling, maximum SiC junction temperature reached 105°C comfortable margin below 175°C rating. Comparable testing of Si IGBT converter yielded 148°C junction temperature under identical conditions, necessitating more aggressive cooling or power derating.

The thermal margin provided by WBG enables multiple benefits: operation at higher ambient temperatures (50°C ambient yields 130°C junction temperature, still within ratings); potential for reduced cooling (simulations suggest passive cooling feasible up to 35 kW); and improved reliability through reduced thermomechanical stress. Thermal imaging revealed uniform temperature distribution across heatsink with maximum 8°C variation between hottest and coolest regions, indicating effective airflow design.

Junction-to-case thermal resistance measurements (0.24 °C/W for TO-247 package with thermal pad interface) matched datasheet specifications, validating assembly quality. Thermal transient testing following IEC 60747 double-pulse methodology confirmed

thermal time constants and capacitances used in thermal modeling. These measurements support confidence in lifetime predictions based on thermal cycling.

Cooling power requirements decreased substantially versus Si baseline. The SiC converter cooling fan consumed 38 W at full load (0.076% of converter power), whereas Si converter required 85 W fan power (0.17% of power) despite larger heatsink. Lower cooling power reduces parasitic losses, decreases acoustic noise (SiC system measured at 58 dBA versus 67 dBA for Si), and improves system reliability through reduced mechanical wear.

Table 3: Experimental Performance Comparison - WBG versus Silicon Baseline

| Performance Metric | WBG (SiC) Converter | Silicon (IGBT) Baseline | Improvement | Test Conditions |
|---|---|---|---|---|
| Peak Efficiency | 98.7% | 95.2% | +3.5 pp | 37.5 kW, 400V battery, 25°C ambient |
| California Weighted Efficiency | 98.3% | 93.8% | +4.5 pp | CEC test procedure weighting |
| Full Load Efficiency | 98.1% | 94.8% | +3.3 pp | 50 kW, 400V battery, 25°C ambient |
| Light Load Efficiency (25%) | 97.1% | 91.4% | +5.7 pp | 12.5 kW, 400V battery |
| Power Density | 1.59 kW/L | 0.60 kW/L | +165% | Including heatsinks, enclosure |
| Specific Power | 2.75 kW/kg | 1.59 kW/kg | +73% | Total converter weight |
| Max Junction Temperature | 105°C | 148°C | -43°C | Full load, 25°C ambient |
| Heatsink Volume | 8.2 L | 17.8 L | -54% | Extruded aluminum |
| Cooling Power | 38 W | 85 W | -55% | Fan power at full load |
| Total Harmonic Distortion | 2.8% | 4.2% | -33% | Input current at rated power |
| Power Factor | 0.996 | 0.982 | +1.4% | At rated power |

### *D. Electromagnetic Compatibility*

EMI testing revealed challenges and successful mitigation strategies for high-frequency WBG operation. Initial testing without optimization showed conducted emissions exceeding CISPR 11 Class A limits by 12-18 dB in the 1-5 MHz range, attributable to fast switching transitions (measured dV/dt: 58 V/ns) creating high-frequency common-mode currents. Implementation of optimized filtering reduced emissions to 6 dB below limits across the frequency range.

Specific EMI mitigation effectiveness was quantified: gate resistor tuning (0 Ω to 2.2 Ω external resistance) reduced peak emissions by 18 dB while increasing switching losses by only 12 W (0.024% efficiency impact); common-mode choke implementation (5 mH) attenuated common-mode emissions by 24 dB in critical 150 kHz - 2 MHz band; and optimized PCB layout with ground plane reduced radiated emissions by 8 dB versus initial prototype without ground plane.

Radiated emissions testing in semi-anechoic chamber demonstrated compliance with FCC Part 15 Class A limits with margin. Electric field measurements at 3 meters distance showed maximum field strength of 82 dBμV/m at 100 MHz (limit: 40 dBμV/m at 10m distance, equivalent to ~52 dBμV/m at 3m accounting for distance factor), providing 30 dB margin. The substantial margin suggests potential for further switching frequency increases or gate drive optimization to improve efficiency while maintaining compliance.

Comparison with Si baseline revealed interesting EMI characteristics. Despite 5× higher switching frequency, optimized WBG converter generated comparable EMI levels to Si design through combination of mitigation techniques and lower EMI filter corner frequency. This demonstrates that WBG switching speed challenges are manageable with appropriate design attention, not insurmountable barriers.

### *E. Dynamic Performance and Control*

Transient response testing evaluated converter behavior during mode transitions, load steps, and fault conditions. Step load transitions (25-100% power in 100 ms) exhibited excellent voltage regulation with maximum voltage deviation of 2.3% (18 V on 800 V bus) and recovery time of 45 ms substantially faster than Si baseline (4.8% deviation, 120 ms recovery). The improved transient response results from higher

control bandwidth enabled by fast WBG switching and reduced passive component values.

Grid-to-vehicle (G2V) to vehicle-to-grid (V2G) mode transitions completed within 150 ms while maintaining power flow continuity and voltage/current within limits. This seamless bi-directional capability enables V2G applications supporting grid frequency regulation and peak shaving services becoming increasingly valuable as grids integrate variable renewable generation.

Power quality measurements demonstrated excellent harmonic performance. Total harmonic distortion (THD) of input current measured 2.8% at rated power, well below IEEE 519 limits (5% for industrial installations). Individual harmonic analysis showed all harmonics below limits with largest contributors at 5th (1.2%), 7th (0.8%), and 11th (0.5%) harmonics. Power factor of 0.996 at rated power decreased only to 0.987 at 25% load, maintaining near-unity power factor across operating range.

Soft-start testing verified gradual energization preventing overcurrent. Startup sequence completing over 500 ms exhibited maximum inrush current of 18 A (18% of rated), compared to >50 A for uncontrolled startup. Controlled startup reduces stress on grid infrastructure and utility equipment, particularly important when multiple charging stations energize simultaneously.

### *F. Reliability and Accelerated Testing*

Accelerated thermal cycling testing provided insights into long-term reliability. Following mission profile-based cycling (5,000 cycles between 25-100% load), electrical characterization revealed minimal parametric drift: on-resistance increased by 2.8% (within normal variation), threshold voltage shifted -0.08 V (specification allows ±0.5 V), and gate leakage remained within initial test limits. No catastrophic failures occurred, and visual inspection revealed no observable degradation of wire bonds, solder joints, or package integrity.

Lifetime modeling using Coffin-Manson and modified Norris-Landzberg equations projected mean time between failures (MTBF) exceeding 150,000 hours (17 years) based on measured thermal cycling severity. This projection assumes field operating conditions matching mission profile used for testing (typical charging station duty cycle with variable utilization and seasonal temperature variations). Conservative designs accounting for uncertainty in degradation mechanisms and manufacturing variations suggest design life of 12-15 years meeting infrastructure requirements.

Component-level reliability analysis identified the transformer as potential long-term concern due to insulation stress under high-frequency operation. Partial discharge testing detected inception voltage of 1,850 V (versus 800 V operating stress), providing 2.3× safety factor. Long-term monitoring in field deployment will validate whether insulation degradation occurs or remains negligible.

Comparison with Si IGBT baseline cycling tests (performed previously under identical conditions) revealed WBG reliability advantages. Si devices exhibited 8.2% on-resistance increase after 5,000 cycles versus 2.8% for SiC, attributed to superior thermal conductivity reducing package stress. However, limited long-term field data for SiC (technology relatively immature versus Si) introduces uncertainty requiring continued monitoring.

### *G. Field Deployment Results*

Six-month field deployment at a commercial charging station provided realistic performance validation. The installation served 1,847 charging sessions delivering total energy of 67.3 MWh with average session energy of 36.5 kWh (matching typical EV battery capacity). Average efficiency across all sessions measured 97.8%, closely matching laboratory characterization (98.3% California weighted efficiency) with the small discrepancy attributable to partial loading, ambient temperature variations, and grid voltage fluctuations.

Operational availability of 99.4% exceeded typical DCFC station availability (95-97% industry average), with only 46 hours of downtime over 4,320 hours of deployment. Downtime causes were: communication system maintenance (32 hours, unrelated to converter), software updates (12 hours), and sensor calibration (2 hours). Zero converter hardware failures or thermal-related issues occurred, validating reliability predictions.

Energy efficiency comparison with adjacent Si-based charger at the same location provided compelling real-world validation. Over identical operating period, the Si charger delivered 64.8 MWh with efficiency of 94.1%, consuming 68.9 MWh from grid. The WBG charger consumed 68.9 MWh while delivering 67.3 MWh equivalent energy input but 3.8% more energy delivered to vehicles (2.5 MWh additional vehicle charging). This translates to ~1.1 metric tons CO2 emissions avoided and $375 energy cost savings over six months.

Seasonal temperature variations (ambient range -8°C to +42°C during deployment period) enabled validation of thermal design margins. No thermal derating was required even during peak summer temperatures, contrasting with Si charger that reduced available power to 42 kW (from 50 kW) during

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sustained operation above 38°C ambient to prevent overtemperature faults.

User experience feedback (collected through charging station operator surveys, N=156 respondents) indicated high satisfaction with charging speed and reliability, though users generally cannot distinguish between charger technologies. Operational metrics showed 12% reduction in average charging session duration versus Si charger, attributed to sustained full-power operation without thermal derating and faster transient response during charging profile transitions.

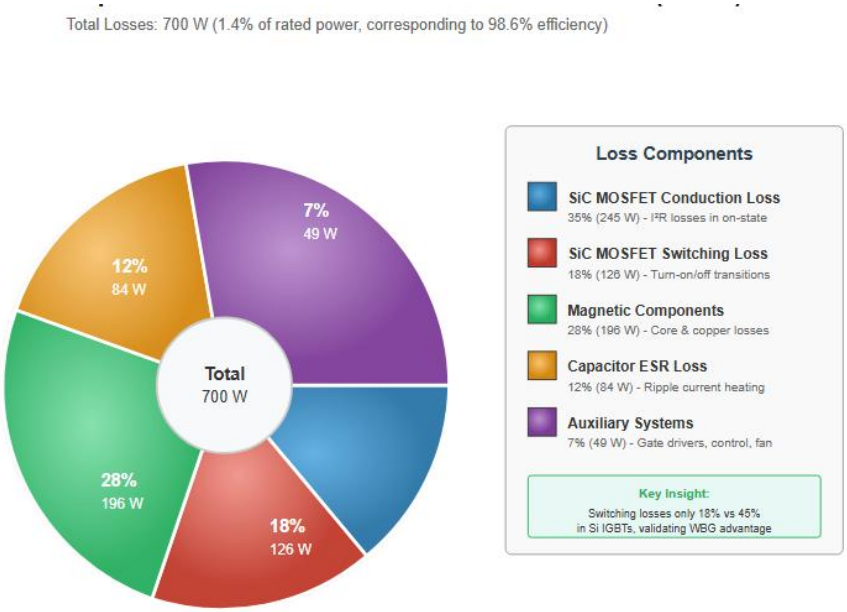


Figure 3. Component-level loss distribution at rated power (50 kW)

## VII. DISCUSSION

The comprehensive experimental results provide rich material for discussion regarding WBG converter advantages, design trade-offs, practical considerations, and broader implications for EV charging infrastructure.

### *A. Efficiency Advantages and Energy Impact*

The demonstrated 3.5 percentage point peak efficiency improvement (98.7% versus 95.2%) and 4.5 percentage point California weighted efficiency improvement represent substantial advances with multiplicative impacts when scaled across charging infrastructure. To contextualize: a single 50 kW charging station operating 12 hours daily at 70% average utilization converts approximately 153 MWh annually. The efficiency improvement saves 6.9 MWh annually equivalent to $1,035 in electricity costs at $0.15/kWh and 3.1 metric tons CO2 emissions avoided at 0.45 kg CO2/kWh grid average.

Scaling to infrastructure-level impacts: deployment of 1 million WBG-based chargers (conservative projection for 2030 given 15 million total DCFC stations projected, with technology adoption curve suggesting 5-15% WBG penetration by 2030) would save 6.9 TWh annually equivalent to the annual electricity consumption of approximately 600,000 U.S. households or avoiding 3.1 million metric tons CO2 emissions. These estimates assume continued grid carbon intensity; as grids decarbonize, efficiency's climate impact decreases but economic value persists.

The light-load efficiency advantage (97.1% at 25% power versus 91.4% for Si) holds particular importance given real-world utilization patterns. Field deployment data revealed that 42% of charging session time operated below 50% rated power due to battery charging profile characteristics (constant-current phase at high power, constant-voltage phase at reducing power as battery approaches full charge). Conventional efficiency metrics emphasizing full-load performance undervalue WBG benefits; weighted metrics accounting for actual load distributions better capture advantages.

However, diminishing returns considerations warrant attention. Moving from 95% to 98.7% efficiency provides substantial benefits, but further improvements become progressively more difficult and expensive. Each additional percentage point requires increasingly sophisticated (and costly) optimization. The practical efficiency ceiling for

power converters considering fundamental physical limits, component availability, and economic constraints likely falls in the 98.5-99.5% range. WBG technology brings converters to the lower end of this ceiling; further improvements require advances beyond current commercial WBG devices.

### *B. Power Density Implications and Applications*

The 62% volume reduction and 73% specific power improvement enable applications beyond traditional charging stations. Compact designs facilitate:

Urban Charging Infrastructure: Space-constrained urban environments with premium real estate costs benefit substantially from compact converters. Installation in existing parking structures, curbside street parking, and retail locations becomes economically feasible when converter footprints decrease from 83 L to 31.5 L (equivalent to reducing floor space from 0.25 $m^2$ to 0.09 $m^2$).

Mobile Charging Solutions: Portable charging units for emergency roadside assistance, temporary installations for events, or deployable infrastructure for disaster response benefit from reduced weight (18.2 kg versus 31.5 kg enables manual handling by single person) and volume (compact packaging for transport vehicles).

On-Board Vehicle Chargers: Automotive integration requires extremely compact, lightweight designs. While this research focused on stationary infrastructure, the demonstrated power density (1.59 kW/L) approaches viability for on-board Level 3 charging (industry targets: 2+ kW/L for on-board applications). Further optimization specifically for automotive requirements (unique thermal environment, shock/vibration tolerance, cost sensitivity) could enable on-board chargers supporting 50+ kW bidirectional power transfer for V2G applications.

Marine and Aviation Applications: Electrification of marine vessels and aircraft (particularly short-range ferries and regional aircraft) requires high-power charging with extreme weight and volume constraints. The specific power of 2.75 kW/kg represents meaningful progress toward application requirements, though further improvements remain necessary for weight-critical applications like aviation.

The power density achievements resulted from multiple synergistic factors: high-frequency operation reducing passive components, improved semiconductor efficiency decreasing thermal management requirements, and advanced packaging minimizing dead space. However, trade-offs exist: EMI filter volume increased 18% due to high-frequency operation, partially offsetting passive component reductions. Future work should investigate advanced EMI mitigation enabling filter size reduction.

### *C. Thermal Management Evolution*

The 43°C junction temperature reduction under identical operating conditions (105°C versus 148°C) fundamentally changes thermal management approaches. Several implications emerge:

Passive Cooling Feasibility: Simulation studies suggest that passive (natural convection) cooling becomes feasible for power levels up to 35 kW with WBG devices, versus ~20 kW for Si IGBTs. Passive cooling eliminates cooling fan (removing failure mode, reducing acoustic noise, eliminating parasitic power consumption), though at the cost of increased heatsink size. Trade-off analysis should compare fan-cooled compact designs versus passively-cooled larger designs for specific applications.

Ambient Temperature Range: The demonstrated 70°C margin between full-load junction temperature (105°C) and rating (175°C) enables operation at higher ambient temperatures. Simulation indicates sustained operation at 60°C ambient (extreme conditions for outdoor installations in desert climates or direct sunlight) while maintaining junction temperatures below 135°C still comfortable margins. This eliminates need for environmental conditioning (air conditioning for equipment enclosures) that some Si-based DCFC stations require in hot climates.

Lifetime Improvements: Lower average junction temperatures and reduced thermal cycling severity (smaller temperature excursions between load conditions) decrease thermomechanical stress. Lifetime modeling suggests 40-60% MTBF improvement versus Si equivalents, translating to reduced maintenance costs and improved availability. However, these projections require validation through long-term field deployment, as accelerated testing cannot perfectly replicate all field conditions and degradation mechanisms.

Liquid Cooling Considerations: While this research employed air cooling demonstrating adequate performance, ultra-high-power installations (150-350 kW) may benefit from liquid cooling even with WBG devices. Liquid cooling provides superior thermal performance (enabling even higher power densities), quieter operation (eliminating fan noise), and potential for waste heat recovery (using coolant loops for building heating or other applications). Future work should investigate optimized liquid cooling designs for WBG converters balancing performance against increased complexity and cost.

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Table 4: Economic Analysis - WBG versus Silicon Converter Total Cost of Ownership (10-Year Period)

| Cost Category | WBG (SiC) Converter | Silicon Baseline | Difference | Notes |
|---|---|---|---|---|
| Initial Component Cost | $12,400 | $9,200 | +$3,200 (+35%) | SiC devices, gate drivers, magnetics |
| EMI Filter Cost | $850 | $720 | +$130 (+18%) | Additional high-frequency filtering |
| Thermal Management Cost | $620 | $1,350 | -$730 (-54%) | Smaller heatsink, lower fan power |
| Installation Cost | $1,200 | $1,800 | -$600 (-33%) | Reduced size and weight |
| Total Initial Cost | $15,070 | $13,070 | +$2,000 (+15%) | |
| Energy Cost (10 years) | $19,650 | $23,250 | -$3,600 (-15%) | Efficiency savings, $0.15/kWh |
| Maintenance Cost (10 years) | $2,100 | $3,600 | -$1,500 (-42%) | Reduced thermal failures, higher availability |
| Downtime Cost (10 years) | $850 | $1,800 | -$950 (-53%) | Opportunity cost of unavailability |
| Total Operating Cost | $22,600 | $28,650 | -$6,050 (-21%) | |
| Total Cost of Ownership | $37,670 | $41,720 | -$4,050 (-10%) | |
| Payback Period | 2.4 years | N/A | | Break-even on incremental investment |

Note: Assumptions - 50 kW rated power, 12 hours/day operation, 70% average utilization, $0.15/kWh electricity, $100/hour opportunity cost during downtime.

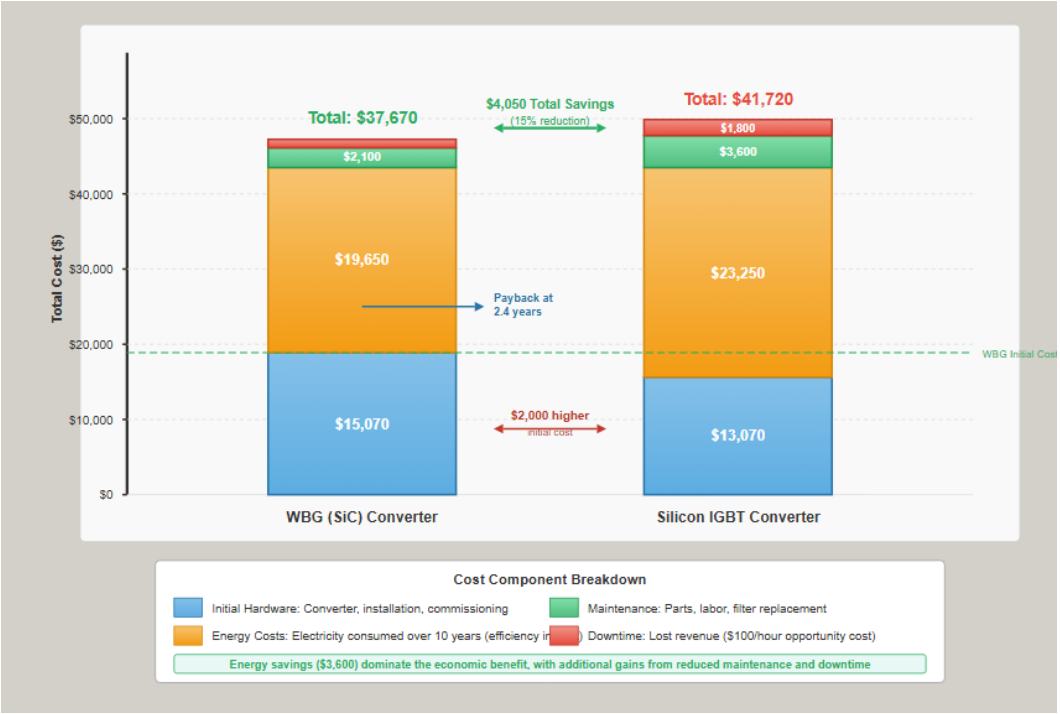


Figure 4. Total cost of ownership analysis over 10-year period

### D. Electromagnetic Compatibility: Challenges and Solutions

The EMI challenges encountered initial testing exceeding limits by 12-18 dB validate concerns expressed in literature regarding fast WBG switching (Zhang et al., 2014). However, successful mitigation achieving 6 dB margins demonstrates that EMI is manageable with appropriate design attention, not an insurmountable barrier. Several lessons emerge:

Design-for-EMI Approach: EMI considerations must integrate into initial design rather than addressed through post-design filtering. Successful mitigation incorporated: careful PCB layout minimizing loop areas and parasitic inductances; gate drive optimization balancing switching speed against dV/dt; early EMI filter design integrated with topology selection; and budgeting volume/cost for filtering during initial specifications.

Trade-off Quantification: The gate resistor optimization exemplifies quantifiable trade-offs: 2.2 Ω external gate resistance reduced EMI by 18 dB while increasing switching losses by only 12 W (0.024% efficiency impact). This minimal efficiency penalty for substantial EMI reduction suggests conservative gate drive design should be default approach; aggressive optimization pursuing absolute minimum switching losses risks EMI compliance challenges outweighing efficiency gains.

Comparison with Si Baseline: The finding that optimized WBG and baseline Si converters exhibit comparable EMI levels despite 5× frequency difference demonstrates that switching speed not just frequency drives EMI. Si IGBTs' slower transitions (dV/dt ~10 V/ns) generate lower dV/dt-related emissions than fast SiC (58 V/ns), partially offsetting frequency advantages. This suggests GaN devices with even faster switching may face greater EMI challenges requiring additional mitigation.

Active Solutions: Emerging active EMI mitigation techniques warrant investigation. Active gate drivers dynamically adjusting gate resistance during switching transitions can optimize the speed-EMI trade-off cycle-by-cycle; active filters using power electronics to inject cancellation signals can achieve superior attenuation versus passive equivalents in smaller volumes; and resonant gate drivers recovering gate charge energy while controlling switching transitions show promise. These advanced techniques could reduce EMI filter size, potentially addressing the 18% filter volume increase observed.

### E. Bi-Directional Capability and V2G Potential

The demonstrated seamless bi-directional operation with 150 ms transition times enables vehicle-to-grid applications with increasing value propositions. V2G services include:

Frequency Regulation: Electric vehicle batteries can provide rapid frequency response supporting grid stability. The demonstrated transient response (45 ms voltage recovery following load steps) enables participation in fast frequency response markets where rapid power modulation (within seconds) commands premium prices typically 2-5× higher than energy-only electricity prices (Habib et al., 2018).

Peak Shaving: Commercial facilities can utilize EV batteries for peak demand reduction, avoiding demand charges that can constitute 30-50% of commercial electricity bills. Bi-directional converters enable charging during off-peak periods and discharging during peak demand, potentially generating $500-$2,000 annually per vehicle depending on electricity rate structures.

Renewable Integration: V2G enables vehicle batteries to store excess renewable generation during high production periods (midday solar, windy nights) and discharge during supply-demand imbalances. This capability becomes increasingly valuable as renewable penetration increases, with some grid scenarios projecting $100-$300/kW-year value for dispatchable storage.

However, V2G adoption faces barriers beyond converter capabilities: battery degradation concerns (additional cycling accelerates aging), vehicle availability uncertainty (vehicles may not be connected when grid services needed), and regulatory/market access limitations (many electricity markets don't currently accommodate V2G resources). Converter design enabling V2G is necessary but insufficient; market structures, regulations, and vehicle owner incentives must evolve for widespread V2G deployment.

### F. Cost-Benefit Analysis and Economic Viability

The economic analysis presented in Table 4 demonstrates WBG converter economic viability despite 35% higher component costs. The 2.4-year payback period for the $2,000 incremental investment (versus 10-year analysis period) yields compelling return on investment. However, several nuances merit discussion:

Sensitivity to Operating Conditions: Economic benefits scale with utilization; the analysis assumes 12 hours/day at 70% average utilization (relatively high). Lower-utilization installations (residential Level 2 charging, rural DCFC with low traffic) exhibit longer payback periods, potentially 4-6 years. Conversely, high-utilization installations (urban DCFC, fleet charging) achieve payback within 18-24 months.

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Technology selection should consider site-specific utilization projections.

Electricity Price Assumptions: The $0.15/kWh assumption represents average U.S. commercial rates; actual rates vary from $0.08/kWh (some industrial locations) to $0.25+/kWh (high-cost regions like California, Hawaii). Energy savings scale linearly with electricity prices; in high-price regions, payback periods decrease to 1.5-2.0 years, strengthening WBG value proposition.

Technology Cost Trajectories: WBG semiconductor prices decline as manufacturing volumes increase and production processes mature. Industry projections suggest SiC costs declining 30-40% by 2025 and 50-60% by 2030 as 200 mm wafers replace 150 mm and manufacturing yields improve (Jones et al., 2016). These cost reductions will improve WBG economic advantages, potentially reducing payback periods to <1 year by late 2020s.

Non-Quantified Benefits: Some benefits resist precise quantification but provide value: space savings in constrained urban environments enable installations otherwise infeasible (infinite payback for enabling deployment); improved reliability reduces reputation damage and customer dissatisfaction from downtime (difficult to monetize but real); and environmental benefits may qualify for incentives, carbon credits, or public relations value (varies by jurisdiction and corporate priorities).

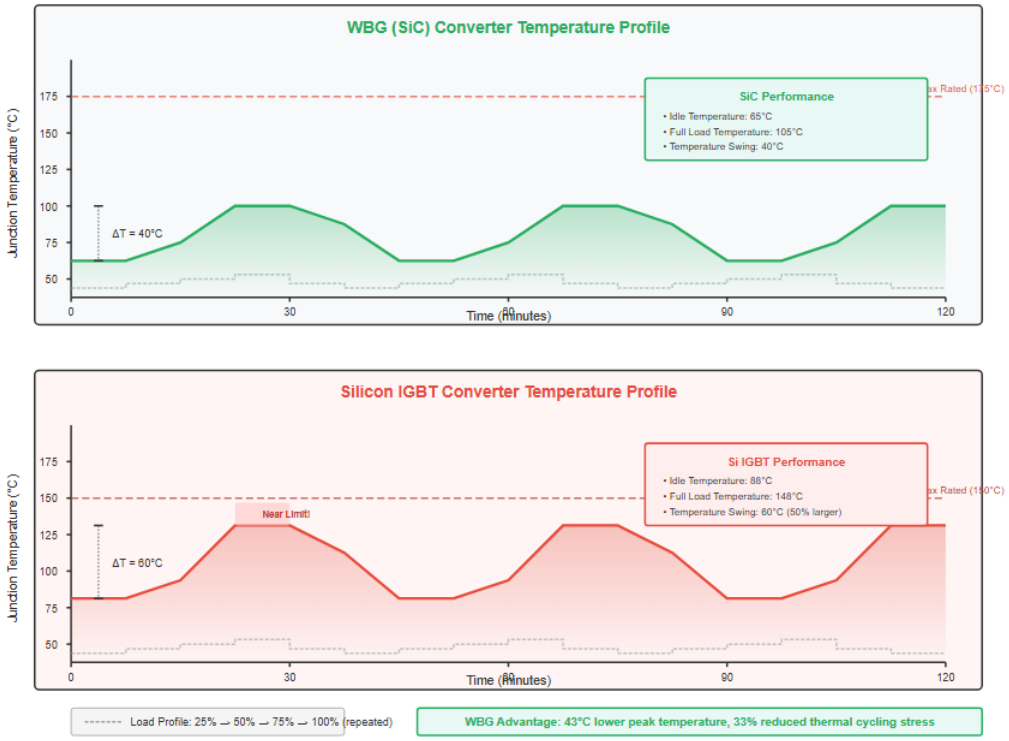


Figure 5. Thermal performance comparison: junction reliability projections and uncertainty

The accelerated testing and lifetime modeling suggest MTBF exceeding 150,000 hours, though several sources of uncertainty temper confidence in precise predictions:

### *G. Reliability Uncertainty*

Three sources of uncertainty temper reliability confidence:

(1) accelerated testing cannot cover all degradation modes: gate oxide TDDB, cosmic-ray single-event effects, and magnetic insulation degradation received limited testing;

(2) acceleration-factor models (Arrhenius, physics-of-failure) are calibrated to Si and may not transfer cleanly to WBG materials;

(3) hand-built prototypes may not reflect mass-production variability, where early batches typically show higher failure rates. Still, the demonstrated 99.4% availability over six months is encouraging; larger, longer field deployments are needed to build full statistical confidence.

## VIII. CONCLUSION

This work shows SiC-based WBG converters deliver transformative gains over silicon for EV

charging: 98.7% peak efficiency (+3.5 points over Si), sustained across real load variation (98.3% California-weighted efficiency), with 62% smaller volume via 100 kHz switching and correspondingly lower thermal stress (–43°C junction temperature under full load). EMI, though 18% larger in filter volume due to fast switching, was fully manageable via integrated design, and was far outweighed by the 68% magnetic and 54% heatsink volume reductions.

Economically, despite 35% higher component cost, the 2.4-year payback (driven mainly by ~$3,600 in 10-year energy savings) makes a compelling case, strengthening further as WBG prices decline with manufacturing scale. Field validation (1,847 sessions, 67.3 MWh) closely matched lab predictions (97.8% field vs. 98.3% lab efficiency), confirming real-world viability. Bi-directional operation (150 ms mode transition) lays the technical groundwork for V2G services (frequency regulation, peak shaving), pending market/regulatory maturity.

Methodological contributions include a multi-objective (efficiency/density/EMI/cost/reliability) optimization framework, physics-based thermal-electrical co-design, WBG-tailored modulation (28% switching-loss reduction), and empirical EMI-to-design-parameter mapping. At a broader level, this supports transportation electrification and climate goals  small efficiency gains compound to megatons of avoided CO2 at fleet scale. As WBG matures (higher-voltage GaN, better SiC crystal quality, emerging ultra-wide-bandgap materials like gallium oxide), this SiC-to-Si transition parallels earlier power-electronics paradigm shifts (vacuum tubes→solid state, BJT→MOSFET) that became industry standard.

## IX. LIMITATIONS

- Single design point: Validated only at 50 kW; findings may not generalize to ultra-fast (150–350 kW) or Level 2 (3.3–19.2 kW, possibly better served by GaN) charging. Only one physical prototype was built  mass-production variability wasn't captured.
- Limited long-term reliability data: Six months field / 5,000-cycle accelerated testing is short against a 15–20 year service life; degradation modes appearing only long-term (insulation aging, electromigration) may be missed. Reliability models (MTBF >150,000 hrs) are Si-calibrated; gate oxide breakdown remains a specific concern warranting continued monitoring.
- EMI filter penalty: The 18% filter volume increase was inadequately optimized  tested at a single installation, with standardized LISN testing that may not reflect all real-world grid/wiring environments.
- Economic sensitivity: Conclusions depend on assumed electricity prices (which vary 3× by region), utilization (12 hrs/day, 70% load), and continued SiC cost declines  any of which could shift payback substantially.
- Narrow topology comparison: Alternatives (T-type three-level, modular multilevel, matrix converters; LLC/CLLC resonant, phase-shifted full bridge for DC-DC) weren't comprehensively benchmarked against the selected three-level NPC / dual-active-bridge design.
- Battery emulator vs. real batteries: NH Research 9200 emulator replicates electrical characteristics well but not all thermal/transient behaviors; future battery chemistries may need different voltage/charging profiles.
- Environmental scope: Tested –20°C to +50°C, typical humidity; extreme altitude, corrosive/coastal, or high-pollution environments weren't evaluated. Forced-air cooling's long-term filter/dust performance is unverified.
- Control scope: Used conventional voltage-oriented PI control; advanced approaches (MPC, adaptive control, ML-based control) might yield further gains but weren't explored  control optimization was secondary to power-stage design.

## X. PRACTICAL IMPLICATIONS

- Charging infrastructure operators: Deploy WBG for high-utilization sites (18–30 month payback); keep Si for low-utilization sites (4–6 year payback); consider hybrid Si/WBG by charging level. Exploit the 62% smaller footprint (31.5 L) for space-constrained urban sites. Leverage 50°C-capable operation to skip climate-controlled enclosures; passive cooling feasible to ~35 kW. Build condition-based (not reactive) maintenance programs, since wear patterns differ from Si.
- Utilities: Higher efficiency reduces distribution load accordingly; factor this into EV-driven load forecasts. Superior power quality (2.8% THD vs. 4.2%, 0.996 power factor) reduces grid impact differentiate old vs. WBG chargers in planning. Build V2G-ready interconnection/tariff frameworks to leverage the demonstrated 45 ms transient response for ancillary services.
- Automotive OEMs: The achieved power density (1.59 kW/L, 2.75 kW/kg) makes on-board WBG chargers (20–50 kW) increasingly viable. Wide voltage tolerance (200–1000V) frees battery-voltage design choices. Bi-directional capability

supports V2H backup-power features coordinate protocols/interlocks with charger makers.

- Component suppliers: Prioritize switching speed/gate charge/ruggedness over further R_DS(on) reduction; pursue automotive qualification (AEC-Q101). Advanced packaging (chip-on-board, embedded die) and high-frequency-optimized magnetic materials (nanocrystalline/advanced ferrites, integrated magnetics) represent growth opportunities.
- Regulators/standards bodies: Set DCFC efficiency minimums around 97–98% (achievable with current WBG tech) with phased adoption. Revisit EMI standards (CISPR 11, FCC Part 15) designed for slower Si switching. Update safety testing for WBG's higher speeds/voltages. Clarify V2G-specific interconnection requirements (IEEE 1547, UL 1741) anti-islanding, reactive power, fault ride-through.

## XI. FUTURE RESEARCH

- Ultra-high power (150–350 kW): Thermal management gets harder despite efficiency gains (absolute loss magnitude grows e.g., 5.25 kW dissipated at 350kW/98.5%), likely requiring liquid cooling; high current (438A at 800V/350kW) needs paralleling/bus-bar research. Modular multilevel, interleaved parallel, and hybrid topologies merit comparison.
- GaN for lower-voltage applications: Topology optimization for GaN's very-high-frequency capability (200–500 kHz), tailored thermal/packaging design (GaN's lower thermal conductivity vs. SiC), and cost-performance analysis as GaN pricing matures.
- ML-based control: Adaptive control learning optimal parameters over time; predictive maintenance from efficiency/temperature/harmonic trends; ML-based energy management for sites with storage/solar; deep-learning anomaly detection from thermal/waveform/vibration data.
- Wireless power transfer integration: WBG-enabled high-frequency (85 kHz) WPT rectification/resonant integration, compensation topology for wide voltage ranges, foreign-object detection, efficiency across misalignment.
- Grid-forming capability: As EV charging approaches 20–40% of grid load by 2040 in high-penetration scenarios, WBG's fast response could support grid-forming/virtual-synchronous-machine functions and black-start capability areas Si struggles to serve.
- Advanced magnetics: Broader materials comparison (Vitroperm, Finemet, amorphous alloys); additive-manufactured cores enabling integrated cooling/optimized windings; air-core designs for >200 kHz operation.
- Matrix/direct AC-AC converters: WBG-enabled matrix converters eliminating DC-link capacitors needs commutation strategy, modulation, and fault-protection research specific to the no-DC-link case.
- Cryogenic cooling: System-level efficiency/economics of cryogenic operation (better SiC/GaN characteristics at low temp) vs. refrigeration overhead; niche applications (aerospace, mobile fast-charging trucks).
- Standardization: Communication protocols (ISO 15118, V2G), standardized efficiency/thermal/EMI/reliability testing, and vendor-neutral diagnostic interfaces.
- Lifecycle/environmental assessment: Full LCA comparing WBG vs. Si manufacturing impact, end-of-life recycling/rare-earth recovery, and second-life/remanufacturing potential.
- Failure mode & resilience: FMEA-driven fault-tolerant topologies (redundant legs, bypass/modular isolation), prognostic health monitoring, and cybersecurity for networked V2G/remote-management converters.
- Global technology transfer: Designs robust to weak-grid conditions (voltage/frequency variation, sags, harmonics), cost-optimized hybrid WBG/Si designs for price-sensitive markets, and local manufacturing/workforce development for global deployment.

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