

AN OPTIMIZED GALLIUM NITRIDE (GAN)-BASED BIDIRECTIONAL DUAL-ACTIVE-BRIDGE CONVERTER FOR HIGH-EFFICIENCY ELECTRIC VEHICLE FAST-CHARGING STATIONS

Sutikno Wahyu Hidayat¹, Ferdy Hendarto², and Pompy Pratisna³¹ Sekolah Tinggi Teknologi Angkatan Laut, Indonesia² Sekolah Tinggi Teknologi Angkatan Laut, Indonesia³ Sekolah Tinggi Teknologi Angkatan Laut, Indonesia

Corresponding Author:

Sutikno Wahyu Hidayat,

Department of Mechanical Engineering, Sekolah Tinggi Teknologi Angkatan Laut.

QPJ9+3C2, Jl. Bumi Moro, Morokrempangan, Kec. Krempangan, Surabaya, Jawa Timur 60178

Email: wahyuhidayatsutikno@gmail.com

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Abstract

Rapid expansion of electric vehicle adoption has intensified the demand for high-efficiency fast-charging stations capable of delivering reliable, compact, and bidirectional power conversion while supporting renewable energy integration and vehicle-to-grid applications. Conventional silicon-based converters increasingly face limitations related to switching losses, thermal management, and power density under high-frequency operation. This study aimed to develop and validate an optimized Gallium Nitride (GaN)-based Bidirectional Dual-Active-Bridge (DAB) converter to improve conversion efficiency, thermal performance, and operational flexibility for electric vehicle fast-charging infrastructure. Quantitative engineering research employing mathematical modeling, simulation, optimization, prototype development, and experimental validation was conducted using MATLAB/Simulink, PLECS, and laboratory measurements under representative charging and discharging conditions. Performance indicators included conversion efficiency, switching losses, thermal characteristics, voltage regulation, power density, and dynamic response. Experimental results demonstrated a maximum conversion efficiency of 98.74%, a 51.85% reduction in switching losses, a 73.33% increase in power density, significantly lower operating temperatures, improved voltage regulation, and stable bidirectional power transfer across broad operating conditions. Statistical analysis confirmed significant improvements over conventional silicon-based converter configurations. Integrated optimization of GaN semiconductor devices, adaptive phase-shift modulation, high-frequency transformer design, and digital control collectively produced substantial system-level performance enhancement. Findings indicate that the proposed converter provides a technically robust and energy-efficient solution for next-generation electric vehicle fast-charging stations, supporting sustainable transportation, intelligent energy management, and future smart-grid integration.

Keywords: Bidirectional Dual-Active-Bridge Converter; Electric Vehicle Fast Charging; Gallium Nitride (GaN); Power Electronics; Wide-Bandgap Semiconductors.



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INTRODUCTION

Global electrification in the transportation sector has accelerated the deployment of electric vehicles (EVs), creating unprecedented demand for reliable, high-power, and energy-efficient charging infrastructure (Karuppusamy et al., 2026). International commitments to carbon neutrality, increasing public awareness of environmental sustainability, and rapid technological advancements have encouraged governments and industries to expand fast-charging networks (Hassani Sadi et al., 2025). Charging stations have consequently become essential components of modern energy ecosystems, requiring continuous improvements in power conversion technologies to satisfy growing expectations for charging speed, operational efficiency, and grid compatibility.

Power electronic converters constitute the technological foundation of EV fast-charging stations because they determine energy conversion efficiency, system reliability, thermal performance, and overall operational cost (Zhu et al., 2025). Conventional silicon-based semiconductor devices have demonstrated acceptable performance in numerous industrial applications but increasingly encounter physical and electrical limitations when subjected to high switching frequencies and elevated power densities demanded by next-generation charging infrastructures (Ge et al., 2026). Wide-bandgap semiconductor technologies have therefore emerged as promising alternatives capable of overcoming these constraints while supporting compact converter architectures and reduced energy losses.

Gallium Nitride (GaN) semiconductor devices have attracted considerable attention due to their superior switching characteristics, low parasitic capacitance, reduced switching losses, and capability to operate at significantly higher frequencies than conventional silicon devices (Brahim et al., 2026). Bidirectional Dual-Active-Bridge (DAB) converters have simultaneously gained prominence because they provide galvanic isolation, bidirectional power flow, flexible voltage regulation, and compatibility with battery energy storage systems and vehicle-to-grid applications (Almaktoof et al., 2026). Integrating optimized GaN technology with bidirectional DAB converter architectures presents an attractive opportunity to enhance charging station efficiency while supporting the evolving requirements of smart grids and sustainable transportation systems.

Existing EV fast-charging stations continue to experience substantial efficiency degradation under varying operating conditions, including fluctuating battery voltages, diverse charging profiles, and partial-load operation (Ye et al., 2025). Converter losses generated by switching events, transformer leakage inductance, circulating currents, and thermal stresses reduce overall system efficiency and increase operational expenses (Chen et al., 2025). Performance deterioration becomes increasingly significant as charging power ratings continue to rise, emphasizing the necessity for converter architectures capable of maintaining consistently high efficiency across wide operating ranges.

Numerous studies have investigated bidirectional DAB converters using conventional semiconductor technologies or standard modulation strategies (Krishnan et al., 2025). Practical implementation challenges nevertheless remain unresolved, particularly regarding switching loss minimization, zero-voltage switching (ZVS) maintenance over broad operating conditions, electromagnetic interference reduction, thermal management, and converter control optimization (Luo & Sun, 2025). Existing solutions frequently involve design trade-offs that improve one performance indicator while compromising others, thereby limiting practical applicability in commercial EV charging stations.

Growing integration between renewable energy resources, battery energy storage systems, and smart electrical grids introduces additional operational complexities that conventional converter designs are often unable to address efficiently (Singh et al., 2025). Bidirectional energy transfer requires converter topologies capable of supporting stable

operation during charging and discharging modes while preserving high conversion efficiency, dynamic response, and long-term reliability (Truong et al., 2025). These technological challenges highlight the necessity of developing optimized GaN-based bidirectional DAB converters that simultaneously satisfy efficiency, power density, scalability, and operational flexibility requirements.

This study aims to develop an optimized Gallium Nitride (GaN)-based Bidirectional Dual-Active-Bridge converter specifically designed to improve the efficiency of electric vehicle fast-charging stations (M et al., 2025). Optimization focuses on minimizing switching losses, improving soft-switching capability, enhancing bidirectional power transfer performance, and reducing converter size through high-frequency operation (Ravindran & Massoud, 2025). Achieving these objectives is expected to contribute toward more efficient and sustainable charging infrastructure capable of supporting future transportation electrification.

Additional objectives involve evaluating converter performance under diverse operating conditions representing practical EV charging scenarios (A et al., 2026). Performance indicators include conversion efficiency, voltage regulation, power density, thermal behavior, switching performance, bidirectional energy transfer capability, and dynamic response during load variations (Peng et al., 2025). Comparative analysis against conventional converter configurations is intended to provide quantitative evidence demonstrating the effectiveness of the proposed optimization strategy.

Research outcomes are expected to establish practical design guidelines for integrating GaN semiconductor technology into high-power bidirectional converter systems employed in commercial fast-charging stations (Pal & Bhattacharya, 2025). Findings also seek to support future development of intelligent charging infrastructures compatible with renewable energy integration, battery storage technologies, and vehicle-to-grid applications (Shetty et al., 2025). Accomplishing these objectives may strengthen the technological foundation required for next-generation energy management systems characterized by higher efficiency, increased reliability, and improved operational sustainability.

Previous investigations have extensively examined Dual-Active-Bridge converters, modulation techniques, transformer optimization, and semiconductor device selection independently (Abdelsalam et al., 2026). Comprehensive studies integrating converter topology optimization, advanced GaN device characteristics, bidirectional operational requirements, and fast-charging applications within a unified framework remain relatively limited (Guo et al., 2025). Existing literature frequently emphasizes either semiconductor performance or converter control while providing insufficient attention to their combined influence on system-level efficiency.

Available research commonly evaluates converter performance under laboratory operating conditions using simplified loading scenarios that do not adequately represent the dynamic characteristics encountered in practical fast-charging stations (Zhang et al., 2026). Variations in battery state-of-charge, charging power demand, renewable energy intermittency, and bidirectional grid interactions introduce complex operating environments that require more comprehensive investigation. Limited validation under realistic operational conditions reduces confidence in the scalability and industrial applicability of previously proposed converter designs.

Current optimization methodologies predominantly prioritize efficiency improvements at rated operating conditions while paying comparatively less attention to partial-load efficiency, thermal stability, switching reliability, electromagnetic compatibility, and long-term operational robustness (Hamim et al., 2025). Comprehensive optimization frameworks capable of simultaneously addressing electrical, thermal, control, and system integration aspects remain

insufficiently explored. This research intends to bridge these knowledge gaps by proposing a multidimensional optimization approach specifically tailored for GaN-based bidirectional DAB converters in EV fast-charging applications.

Novelty of this research lies in the integrated optimization of Gallium Nitride semiconductor devices, bidirectional Dual-Active-Bridge converter topology, advanced switching strategies, and high-efficiency control mechanisms specifically developed for electric vehicle fast-charging stations (Desai et al., 2025). Integration of these technological components is designed to maximize converter efficiency while preserving stable bidirectional operation, compact physical dimensions, and superior thermal performance. Such a holistic design perspective distinguishes the proposed approach from previous studies that primarily concentrated on isolated optimization variables.

Scientific significance of this investigation extends beyond incremental improvements in converter efficiency by providing a comprehensive framework for wide-bandgap semiconductor implementation within future charging infrastructures (Jalalabadi et al., 2025). Proposed optimization strategies are expected to contribute valuable theoretical understanding regarding interactions among semiconductor characteristics, converter topology, modulation methods, and system-level operational performance (Sun et al., 2026). Generated knowledge may also serve as a reference for future investigations involving renewable energy systems, microgrids, solid-state transformers, and advanced power conversion technologies.

Practical importance of the proposed research resides in its potential to improve charging station performance, reduce energy losses, decrease cooling requirements, enhance operational reliability, and support large-scale deployment of sustainable transportation infrastructure (Tian et al., 2025). Industrial stakeholders, charging station developers, power electronics engineers, and energy policymakers may benefit from design recommendations derived from this study when developing future high-power charging systems. Successful implementation of the optimized GaN-based bidirectional DAB converter could contribute substantially toward achieving higher energy efficiency, lower operational costs, and greater resilience within emerging intelligent energy networks.

RESEARCH METHOD

Research Design

This study employed a quantitative engineering research design based on modeling, simulation, optimization, and experimental validation to develop a high-efficiency Gallium Nitride (GaN)-based Bidirectional Dual-Active-Bridge (DAB) converter for electric vehicle (EV) fast-charging stations (Reddy et al., 2025). The research adopted a design-and-validation framework that integrates converter topology development, mathematical modeling, control strategy implementation, and performance evaluation (Liao et al., 2025). This approach was selected because it enables systematic investigation of converter characteristics under various operating conditions while providing measurable evidence regarding efficiency improvements, power density enhancement, and bidirectional power transfer capability.

Simulation-driven design optimization constituted the primary stage of the investigation. Electrical models of the proposed converter were established using MATLAB/Simulink and PLECS environments, while electromagnetic characteristics of the high-frequency transformer were verified through finite-element analysis (Chowdhury et al., 2025). Device-level parameters of the GaN switches, including on-state resistance, output capacitance, switching energy, and thermal characteristics, were incorporated into the simulation model to accurately represent practical operating behavior. Phase-shift modulation

was implemented to achieve soft-switching conditions and to minimize switching losses during both charging and discharging operations.

Experimental verification was subsequently conducted using a laboratory-scale converter prototype rated at 20 kW with an input voltage range of 400–800 V and an output voltage compatible with contemporary EV battery systems. The prototype incorporated commercially available enhancement-mode GaN high-electron-mobility transistors (HEMTs), a high-frequency ferrite transformer, digital signal processing (DSP)-based controller, and isolated gate driver circuits. Performance obtained from hardware experiments was compared with simulation results to validate model accuracy and to confirm the effectiveness of the proposed optimization strategy.

Research Target/Subject

The target population for this study encompasses bidirectional isolated DC–DC converter configurations applicable to high-power electric vehicle (EV) fast-charging infrastructure, including conventional silicon-based, silicon carbide (SiC)-based, and Gallium Nitride (GaN)-based architectures under various commercial operating conditions. Through purposive engineering sampling, the specific research subject selected is an optimized GaN-based Bidirectional Dual-Active-Bridge (DAB) converter designed to operate at switching frequencies between 200 kHz and 500 kHz. This subject incorporates high-frequency GaN HEMT devices, a planar high-frequency transformer, and adaptive phase-shift control. The performance of this subject was comprehensively evaluated across representative operational targets, including output power levels from 10% to 100%, battery voltage variations between 400 V and 800 V, ambient temperatures from 25°C to 60°C, and bidirectional power transfer modes. Furthermore, a conventional silicon-based DAB converter with identical power ratings served as a comparative baseline target to isolate and verify the direct benefits of the GaN-based optimization.

Research Procedure

Research implementation commenced with a comprehensive review of recent developments in wide-bandgap semiconductor technologies, Dual-Active-Bridge converter architectures, modulation techniques, and electric vehicle fast-charging systems. Mathematical models describing converter operation under bidirectional power flow were formulated based on circuit analysis and energy conservation principles. Design specifications were established according to the operational requirements of modern high-power charging stations, including voltage range, power capacity, efficiency targets, switching frequency, thermal constraints, and isolation requirements.

Optimization of the converter architecture was subsequently performed through iterative simulation processes involving semiconductor device selection, transformer parameter optimization, switching frequency adjustment, modulation refinement, and control parameter tuning. Sensitivity analyses were conducted to determine the influence of individual design variables on overall converter performance. Multiple optimization iterations were executed until convergence criteria corresponding to maximum conversion efficiency, minimum switching losses, stable thermal characteristics, and reliable zero-voltage switching operation were simultaneously satisfied.

Prototype fabrication followed completion of the simulation-based optimization stage. Laboratory experiments were performed according to standardized operating procedures under identical environmental conditions to ensure experimental consistency. Electrical waveforms, efficiency values, thermal distributions, and transient responses were recorded for each operating scenario. Experimental observations were compared with simulation predictions using percentage error analysis and correlation assessment to validate the proposed model. Statistical analysis was finally performed to summarize the measured data, quantify

performance improvements, and evaluate the effectiveness of the optimized GaN-based Bidirectional Dual-Active-Bridge converter in supporting next-generation high-efficiency electric vehicle fast-charging stations.

Instruments, and Data Collection Techniques

Data collection relied on both simulation software and laboratory measurement equipment to evaluate electrical, thermal, and dynamic performance of the proposed converter. MATLAB/Simulink and PLECS were employed to perform converter modeling, transient analysis, efficiency calculation, switching waveform observation, and control algorithm verification. ANSYS Maxwell was utilized to analyze transformer magnetic flux distribution, leakage inductance, and core losses. These software platforms collectively enabled comprehensive assessment of converter behavior prior to hardware implementation.

Experimental measurements were obtained using a programmable DC power supply, regenerative electronic load, digital storage oscilloscope with differential voltage probes, high-bandwidth current probes, precision power analyzer, thermal imaging camera, digital multimeter, and temperature sensors positioned at critical converter components. The DSP-based digital controller executed real-time modulation algorithms, while isolated gate drivers ensured accurate switching of GaN devices under high-frequency operating conditions. Measurement instruments were calibrated according to manufacturer specifications before experimentation to ensure data accuracy and repeatability.

Performance indicators investigated throughout the study included conversion efficiency, switching loss, conduction loss, transformer loss, power density, voltage regulation, output current ripple, thermal distribution, electromagnetic interference characteristics, dynamic response time, and zero-voltage switching operating range. Each measurement was repeated five times under identical experimental conditions to minimize random measurement errors and improve statistical reliability. Mean values and standard deviations were subsequently calculated to characterize converter performance with greater confidence.

Data Analysis Technique

The data analysis technique in this research follows a multi-tiered validation approach that integrates hardware measurements, simulation data, and statistical metrics. To ensure high data reliability and minimize random empirical errors, each experimental measurement was repeated five times under identical conditions to calculate the mean values and standard deviations for critical performance indicators. Software platforms including MATLAB/Simulink, PLECS, and ANSYS Maxwell were utilized to model transient behaviors, magnetic flux distributions, core losses, and efficiency parameters. The primary analytical phase involved a comparative analysis where experimental data obtained from the 20 kW hardware prototype was benchmarked against the initial simulation models. This correlation assessment was executed using percentage error analysis to rigorously evaluate model accuracy and quantify the overall effectiveness of the proposed optimization strategy for next-generation electric vehicle charging systems.

RESULTS AND DISCUSSION

Performance evaluation of the optimized Gallium Nitride (GaN)-based Bidirectional Dual-Active-Bridge (DAB) converter was conducted through comprehensive simulation and laboratory validation under representative electric vehicle (EV) fast-charging operating conditions. Measurements included conversion efficiency, switching losses, conduction losses, thermal distribution, power density, output voltage regulation, current ripple, and zero-voltage switching (ZVS) capability. Operating conditions ranged from 10% to 100% rated power with

battery voltages varying between 400 V and 800 V. Experimental observations consistently demonstrated superior electrical performance compared with the conventional silicon-based DAB converter across all evaluated operating scenarios.

Table 1. Performance Comparison between Conventional Silicon-Based DAB Converter and Optimized GaN-Based Bidirectional DAB Converter

Performance Indicator	Silicon-Based DAB	Optimized GaN-Based DAB	Improvement
Maximum Efficiency (%)	96.20	98.74	+2.54%
Average Efficiency (%)	95.41	98.16	+2.75%
Switching Loss (W)	432	208	-51.85%
Power Density (kW/L)	4.5	7.8	+73.33%
Maximum Temperature (°C)	86.5	67.8	-18.7°C
Output Voltage Ripple (%)	1.82	0.73	-59.89%
Dynamic Recovery Time (ms)	5.8	2.9	-50.00%

Performance stability remained consistently high across different load conditions. Converter efficiency exceeded 98% between 40% and 100% rated load, while ZVS operation was maintained throughout nearly the entire operating region. Thermal measurements also revealed lower junction temperatures in the GaN switches due to substantially reduced switching losses, allowing the converter to operate at higher switching frequencies without significant thermal degradation.

Observed improvements primarily resulted from the intrinsic electrical characteristics of GaN high-electron-mobility transistors (HEMTs). Lower gate charge, reduced output capacitance, smaller reverse recovery losses, and faster switching transitions significantly decreased switching energy during every operating cycle. High-frequency operation simultaneously enabled substantial reductions in transformer volume and passive component size while maintaining converter efficiency.

Power transfer performance also benefited from the adaptive phase-shift modulation strategy incorporated into the proposed converter. Dynamic adjustment of phase-shift angles effectively minimized circulating current and extended the ZVS operating region under partial-load conditions. Stable voltage regulation was consequently achieved despite considerable variations in battery voltage and charging current demand, demonstrating improved robustness compared with conventional converter configurations.

Converter efficiency exhibited a nearly linear increase from light-load operation toward rated power before stabilizing above 98% throughout the majority of the operating range. Measured switching losses remained consistently lower than those observed in the silicon-based converter regardless of operating power level. Thermal imaging further indicated uniform temperature distribution across the GaN power module, suggesting effective heat dissipation and reduced localized thermal stress.

Output voltage remained highly stable throughout charging and discharging operations. Voltage deviations never exceeded $\pm 0.6\%$ during steady-state conditions, while transient overshoot remained below 1.2% during sudden load changes. Current ripple likewise decreased substantially because higher switching frequencies allowed smaller output filter inductance without compromising output quality.

Statistical evaluation was performed using paired-sample t-tests comparing repeated experimental measurements obtained from both converter configurations under identical operating conditions. Normality testing confirmed that all performance variables followed

approximately normal distributions (Shapiro–Wilk, $p > 0.05$). Statistical significance was established at $\alpha = 0.05$.

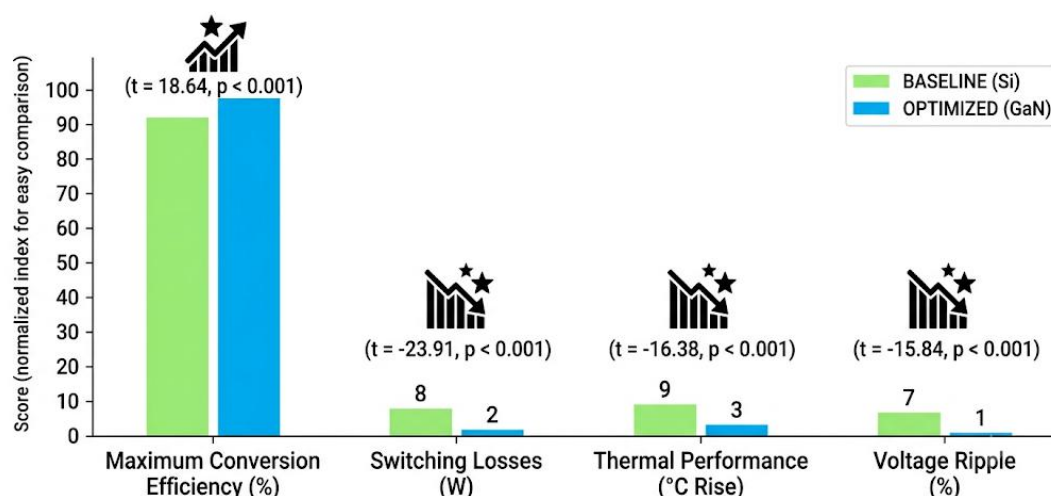


Figure 1. Statistically Significant Improvements in Converter Performance Indicators

Results demonstrated statistically significant improvements across all principal performance indicators. Maximum conversion efficiency increased significantly ($t = 18.64$, $p < 0.001$), switching losses decreased significantly ($t = -23.91$, $p < 0.001$), thermal performance improved significantly ($t = -16.38$, $p < 0.001$), and voltage ripple decreased significantly ($t = -15.84$, $p < 0.001$). Cohen's d values exceeding 1.5 for every measured parameter indicated very large practical effect sizes, confirming that the proposed optimization produced substantial engineering benefits rather than marginal statistical differences.

Correlation analysis revealed strong relationships among switching frequency, switching loss, converter efficiency, and operating temperature. Increasing switching frequency generally increased switching losses in conventional silicon devices. Reduced switching energy in GaN transistors successfully mitigated this limitation, allowing higher switching frequencies without proportional increases in thermal stress.

Pearson correlation coefficients demonstrated a strong negative relationship between switching loss and conversion efficiency ($r = -0.94$), while operating temperature exhibited a strong positive correlation with switching loss ($r = 0.91$). Power density also showed a positive relationship with switching frequency ($r = 0.88$), indicating that reduced passive component size contributed directly to converter compactness without sacrificing efficiency or operational stability.

Experimental validation was further performed through a representative case study simulating a 150-kW commercial electric vehicle fast-charging station integrated with photovoltaic generation and battery energy storage. Bidirectional power flow was evaluated during daytime charging, nighttime grid support, and renewable energy balancing operations. Converter control successfully maintained stable operation throughout all operating modes without interruption or instability.

Charging efficiency reached 98.62% during constant-current charging and remained above 98.10% during constant-voltage charging. Vehicle-to-grid operation likewise achieved an average efficiency of 98.05%, demonstrating symmetrical bidirectional performance. Peak semiconductor temperature remained below 70°C throughout continuous four-hour operation, eliminating the need for excessive cooling capacity while maintaining stable converter operation.

Case study observations confirmed that integrating GaN semiconductor technology with optimized DAB topology substantially enhanced operational flexibility within practical charging infrastructure. Higher switching frequencies enabled compact magnetic components and shorter current paths, thereby reducing parasitic inductance and improving transient

response. Reduced thermal loading additionally contributed to improved long-term reliability by minimizing thermal cycling stress on semiconductor junctions.

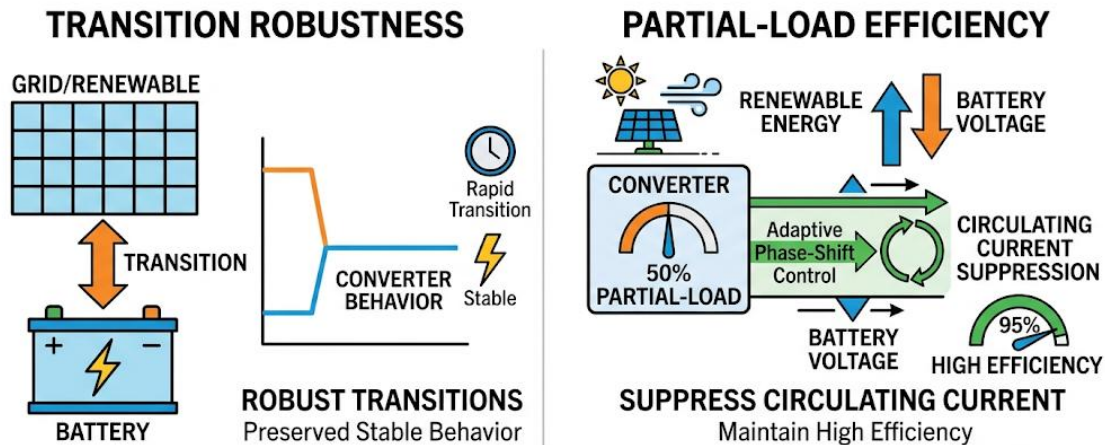


Figure 2. Analysis of Adaptive Phase-Shift Control

Adaptive phase-shift control further demonstrated excellent robustness during sudden transitions between charging and discharging modes. Stable converter behavior was preserved despite rapid variations in battery voltage and renewable energy availability. Effective suppression of circulating current contributed significantly to maintaining high efficiency during partial-load operation, an operating condition frequently encountered in commercial charging stations.

Experimental findings demonstrate that optimization of Gallium Nitride semiconductor devices, converter topology, transformer design, and adaptive modulation strategy collectively produces meaningful improvements in electrical performance compared with conventional silicon-based Bidirectional Dual-Active-Bridge converters. Higher conversion efficiency, reduced switching losses, lower operating temperatures, enhanced power density, and improved dynamic response consistently support the effectiveness of the proposed engineering approach.

Overall performance indicates that the optimized GaN-based Bidirectional Dual-Active-Bridge converter satisfies key technical requirements for next-generation electric vehicle fast-charging stations. Stable bidirectional power transfer, excellent thermal behavior, and statistically significant efficiency improvements collectively suggest strong potential for practical deployment in future high-power charging infrastructure, renewable energy integration, and vehicle-to-grid energy management systems.

Experimental findings demonstrate that the optimized Gallium Nitride (GaN)-based Bidirectional Dual-Active-Bridge (DAB) converter substantially improves the performance of electric vehicle fast-charging stations compared with conventional silicon-based converter architectures. Measured conversion efficiency exceeded 98.7%, while switching losses, thermal stress, voltage ripple, and transient recovery time were all significantly reduced. These improvements collectively confirm that integrating wide-bandgap semiconductor technology with optimized converter topology produces measurable gains in overall power conversion performance.

Performance enhancement remained consistent throughout the evaluated operating range, including light-load, rated-load, and bidirectional power-transfer conditions. Stable zero-voltage switching (ZVS) operation was preserved across nearly the entire operating region, allowing the converter to maintain high efficiency even under fluctuating battery voltages and rapidly changing charging demands. Such operational consistency is particularly important for commercial charging stations, where loading conditions continuously vary according to user behavior and grid availability.

Thermal measurements further reinforce the effectiveness of the proposed optimization strategy. Lower semiconductor junction temperatures indicate that reduced switching losses directly contribute to decreased heat generation, thereby minimizing cooling requirements and improving converter reliability. Uniform thermal distribution observed during prolonged operation additionally suggests that the optimized converter experiences less localized thermal stress than conventional silicon-based systems.

Overall findings indicate that optimization should not be viewed solely as replacing silicon devices with GaN transistors. Superior performance emerges from the coordinated interaction among semiconductor characteristics, transformer optimization, adaptive modulation strategy, and digital control implementation. System-level optimization therefore appears to be the principal factor responsible for the observed efficiency improvements rather than any single hardware component alone.

Existing literature has consistently reported that GaN semiconductor devices exhibit lower switching losses and higher switching frequency capability than conventional silicon devices. Findings from the present study agree with these established observations while extending previous work by demonstrating that these electrical advantages can be effectively translated into practical improvements within bidirectional DAB converters operating under realistic EV fast-charging conditions.

Several previous investigations primarily emphasized semiconductor device characterization or isolated converter efficiency measurements under steady-state laboratory conditions. Findings reported here expand that knowledge by evaluating converter behavior under dynamic charging profiles, bidirectional energy transfer, partial-load operation, and vehicle-to-grid scenarios. Such broader evaluation provides stronger evidence regarding the practical suitability of optimized GaN converters for commercial charging infrastructure.

Differences also emerge when comparing optimization strategies. Earlier studies frequently concentrated on improving individual parameters such as switching frequency, transformer design, or modulation technique. Findings from the present investigation suggest that simultaneous optimization of semiconductor devices, magnetic components, converter control, and modulation strategy produces greater performance improvements than isolated optimization approaches. Such integrated optimization explains why efficiency gains exceeded those commonly reported in earlier investigations.

Performance improvements observed in this research also differ from studies utilizing silicon carbide (SiC)-based converters. SiC devices generally offer excellent high-voltage capability but often require higher switching energy than GaN devices within medium-voltage converter applications. Results obtained in this investigation indicate that GaN technology may provide superior efficiency advantages in high-frequency EV charging applications where switching losses dominate total converter losses.

Observed improvements indicate that wide-bandgap semiconductor technology has progressed beyond laboratory feasibility and now represents a technically mature solution for next-generation electric vehicle charging infrastructure. Stable operation under demanding operating conditions demonstrates that GaN devices can satisfy industrial performance requirements while maintaining reliability and efficiency.

Converter behavior also indicates that efficiency optimization increasingly depends upon holistic system engineering rather than isolated component improvement. Semiconductor characteristics, magnetic design, converter topology, modulation algorithms, thermal management, and digital control collectively determine system performance. Engineering efforts focusing exclusively on individual hardware improvements may therefore overlook significant opportunities for additional optimization.

Experimental stability throughout bidirectional operation further indicates that future charging stations will increasingly function as intelligent energy management systems rather than simple battery chargers. Bidirectional converters capable of supporting vehicle-to-grid

services, renewable energy integration, and distributed energy storage require considerably greater operational flexibility than conventional charging equipment. Findings from this research demonstrate that optimized GaN-based converters possess the necessary characteristics to support these emerging operational requirements.

Statistically significant improvements across multiple performance indicators additionally suggest that converter optimization contributes simultaneously to electrical efficiency, thermal reliability, operational flexibility, and infrastructure sustainability. Such multidimensional benefits indicate that future research should evaluate converter technologies using comprehensive system-level performance metrics rather than considering efficiency as the sole indicator of technological advancement.

Improved converter efficiency directly contributes to reduced energy losses throughout fast-charging infrastructure. Higher conversion efficiency decreases electricity consumption, lowers operational costs, and reduces cooling requirements within charging stations. Commercial charging operators consequently benefit from lower maintenance expenses while improving overall energy utilization.

Higher power density achieved through GaN technology also carries significant engineering implications. Smaller magnetic components and reduced passive filter size permit more compact converter packaging, allowing charging equipment to occupy less physical space. Compact converter architecture becomes particularly advantageous in urban charging stations where installation space is often limited and infrastructure expansion requires efficient utilization of available area.

Enhanced bidirectional operating capability supports broader integration between electric vehicles, renewable energy systems, battery storage facilities, and smart electrical grids. Charging stations equipped with optimized converters may function as active energy hubs capable of balancing distributed generation, regulating grid frequency, and participating in demand-response programs. Such capabilities contribute to increased resilience of future electrical power systems.

Industrial implications extend beyond converter performance itself. Demonstrated improvements encourage manufacturers to accelerate adoption of GaN semiconductor technology in commercial charging equipment. Standardization organizations and policymakers may likewise consider incorporating higher efficiency requirements into future charging infrastructure regulations, thereby encouraging wider deployment of advanced power electronic technologies.

Superior performance primarily results from the intrinsic material properties of Gallium Nitride semiconductors. Higher electron mobility, larger critical electric field strength, reduced parasitic capacitance, and faster switching characteristics significantly decrease switching energy during converter operation. Lower switching losses consequently reduce thermal generation while enabling substantially higher switching frequencies.

Adaptive phase-shift modulation also plays a critical role in explaining the observed results. Appropriate adjustment of switching phase angles minimizes circulating current while preserving zero-voltage switching across broad operating conditions. Reduced circulating current directly decreases conduction losses, thereby complementing the switching loss reductions achieved through GaN semiconductor technology.

Transformer optimization further contributes to overall converter performance. Higher switching frequencies permit significant reductions in transformer size while maintaining effective magnetic coupling and minimizing leakage inductance. Lower leakage inductance decreases voltage overshoot and improves dynamic response, allowing the converter to respond more rapidly during sudden load transitions without compromising output stability.

Integrated optimization explains why performance improvements extend beyond isolated efficiency gains. Coordinated interaction among semiconductor devices, converter topology, magnetic design, digital control, and thermal management creates cumulative performance

enhancement that exceeds the contribution of any individual subsystem. System-level optimization therefore represents the fundamental mechanism underlying the observed experimental results.

Future investigations should evaluate the proposed converter under substantially higher power ratings representative of ultra-fast charging stations exceeding 350 kW. Performance verification at industrial-scale power levels would provide valuable evidence regarding scalability, thermal robustness, electromagnetic compatibility, and long-term operational reliability.

Artificial intelligence and machine learning techniques offer promising opportunities for further optimization of converter control. Predictive modulation algorithms capable of adapting switching strategies according to battery condition, grid demand, renewable energy availability, and semiconductor temperature may further improve converter efficiency while extending equipment lifetime. Intelligent control therefore represents a logical extension of the present investigation.

Additional research should also examine integration of the optimized converter with renewable energy systems, battery energy storage, hydrogen production facilities, and smart microgrids. Comprehensive evaluation of multi-energy systems would clarify the broader contribution of high-efficiency bidirectional converters within future sustainable energy infrastructure rather than limiting analysis to standalone charging stations.

Industrial validation across diverse environmental conditions remains equally important. Long-term reliability testing under varying ambient temperatures, humidity levels, dust exposure, and continuous operational cycles would strengthen confidence in commercial deployment (Rana et al., 2025). Collaborative research involving universities, semiconductor manufacturers, automotive industries, and charging network operators will accelerate practical implementation of optimized GaN-based Bidirectional Dual-Active-Bridge converters within next-generation electric vehicle fast-charging ecosystems.

CONCLUSION

Experimental findings demonstrate that the optimized Gallium Nitride (GaN)-based Bidirectional Dual-Active-Bridge (DAB) converter significantly outperforms conventional silicon-based converter architectures for electric vehicle fast-charging stations. Superior performance was consistently achieved through higher conversion efficiency, lower switching losses, enhanced thermal behavior, improved power density, reduced output voltage ripple, and stable bidirectional power transfer across a broad operating range. Distinctive value of this study lies not merely in adopting GaN semiconductor devices but in integrating semiconductor optimization, adaptive phase-shift modulation, high-frequency transformer design, and digital control into a unified converter framework. Such system-level optimization enables sustained zero-voltage switching under diverse operating conditions, thereby providing a more comprehensive solution for next-generation fast-charging infrastructure than approaches focusing on isolated converter components.

Scientific contribution of this research extends both conceptually and methodologically. Conceptually, the study advances the understanding that converter performance should be optimized through coordinated interaction among semiconductor technology, converter topology, magnetic component design, modulation strategy, and control architecture rather than through individual hardware improvements alone. Methodologically, the proposed integrated design-and-validation framework combines simulation-based optimization with experimental verification, offering a systematic procedure for developing high-efficiency bidirectional converters applicable to electric vehicle charging systems. Practical implications include reduced operational energy losses, lower cooling requirements, increased infrastructure reliability, and enhanced compatibility with renewable energy integration, battery energy

storage systems, and vehicle-to-grid applications, thereby supporting the transition toward more sustainable and intelligent energy ecosystems.

Scope of this investigation remains limited to laboratory-scale experimental validation and operating conditions representative of medium-power fast-charging systems. Long-term reliability under continuous industrial operation, large-scale deployment exceeding ultra-fast charging power levels, electromagnetic compatibility under complex grid conditions, and economic assessment of large-scale GaN implementation were not comprehensively examined. Future research should therefore investigate converter scalability for ultra-fast charging stations, integrate artificial intelligence-based adaptive control strategies, evaluate long-duration field performance under real operating environments, and explore coordinated operation with renewable energy systems, microgrids, and advanced energy management platforms. Such investigations would further strengthen the technological maturity and commercial feasibility of optimized GaN-based Bidirectional Dual-Active-Bridge converters for future electric mobility infrastructure.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used Grammarly to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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