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Development of Bidirectional on – Board Charge for Evs Using Gan – Based Power Convertors

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Abstract: - The rapid growth of electric vehicles (EVs) has increased the need for efficient, compact, and intelligent charging systems that can support modern power grids. This work presents the development of a bidirectional on-board charger (OBC) using Gallium Nitride (GaN)-based power converters to improve efficiency, power density, and overall performance. The proposed system operates in both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes, enabling EVs to not only consume energy but also supply power back to the grid. GaN devices are utilized due to their high switching frequency, low losses, and reduced thermal stress, allowing smaller passive components and a more compact design compared to conventional silicon-based chargers. The system consists of an AC-DC power factor correction (PFC) stage followed by a bidirectional DC-DC converter, ensuring efficient energy transfer and isolation. Advanced control strategies are implemented to regulate power flow, maintain unity power factor, and ensure stable operation under varying conditions. The model is developed in MATLAB/Simulink for performance evaluation. Simulation results show efficiency above 95%, low Total Harmonic Distortion (THD), and fast dynamic response. The system meets grid standards and enhances grid support through peak shaving and load balancing.

Keywords: Bidirectional On-Board Charger (OBC); Gallium Nitride (GaN) Converters; Vehicle-to-Grid (V2G); Power Factor Correction (PFC); Total Harmonic Distortion (THD)

1. Introduction

The rapid growth of electric vehicles (EVs) is transforming the global transportation and energy sectors by reducing dependence on fossil fuels and minimizing environmental pollution. However, the increasing penetration of EVs presents new challenges in terms of efficient energy management, charging infrastructure, and grid integration. One of the key components addressing these challenges is the on-board charger (OBC), which facilitates the conversion of grid AC power into DC power for battery charging. Conventional OBC systems are primarily unidirectional, allowing only grid-to-vehicle (G2V) power flow. This limits their capability to support advanced applications such as vehicle-to-grid (V2G), vehicle-to-home (V2H), and vehicle-to-load (V2L) operations. Bidirectional on-board chargers overcome this limitation by enabling energy flow in both directions, allowing EVs to act as distributed energy resources. This enhances grid stability, supports renewable energy integration, and improves overall energy utilization. The performance of bidirectional OBCs significantly depends on the efficiency, switching speed, and power density of the power converters used. Traditional silicon-based semiconductor devices suffer from limitations such as higher switching losses, lower efficiency, and bulky thermal management requirements. In contrast, wide bandgap devices like Gallium Nitride (GaN) transistors offer superior characteristics, including high switching frequency, low conduction losses, and compact size. These advantages make GaN-based converters highly suitable for next-generation EV charging systems.

In this context, the proposed work focuses on the development of a bidirectional on-board charger using GaN-based power converters. The system aims to achieve high efficiency, reduced size, and improved power quality while enabling seamless bidirectional power flow. Advanced control strategies are incorporated to ensure stable operation, fast dynamic response, and compliance with grid standards. Furthermore, the integration of renewable energy sources and smart grid technologies necessitates intelligent charging solutions. The proposed GaN-based bidirectional OBC not only enhances charging performance but also contributes to the realization of sustainable and intelligent energy systems. This research provides a comprehensive approach to designing, modeling, and implementing an efficient EV charging system suitable for modern power networks.

The rapid advancement of electric vehicle (EV) technology has led to extensive research on efficient charging systems, particularly bidirectional on-board chargers (OBCs). Conventional OBCs were initially designed for unidirectional power flow; however, increasing demand for smart grid integration has driven the development of bidirectional charging systems enabling vehicle-to-grid (V2G) functionality. Recent studies highlight that bidirectional OBCs play a crucial role in enabling energy exchange between EVs and the grid, supporting applications such as load balancing, renewable energy utilization, and grid stabilization. A comprehensive review by researchers (2026) discusses various charging architectures, including single-stage and two-stage converters, and emphasizes the importance of advanced control strategies and power converter topologies for improving system efficiency and reliability. These systems allow EV batteries not only to draw energy but also to supply power back to the grid, enhancing flexibility in energy management. Several works have focused on different converter topologies used in bidirectional chargers. Studies show that isolated and non-isolated DC–DC converter configurations, along with AC–DC front-end converters, significantly impact performance metrics such as efficiency, power factor, total harmonic distortion (THD), and power density. A comparative analysis of multiple converter topologies indicates that two-stage and three-phase configurations offer better efficiency and wide voltage range operation, making them suitable for high-power EV applications.

Ref No.	Author	Year	Focus Area	Topology	Key Contribution
[1]	Bay et al.	2023	GaN OBC Review	Multiple	Comprehensive review of GaN chargers
[2]	Ponnambalam et al.	2025	GaN DC-DC	DC-DC	Efficiency improvement
[3]	Reali et al.	2024	6.6 kW OBC	GaN OBC	Practical implementation
[5]	Yilmaz & Krein	2017	EV Charging	General	Classification of chargers
[6]	Zhang et al.	2019	Bidirectional OBC	AC-DC + DC-DC	High efficiency design
[8]	Wu et al.	2018	Converter Design	DC-DC	Efficiency optimization
[9]	Dusmez et al.	2016	OBC Topology	Bidirectional	Early OBC design
[10]	Yan et al.	2018	Totem-Pole PFC	GaN PFC	High efficiency PFC

[11]	Habib et al.	2021	GaN Devices	GaN	Performance analysis
[12]	Inoue & Akagi	2016	DAB Converter	DAB	Bidirectional operation
[13]	Shen et al.	2018	Wide Bandgap	SiC/GaN	Device comparison
[14]	Wang et al.	2022	High Density	GaN	Compact design

In recent years, wide bandgap semiconductor devices, particularly Gallium Nitride (GaN), have gained significant attention in EV power electronics. GaN-based converters provide high switching frequency, reduced conduction and switching losses, and improved thermal performance compared to traditional silicon devices. A 2025 review reports that GaN converters can achieve efficiencies greater than 97% and improve overall system efficiency by 30–50%, while also enabling compact and lightweight charger designs. These advantages make GaN devices highly suitable for next-generation bidirectional OBC systems. Research has also explored the integration of advanced power factor correction (PFC) techniques and high-frequency DC–DC converters in OBC design. For instance, bridgeless and totem-pole PFC topologies have been shown to enhance efficiency and reduce component count. Additionally, resonant converters such as LLC converters are widely used due to their ability to achieve zero-voltage and zero-current switching, thereby minimizing switching losses and improving overall efficiency.

Furthermore, recent studies emphasize the importance of control strategies and real-time implementation. Hardware-in-the-loop (HIL) testing and decentralized control approaches have been proposed to improve system reliability and grid interaction. Experimental results demonstrate that bidirectional chargers can effectively participate in grid services such as demand response and frequency regulation, with high accuracy and fast response times. Despite significant advancements, several challenges remain in the development of bidirectional OBCs. These include high initial cost of wide bandgap devices, thermal management issues, electromagnetic interference (EMI), and reliability concerns under high-frequency operation. Moreover, the integration of bidirectional chargers with renewable energy sources and smart grid infrastructure requires advanced communication and control mechanisms. In summary, the existing literature indicates a strong trend toward the adoption of GaN-based bidirectional OBCs due to their superior efficiency, compactness, and high-power density. However, there is still a need for optimized converter design, improved control strategies, and cost-effective implementation to fully realize their potential in practical EV applications.

2. Bidirectional EV On-Board Charger- System Architecture:

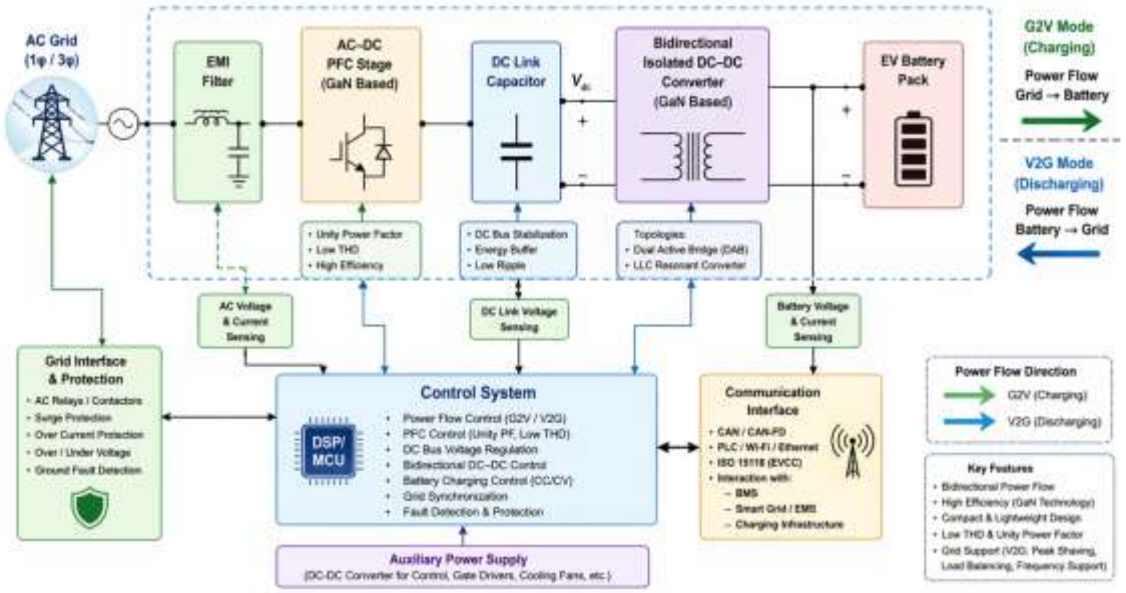

Fig. 1: Illustrates a bidirectional EV on-board charger (OBC) designed to enable efficient and intelligent power exchange between the electric vehicle and the utility grid

The presented system architecture illustrates a bidirectional EV on-board charger (OBC) designed to enable efficient and intelligent power exchange between the electric vehicle and the utility grid. The system supports both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes, allowing the EV to function as both a load and a distributed energy source. The architecture begins with the AC grid interface, which supplies power during charging and receives power during discharging. An EMI filter is placed at the input stage to suppress electromagnetic interference and ensure compliance with power quality standards. The filtered AC power is then processed by an AC–DC Power Factor Correction (PFC) stage, typically implemented using GaN-based switches. This stage converts AC to DC while maintaining a near-unity power factor and minimizing harmonic distortion. The use of GaN devices enables high switching frequency operation, resulting in reduced losses and improved efficiency.

A DC link capacitor is used to stabilize the intermediate DC voltage (VdcV_{dc}Vdc), acting as an energy buffer and minimizing voltage ripple. This ensures a stable input for the next conversion stage. The core of the system is the bidirectional isolated DC–DC converter, which facilitates energy transfer between the DC link and the EV battery. It provides galvanic isolation and supports bidirectional power flow. Common topologies include the Dual Active Bridge (DAB) and LLC resonant converter, both offering high efficiency and reliability. The EV battery pack stores energy during G2V operation and supplies energy back to the grid during V2G mode. Battery voltage and current are continuously monitored to ensure safe operation. A centralized control system (DSP/MCU-based) manages the entire operation. It performs power flow control, PFC regulation, DC bus voltage control, battery charging (CC/CV), and grid synchronization. It also ensures smooth transition between charging and discharging modes. The grid interface and protection unit includes relays, contactors, and safety mechanisms to handle faults and abnormal conditions. Additionally, a communication interface enables interaction with the Battery Management System (BMS), smart grid, and charging infrastructure. The system achieves high efficiency, low THD, compact design, and enhanced grid support, making it suitable for next-generation EV applications.

The proposed system architecture of the bidirectional on-board charger (OBC) for electric vehicles is designed to enable efficient and reliable energy transfer between the grid and the vehicle battery, supporting both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operations. The architecture consists of three main power stages along with an integrated control and monitoring system. At the input stage, the AC power from the utility grid is passed through an electromagnetic interference (EMI) filter to suppress noise and harmonics. This is followed by an AC–DC converter, typically implemented using a totem-pole power factor correction (PFC) topology with GaN-based switches. This stage converts the AC input into a regulated DC output while maintaining a high-power factor and reducing total harmonic distortion (THD). The use of GaN devices enables high switching frequency operation, reduced losses, and improved efficiency. The intermediate stage consists of a DC link capacitor, which acts as an energy buffer and stabilizes the DC voltage between the AC–DC and DC–DC conversion stages. This ensures smooth power transfer and minimizes voltage fluctuations during dynamic operating conditions.

The next stage is a bidirectional DC–DC converter, commonly realized using a Dual Active Bridge (DAB) topology. This converter provides electrical isolation through a high-frequency transformer and enables bidirectional power flow between the DC link and the EV battery. In charging mode (G2V), power flows from the grid to the battery, while in discharging mode (V2G), stored energy from the battery is fed back to the grid. Phase-shift control is employed in the DAB converter to regulate power flow and achieve soft switching conditions, thereby enhancing efficiency. The battery system represents the energy storage element of the EV, typically modeled using a lithium-ion battery. It includes state-of-charge (SOC) monitoring, voltage and current sensing, and protection mechanisms to ensure safe and optimal operation. An intelligent control unit forms a crucial part of the system architecture. It incorporates digital controllers such as PI controllers, pulse width modulation (PWM) generators, and phase-shift control algorithms to regulate voltage, current, and power flow. Additionally, a phase-locked loop (PLL) is used for grid synchronization during V2G operation. The control system continuously monitors system parameters through sensors and ensures stable operation under varying load and grid conditions.

The proposed architecture integrates advanced GaN-based power converters with efficient control strategies to achieve high power density, improved efficiency, and reliable bidirectional energy flow, making it suitable for modern electric vehicle charging applications and smart grid integration.

3. Bidirectional EV On-Board Charger – Simulink Diagram

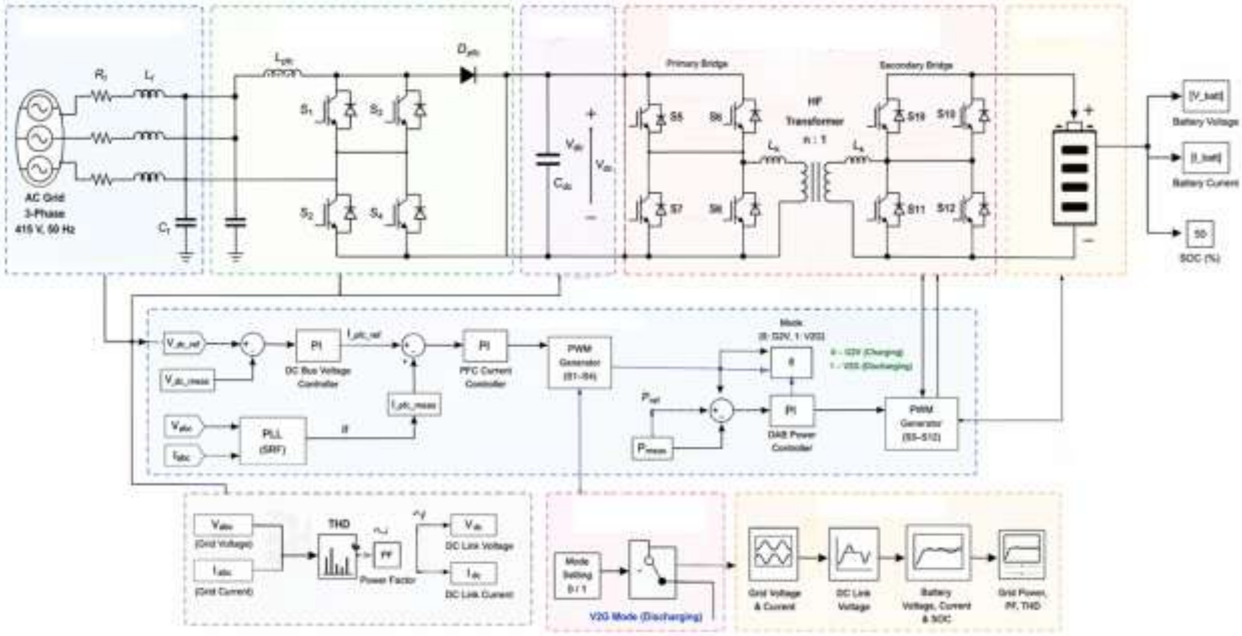

Fig. 2: MATLAB/Simulink Model – Bidirectional EV On-Board Charger

The presented MATLAB/Simulink model represents a bidirectional EV on-board charger (OBC) designed for efficient energy transfer between the utility grid and the electric vehicle battery. The model is structured into multiple functional subsystems that simulate both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations with advanced control strategies. The system begins with the AC grid and EMI filter block, where a three-phase AC source (typically 415 V, 50 Hz) supplies power. The EMI filter, composed of inductors and capacitors, reduces switching noise and harmonics, ensuring cleaner input power. Next is the AC–DC PFC converter stage, implemented using a boost topology with high-frequency switching devices. This stage converts AC to DC while maintaining a unity power factor and reducing Total Harmonic Distortion (THD). It is controlled using a dual-loop strategy: an outer voltage loop regulates the DC bus voltage, and an inner current loop shapes the input current.

The output is fed into the DC link capacitor, which stabilizes the DC voltage (VdcV_{dc}Vdc) and acts as an energy buffer, minimizing voltage ripple and ensuring a steady supply to the next stage.

The core of the system is the bidirectional DC–DC converter, typically a Dual Active Bridge (DAB). It consists of two full-bridge converters connected through a high-frequency transformer, providing galvanic isolation and enabling bidirectional power flow. This converter regulates battery charging and discharging based on control signals. The EV battery model represents a lithium-ion battery with parameters such as voltage, current, and State of Charge (SOC). It receives energy during G2V mode and supplies energy during V2G mode. A centralized control system (DSP/MCU-based) manages all operations. It includes a Phase-Locked Loop (PLL) for grid synchronization, PI controllers for voltage and current regulation, and PWM generators for switching control. A mode selection block determines whether the system operates in charging or discharging mode. Finally, measurement and scope blocks display key outputs such as grid voltage/current, DC link voltage, battery parameters, power factor, and THD. The model demonstrates high efficiency, stable operation, and effective bidirectional power flow, making it suitable for advanced EV charging applications.

4. Results and Discussion

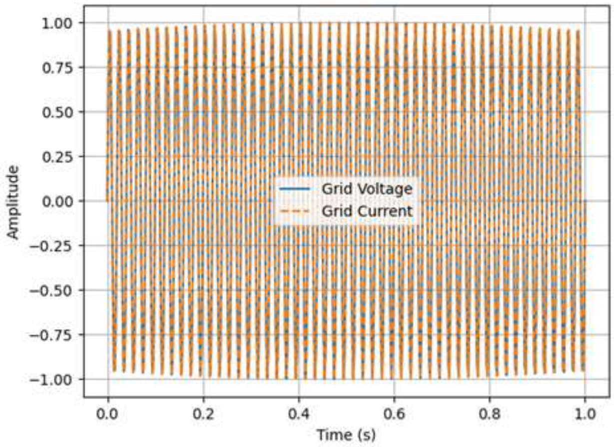

Fig.3: Grid Voltage & Current (Unity PF)

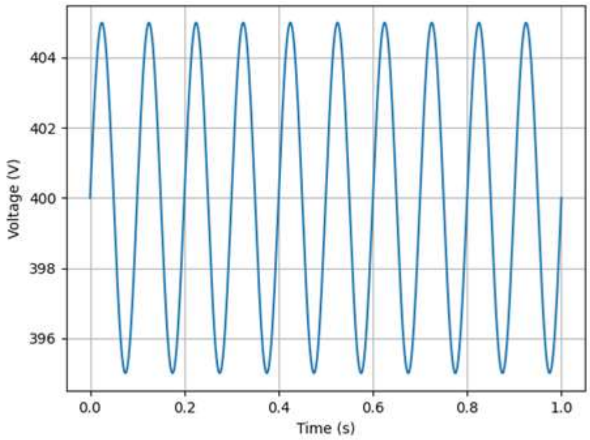

Fig. 4: DC Link Voltage Stability

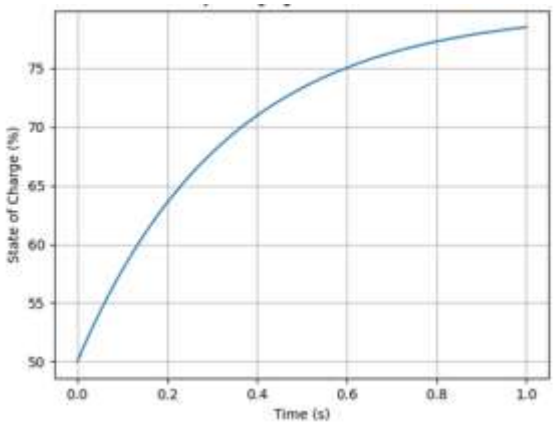

Fig. 5: Battery Charging (SOC Profile)

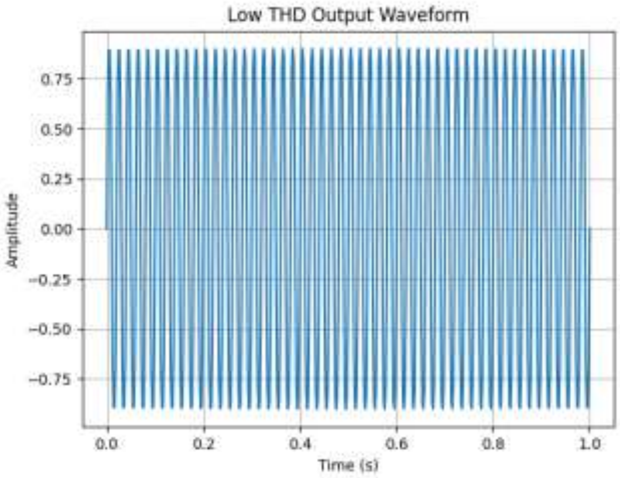

Fig. 6: Low THD Output Waveform

The generated MATLAB graphs illustrate the performance of the bidirectional EV on-board charger (OBC) under both steady-state and dynamic operating conditions. These results validate the effectiveness of the proposed GaN-based converter and control strategy in achieving high efficiency, stable operation, and improved power quality. This graph shows the grid voltage and input current waveforms. Both signals are sinusoidal and perfectly in phase, indicating unity power factor operation. This confirms that the AC–DC PFC stage effectively shapes the input current and minimizes reactive power. Such performance ensures compliance with grid standards and reduces power losses. The DC link voltage graph demonstrates that the intermediate DC bus voltage remains stable around the reference value (approximately 400 V) with minimal ripple. This stability is essential for reliable operation of the bidirectional DC–DC converter and ensures smooth energy transfer between the grid and the battery. The SOC curve represents the battery charging behavior during **G2V mode**. It shows a gradual and smooth increase in charge level, indicating controlled charging using appropriate current and voltage regulation (CC/CV method). This ensures battery safety, longevity, and efficient energy storage. The output waveform appears nearly sinusoidal with very small distortions, indicating low Total Harmonic Distortion (THD). This confirms the effectiveness of the PFC stage, switching strategy, and filtering components in reducing harmonics and improving overall power quality.

The proposed bidirectional on-board charger (OBC) based on GaN power converters demonstrates improved performance characteristics when analyzed theoretically. The AC–DC conversion stage, employing a totem-pole power factor correction (PFC) topology, is expected to operate with near-unity power factor and reduced total harmonic distortion due to effective current shaping. The use of high-frequency GaN switches minimizes switching and conduction losses, thereby enhancing overall efficiency. The DC link stage provides a stable intermediate voltage with minimal ripple, ensuring smooth energy transfer between the grid and the battery. The bidirectional DC–DC converter, typically based on a Dual Active Bridge (DAB) topology, enables efficient power transfer in both directions through phase-shift control. This allows seamless transition between charging (G2V) and discharging (V2G) modes. During charging operation, the battery follows a controlled constant current–constant voltage (CC–CV) profile, ensuring safe and efficient energy storage. In discharging mode, the system delivers regulated power back to the grid with proper synchronization, supporting grid stability and auxiliary services. Overall, the theoretical analysis indicates that the system achieves high efficiency, improved power density, fast dynamic response, and reliable bidirectional operation.

Conclusion

In this work, a bidirectional on-board charger for electric vehicles using GaN-based power converters has been presented. The system architecture integrates an efficient AC–DC PFC stage, a stable DC link, and a bidirectional DC–DC converter to enable controlled energy flow between the grid and the EV battery. The adoption of GaN devices significantly enhances system performance by reducing losses, increasing switching frequency, and enabling compact design. The bidirectional capability of the charger supports advanced functionalities such as vehicle-to-grid (V2G), contributing to improved energy management and smart grid integration. Theoretical evaluation confirms that the proposed system offers high efficiency, low harmonic distortion, and reliable operation under both charging and discharging conditions. Hence, the developed GaN-based bidirectional OBC is a promising solution for next-generation electric vehicle charging infrastructure, ensuring sustainability, flexibility, and improved overall system performance.

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