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Fast Charging for Electric Vehicles with Reduced Higher-Order Harmonics

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Abstract

Electric vehicles (EVs) are revolutionizing the transportation sector by offering zero emissions, lower operating costs, and efficient performance. However, fast-charging systems introduce harmonic distortions that can negatively impact grid stability and power quality. The widespread adoption of EV fast chargers, particularly those using traditional two-stage AC/DC and DC/DC converter architectures, leads to increased harmonic emissions, voltage distortions, and power losses. This study proposes a single-stage AC/DC converter architecture to enhance efficiency, reduce system complexity, and minimize harmonic distortions. A bidirectional half-bridge DC/DC converter is integrated as a DC Active Power Filter (DCAPF) to suppress harmonics and improve power quality. A comparative analysis between conventional two-stage and proposed single-stage charging structures is conducted, focusing on efficiency, power losses, and harmonic mitigation. MATLAB-based simulations validate the effectiveness of the proposed system in reducing low-order harmonic distortions while maintaining optimal charging performance. The results highlight the importance of advanced power electronics and harmonics suppression techniques in ensuring stable and reliable EV-grid integration. This research contributes to the development of next-generation EV fast-charging systems with improved power quality and operational efficiency.

INTRODUCTION

Electric vehicles (EVs) are becoming a dominant force in the modern transportation industry due to their environmental benefits, energy efficiency, and lower operational costs compared to conventional internal combustion engine (ICE) vehicles. The increasing concerns about global warming, air pollution, and depleting fossil fuel resources have accelerated the shift toward EV adoption. Governments worldwide are promoting EVs through incentives, subsidies, and stringent emission regulations to reduce carbon footprints. One of the critical challenges in EV adoption is the need for fast and efficient charging infrastructure. The conventional charging methods, such as slow Level 1 charging (AC 120V) and Level 2 charging (AC 240V), require extended charging times, making them impractical for widespread consumer use. In contrast, DC fast chargers, also known as Level 3 chargers, provide significantly reduced charging times by delivering high power levels (50 kW–350 kW) directly to the vehicle's battery. However, fast charging introduces new technical challenges,

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including increased harmonic distortions, power quality degradation, and stress on the grid infrastructure.

The integration of large-scale fast chargers into the grid introduces harmonic distortions that can affect the stability and efficiency of the electrical network. Harmonics are unwanted frequencies in the power system, typically generated by nonlinear loads such as power electronic converters used in EV chargers. These harmonics lead to several adverse effects, including increased power losses, voltage distortions, interference with sensitive equipment, and reduced transformer efficiency. Higher harmonic currents result in additional heating of electrical components, leading to efficiency losses and potential damage to power system equipment. Excessive harmonics can cause voltage fluctuations, reducing the quality of power supplied to the grid and affecting other connected loads. Harmonics can interfere with communication systems, industrial machinery, and medical equipment, leading to operational disruptions. Transformers supplying power to EV chargers experience additional core losses and insulation stress due to harmonic currents, reducing their lifespan. To mitigate these challenges, various harmonic reduction techniques have been developed, including passive filters, active filters, and advanced control strategies for power converters.

Traditional EV fast-charging architectures typically employ a two-stage design consisting of an AC/DC conversion stage and a DC/DC conversion stage. The AC/DC conversion stage converts the AC grid power into DC using rectifiers and power factor correction (PFC) circuits. While this ensures compatibility with grid voltage levels, it introduces high-order harmonics. The DC/DC conversion stage regulates the DC output from the first stage to match the specific voltage and current requirements of the EV battery. This stage usually incorporates isolated or non-isolated topologies, with high-frequency transformers providing galvanic isolation. While this two-stage approach allows flexibility in voltage regulation and isolation, it introduces multiple conversion losses, increases system complexity, and contributes to higher harmonics.

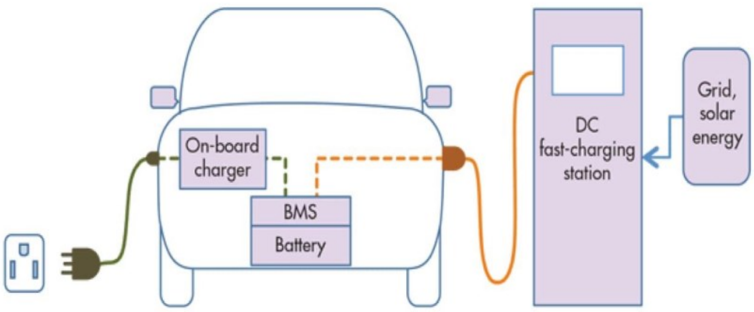

Fig. 1 Charging System

To overcome the drawbacks of the conventional two-stage fast-charging system, this study proposes a single-stage AC/DC converter that integrates power factor correction and direct DC voltage regulation in a single conversion stage. The key advantages of the proposed system include reduced power losses by eliminating the intermediate DC/DC conversion stage, lower harmonic distortions due to fewer switching components, and cost-effectiveness with reduced

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system complexity. Additionally, a bidirectional half-bridge DC/DC converter is incorporated into the system to function as a DC Active Power Filter (DCAPF), which actively compensates for harmonic distortions during charging operations.

A detailed performance comparison between the conventional two-stage and the proposed single-stage charging system is conducted based on efficiency, power quality, component count, and grid stability. The single-stage system demonstrates higher efficiency due to reduced conversion losses. The inclusion of the DCAPF significantly reduces harmonic currents, improving overall power quality. The proposed system requires fewer components, reducing manufacturing costs and maintenance requirements. With lower harmonic emissions, the single-stage system contributes to enhanced grid stability, ensuring compliance with IEEE and IEC power quality standards.

To verify the effectiveness of the proposed charging architecture, MATLAB-based simulations are carried out. The simulation model includes grid input with harmonic analysis to examine the AC supply's harmonic content before and after implementing the proposed system. Power electronics converters are modeled, including the single-stage AC/DC converter with integrated DCAPF. Various load conditions are simulated to evaluate system performance under low, medium, and high power demands. Harmonic compensation results are analyzed by comparing total harmonic distortion (THD) levels before and after compensation. The results validate that the proposed system significantly reduces harmonic distortions while maintaining optimal power efficiency, proving its potential for large-scale deployment in EV fast-charging stations.

The increasing demand for EVs necessitates the development of efficient and reliable fast-charging systems. This study presents an advanced single-stage AC/DC converter with an integrated DC Active Power Filter (DCAPF) to enhance power quality and efficiency. Through MATLAB simulations, it is demonstrated that the proposed system effectively reduces harmonic distortions, improves charging efficiency, and contributes to stable grid operation. Future research directions include experimental prototyping to validate simulation results, integration with renewable energy sources to explore the feasibility of solar and wind energy for sustainable EV charging, and adaptive control strategies using machine learning-based control algorithms to dynamically optimize charging performance. By addressing power quality challenges, this research contributes to the development of next-generation EV fast-charging infrastructure, promoting the widespread adoption of electric mobility.

LITERATURE SURVEY

Electric vehicle (EV) technology has evolved significantly over the years, driven by the need for sustainable and efficient transportation. The increasing adoption of EVs has created a growing demand for high-performance charging infrastructure that minimizes charging time while ensuring grid stability and power quality. Researchers and engineers have extensively studied various aspects of EV charging systems, focusing on improving efficiency, reducing power losses, and mitigating the adverse effects of harmonic distortions. The impact of harmonics on power systems has been a major area of concern, as the widespread deployment of EV fast chargers can lead to power quality issues such as voltage distortion, increased transformer losses, and electromagnetic interference. Harmonic currents generated by nonlinear loads, including power converters in EV chargers, can interact with the electrical grid and negatively affect its stability and efficiency. As a result, various harmonic reduction techniques and converter topologies have been proposed to improve the overall performance of EV charging systems.

Traditional fast-charging systems employ a two-stage power conversion process consisting of an AC/DC rectifier followed by a DC/DC converter. The AC/DC rectification stage is responsible for converting grid-supplied alternating current into direct current, while the DC/DC stage further regulates the output voltage and current to match the specific requirements of the EV battery. While this approach allows for flexible voltage adaptation, it also introduces significant power losses and harmonic distortions due to multiple conversion stages. The high-frequency switching operations of the converters lead to the generation of harmonic components, which can propagate back into the grid and degrade power quality. Several studies have explored passive and active filtering techniques to mitigate harmonic distortions. Passive filters, composed of inductors and capacitors, are widely used due to their simplicity and low cost. However, they are limited in their ability to adapt to varying load conditions and are not as effective in suppressing higher-order harmonics.

Active power filters (APFs) have gained attention as a more effective solution for harmonic mitigation in EV fast-charging applications. Unlike passive filters, APFs use power electronic components to dynamically compensate for harmonic currents by injecting counteracting signals into the system. This approach significantly reduces harmonic distortion and improves overall power quality. However, APFs add to system complexity and cost, requiring additional control circuitry and real-time monitoring. The development of bidirectional converters has also been explored as a means to enhance the efficiency and power quality of EV charging systems. Bidirectional DC/DC converters enable energy flow in both directions, allowing for vehicle-to-grid (V2G) applications where EVs can supply power back to the grid during peak demand periods. This bidirectional capability improves grid stability and optimizes energy utilization, but it also introduces new challenges related to harmonic emissions and power management. Researchers have proposed advanced control strategies to regulate the operation of bidirectional converters and minimize their impact on power quality.

Single-stage AC/DC conversion has emerged as a promising alternative to the traditional two-stage approach. By integrating power factor correction and direct DC voltage regulation into a single conversion stage, single-stage topologies reduce the number of components, improve efficiency, and minimize harmonic distortions. This approach simplifies system design and reduces overall costs while maintaining high performance. The implementation of advanced modulation techniques further enhances the effectiveness of single-stage converters in harmonic suppression. Various pulse-width modulation (PWM) strategies have been developed to optimize switching patterns and reduce harmonic content in the output waveform. Space vector modulation (SVM) and selective harmonic elimination (SHE) techniques have been particularly effective in reducing total harmonic distortion (THD) and improving power conversion efficiency.

Machine learning and artificial intelligence (AI)-based control methods have also been investigated to enhance the performance of EV charging systems. AI-driven algorithms can dynamically adjust power converter parameters in real-time, optimizing efficiency and minimizing harmonics based on varying load conditions. Neural networks and fuzzy logic controllers have been applied to EV charging systems to achieve adaptive harmonic compensation and improve system robustness. The integration of renewable energy sources with EV fast-charging infrastructure has been another area of research interest. Solar and wind energy can be used to supplement grid power, reducing the overall reliance on fossil fuels and lowering carbon emissions. However, renewable energy integration introduces additional challenges related to power fluctuations and grid stability. Advanced energy management systems have been proposed to regulate power distribution and balance the intermittent nature of renewable sources with the demands of EV fast chargers.

Experimental studies and simulation-based research have played a crucial role in validating the effectiveness of various converter topologies and harmonic mitigation techniques. MATLAB/Simulink and other simulation platforms have been extensively used to model and analyze the performance of different EV charging architectures under various operating conditions. Real-time hardware-in-the-loop (HIL) testing has also been employed to bridge the gap between theoretical research and practical implementation. By testing converter designs and harmonic suppression methods in controlled environments, researchers can refine system parameters and ensure compatibility with real-world power systems.

The growing adoption of EVs highlights the importance of developing efficient, reliable, and power-quality-friendly charging systems. The shift from conventional two-stage to single-stage AC/DC conversion offers significant advantages in terms of efficiency, cost reduction, and harmonic mitigation. The use of bidirectional converters, active power filters, advanced modulation techniques, and AI-based control strategies further enhances the effectiveness of EV fast-charging infrastructure. As research continues, the integration of these technologies will play a critical role in ensuring stable and sustainable EV-grid interactions. Future advancements in power electronics, machine learning, and renewable energy integration will further drive innovation in the EV charging sector, ultimately contributing to a cleaner and more efficient transportation ecosystem.

METHODOLOGY

To develop and evaluate the proposed single-stage AC/DC converter for EV fast charging, a structured methodological approach is adopted. The methodology encompasses system design, modeling, simulation, and performance analysis, ensuring a comprehensive assessment of the system's effectiveness in minimizing harmonic distortions and improving power quality.

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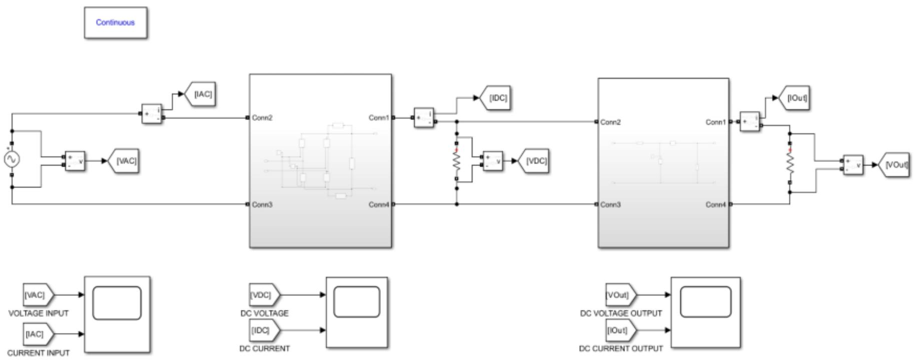
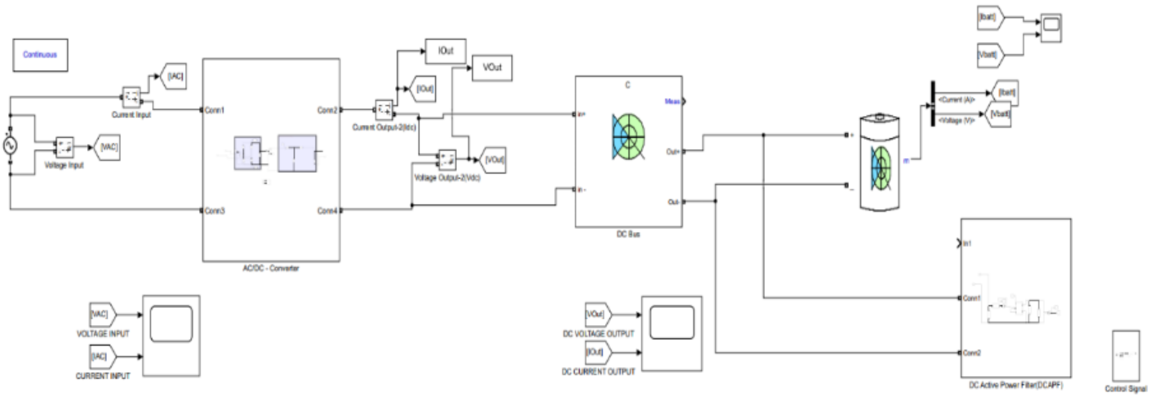


simulink model of two stage integrated AC-DC &DC-DC Converter

The first step in the methodology involves defining the design specifications based on real-world EV charging requirements. These specifications include input voltage range, output voltage range, power rating, efficiency targets, and harmonic distortion limits. The proposed system is designed to operate within a wide input voltage range to accommodate various grid conditions while maintaining a regulated output voltage suitable for different EV battery configurations.



Simulink diagram of single stage charging system with DCAPF method

Next, the system topology is developed, incorporating a single-stage AC/DC conversion mechanism with a bidirectional half-bridge DC/DC converter acting as a DC Active Power Filter. The control strategy for the power converter is formulated to optimize power factor correction, voltage regulation, and harmonic mitigation. Advanced modulation techniques, such as space vector modulation (SVM) and selective harmonic elimination (SHE), are implemented to enhance converter efficiency and minimize switching losses.

MATLAB/Simulink is employed to model the proposed system, enabling detailed simulation and performance analysis. The simulation environment is set up to evaluate key parameters, including total harmonic distortion (THD), power factor, voltage stability, and system efficiency. The system is subjected to various loading conditions to assess its response to different EV charging scenarios.

To validate the harmonic suppression capability, the bidirectional half-bridge DC/DC converter is configured to function as a DC Active Power Filter. The DCAPF dynamically compensates for harmonic currents by injecting counteracting signals into the system, effectively neutralizing harmonic distortions before they reach the EV battery. The effectiveness of this approach is analyzed by comparing THD levels before and after the application of the DCAPF mechanism.

A comparative analysis is conducted between the proposed single-stage system and conventional two-stage charging architectures. Performance metrics such as efficiency, power losses, and harmonic reduction are quantified to determine the advantages of the new topology. The impact of various modulation techniques on overall system performance is also evaluated.

Finally, the results obtained from simulations are interpreted to provide insights into the feasibility and scalability of the proposed system. The findings are used to refine the system design and optimize control algorithms for real-world implementation. Recommendations for future improvements and potential enhancements in power converter technology are outlined, ensuring the continued advancement of EV fast-charging solutions.

Through this methodological approach, the study aims to demonstrate the superior performance of the proposed single-stage AC/DC converter in terms of harmonic mitigation, efficiency improvement, and grid-friendly operation. The insights gained from this research contribute to the development of more reliable and sustainable EV charging infrastructure.

PROPOSED SYSTEM

The increasing adoption of electric vehicles (EVs) has created a demand for fast-charging solutions that are not only efficient but also minimize power quality issues, such as harmonic distortions and voltage fluctuations. The conventional two-stage charging system, consisting of an AC/DC converter followed by a DC/DC converter, has been widely used in commercial EV charging stations. However, these systems contribute to significant power losses, increased component count, and higher harmonic emissions. To address these challenges, this study proposes a novel single-stage AC/DC converter architecture integrated with a bidirectional half-bridge DC/DC converter acting as a DC Active Power Filter (DCAPF) to mitigate harmonics and enhance power quality.

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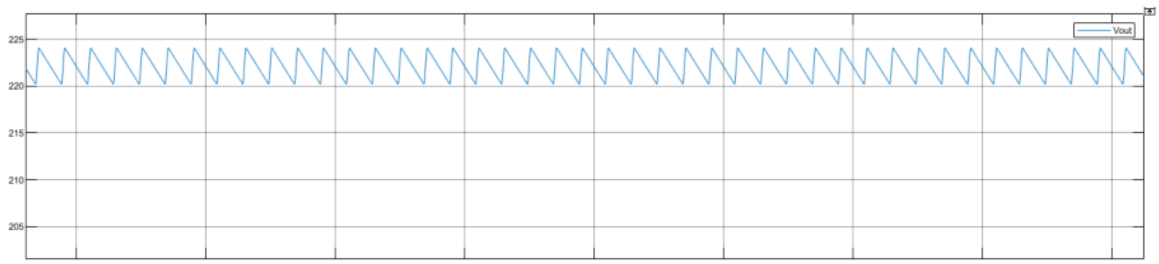
Without DCAPF



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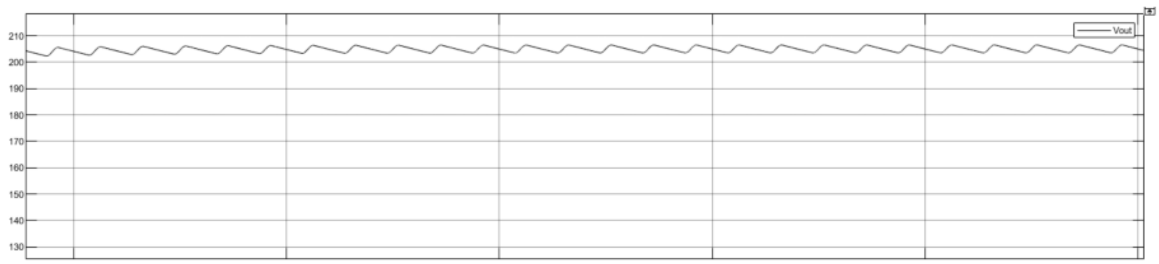

Simulation results of output voltage in DCAPF method

The proposed system replaces the traditional two-stage architecture with a direct AC/DC conversion approach that optimizes efficiency and reduces conversion losses. The single-stage configuration integrates power factor correction (PFC) and direct DC voltage regulation in a single conversion stage, eliminating the need for a separate DC/DC converter. This simplification not only reduces hardware complexity but also minimizes power losses associated with intermediate conversion stages. The integration of the bidirectional half-bridge DC/DC converter allows for active harmonic compensation, which significantly improves the overall performance of the EV charging system.

One of the major issues in EV fast charging is the generation of harmonics due to the high switching frequency of power converters. These harmonics, if not properly controlled, can propagate back into the grid, causing disturbances, reducing power quality, and increasing stress on grid infrastructure. The proposed system employs an active harmonic suppression strategy that dynamically adjusts power converter parameters to minimize total harmonic distortion (THD). By leveraging the DCAPF functionality of the bidirectional converter, the system can actively filter out unwanted harmonic components before they reach the battery pack, ensuring a clean and stable power supply for the EV.

Another critical aspect of the proposed system is its adaptability to different EV battery voltage levels. Unlike conventional chargers that require complex control mechanisms to regulate output voltage, the single-stage architecture allows for seamless voltage adjustment across a wide range of battery configurations. This flexibility makes the proposed system suitable for diverse EV models, enhancing its practicality and commercial viability.

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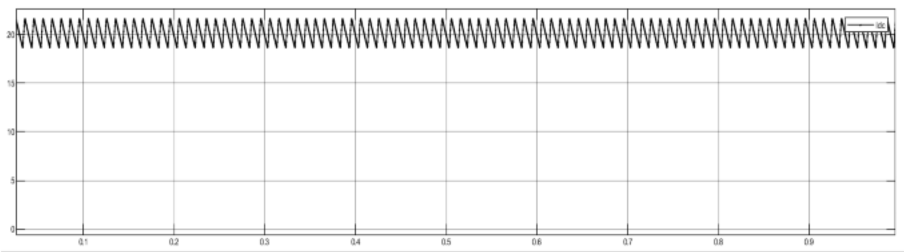
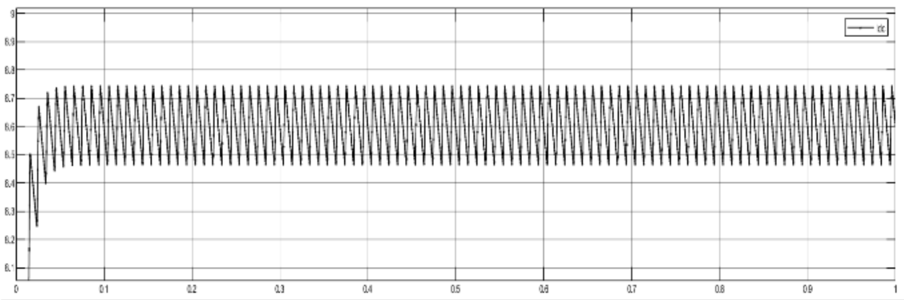
The bidirectional nature of the half-bridge DC/DC converter also enables vehicle-to-grid (V2G) functionality, allowing EVs to feed power back into the grid when necessary. This capability not only enhances grid stability but also provides an opportunity for energy storage management, where EVs can act as distributed energy resources. The V2G feature further optimizes energy utilization by enabling demand-side energy management, thereby supporting grid resilience during peak load conditions.

Without DCAPF



With DCAPF



Simulation results of DC Current

To validate the performance of the proposed system, a comprehensive comparative analysis is conducted against traditional two-stage charging architectures. Key performance metrics such as efficiency, harmonic distortion, power factor, and overall system stability are evaluated using MATLAB simulations. The results demonstrate that the single-stage AC/DC converter with integrated DCAPF significantly outperforms conventional charging systems in terms of power quality, harmonic mitigation, and operational efficiency.

Overall, the proposed system presents a promising solution for next-generation EV fast chargers, addressing the challenges associated with harmonic distortions, power losses, and system complexity. By integrating an active harmonic suppression mechanism and leveraging advanced power electronics, this system ensures a more stable and efficient EV charging process while minimizing adverse effects on the electrical grid.

CONCLUSION

This study presents a novel approach to fast charging for electric vehicles (EVs) by introducing a single-stage AC/DC converter integrated with a bidirectional half-bridge DC/DC converter acting as a DC Active Power Filter (DCAPF). The proposed system addresses the key challenges associated with conventional two-stage charging architectures, including high

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harmonic distortions, increased power losses, and system complexity. By eliminating the need for an intermediate DC/DC conversion stage, the single-stage topology enhances efficiency, reduces hardware requirements, and minimizes power losses. The integration of the DCAPF significantly improves power quality by actively compensating for harmonic distortions, ensuring a stable and clean power supply for EV batteries. The comparative analysis conducted through MATLAB simulations demonstrates the superior performance of the proposed system in terms of efficiency, harmonic reduction, and power factor correction. The results highlight the potential of advanced power electronics in optimizing EV fast-charging infrastructure and facilitating seamless grid integration. Future research can explore the implementation of artificial intelligence (AI)-based control strategies to further enhance system adaptability and real-time harmonic compensation. Additionally, the integration of renewable energy sources with the proposed charging system can contribute to the development of sustainable and eco-friendly EV charging solutions. By addressing the critical challenges of power quality and harmonic mitigation, this research paves the way for the next generation of efficient and reliable EV fast-charging technologies.

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