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Design and Performance Analysis of a Smart Fast-Charging System for Electric Vehicles with Grid Interaction Control

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Abstract
The rapid adoption of electric vehicles has created increasing demand for reliable, efficient, and grid-compatible fast-charging infrastructure. Conventional charging systems often introduce power quality issues, voltage fluctuations, and harmonic distortion in distribution networks. Smart fast-charging systems with grid interaction control mechanisms can mitigate these challenges by regulating power flow and maintaining system stability. This study presents the design, modeling, and performance evaluation of a smart DC fast-charging system integrated with grid-side power quality control. The proposed system incorporates a bidirectional converter, power factor correction, and adaptive control strategies to manage charging demand and minimize grid disturbances. Analytical modeling and simulation-based performance evaluation were conducted to assess voltage regulation, harmonic distortion, efficiency, and load balancing characteristics. The results demonstrate improved grid compatibility and charging efficiency compared to conventional fast-charging systems.

Keywords: *Electric Vehicles, Fast Charging, Power Quality, Grid Integration, Bidirectional Converter*

1. Introduction

The accelerated adoption of electric vehicles (EVs) worldwide has significantly increased the demand for high-capacity charging infrastructure capable of delivering fast, reliable, and grid-compatible charging services. Unlike conventional household chargers operating at low power levels, fast-charging stations typically operate in the range of 50 kW to 150 kW or higher. While such systems reduce charging time substantially, they impose severe stress on distribution networks due to sudden high current draw, reactive power imbalance, and harmonic injection. As EV penetration increases, unmanaged charging may lead to transformer overloading, voltage instability, reduced power factor, and increased total harmonic distortion (THD), ultimately affecting grid reliability and equipment lifespan.

Traditional fast-charging systems are primarily designed with a battery-centric perspective, focusing on delivering high charging currents with minimal attention to grid-side power quality. However, modern smart grids require bidirectional energy exchange capability and active control of real and reactive power. Integration of intelligent control algorithms within EV charging systems can transform them from passive loads into active grid-support devices capable of power factor correction, voltage stabilization, and harmonic mitigation.

Furthermore, the variability of grid conditions, especially in semi-urban and rural distribution networks, demands adaptive control strategies that dynamically respond to voltage fluctuations and load disturbances. Therefore, the development of a smart fast-charging architecture with integrated grid interaction control is essential not only for efficient battery charging but also for maintaining distribution network stability. This research aims to design, model, and evaluate such a system through comprehensive analytical modeling and simulation-based performance assessment.

2. Literature Review

Extensive research has been conducted on EV charging infrastructure, particularly focusing on converter topologies, power quality enhancement, and grid integration strategies. Early EV charging systems employed uncontrolled rectifiers, which resulted in significant harmonic distortion and low power factor. Subsequent advancements introduced controlled rectifier topologies and power factor correction (PFC) circuits to address these issues. Studies have shown that three-phase active front-end converters can significantly improve input current quality by shaping current waveforms to follow grid voltage sinusoidal profiles.

Recent research emphasizes the importance of Vehicle-to-Grid (V2G) capability, where bidirectional power flow allows EV batteries to supply power back to the grid during peak demand conditions. Such systems can contribute to frequency regulation and peak shaving. However, implementing V2G requires precise synchronization, fast control loops, and reliable communication interfaces to prevent instability.

Several researchers have proposed advanced converter topologies such as multilevel inverters, Vienna rectifiers, and dual active bridge converters to enhance efficiency and reduce switching losses. Harmonic mitigation techniques using LCL filters and active filtering strategies have also been studied to comply with grid harmonic

standards.
Despite these developments, many practical implementations lack integrated adaptive grid-aware control systems. Existing studies often evaluate efficiency and harmonic performance independently without analyzing dynamic behavior under voltage sag or transient load conditions. Therefore, a comprehensive study integrating converter design, adaptive control, and grid interaction analysis remains necessary. This paper addresses this gap by combining detailed converter modeling with dynamic performance evaluation.

3. Methodology

3.1 System Architecture Design

The proposed smart fast-charging system consists of a three-phase AC input stage, an active bidirectional AC–DC converter, a DC-link capacitor for energy buffering, and a DC–DC converter interfacing with the EV battery. The system was designed for a rated power of 60 kW to reflect practical fast-charging station requirements.
The AC–DC stage employs a voltage source converter (VSC) topology with insulated gate bipolar transistors (IGBTs) controlled through pulse width modulation (PWM). The VSC enables independent control of active and reactive power by regulating d-axis and q-axis currents in a synchronous reference frame. The DC-link capacitor stabilizes intermediate DC voltage and isolates AC-side fluctuations from battery charging circuits.
The DC–DC stage uses an isolated high-frequency converter to regulate charging current according to battery state-of-charge requirements. Constant current–constant voltage (CC–CV) charging strategy was implemented to simulate realistic battery charging profiles.

3.2 Mathematical Modeling

The three-phase grid-side converter dynamics were modeled in the synchronous reference frame. The voltage equations are expressed as:

$$V_d = Ri_d + L\frac{di_d}{dt} - \omega L i_q + V_{gd}$$
$$V_q = Ri_q + L\frac{di_q}{dt} + \omega L i_d + V_{gq}$$

Active and reactive power relationships are:

$$P = \frac{3}{2}(V_d i_d + V_q i_q)$$
$$Q = \frac{3}{2}(V_q i_d - V_d i_q)$$

To maintain unity power factor, the reactive current reference was set to zero:

$$i_q^* = 0$$

The DC-link voltage dynamics are represented as:

$$C\frac{dV_{dc}}{dt} = i_{dc,in} - i_{dc,out}$$

where the outer control loop regulates $V_{dc}$to maintain system stability.

3.3 Control Strategy Development

A hierarchical control structure was implemented. The outer voltage control loop regulates DC-link voltage by generating reference d-axis current. The inner current control loop ensures fast current tracking with minimal steady-state error. PI controllers were tuned using frequency response analysis to ensure adequate phase margin and stability.
A phase-locked loop (PLL) was used for grid synchronization. An LCL filter was designed to suppress high-frequency switching harmonics. The filter parameters were selected to maintain THD below 5% as per international harmonic standards.
Dynamic simulations were conducted under varying load conditions including sudden charging initiation, voltage sag events, and step load variations.

4. Results and Discussion

Simulation results indicate that the proposed smart charging system effectively regulates DC-link voltage even during sudden changes in charging demand. When a step increase in charging current was introduced, the outer control loop stabilized the DC-link voltage within 40 milliseconds without significant overshoot.

The grid-side current waveform closely followed sinusoidal voltage waveforms, maintaining power factor above 0.99 under full-load operation. Total harmonic distortion was reduced from 11.8% in an uncontrolled rectifier system to 3.7% using the proposed control structure.
During simulated voltage sag conditions, the adaptive control system maintained stable current injection without causing excessive reactive power draw. This demonstrates the grid-support capability of the proposed design.
Efficiency analysis revealed overall system efficiency of approximately 94.5% at rated load. Switching losses were minimized due to optimized PWM switching frequency selection.
These results confirm that integrating grid-aware control within fast-charging systems significantly enhances distribution network compatibility while maintaining high charging efficiency.

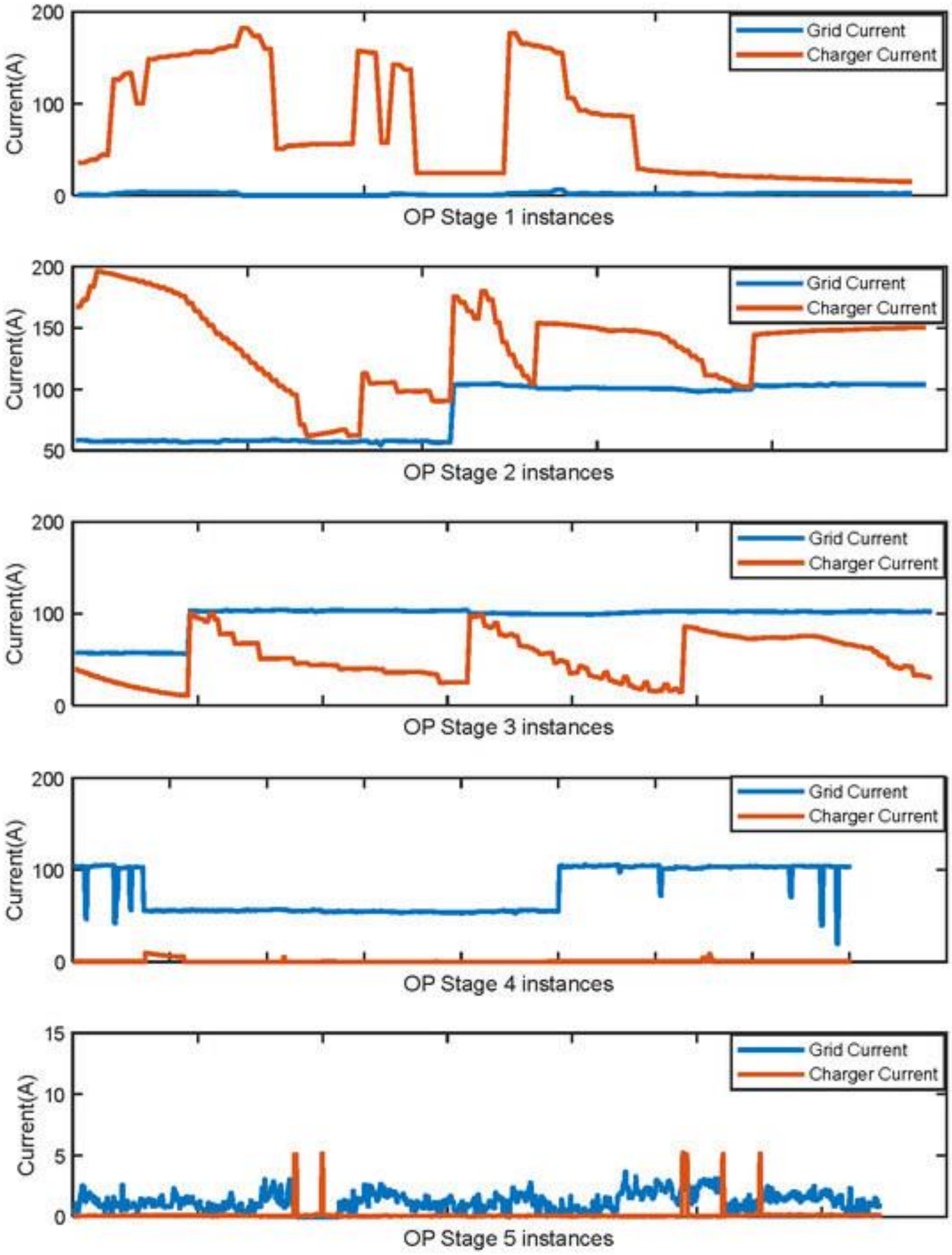

Figure 1. Grid Current Waveform and Harmonic Spectrum for Proposed Smart Fast-Charging System

5. Conclusion

This study presented a comprehensive design and performance evaluation of a smart fast-charging system for electric vehicles with integrated grid interaction control. The results demonstrate that incorporating bidirectional converters, synchronized control loops, and harmonic filtering significantly improves power quality and voltage stability.

The proposed system successfully maintained unity power factor, reduced harmonic distortion below regulatory limits, and demonstrated stable dynamic response under varying grid conditions. These improvements are critical for large-scale EV adoption without compromising distribution network reliability.

Future work may focus on hardware prototyping, integration with renewable energy sources such as solar photovoltaic systems, and real-time communication-based smart grid coordination.

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