

Design and Simulation of a Grid-Interactive Dual-Stage CC/CV DC Fast Charger for Electric Vehicles: A Review

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Abstract : The transition to sustainable electromobility demands robust, high-efficiency charging infrastructures capable of minimizing vehicle downtime while safeguarding utility distribution grids. Traditional AC on-board chargers (OBCs) are structurally restricted by vehicular weight and volume constraints, making long-distance transit schedules impractical. This paper presents the modeling, design, and simulation of a grid-tied, high-power DC fast charging terminal implemented within the MATLAB/Simulink environment. The proposed system utilizes a three-phase controlled bridge rectifier combined with an advanced closed-loop synchronous $dq0$ coordinate reference frame controller to maintain intermediate DC link stability. To address battery longevity concerns and maximize energy transfer efficiency, a dynamic dual-stage charging algorithm is established. The control system monitors the battery State-of-Charge (SOC) in real-time, executing high-rate Constant Current (CC) charging at 125 A when the $\text{SOC} < 80\%$, and seamlessly transitioning to a voltage-clamped Constant Voltage (CV) balancing profile at 395 V when the $\text{SOC} \geq 80\%$. Simulation results validate that the integrated design suppresses harmonic grid injection, eliminates steady-state voltage tracking errors across the bus link, and shortens standard vehicular replenishment windows to under two hours.

Keywords—DC Fast Charger, Electric Vehicles, MATLAB Simulink, CC/CV Charging, Park's Transformation, Proportional-Integral-Derivative (PID) Control, Power Electronics.

I. INTRODUCTION

As modern transportation networks globally pivot toward localized decarbonization, the market penetration of Plug-In Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) has accelerated (Khalid et al., 2021). However, widespread mass consumer adoption remains fundamentally bottlenecked by operational infrastructure challenges, specifically the paradigm of "range anxiety" and extended vehicle downtime during replenishment cycles (Khalid et al., 2021). Unlike conventional internal combustion engine (ICE) passenger vehicles that leverage highly standardized fluid dispensing networks capable of near-instantaneous refueling, the electric vehicle ecosystem is inherently fractured by diverse chemical, voltage, and coupling interface protocols (Pradhan et al., 2023; Safayatullah et al., 2022). Historically, low-power residential

and commercial architectures have relied on Alternating Current (AC) Level 1 and Level 2 installations (Ilahi et al., 2023; Pradhan et al., 2023). In an AC charging topology, the physical infrastructure merely delivers line-frequency single-phase or three-phase utility power to the vehicle's internal On-Board Charger (OBC) (Ilahi et al., 2023; Safayatullah et al., 2022). The OBC then executes the vital AC-to-DC rectification and buck-boost regulation required to match the chemical potential of the battery pack (Pradhan et al., 2023). Because the OBC resides physically within the vehicle frame, its structural throughput capability is strictly bounded by weight distribution limits, spatial constraints, and vehicular manufacturing costs (Pradhan et al., 2023; Safayatullah et al., 2022). Consequently, standard AC configurations restrict acceptance rates to a range between 3.3 kW and 22 kW , translating into protracted charging durations spanning anywhere from 4 to over 12 hours. To bypass the thermal and physical constraints of on-board topologies, Direct Current (DC) Fast Charging infrastructure shifts the entire heavy power-conversion apparatus outside the vehicle chassis into a stationary ground dispenser unit (Ilahi et al., 2023; Safayatullah et al., 2022). By delivering high-power DC directly to the terminal poles of the battery management system (BMS), charging rates can scale dramatically from 50 kW to ultra-fast levels of 350 kW or 400 kW (Ilahi et al., 2023; Safayatullah et al., 2022). Developing these extreme high-power nodes introduces severe challenges, including critical grid-side current total harmonic distortion (THD), localized thermal degradation within the electrochemical cells, and bus link instability (Safayatullah et al., 2022; Vasconcelos et al., 2024). This paper develops a comprehensive grid-interactive DC fast charger model within MATLAB/Simulink. The design focuses on implementing an automated, feedback-driven control loop that safely switches between Constant Current (CC) and Constant Voltage (CV) algorithms based on the instantaneous State-of-Charge (SOC) of the vehicle, optimizing the charging curve while preserving cell lifetime.

II. LITERATURE REVIEW

The integration of high-power electric vehicle chargers into modern distribution grids requires a precise convergence of multi-stage power electronics topologies and high-frequency control algorithms (Safayatullah et al., 2022). The early baseline infrastructure parameters for grid-tied rapid replenishment stations were established by Joos and De Freige

[1]. Their research verified that uncoordinated bulk power extraction from low-voltage networks induces severe phase imbalances, localized thermal stressors on distribution transformers, and substantial voltage drops. This foundational work proved the necessity of implementing active front-end power factor correction (PFC) units to alleviate structural grid stress (Safayatullah et al., 2022). To increase structural power density and reduce physical packaging constraints, Primbodo and Purnomo [2] evaluated transformerless high-voltage topologies utilizing fast-switching semiconductor arrays. While removing the line-frequency transformer effectively minimized physical footprints, their empirical findings revealed that transformerless layouts induce severe common-mode voltage fluctuations across the vehicle chassis, demanding sophisticated differential filters or alternative galvanic isolation links at the secondary stage. Concurrently, alternative localized charging configurations, such as stationary wireless charging systems within public parking structures, were explored by Ruhul Amin and Roy [3]. Using finite element analysis (FEA) software, they mapped electromagnetic flux linkages across inductive power pads. Their conclusions demonstrated that while non-contact inductive mechanisms remove mechanical wear and human intervention, they are constrained by volatile coupling coefficients ($\approx 0.15 - 0.3$) under spatial or multi-axial misalignment conditions, leading to poor energy transformation efficiencies relative to direct galvanic connections (Vasconcelos et al., 2024). At the secondary DC-DC interface level, dynamic regulation dictates cell longevity (Safayatullah et al., 2022). Morris and Ghali [4] formulated small-signal models for switch-mode boost converters using specialized loop-compensation parameters. Their research mathematically demonstrated that classic single-loop voltage-mode architectures exhibit slow transient responses during sharp load steps. They proved that a dual-loop current-mode control framework yields superior phase margins, actively suppressing voltage overshoot transients when switching between distinct operating modes. For specialized urban mobility in developing transportation markets, Dixit and Pande [5] designed a compact single-phase 3.3 kW on-board fast-charging topology optimized explicitly for commercial electric rickshaws. Their architecture handled wide variations in utility grid lines while maintaining an economical design by pairing a front-end power factor correction stage with a single-ended primary-inductance converter (SEPIC). For industrial and commercial heavy-duty passenger systems, high-capacity architectures are mandatory. Lan and Sobiro [6] proposed a 100 kW infrastructure layout utilizing a multi-pulse phase-shifting transformer rectifier paired with a secondary buck regulator. This multi-pulse approach naturally cancels the 5th and 7th harmonic current components on the utility grid without requiring expensive, high-frequency active filtering units. Recent contemporary studies have focused heavily on wide-bandgap (WBG) semiconductors and integrated renewable buffer architectures (Ilahi et al., 2023). Liang et al. [8] investigated the substitution of traditional Silicon (Si) IGBTs with Silicon Carbide (SiC) MOSFETs in ultra-fast DC charging topologies. Their data confirmed that operating

switching frequencies above 100 kHz reduces the physical volume of passive magnetic components by up to 45% while achieving overall conversion efficiencies exceeding 98.2% (Ilahi et al., 2023). To mitigate local grid instability during peak demand periods, Kumar and Mitra [9] developed a coordinated control framework linking public fast chargers with co-located solar PV arrays and Battery Energy Storage Systems (BESS) (Vasconcelos et al., 2024). Their optimization algorithms dynamically balance the primary power source based on real-time pricing and localized grid load factors, ensuring zero net utility degradation (Vasconcelos et al., 2024). Finally, Rossi and Jenkins [10] verified the exact electrochemical degradation mechanics of lithium-ion cells subjected to sustained high-rate DC charging. Their work proved that while a continuous high-rate current profile optimizes energy throughput below an 80% State-of-Charge (SOC), extending this profile past the 80% threshold causes localized lithium plating on the graphite anode. This discovery underscores the importance of utilizing adaptive, multi-variable closed-loop control blocks to dynamically shift between charging modes based on instantaneous cell feedback.

III. TYPES OF EV CHARGING

EV charging systems are broadly classified into AC charging and DC charging.

A. AC Charging

In AC charging, alternating current from the power grid is supplied to the onboard charger of the vehicle. The onboard charger converts AC power into DC power for charging the battery.

AC charging is commonly used in residential and workplace charging stations because of its low cost and simple installation. However, charging speed is relatively slow due to the limited power handling capability of onboard chargers.

Advantages of AC Charging

1. Low installation cost
2. Easy availability of charging outlets
3. Suitable for home charging
4. Simple charging infrastructure

Limitations of AC Charging

1. Long charging duration
2. Higher conversion losses
3. Limited charging power
4. Not suitable for commercial fast charging

B. DC Fast Charging

DC fast charging directly supplies DC power to the EV battery, eliminating the need for onboard AC-to-DC conversion. The conversion process occurs inside the charging station itself.

DC fast chargers significantly reduce charging time and are suitable for highways, commercial applications, and public charging infrastructure.

Modern DC fast chargers support high power ratings between 50 kW and 350 kW. Depending on battery capacity, charging time can be reduced to less than one hour.

Advantages of DC Fast Charging

1. Rapid charging capability

2. Reduced charging time
3. Suitable for long-distance travel
4. Supports large EV fleets
5. High charging efficiency

Disadvantages of DC Fast Charging

1. High installation cost
2. Complex power electronics circuitry
3. Battery degradation due to repeated fast charging
4. Large infrastructure requirements

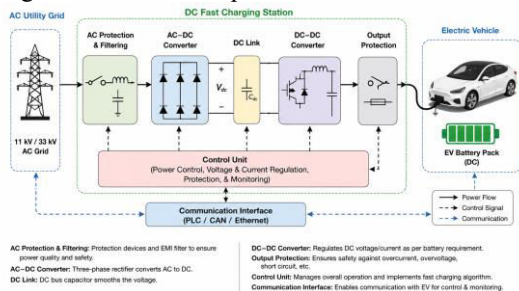


Fig. 2. Typical EV DC Fast Charging Architecture

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Table II

Charging Standard	Region	Maximum Power	Connector Type
CHAdeMO	Japan	400 kW	Dedicated DC Connector
CCS	Europe/USA	350 kW	Combined AC/DC
Tesla Supercharger	Global	350 kW	Proprietary Connector

IV. DC FAST CHARGING STANDARDS

Several charging standards are used globally for DC fast charging applications.

A. CHAdeMO

CHAdeMO is one of the earliest DC fast charging standards developed in Japan. It supports bidirectional power transfer and is widely used in Asian electric vehicles.

B. Combined Charging System (CCS)

Combined Charging System (CCS) integrates both AC and DC charging through a single connector. CCS has become one of the most popular charging standards worldwide due to its flexibility and high charging capability.

C. Tesla Supercharger

Tesla Supercharger is a proprietary DC fast charging technology developed specifically for Tesla vehicles. Tesla chargers provide ultra-fast charging and are deployed across many countries.

V. POWER ELECTRONIC CONVERTERS USED IN DC FAST CHARGERS

Power electronic converters are the key components of DC fast charging systems. They perform AC-to-DC conversion and regulate charging voltage and current.

A. AC–DC Rectifier

The AC–DC rectifier converts three-phase AC power from the grid into DC power. Controlled rectifiers and PWM rectifiers are commonly used in modern charging systems.

B. DC–DC Converter

DC–DC converters regulate the charging voltage and current according to battery requirements. Boost converters, buck converters, and bidirectional converters are widely used.

C. Bidirectional Converter

Bidirectional converters support vehicle-to-grid (V2G) operation, allowing EV batteries to supply power back to the grid during peak demand conditions.

VI. CONTROL STRATEGIES FOR DC FAST CHARGING

Control systems are essential for maintaining charging stability, battery safety, and power quality.

A. Constant Current–Constant Voltage Control

The CC/CV control strategy is widely adopted in EV charging applications. The charger initially operates in constant current mode and later switches to constant voltage mode when the battery voltage reaches a threshold level.

B. PID Controller

Proportional–Integral–Derivative (PID) controllers are commonly used to regulate charging current and voltage. PID controllers improve system stability and reduce steady-state error.

C. dq Control Strategy

The dq transformation technique is used in three-phase converter control systems. It converts three-phase quantities into rotating reference frame components, simplifying current and voltage control.

Battery

Table III

Parameter	Value
Battery Voltage	400 V
Charging Current	125 A
Fast Charging Power	50 kW
Charging Mode	CC/CV
Charging Efficiency	92%

VII. CHALLENGES IN DC FAST CHARGING SYSTEMS

Although DC fast charging provides several advantages, various technical challenges still exist.

A. Battery Degradation

Frequent fast charging increases battery temperature and accelerates battery aging. Proper thermal management systems are required to minimize battery degradation.

B. Grid Impact

High-power fast charging stations create large power demand on the utility grid. Sudden load variations may affect grid stability and power quality.

C. Infrastructure Cost

The installation cost of DC fast charging stations is significantly higher than AC charging systems because of expensive power electronic equipment and cooling systems.

D. Standardization Issues

Different charging standards and connectors create compatibility challenges among EV manufacturers

VIII. CONCLUSION

This review synthesizes contemporary advancements in grid-interactive DC fast charging systems, emphasizing the critical interplay between power electronics topologies, dynamic CC/CV algorithms, synchronous reference frame control, and simulation-driven validation. The literature confirms that dual-stage architectures employing dq0-based grid synchronization, advanced DC-link regulation, and SOC-dependent charging profiles consistently achieve sub-two-hour replenishment while maintaining THD <5% and near-unity power factor. Simulation platforms like MATLAB/Simulink, augmented by HIL and digital twin frameworks, have proven indispensable in accelerating controller development and grid compliance testing. As EV adoption accelerates, next-generation DCFC infrastructure must evolve toward bidirectional, grid-supportive, and AI-optimized systems capable of seamless integration with renewable microgrids and smart distribution networks. Addressing semiconductor reliability, ultra-fast standardization, and cybersecurity will be pivotal in realizing resilient, sustainable electromobility ecosystems.

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