Fast-Charging EV Infrastructure Converters with Minimal Losses

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ABSTRACT

Fast-charging electric vehicle (EV) charging stations have emerged as a key enabler for widespread EV adoption. Central to this is the power converter technology which ensures efficient delivery of high power levels with minimal losses. This review paper focuses on fast-charging EV infrastructure converters and examines various converter topologies, control techniques, thermal management strategies, and emerging semiconductor technologies that reduce losses. The paper also addresses challenges in high power density design and discusses industry trends toward high efficiency and reliability. Though many research works propose advanced converter concepts, practical deployment faces issues of cost, complexity and thermal stress. Through a systematic analysis of converter designs and real world requirements, this paper aims to guide researchers and engineers towards the next generation of efficient fast-charging systems.

KEYWORDS: - *Electric Vehicles, Fast Charging, Power Converters, Efficiency, Wide-Bandgap Semiconductors, Thermal Management, EV Infrastructure*

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INTRODUCTION

Electric Vehicles (EVs) are quickly becoming mainstream as automotive industries and governments push for reduced emissions. However, one of the major obstacles for consumer acceptance is the charging time and convenience. Fast-charging stations aim to drastically reduce the time it takes to recharge an EV battery, but this calls for high power electronic converters that can handle several hundreds of kilowatts of power. These converters must operate with minimal losses to ensure high efficiency, reduce thermal stress, and lower operating costs.

In principle, EV charging infrastructure converters take input from the grid (often AC) and convert it to the DC required by EV batteries, while also regulating voltage, current, power quality and safety. The design of these converters is challenging because they have to balance efficiency, cost, complexity and reliability. This paper reviews the current state of fast-charging converters, technologies used to minimize losses, and the directions for future research.

EV FAST-CHARGING INFRASTRUCTURE OVERVIEW

Electric vehicle fast-charging infrastructure plays a critical role in reducing charging time and improving user convenience, especially for commercial fleets and highway charging stations. Unlike conventional home chargers, fast chargers are designed to deliver high power levels while maintaining grid compatibility, safety, and battery health. The infrastructure generally consists of power conversion units, communication interfaces, protection systems, cooling mechanisms, and grid-side support equipment.

Fast charging systems are commonly classified based on the amount of power delivered to the vehicle battery. This classification helps in understanding infrastructure requirements, converter ratings, and deployment scenarios.

1. Classification of EV Charging Levels

Fast charging is broadly categorized into multiple levels depending on voltage, current, and power ratings. Table 1 summarizes the commonly accepted charging levels.

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Table 1: Classification of EV charging levels.

Charging Level	Power Range	Typical Use
Level 1	< 3.3 kW	Home charging
Level 2	3.3 – 22 kW	Public and home
DC Fast Charging	22 – 150 kW	Public quick charge
Ultra-Fast	> 150 kW	Highway fast charge

KEY CONVERTER TOPOLOGIES

Power converter topology selection plays a decisive role in determining the efficiency, reliability, and scalability of fast-charging EV infrastructure. Since fast chargers operate at high power levels and must comply with grid power-quality standards while meeting diverse battery requirements, the choice of converter architecture significantly impacts overall system performance. Broadly, fast-charging converters are classified into two major categories: two-stage and single-stage conversion systems.

1. Two-Stage AC-DC + DC-DC Architecture

The two-stage conversion architecture is the most widely adopted approach in commercial fast-charging stations. In this design, the power conversion process is divided into two independent stages, allowing each stage to be optimized for a specific function.

AC-DC Conversion Stage

The first stage converts the grid AC supply into a regulated DC voltage. This stage typically employs active power factor corrected (PFC) rectifiers such as:

- Three-phase Vienna rectifiers
- Active front-end (AFE) converters
- Interleaved boost PFC converters

The primary objective of the AC-DC stage is to ensure near-unity power factor and low harmonic distortion, which is essential for grid compliance. By shaping the input current to follow the grid voltage waveform, PFC rectifiers reduce stress on the utility network and improve overall system

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efficiency. This stage usually operates at a fixed DC-link voltage that acts as an energy buffer between the grid and the vehicle.

DC-DC Conversion Stage

The second stage is responsible for regulating the output voltage and current according to the EV battery charging profile. Since EV batteries operate over a wide voltage range, the DC-DC converter must provide high controllability and galvanic isolation in most cases. Common DC-DC topologies include:

- Phase-shifted full bridge (PSFB)
- LLC resonant converters
- Dual active bridge (DAB) converters

This stage allows precise control of constant-current (CC) and constant-voltage (CV) charging modes, which are essential for battery safety and longevity.

Advantages and Limitations

The two-stage architecture offers several advantages, including modular design, easier control, and independent optimization of power quality and voltage regulation. It also supports scalability by paralleling multiple converter modules. However, the main drawback is the increased number of components, which leads to higher cost, larger size, and cumulative losses across stages.

2. Single-Stage Conversion

Single-stage converters combine AC-DC conversion and DC-DC regulation into a single power processing unit. This approach aims to reduce component count, system size, and energy losses associated with multiple conversion stages.

In a single-stage design, the converter simultaneously performs power factor correction and output voltage regulation. This integration can improve efficiency by eliminating intermediate DC-link losses and reducing passive components. However, the control strategy becomes more complex, as power quality and battery regulation must be handled concurrently.

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Single-stage converters are generally more sensitive to load and grid variations, and maintaining high power factor across a wide operating range is challenging. As a result, these topologies are less commonly used in ultra-fast chargers but remain attractive for compact or cost-sensitive charging systems.

3. Common Converter Topologies in Fast-Charging Applications

Several converter topologies are commonly used in both two-stage and single-stage architectures, each with distinct advantages and limitations.

LLC Resonant Converters

LLC resonant converters are widely used in fast-charging systems due to their high efficiency and soft-switching capability. By operating near resonance, these converters achieve zero-voltage switching (ZVS), significantly reducing switching losses. Additionally, the presence of a high-frequency transformer provides galvanic isolation and voltage scaling. However, LLC converters require careful design to maintain efficiency under wide voltage variations.

Phase-Shifted Full Bridge (PSFB) Converters

PSFB converters are well-suited for high-power applications due to their ability to handle large currents and high voltages. Phase-shift control enables partial soft-switching, improving efficiency at high load conditions. Despite these advantages, PSFB converters involve complex control and can suffer from circulating currents at light loads, which reduces efficiency.

Bidirectional Converters

Bidirectional converter topologies are increasingly important as vehicle-to-grid (V2G) functionality gains attention. These converters allow power flow in both directions, enabling EVs to act as distributed energy storage units. Dual active bridge (DAB) converters are commonly used for this purpose due to their symmetrical structure and ease of bidirectional operation. However, bidirectional designs add control complexity and require precise synchronization.

4. Comparative Assessment of Topologies

Each converter topology presents trade-offs between efficiency, complexity, controllability, and

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cost. Two-stage architectures provide robustness and grid compliance, while single-stage converters offer compactness and potential efficiency gains. Resonant and soft-switching topologies reduce losses but demand precise tuning and control.

Selecting the appropriate topology depends on application requirements such as charging power level, grid constraints, cost targets, and future scalability.

LOSS MECHANISMS IN FAST-CHARGING CONVERTERS

Losses in fast-charging converters directly impact system efficiency, thermal stress, reliability, and operating cost. Since fast chargers operate continuously at high power levels, even small inefficiencies can lead to significant energy wastage and excessive heat generation. Understanding the different loss mechanisms is therefore essential for optimizing converter design and achieving minimal-loss operation.

Converter losses can broadly be categorized into conduction losses, switching losses, magnetic losses, and auxiliary losses related to control and gate driving circuits.

1. Conduction Losses

Conduction losses occur when current flows through power semiconductors and passive components such as inductors, transformers, and cables. These losses are proportional to the square of the current and the effective resistance of the conduction path.

In power semiconductor devices such as MOSFETs and IGBTs, conduction loss mainly depends on parameters like on-state resistance (R_{DS(on)}) or saturation voltage. At high current levels typical of fast chargers, even small resistance values can result in considerable power dissipation. Similarly, diodes contribute conduction losses due to their forward voltage drop, particularly in high-current rectification stages.

Passive components also contribute to conduction losses through copper losses in windings and interconnections. High current density in inductors and transformers leads to resistive heating, which increases further with temperature. To minimize conduction losses, designers often use:

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- Low-resistance wide-bandgap devices
- Parallel device configurations
- Thick copper layers and busbars
- Optimized current paths to reduce parasitic resistance

Although these measures improve efficiency, they may increase system cost and size if not carefully optimized.

2. Switching Losses

Switching losses arise during the turn-on and turn-off transitions of power semiconductor devices. During these transitions, voltage and current overlap across the device, causing energy dissipation. In fast-charging converters, high switching frequencies are often used to reduce passive component size, which further increases switching losses.

The magnitude of switching loss depends on:

- Switching frequency
- Device voltage and current ratings
- Switching speed and gate drive characteristics
- Parasitic inductance and capacitance

Hard-switched converters experience significant switching losses, especially at high power levels. To mitigate this, soft-switching techniques such as zero-voltage switching (ZVS) and zero-current switching (ZCS) are widely employed. Resonant and phase-shifted converter topologies are commonly used to achieve these conditions.

Additionally, wide-bandgap semiconductors like SiC and GaN exhibit faster switching with lower energy loss per transition, making them highly suitable for fast-charging applications. However, their high switching speed also increases electromagnetic interference if not properly managed.

3. Magnetic Losses

Magnetic losses occur in inductors and transformers used for energy storage, filtering, and isolation. These losses are particularly significant in fast-charging converters due to high operating currents and elevated switching frequencies.

Magnetic losses consist mainly of:

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- **Core losses**, caused by hysteresis and eddy currents in the magnetic core material
- **Copper losses**, caused by AC and DC resistance of the windings

At high frequencies, skin and proximity effects increase effective winding resistance, leading to additional losses. Interleaved converter designs, while beneficial for current sharing and ripple reduction, may further complicate magnetic design due to uneven flux distribution.

To reduce magnetic losses, modern fast-charging converters employ advanced ferrite or nanocrystalline core materials, optimized winding techniques such as litz wire, and careful thermal management. Proper magnetic design plays a crucial role in achieving high efficiency and power density.

4. Control and Driver Losses

Control and driver losses are often overlooked but become noticeable in high-power fast-charging systems. These losses originate from gate driver circuits, digital controllers, sensors, communication modules, and auxiliary power supplies.

Gate drivers consume power during each switching cycle to charge and discharge the gate capacitances of power devices. At high switching frequencies, this gate drive loss becomes significant. Similarly, current and voltage sensors, isolation amplifiers, and control processors contribute to continuous power consumption.

In large fast-charging installations with multiple parallel converter modules, cumulative control losses can reduce overall system efficiency. Low-power control ICs, optimized gate drive strategies, and efficient auxiliary power supplies are therefore essential to minimize these losses.

5. Overall Impact on Converter Performance

The combined effect of conduction, switching, magnetic, and control losses determines the thermal profile and efficiency of fast-charging converters. Excessive losses not only reduce efficiency but also increase cooling requirements and shorten component lifetime.

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Effective loss management requires a holistic design approach that balances electrical performance, thermal design, cost, and reliability. As fast-charging power levels continue to increase, loss reduction remains a critical research and design focus.

TECHNIQUES TO MINIMIZE LOSSES

1. Wide-Bandgap Semiconductors

Wide-bandgap (WBG) devices like Silicon-Carbide (SiC) and Gallium-Nitride (GaN) have lower switching and conduction losses compared to conventional silicon MOSFETs.

Benefits include higher switching frequencies, less cooling needs, and smaller passive components, enabling high power density.

2. Soft-Switching Techniques

Converters using soft-switching like zero-voltage switching (ZVS) or zero-current switching (ZCS) reduce switching losses significantly. LLC resonant converters are a popular choice here.

3. Thermal Management

Minimizing thermal resistance through heat sinks, liquid cooling, and optimized airflow helps maintain device efficiency and reliability.

4. Interleaved and Multi-Phase Designs

Interleaving spreads currents across phases, reducing peak current and associated losses. It also lowers ripple making passive size smaller.

CASE STUDIES AND RECENT ADVANCES

1. Industry Deployments

Most commercial fast chargers (up to 350 kW) use modular converter arrays with built-in cooling and real-time monitoring. These units typically achieve 94–97% efficiency with SiC-based converters.

2. Research Prototypes

Recent studies show advanced topologies like dual active bridge (DAB) converters with SiC

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achieving high power (> 250 kW) with reduced losses. However, complexity and control challenges remain.

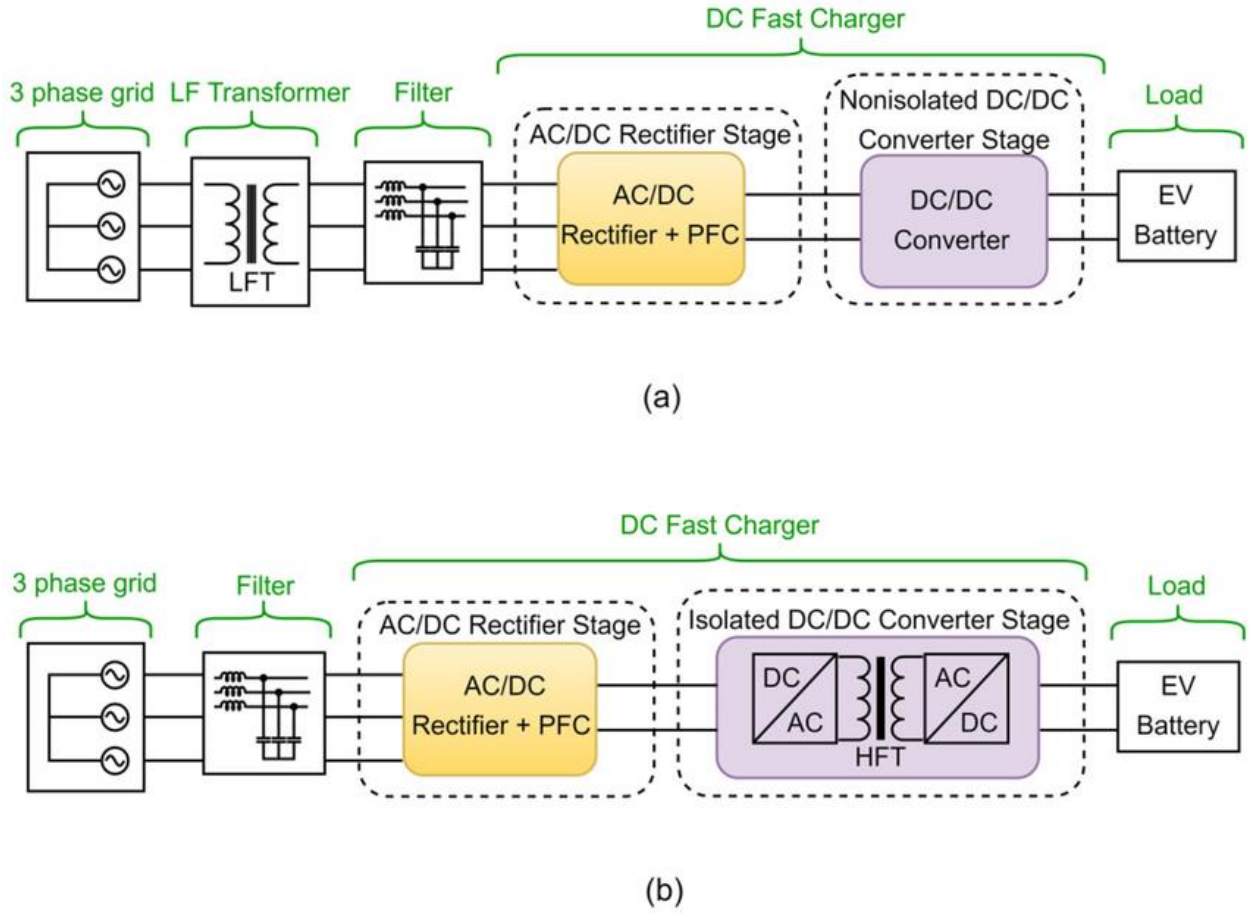


Figure 1: Simplified fast charging converter architecture.

CHALLENGES IN DEPLOYMENT

Despite advances, several challenges persist:

1. Cost of SiC and GaN Devices

Wide bandgap semiconductors are more expensive than silicon devices, affecting overall charger cost.

2. Complexity of Control

Soft-switching and interleaved designs require sophisticated control algorithms which increases software complexity and tuning effort.

3. EMI and Filtering

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High switching speeds produce electromagnetic interference, requiring careful layout and filtering design.

4. Standards and Interoperability

Compatibility with multiple EV battery chemistries and standards (e.g., CCS, CHAdeMO) demands flexible power conversion solutions.

FUTURE TRENDS

Several emerging trends promise better efficiency and performance:

1. Integrated Power Modules

Combining semiconductors and magnetics into compact modules reduces parasitics and losses.

2. AI-Based Control

Adaptive control using machine learning can optimize switching patterns for real-time efficiency gains.

3. Vehicle-to-Grid (V2G)

Bidirectional converters that support V2G can leverage EV batteries as distributed storage, requiring high efficiency in both directions.

CONCLUSION

Fast-charging infrastructure converters are vital for EV adoption. Minimizing losses in these converters ensures high efficiency, lower operating costs, and longer equipment life. Advances in wide bandgap semiconductors, soft-switching topologies, and thermal design significantly improve converter performance. However, cost and complexity remain barriers. Continued research and industry collaboration are essential to develop efficient, reliable and affordable fast-charging solutions.

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