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Power Conversion Technologies and Power Quality Challenges in EV Fast-Charging Stations: A Comprehensive Review

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Abstract

The rapid growth of electric vehicles (EVs) has accelerated the demand for efficient, reliable, and high-power fast-charging infrastructures capable of supporting sustainable transportation systems. Fast-charging stations have become a critical component of modern EV deployment due to their ability to significantly reduce charging time while supporting public transportation, commercial fleets, and long-distance mobility applications. However, high-power charging introduces major technical challenges related to converter efficiency, harmonic distortion, thermal management, power quality, and grid integration. This paper presents a comprehensive review of techniques used in EV fast-charging stations, focusing on charging architectures, power electronic converter topologies, bidirectional vehicle-to-grid (V2G) systems, wide-bandgap semiconductor technologies, and harmonic mitigation approaches. The study reviews modern AC–DC and DC–DC converter structures, including multilevel converters, active front-end rectifiers, LLC resonant converters, and dual-active-bridge converters used in high-power charging applications. In addition, the impacts of fast charging on electrical power systems are critically analyzed, including low-order harmonic distortion, supra-harmonic emissions, voltage instability, and distribution-network loading. Recent developments in silicon carbide (SiC) and gallium nitride (GaN) semiconductor devices are also discussed in terms of switching performance, thermal efficiency, and power density improvement. Furthermore, renewable-energy-assisted charging systems and bidirectional charging technologies are examined as promising solutions for future smart-grid integration. The review concludes that advanced converter technologies, harmonic mitigation methods, and intelligent grid-compatible charging infrastructures will play a major role in enabling scalable, efficient, and sustainable next-generation EV fast-charging systems.

Keywords:

Smart Electric Vehicles (EVs), Fast-Charging Stations, Smart Grid Integration, Vehicle-to-Grid (V2G).

I. INTRODUCTION

THE rapid growth of electric vehicles (EVs) has significantly transformed the transportation sector and accelerated the global transition toward sustainable and low-emission mobility systems. Increasing environmental concerns, strict carbon-emission regulations, and advances in battery technology have encouraged governments and industries worldwide to adopt EVs as a major alternative to conventional internal combustion engine vehicles [1], [2]. However, the large-scale deployment of EVs requires the development of reliable, efficient, and high-power charging infrastructure capable of supporting fast and convenient

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charging operations [2], [3].

Among the different charging technologies, fast-charging stations have emerged as one of the most important enabling technologies for modern EV transportation systems. Unlike conventional slow chargers, fast chargers significantly reduce charging time by delivering high power levels directly to vehicle batteries [4]. This capability is essential for long-distance transportation, commercial fleets, public charging networks, and high-utilization urban environments [5], [6]. Nevertheless, high-power charging introduces several technical challenges related to power conversion efficiency, battery safety, thermal management, harmonic distortion, and grid stability [7]-[10].

Modern EV fast-charging stations rely heavily on advanced power electronic converters and intelligent control systems to ensure efficient energy transfer between the electrical grid and EV batteries. Various converter topologies, including isolated and non-isolated DC–DC converters, multilevel inverters, bidirectional converters, and modular charging architectures, have been proposed to improve charging efficiency, reduce power losses, and enhance operational flexibility [11]. In addition, recent developments in wide-bandgap semiconductor devices such as silicon carbide (SiC) and gallium nitride (GaN) technologies have enabled higher switching frequencies, improved thermal performance, and increased power density in fast-charging systems [12]-[16].

Another major challenge associated with EV fast charging is its impact on electrical power systems. Large-scale deployment of high-power chargers may lead to voltage fluctuations, harmonic distortion, transformer overloading, and increased peak demand [17].

To address these issues, modern charging stations increasingly incorporate smart-grid integration, renewable energy sources, energy storage systems, and intelligent energy-management strategies.

Vehicle-to-grid (V2G) technology has also gained significant attention because it enables bidirectional energy exchange between EVs and the power grid, thereby supporting grid stabilization and distributed energy management.

Furthermore, advanced charging-control techniques such as constant-current/constant-voltage (CC/CV) charging, adaptive charging algorithms, fuzzy logic control, model predictive control, and artificial intelligence-based optimization methods have been investigated to improve charging speed while minimizing battery degradation and thermal stress [18], [19]. Emerging technologies including wireless charging, ultra-fast charging, and AI-assisted charging management are expected to further transform future EV charging infrastructures [20]. Figure 1 illustrates the general architecture of a modern EV fast-charging station integrated with smart-grid and energy-management functionalities.

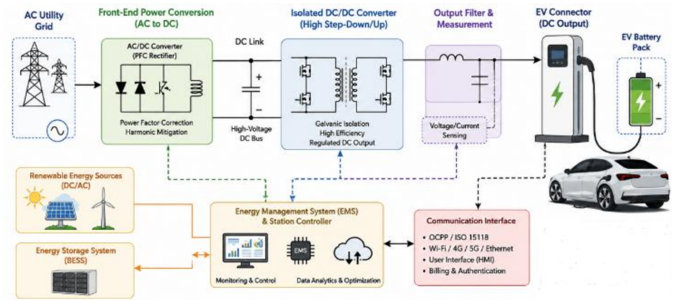

Fig. 1. General Architecture of an EV Fast-Charging Station.

This paper presents a comprehensive review of techniques used in EV fast-charging stations, focusing on charging architectures, converter topologies, control methods, power quality improvement, thermal management, renewable-energy integration, and smart-grid interaction. In addition, recent technological advancements, major technical challenges, and future research directions toward intelligent and sustainable EV fast-charging infrastructure are critically discussed.

II. LITERATURE REVIEW

The rapid expansion of electric vehicles has accelerated research on high-efficiency charging infrastructures capable of supporting fast, reliable, and grid-compatible charging operations. EV charging technologies are generally classified into Level 1, Level 2, DC fast charging, ultra-fast charging, and wireless charging systems according to charging power and operating architecture [21]. Among these technologies, DC fast charging has become the most widely investigated solution because it significantly reduces charging time while supporting long-distance transportation and commercial EV applications.

Conventional Level 1 and Level 2 chargers typically operate using AC power supplied directly from residential or commercial electrical systems. Although these chargers are relatively simple and cost-effective, their charging speed is limited because onboard vehicle chargers usually restrict the allowable charging power. In contrast, DC fast chargers perform AC/DC conversion externally within the charging station, enabling direct high-power DC charging of the EV battery. Modern DC fast-charging systems commonly operate within power ranges from 50 kW to more than 350 kW [22]. Emerging ultra-fast charging systems have recently exceeded 500 kW and even approached megawatt-scale charging for heavy-duty transportation applications [23].

Recent developments in ultra-fast charging technologies have focused on minimizing charging time while maintaining battery safety and thermal stability. These systems require advanced converter topologies, high- efficiency semiconductor devices, and intelligent thermal-management techniques to handle high current and voltage levels efficiently. Furthermore, mobile charging stations have been proposed as flexible charging solutions for remote or infrastructure-limited regions [24]. Figure 2 presents the classification of EV charging technologies based on charging level, charging speed, and power delivery architecture.

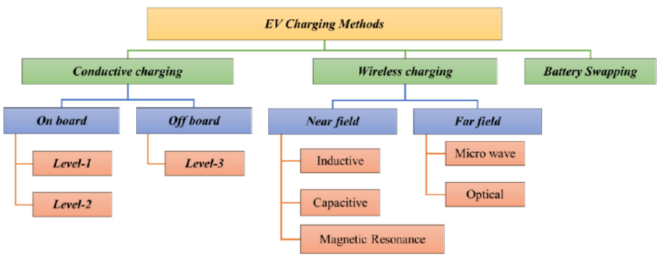

Fig. 2. Classification of EV charging technologies [23].

Power electronic converters represent the core component of EV fast-charging stations. Various converter architectures have been proposed to improve conversion efficiency, power density, power quality, and charging flexibility. Commonly used converter topologies include; buck, boost, buck-boost, Cuk, SEPIC, resonant converters, multilevel converters, isolated full-bridge architectures, and modular multilevel converter (MMC) architectures.

Bidirectional converters have gained considerable attention because they support vehicle-to-grid (V2G) operation, allowing EV batteries to exchange energy with the power grid. In addition, modular multilevel converter (MMC) architectures are increasingly investigated for high-power fast-charging stations because of their scalability, improved harmonic performance, and reduced switching stress [25]. Wide-bandgap semiconductor technologies based on silicon carbide (SiC), and gallium nitride (GaN) have further improved converter performance by enabling higher switching frequencies, lower switching losses, improved thermal efficiency, and higher power density [26].

Charging-control techniques play an essential role in battery protection, charging efficiency, and charging speed optimization. The most widely used charging method is the constant-current/constant-voltage (CC/CV) strategy, where the battery is initially charged under constant current and later transitions to constant voltage as the battery approaches full charge.

Recent research has introduced more advanced charging-control methods such as fuzzy logic control, model predictive control, adaptive charging, neural-network-based optimization, and artificial intelligence-assisted energy management.

These methods aim to minimize battery degradation, reduce charging time, improve thermal performance, and enhance charging reliability. Battery management systems (BMSs) are also integrated with charging controllers to continuously monitor battery temperature, state of charge (SOC), state of health (SOH), voltage balancing, and fault conditions [27]. The increasing deployment of high-power fast chargers introduces significant challenges to electrical distribution networks, including harmonic distortion, transformer overloading, voltage fluctuations, and peak-demand increase.

To address these issues, modern charging stations increasingly integrate renewable energy systems, battery energy storage systems (BESS), smart-grid communication, and intelligent energy-management systems. Vehicle-to-grid (V2G) technology has emerged as an important research area because it enables bidirectional power transfer between EVs and the electrical grid. V2G systems can support load balancing, frequency regulation, renewable-energy stabilization, and distributed energy management. Furthermore, wireless charging and dynamic charging technologies are receiving growing research attention due to their ability to improve charging convenience and automation [28]-[32].

Despite significant technological progress, several challenges remain in EV fast-charging infrastructure development. High-power charging systems continue to face limitations related to thermal management, converter efficiency, electromagnetic interference (EMI), battery degradation, cybersecurity, and charging standard interoperability. Future research is expected to focus on ultra-fast charging systems, AI-based charging optimization, solid-state transformer integration, advanced cooling techniques, and renewable-powered charging stations. The integration of intelligent control, wide-bandgap semiconductor devices, and smart-grid technologies is expected to play a major role in developing sustainable and highly efficient next-generation EV fast-charging infrastructures.

III. FAST-CHARGING STATION ARCHITECTURES

The continuous increase in electric vehicle (EV) deployment has accelerated the development of advanced fast-charging infrastructures capable of supporting high-power, reliable, and grid-compatible charging operations. Modern fast-charging stations rely on sophisticated power electronic architectures, intelligent charging coordination, and bidirectional energy-management systems to achieve high efficiency, reduced charging time, and stable grid interaction [22], [26], [28]. This section reviews the major fast-charging architectures and the power-conversion technologies used in modern EV charging systems.

A. EV Fast-Charging Architectures

EV charging systems are generally classified into; AC charging, DC fast charging, ultra-fast charging, and wireless charging systems. Among these technologies, DC fast charging has become the dominant solution for public charging infrastructure because it allows direct high-power charging of EV batteries while significantly reducing charging duration [11], [20].

Conventional AC chargers rely on onboard converters integrated within the EV, which limit charging power due to space and thermal constraints. In contrast, DC fast chargers perform AC/DC conversion externally at the charging station, enabling charging capacities ranging from 50 kW to more than 350 kW [11], [13].

Modern fast-charging stations are commonly employed; centralized charging architectures, distributed modular charging systems, and hybrid renewable-assisted charging structures. Centralized architectures use a common high-power DC bus shared among multiple charging outlets, whereas distributed charging systems allocate dedicated converter modules for each charging point. Distributed architectures improve scalability, redundancy, and maintenance flexibility [8], [20].

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Recent studies have also investigated renewable-assisted charging stations integrating; PV generation, wind-energy systems, and battery energy storage systems (BESS) to reduce peak grid demand and improve sustainability [4], [10], [18], [20].

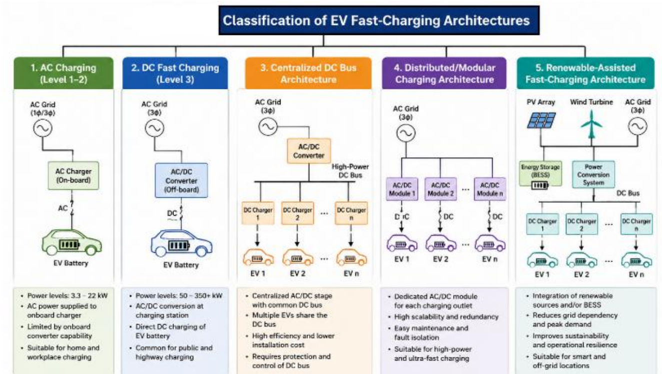

Fig. 3. Classification of EV fast-charging architectures.

B. AC–DC Converter Technologies

The AC–DC conversion stage represents one of the most critical components of EV fast-charging stations because it directly affects power quality, harmonic distortion, power factor, and conversion efficiency. Modern charging systems increasingly employ active front-end (AFE) rectifiers and power-factor-correction (PFC) converters to achieve near-unity power factor and reduced total harmonic distortion (THD) [12], [13], [14].

Common AC–DC converter topologies include two-level PWM rectifiers, Vienna rectifiers, three-level neutral-point-clamped (NPC) converters, and modular multilevel converters (MMCs). Vienna rectifiers are particularly attractive for fast-charging applications due to lower switching losses, high efficiency, and reduced harmonic emissions. Multilevel converter architectures provide improved voltage quality and lower switching stress, especially in ultra-fast charging systems operating at high voltage levels [13].

Recent research has focused extensively on harmonic mitigation techniques because EV chargers behave as nonlinear loads capable of introducing low-order harmonics, high-order harmonics, and supra-harmonic emissions into distribution networks [7], [12], [14]. Studies demonstrated that harmonic distortion generated by fast chargers may negatively affect transformer performance, voltage regulation, and nearby sensitive electronic equipment [7], [14]. Table 1 compares the major AC–DC converter topologies used in EV fast-charging stations in terms of efficiency, harmonic performance, bidirectional capability, complexity, and application suitability.

C. DC–DC Converter Topologies

DC–DC converters are responsible for regulating charging voltage and current according to battery requirements. Converter selection strongly influences charging efficiency, ripple performance, thermal behavior, and power density. Common DC–DC converter topologies used in EV fast charging include buck converters, boost converters, buck–boost converters, Cuk converters, SEPIC converters, LLC resonant converters, and dual-active-bridge (DAB) converters. Isolated converter topologies employing high-frequency transformers are widely preferred in fast-charging systems because they provide galvanic isolation, improved safety, and higher voltage adaptability [13], [20].

Among the available topologies, LLC resonant converters and DAB converters have received considerable research attention because they support soft-switching operation, reduced switching losses, high-frequency operation, and bidirectional power flow capability. Wide-bandgap semiconductor devices such as silicon carbide (SiC), and gallium nitride (GaN) have significantly improved converter performance by enabling higher switching frequencies, reduced converter size, improved thermal efficiency, and higher power density [13]. Figure 4 shows the typical DC fast charging structure.

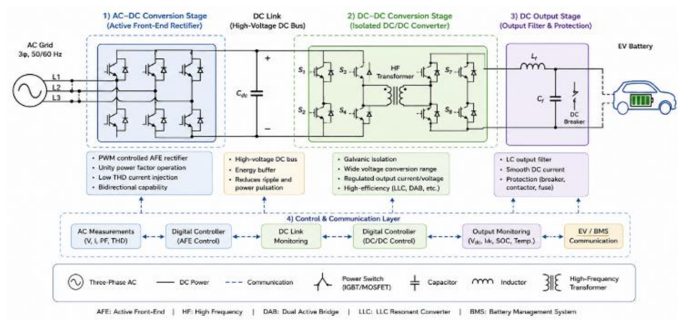

Fig. 4. Typical DC fast-charging power conversion structure.

D. Bidirectional Charging and Vehicle-to-Grid (V2G)

Vehicle-to-grid (V2G) technology has emerged as one of the most promising developments in EV charging infrastructure. Unlike conventional unidirectional charging systems, V2G architectures allow bidirectional energy exchange between EV batteries and the electrical grid [1], [2], [15], [16]. Bidirectional charging enables EVs to operate as distributed energy-storage units capable of supporting peak shaving, frequency regulation, voltage stabilization, renewable-energy balancing, and emergency backup support.

Several recent studies proposed aggregator-based charging frameworks for coordinating large groups of EVs participating in grid-support services [1], [3], [4], [17], [18]. Aggregators can optimize charging and discharging schedules based on electricity pricing, renewable-energy availability, grid loading conditions, and user charging preferences. Optimization-based charging coordination methods have demonstrated significant improvements in load balancing, charging economics, and distribution-system reliability [3], [9], [17].

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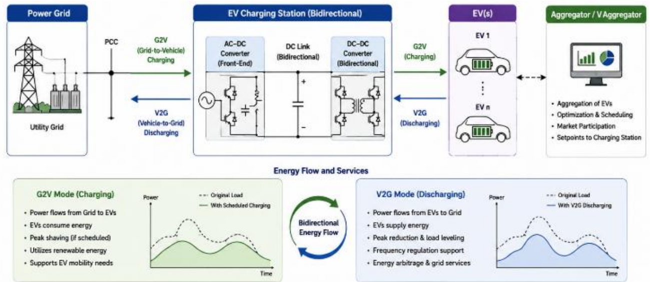

Fig. 5. Bidirectional V2G Energy Flow Framework.

E. Wide-Bandgap Semiconductor Technologies

The increasing power demand of fast-charging systems has accelerated the adoption of wide-bandgap semiconductor technologies. Silicon carbide (SiC) and gallium nitride (GaN) devices offer several advantages over conventional silicon-based devices, including lower switching losses, higher breakdown voltage, higher switching frequency capability, and improved thermal performance.

These characteristics enable compact converter design, higher power density, improved cooling performance, and higher charging efficiency. Wide-bandgap devices are increasingly integrated into ultra-fast charging systems, modular converter architectures, and high-efficiency bidirectional charging stations. As charging power levels continue to increase toward megawatt-scale charging applications, wide-bandgap semiconductor technologies are expected to play a major role in future EV charging infrastructures. Table 3 presents a concise technical comparison between conventional silicon devices and modern wide-bandgap semiconductor technologies used in EV fast-charging systems.

IV. **POWER QUALITY, HARMONICS, AND TECHNICAL CHALLENGES**

The increasing deployment of EV fast-charging stations introduces significant challenges to electrical power systems due to the high-power and nonlinear characteristics of charging converters. Fast chargers operate using high-frequency switching devices and power electronic interfaces that can generate harmonic distortion, voltage fluctuations, supra-harmonics, and electromagnetic interference (EMI) [19]. As charging power levels continue to increase toward ultra-fast charging applications, maintaining acceptable power quality and grid stability has become a critical research concern.

A. Harmonic Distortion in Fast-Charging Systems

Modern EV fast chargers behave as nonlinear loads because they employ switching-based AC–DC and DC–DC converters. These converters inject harmonic currents into the electrical grid, resulting in waveform distortion, increased power losses, transformer overheating, capacitor stress, and reduced equipment lifespan [12], [14]. Additionally, low-order harmonics generated by charging converters can negatively affect voltage quality, distribution-network stability, and nearby sensitive loads. Furthermore, recent studies identified the growing importance of supra-harmonics in the frequency range between 2 kHz and 150 kHz, particularly in high-frequency charging systems [33]. Supra-harmonic propagation may interfere with communication systems, smart-grid devices, protection systems, and power-line communication networks [34].

Recent experimental studies demonstrated that fast-charging stations operating under high-power conditions can significantly increase both low-order and high-order harmonic distortion levels in low-voltage distribution systems [6]. Harmonic interactions among multiple simultaneously operating chargers may further increase distortion severity and network instability [19]. Table 3 summarizes the major low-order harmonic and supra-harmonic emission characteristics reported in recent EV fast-charging studies and their corresponding impacts on power-system performance.

Large-scale integration of EV charging infrastructure introduces several power quality issues, including voltage sag, voltage swell, flicker, current imbalance, reduced power factor, and transient disturbances [1], [19]. Ultra-fast charging stations require very high instantaneous power demand, which can create substantial stress on transformers, feeders, and distribution substations.

Furthermore, rapid charging and discharging operations associated with V2G systems may introduce additional transient phenomena and dynamic instability under weak-grid conditions [17]. Power quality degradation becomes more severe when multiple charging stations are concentrated in urban areas or transportation hubs where simultaneous charging demand is high [9]. To reduce harmonic distortion and improve grid compatibility, modern EV charging systems increasingly incorporate active power filters (APFs), passive filters, hybrid filters, multilevel converter topologies, and advanced modulation techniques [35]. Active front-end (AFE) rectifiers and power-factor-correction (PFC) converters are widely used because they provide near-unity power factor, reduced THD, bidirectional operation capability, and improved grid synchronization [13]. Multilevel converters such as neutral-point-clamped (NPC), flying capacitor, and modular multilevel converter (MMC) architectures can significantly reduce harmonic content by producing output waveforms closer to sinusoidal form.

Recent studies also investigated adaptive PWM techniques, selective harmonic elimination, and model predictive control (MPC) for improving harmonic performance under varying charging conditions [36].

B. Reliability Challenges

High-power charging operation generates considerable thermal stress in semiconductor devices, transformers, cables, and battery systems. Excessive temperature rise may reduce converter efficiency, switching reliability, battery lifespan, and overall charging-system durability.

Although wide-bandgap semiconductor devices such as SiC and GaN improve thermal performance, effective cooling systems remain essential in ultra-fast charging stations operating above 150 kW. Common thermal-management methods include forced-

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air cooling, liquid cooling, phase-change materials, and integrated thermal monitoring systems.

Battery degradation also remains one of the major concerns associated with ultra-fast charging because high charging current can accelerate lithium plating, internal resistance increase, and thermal runaway risk.

C. Grid Integration and Infrastructure Challenges

The expansion of EV fast-charging infrastructure requires substantial upgrades to existing electrical distribution systems. High charging demand may exceed local feeder capacity and require transformer reinforcement, distribution-network expansion, additional substations, and advanced grid-monitoring systems [13], [20]. In addition, interoperability among charging standards, communication protocols, and charging-network operators remains a significant technical challenge. Cybersecurity has also emerged as an important concern because modern charging stations increasingly depend on cloud connectivity, IoT communication, and smart-grid coordination platforms.

Future EV charging infrastructures are therefore expected to incorporate intelligent monitoring, adaptive energy management, predictive maintenance, and AI-assisted fault diagnosis to improve reliability, operational flexibility, and power-system resilience.

V. Conclusion

The rapid expansion of electric vehicles has accelerated the development of high-power fast-charging infrastructures capable of supporting efficient, reliable, and sustainable transportation systems. This review examined the major technologies and techniques used in EV fast-charging stations, including charging architectures, power electronic converter topologies, bidirectional V2G systems, wide-bandgap semiconductor devices, and harmonic mitigation approaches. The study showed that modern fast-charging systems increasingly rely on advanced AC–DC and DC–DC converter technologies to achieve high efficiency, reduced charging time, improved power density, and enhanced grid compatibility. Wide-bandgap semiconductor devices such as SiC and GaN have significantly improved converter performance through higher switching frequency capability, lower switching losses, and superior thermal characteristics. Despite these advancements, EV fast-charging stations continue to introduce major technical challenges related to harmonic distortion, supra-harmonic emissions, voltage instability, thermal management, and distribution-network loading. Recent research demonstrated that uncontrolled high-power charging may negatively affect power quality and increase stress on electrical infrastructure. Consequently, harmonic mitigation methods, advanced converter control techniques, filtering systems, and coordinated charging strategies have become essential for maintaining stable and reliable grid operation. The review further highlighted the growing importance of renewable-energy-assisted charging stations and bidirectional V2G technologies for improving energy flexibility and supporting future smart-grid applications. As charging demand continues to increase toward ultra-fast and megawatt-scale charging systems, future research is expected to focus on intelligent energy management, AI-assisted charging optimization, advanced thermal-management systems, high-efficiency converter architectures, and grid-resilient charging infrastructures. Overall, EV fast charging technology represents a key enabling component of next-generation sustainable transportation systems, and continued research in power electronics, power quality improvement, and grid integration will play a critical role in supporting future large-scale EV deployment

TABLE I
Comparison of AC–DC converter topologies for EV fast charging

Converter Topology	Isolation	Bidirectional Capability	Efficiency	Harmonic Performance	Switching Complexity	Main Advantages	Main Limitations	Typical Application
Two-Level PWM Rectifier	No	Yes	High	Moderate	Moderate	Simple control, mature technology	Higher switching losses and THD	Medium-power DC fast charging
Vienna Rectifier	No	No	Very High	Excellent	Moderate	High PF, low THD, reduced losses	Unidirectional operation	High-efficiency front-end chargers
Three-Level NPC Converter	No	Yes	High	Very Good	High	Reduced voltage stress and harmonic distortion	Complex control and balancing	High-power fast chargers
Modular Multilevel Converter (MMC)	Optional	Yes	Very High	Excellent	Very High	Scalability, low harmonics, modular structure	High cost and control complexity	Ultra-fast charging stations

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Active Front-End (AFE) Rectifier	No	Yes	High	Very Good	Moderate	Bidirectional operation and grid support	Requires advanced control	Smart-grid-integrated charging
Interleaved Boost PFC Converter	No	Limited	High	Good	Moderate	Reduced current ripple and improved PF	Increased component count	Front-end PFC stages
Full-Bridge Isolated Converter	Yes	Yes	High	Good	High	Galvanic isolation and safety	Larger transformer size	High-voltage charging systems
LLC Resonant Converter	Yes	Limited	Very High	Excellent	High	Soft switching and low switching loss	Narrow optimal operating range	High-efficiency DC charging
Dual Active Bridge (DAB) Converter	Yes	Yes	Very High	Excellent	High	Bidirectional power flow and isolation	Complex modulation control	V2G and ultra-fast charging
Cuk Converter	Optional	Limited	Moderate	Good	Low	Low ripple current characteristics	Lower power density	Low- to medium-power charging
SEPIC Converter	Optional	Limited	Moderate	Moderate	Low	Wide input/output voltage range	Reduced efficiency at high power	Auxiliary charging stages
Boost Converter	No	No	High	Moderate	Low	Simple structure and low cost	High ripple and limited isolation	Basic DC charging stages
Two-Level PWM Rectifier	No	Yes	High	Moderate	Moderate	Simple control, mature technology	Higher switching losses and THD	Medium-power DC fast charging

TABLE II

TECHNICAL COMPARISON OF WIDE-BANDGAP SEMICONDUCTOR DEVICES FOR EV FAST CHARGING

Parameter	Silicon (Si)	Silicon Carbide (SiC)	Gallium Nitride (GaN)
Typical Switching Frequency	Up to ~50 kHz	50–200 kHz	200 kHz – 1 MHz
Switching Loss	High	Low	Very Low
Thermal Performance	Moderate	Excellent	Excellent
Voltage Capability	Up to ~900 V	Up to 10 kV	Up to ~1.2 kV
Typical Efficiency	92–94%	96–98%	98–99%
Power Density	Moderate	High	Very High
Typical EV Charging Applications	Conventional chargers	Ultra-fast chargers, V2G systems	Compact high-frequency chargers

TABLE III

LOW-ORDER HARMONIC AND SUPRA-HARMONIC EMISSIONS IN EV FAST-CHARGING SYSTEMS

Reference	Charging System / Study Focus	Frequency Range	Main Harmonic / Supra-harmonic Findings	Reported Impact
[19]	EV chargers in low-voltage grids	2–150 kHz	Significant propagation of supra-harmonics between neighboring EV chargers	Interference with nearby equipment and increased network distortion

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[20]	Three-phase four-leg AFE AC/DC converter	Low-order harmonics	Current ripple harmonics generated by switching converters	Reduced power quality and increased THD
[6]	Fast-charging stations in distribution systems	Low- and high-order harmonics	Fast chargers produce substantial harmonic distortion under heavy loading	Voltage distortion, transformer stress, and network instability
[7]	EV integration in microgrids	Harmonic spectrum analysis	Harmonic disturbances increase with high EV penetration	Hosting-capacity limitations and power-quality degradation
[5]	Bidirectional EV charging station	Low-order harmonics	Active filtering and converter optimization reduced THD significantly	Improved power quality and grid compatibility
[37]	AC–DC power electronic converters	2–150 kHz	Supra-harmonic emissions generated by high-frequency switching converters	Electromagnetic interference and communication-system disruption
[33]	Smart-grid power-quality monitoring	Harmonics and supra-harmonics	Identified supra-harmonics as a major emerging smart-grid issue	Measurement and detection challenges in smart grids
[34]	Time-varying nonlinear load modelling	Harmonic spectrum variability	Harmonic emissions vary dynamically with EV charging demand	Increased complexity of harmonic prediction
[3]	Hybrid fast-charging station	Harmonics from DC fast charging	Fast charging introduces voltage-quality problems and harmonic distortion	Grid stress and increased peak demand
[4]	Grid management with EV penetration	Harmonic-related grid issues	Large EV penetration increases distortion and operational challenges	Need for coordinated charging and mitigation methods

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