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Exploring Review of Advancements in Fast-Charging Techniques and Infrastructure for Electric Vehicles Revolution

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ABSTRACT

The rapid growth of the electric vehicle (EV) industry has increased the demand for efficient and reliable fast-charging infrastructure. This paper comprehensively reviews advancements in fast-charging techniques, focusing on DC fast charging, evolving standards, and charging modes. A detailed analysis of on-board and off-board EV chargers is presented, including DC–DC conversion stages with a comparison of isolated and non-isolated topologies. Key control strategies, such as voltage and current regulation and AI-driven approaches, are examined to optimize performance and reliability. Thermal management strategies using advanced sensors to enhance safety and battery longevity are also discussed. This paper highlights recent research contributions and emerging challenges, with insights into infrastructure development, energy storage integration, and policy implications. Notably, projections indicate that global EV sales could rise to 35% by 2030, with fast-charging infrastructure supporting charging times as low as 15 min for 80% battery capacity. Advancements in bidirectional charging and AI-driven optimization are shaping the next generation of smart EV charging stations. This review serves as a valuable resource for researchers, engineers, and policymakers engaged in EV technology and infrastructure development.

1 | Introduction

The increasing adoption of electric vehicles (EVs) is transforming sustainable transportation, reducing emissions, and promoting cleaner energy. The demand for efficient charging solutions has led to significant advancements in fast-charging technology [1]. The market for EVs has expanded rapidly, with global EV sales reaching 14% of new car sales in 2022 and expected to grow to 35% by 2030 [2], the need for efficient charging solutions has become critical. Fast-charging technology is advancing to support longer trips, reduce downtime, and enhance user convenience [3]. Fast charging is categorized into two main types: alternating current (AC) charging and direct current (DC) fast charging, with DC charging offering higher power levels and significantly reduced charging durations [4]. Charging stations are evolving to accommodate the increasing variety of battery EVs (BEVs), integrating diverse charging technologies such as conductive and inductive charging, wireless charging systems, and battery-swapping solutions [5, 6]. These advancements ensure broad compatibility with various EV models and improve overall charging efficiency [7]. An essential innovation in charging infrastructure is the integration of bidirectional chargers for vehicle-to-grid (V2G) applications, which allow EVs to inject power back into the grid, supporting grid stability, load leveling, and renewable energy integration [8–11]. Moreover, advanced control strategies in fast-charging systems, such as voltage and current regulation and artificial intelligence (AI)-based predictive control, are improving charging efficiency and minimizing energy losses [12–14]. Recent research highlights the significance of integrating renewable energy sources, such as solar and wind, into fast-charging stations to reduce carbon emissions and operational costs [15–17].

Additionally, intelligent charging algorithms leverage AI and machine learning to dynamically adjust charging rates based on grid conditions and demand, further optimizing energy distribution and reducing peak loads [18–20]. A fundamental aspect of fast-charging station design is the use of DC–DC converters, which regulate the voltage and current supplied to EV batteries [21]. These converters play an essential role in both AC–DC and DC–DC conversion stages, with a comparative analysis of isolated and non-isolated topologies providing insights into their efficiency and performance [22]. To ensure safety and longevity, thermal management systems have been incorporated into fast chargers [23]. These systems include advanced cooling mechanisms, such as liquid cooling and phase-change materials, to prevent battery overheating and degradation during high-power charging sessions [24, 25].

This paper explores the latest developments in DC fast-charging infrastructure, including established standards, various charging modes, and the classification of DC–DC converters. Additionally, it addresses emerging challenges and opportunities in the field, such as energy storage integration, grid compatibility, and advancements in control strategies. This comprehensive review serves as a valuable resource for researchers, engineers, and policymakers working on the continued advancement of EV charging technology and infrastructure.

2 | Advancements and Innovations in Electrical Vehicle's Fast-Charging Techniques

Ongoing research and development efforts are concentrated on advancing fast-charging methods for EVs, aiming to shorten charging durations and improve user convenience [26]. The global EV market has experienced rapid expansion, with EVs making up 14% of new car sales worldwide in 2022, a jump from 9% in 2021 and under 5% in 2020 [27]. In the first quarter of 2023 alone, over 2.3 million electric cars were sold, reflecting a 25% increase compared to the same period the previous year [2]. Projections Implications indicate that by the close of 2023, around 14 million electric cars will have been sold, with EVs potentially accounting for 18% of total car sales for the year [2]. According to the International Energy Agency (IEA), global electric car sales could rise to 35% by 2030 [7]. To support this accelerating adoption, the development of efficient fast-charging technologies is essential, as they are key to meeting the rising demand for high-power charging solutions (Figure 1).

Inductive charging enables energy transfer without physical connectors, relying on wireless power transfer (WPT) technology [13]. It is classified into static and dynamic charging, with dynamic systems allowing vehicles to charge while in motion [28]. The principles of WPT date back to Nikola Tesla's experiments in the 1910s, which laid the groundwork for

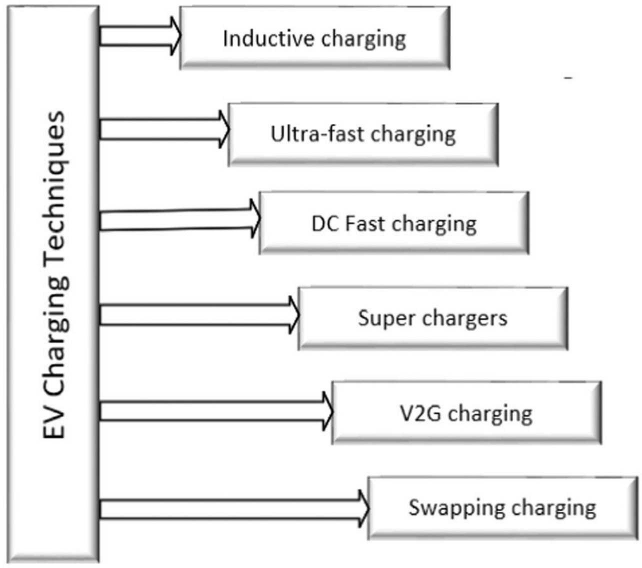

FIGURE 1 | EV charging techniques.

modern wireless charging technologies, now playing a pivotal role in the development of smart cities [28]. Control strategies in inductive charging systems manage efficiency and safety. Static charging systems are used in parking areas and toll plazas, while dynamic inductive charging charges EVs while in motion using buried infrastructure [29]. Ultra-fast charging (UFC) technologies provide high-power levels exceeding 350 kW, significantly reducing charging durations [29]. DC fast-charging stations operate at voltage levels ranging from 400 to 800 V, enabling rapid battery replenishment [30]. Tesla's Superchargers deliver power levels up to 250 kW, allowing vehicles to gain approximately 200 miles of range in just 15 min [31]. V2G integration facilitates energy exchange between EVs and the grid, supporting peak load balancing and renewable energy utilization [8]. Battery swapping provides a quick alternative to traditional charging, minimizing downtime for businesses and long-distance travelers [32]. Solar and wind energy sources are increasingly integrated into fast-charging stations to reduce grid dependency and improve sustainability [33]. Hybrid energy storage systems, combining lithium-ion batteries with supercapacitors, have enhanced energy management and reliability in renewable-powered charging stations [34, 35].

Nevertheless, challenges like the standardization of designs and the high costs of infrastructure must be resolved to enable broader adoption and implementation.

The paper evaluates different EV fast-charging methods based on critical factors such as convenience, safety, durability, infrastructure integration, compatibility, battery degradation, scalability, and efficiency. Ultra-fast charging stands out for high convenience, safety, and compatibility, while DC fast charging and Tesla Superchargers also perform well in these areas. Bidirectional Charging offers high safety and durability but may lag in convenience and compatibility. Inductive charging and battery swapping have their own strengths and weaknesses. In general, the summary provides a comprehensive overview to aid decision-making in EV charging infrastructure.

3 | Advanced Enhanced Infrastructure DC Fast Charging for Electric

An essential facet of the changing EV scene revolves around the advancement of sophisticated infrastructure tailored for rapid DC charging. This encompasses the deployment of cutting-edge systems and technologies designed to facilitate the swift and efficient charging of EVs [36]. This involves implementing sophisticated systems and technologies designed to charge EVs quickly and efficiently. Table 1 outlines the classification standards and power level ratings for charging stations, organized by supply system, maximum power output (in kilowatts), and maximum current rating (in amperes). The table also highlights the characteristics of DC fast charging, commonly referred to as Level 3 charging in research [17], markedly shortens charging times relative to other levels by using a higher-voltage power supply, typically between 400 and 800 V, allowing EVs to charge at an accelerated rate. This allows EVs to attain up to 80% charge in as little as approximately 20 min, significantly reducing charging durations [39].

3.1 | Charging Standards

Setting and following charging standards is essential for the development of advanced infrastructure for DC fast charging. These standards guarantee that EV owners experience consistent compatibility and interoperability, facilitating seamless charging across different networks and hardware providers [40]. Standards play a pivotal role in driving the widespread adoption of EV technology by ensuring its safety, reliability, and compatibility [41]. They encompass various facets such as charging infrastructure, integration with the power grid, and safety protocols. Major contributors to these standards are organizations such as the Society of Automotive Engineers (SAE) and the International Electrotechnical Commission (IEC) [42].

3.1.1 | Organization for Standardization

Leading organizations such as the IEC, the SAE, and the International Organization for Standardization (ISO) are at the forefront of setting and maintaining charging standards for EVs [43]. They work closely with industry stakeholders to establish technical specifications and protocols [44]. These standards ensure uniformity and compatibility for connectors, plugs, and inlets, with SAE J1772 and IEC 62196 being the primary sources. AC charging systems comply with standards such as SAE J1772 and GB/T 20234, while DC systems follow IEC 61851, CHAdeMO [43], and CCS Combo standards [45]. Grid integration standards, overseen by entities such as IEEE and Underwriters' Laboratories (UL), ensure seamless integration of EVs with the power grid, with IEEE 1547 focusing on distributed energy resource interconnection and UL 1741 prioritizing safety [46]. These efforts support the reliable and widespread adoption of EV technology by ensuring comprehensive and universally applicable charging infrastructure standards.

3.1.1.1 | Organization for Standardization. Charging standards specify the connector types and configurations necessary for a secure and effective connection between EVs and charging stations. For DC fast charging, common connectors include CHAdeMO and CCS, which ensure compatibility across various EV models and provide a smooth charging experience [19]. Additionally, connectors adhering to GB/T 20234-3 support dual functionality for charging the auxiliary battery and accommodating both charging types through a single port [47]. Tesla, on the other hand, employs a unique connector for DC charging in Europe, following the IEC 62196 standard, which can deliver up to 56 kW of power to the vehicle [48, 49].

3.1.1.2 | Communication Protocols. Charging standards incorporate communication protocols that facilitate data exchange between the EV and the charging station. These protocols are critical for key operations such as vehicle identification, managing power distribution, and real-time monitoring of charging parameters. Communication standards such as IEEE 2030.5 and ISO 15118 provide standardized methods for controlling EVs through secure data exchange and control protocols [13]. The flow of current and communication between EVs and charging stations are managed to ensure safe power delivery. Additionally, safety standards such as ISO 64691-3 and ISO/DIS 21498 govern aspects such as lithium-ion battery packs and high-voltage EV systems, respectively [42].

3.1.1.3 | Power levels and charging speeds. Charging standards specify the power levels and charging speeds that the infrastructure can accommodate. In the case of DC fast charging, these standards establish power outputs ranging from 50 kW to several hundred kW, facilitating significantly reduced charging times [50]. The guidelines also establish maximum power and voltage thresholds to ensure both safety and efficiency during the charging process.

TABLE 1 | Charging power rating level [37, 38].

Charging type use	Power source	Voltage (V)	Max power	Max current	Typical use
Level 1 (AC)	Home outlet	120 V (SAE) or 240 V	Up to 2 KW	16 A	Overnight charging
Level 2 (AC)	Wallbox	(IEC) 240 V	4–20 KW	16–80 A	Home charging (faster than level 1)
Level 3 (DC)	Public charging station	(IEC) Or 208-240 V (SAE) 200-600	40–200 KW	80–400 A	Public charging (fastest option)

Note: Several critical factors and considerations are pivotal in advancing the infrastructure for DC fast charging. Key aspects include the development of charging standards and the implementation of various charging control modes.

3.1.2 | Charging Modes

Charging modes play a crucial role in contemporary fast-charging infrastructure for EVs. These modes include constant current, constant voltage, constant power, demand-response, and bidirectional power flow, each designed to enhance charging efficiency and facilitate grid integration [51]. Each mode caters to specific needs, adapting to the battery's state, grid conditions, and user preferences to optimize charging performance while maintaining battery longevity and grid stability. Integration of intelligent algorithms and communication protocols facilitates reliable operations and enhances the EV owner experience, promoting optimal energy usage and supporting the widespread adoption of EVs as a sustainable transportation option [52, 53].

Monitoring and controlling temperature during DC fast charging is essential to prevent battery overheating and ensure safe and efficient charging operations. Sensors in the battery pack monitor temperature, allowing adjustments to parameters like current and voltage for safe charging [54, 55]. Accurate state of charge estimation based on voltage, current, and temperature measurements ensures efficient charging, preventing undercharging or overcharging. These strategies ensure battery safety, efficiency, and longevity.

4 | EV Battery Chargers Category

EV battery chargers can be classified based on charging capabilities, form factors, and intended use, as illustrated in, Figure 2, on-board or off-board EV fast chargers.

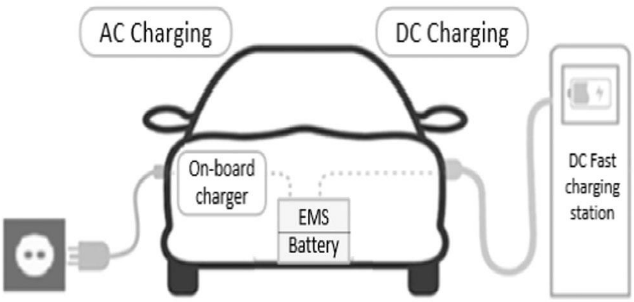

FIGURE 2 | Depicts both on-board/off-board fast-charging solutions for EVs.

4.1 | On-Board Charging

On-board chargers are built into EVs, managing charging rates based on battery capacity and compatible with various charging infrastructure. On-board charging involves converting external AC power into DC power for the battery pack, utilizing components like rectifiers and transformers [56]. This system can either be incorporated into the vehicle's powertrain or positioned near the battery pack. Level 1 charging employs standard household outlets, whereas Level 2 charging necessitates specialized stations that provide higher voltage for faster charging [57]. On-board chargers offer convenience and cost-effectiveness, providing EV owners with flexibility in charging locations compared to off-board chargers. Table 2 outlines the advantages and disadvantages of both charger types.

4.2 | Off-Board Charging

Off-board charging refers to the process of charging EVs outside of the vehicle, usually at public charging stations. Research is ongoing to improve the power quality and efficiency of off-board and DC-based charging systems [58]. Typical off-board charging methods include DC fast charging, known for its rapid charging capabilities, and wireless charging, which delivers a cable-free charging experience [59]. Off-board and DC-based charging involve fewer conversion stages, increasing efficiency and minimizing power quality concerns. Off-board DC chargers can integrate solar power and operate in grid-connected or V2G mode with bidirectional converters [60]. Charger control is typically handled by a unidirectional DC–DC converter, where isolated converters for high-voltage applications, while non-isolated converters are used for lower power levels. Despite their advantages, off-board DC chargers are not yet widely adopted in EVs [61]. Nonetheless, off-board charging methods present efficient, flexible, and potentially sustainable ways to recharge EVs.

5 | Classification of DC–DC Converters for a DC Fast-Charging Station

High-power DC–DC converters are essential for fast-charging stations as they convert high-voltage DC power to the specific voltage required by EV batteries. Isolated converters, such as dual active bridge (DAB) converters, provide enhanced safety

TABLE 2 | Comparison between on-board and off-board chargers [37].

Features	On-board charger	Off-board charger
Energy transfer rate	Lower (KW)	Higher (KW)
Convenience	More convenient (use standard outlets)	Less convenient (requires specific charging stations)
Weight	Increases vehicle weight	Reduces vehicle weight.
Battery management	Controlled by on-board rectifier.	Enhanced MBS systems
Charging Speed	Slower	Faster
Power levels	Limited	Higher power options available
Infrastructure dependence	Reliant on standard outlets	Reliant on charging stations
Cost	Generally lower cost	Generally higher cost

and galvanic isolation, making them ideal for high-power applications, while non-isolated converters offer higher efficiency and reduced component costs [62]. Experimental studies indicate that isolated topologies can achieve efficiency levels above 97% under optimal operating conditions [63]. Various topologies, including buck-boost, SEPIC, and Zeta converters, are explored to improve power conversion efficiency, with multi-switch options for high-gain applications. Soft-switching techniques are being adopted to mitigate switching losses, thereby enhancing system performance. Efforts are underway to reduce EV charging time to enhance viability in public transportation. Galvanic isolation between the EV battery pack and the grid is essential, with low-frequency and HFT options available [64]. Boosting the output power of DC fast chargers can be accomplished by linking multiple modules in parallel [65]. Current research focuses on improving charging efficiency and minimizing the component count in DC-DC converters used in EV powertrains. Figure 3 illustrates a broad classification of DC–DC converter topologies used in EV powertrains.

The article recommends adding a filter at the input stage of DC fast-charging stations to minimize harmonic distortion produced by the rectifier. It suggests using LC or LCL filters instead of L filters due to their greater effectiveness in improving performance. The advantages and specifications of these filters are detailed in the referenced materials [66]. Figure 4 illustrates the structure of a conventional power system for DC fast chargers, which is composed of two primary conversion stages. The first stage involves converting three-phase AC power into DC power. This is achieved through a rectification process that includes a power factor correction (PFC) circuit, ensuring compliance with grid code specifications by improving the power factor and reducing harmonics [67]. The second stage performs DCPower Factor

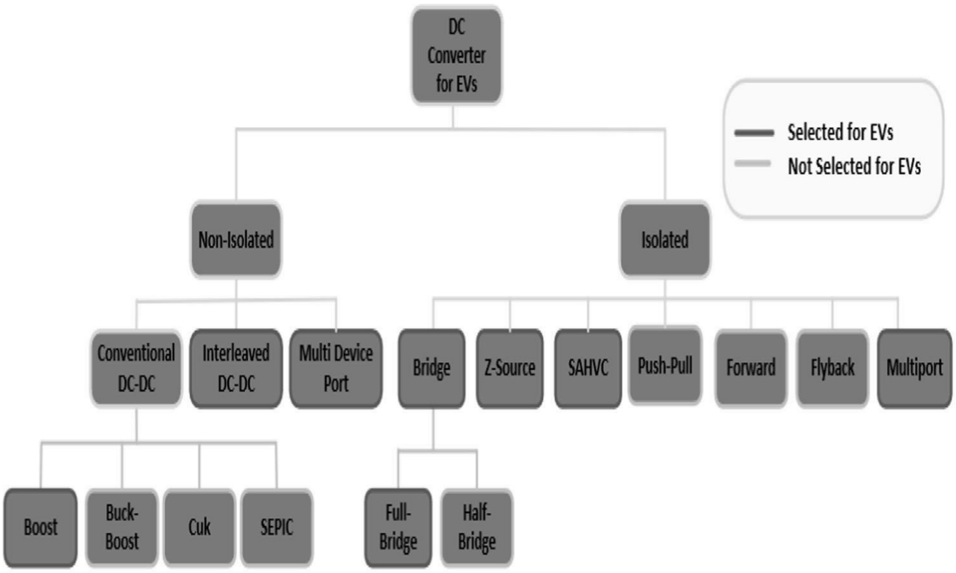

FIGURE 3 | Classification of DC–DC converters utilized for EV charging system.

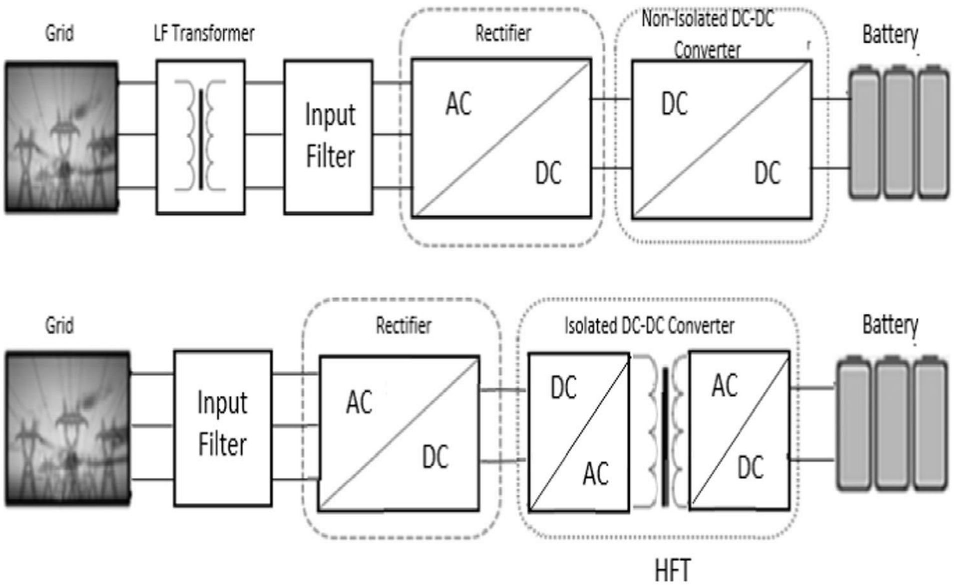

FIGURE 4 | Power conversion stage of DC fast charger. (a) LFT configuration and (b) SST-based HFT configuration.

CorrectionDC conversion with galvanic isolation to ensure safety and prevent electrical faults from propagating between the input and output. This isolation is achieved using either a low-frequency transformer (LFT) or a high-frequency transformer (HFT) [68]. LFTs are commonly used for lower power applications due to their robustness and simplicity, while HFTs are preferred for higher power levels because they allow for a more compact design and higher efficiency [69].

Additionally, the system may incorporate advanced control strategies to manage the power flow and optimize the charging process. These controls ensure that the system operates efficiently across various load conditions and integrates seamlessly with the electrical grid. The figure also demonstrates the use of a single module charger with the option to scale up by connecting multiple modules in parallel to meet higher power demands.

5.1 | AC–DC Converter Stage

The AC–DC converter stage in EV chargers is essential for transforming grid AC into DC power for EV battery charging. It employs rectifier circuits, such as unidirectional rectifiers, to facilitate one-way power flow from the grid to the vehicle, thereby ensuring efficient charging. Bidirectional rectifiers allow for two-way power flow, enabling applications like V2G integration for grid stability enhancement [64]. This converter stage is critical for efficient charging and facilitating bidirectional power flow in EV charging systems.

5.1.1 | Unidirectional AC–DC Rectifiers

It begins by discussing unidirectional rectifiers such as diode bridges and Vienna rectifiers, highlighting the simplicity and cost-effectiveness of diode bridges while noting their tendency to introduce harmonic distortion [70]. It also introduces a proposed 12-pulse active diode rectifier paired with a bidirectional buck-boost DC–DC converter to mitigate grid demand [71]. Additionally, it explores methods like auxiliary voltage supplies and variable frequency techniques to enhance power quality. The Vienna rectifier, renowned for its low harmonic content and high efficiency, is further investigated, along with its control intricacies [72].

5.1.1.1 | bidirectional AC–DC rectifiers. Shifting examines bidirectional rectifiers, particularly pulse width modulated (PWM) rectifiers and neutral point clamped (NPC) rectifiers. PWM rectifiers provide precise control over bidirectional energy flow but necessitate large input filter inductors [73]. A proposed bidirectional active power-conversion rectifier enables both active and reactive power exchange between the grid and the DC–DC converter, ensuring smooth charging current output and adaptability to diverse grid conditions [74]. Additionally, an innovative bidirectional active power-conversion rectifier is introduced for seamless adaptation to various grid conditions [75]. The NPC rectifier, known for reduced harmonics and the ability to split the DC bus, is examined, along with proposed enhancements like a four-leg three-phase active NPC rectifier for fault-tolerant operation [76].

Simulations were performed to evaluate Vienna, PWM, and NPC topologies, comparing their efficiency, losses, and cost-effectiveness. Both Vienna and PWM rectifiers were highlighted for their favourable cost-to-efficiency ratios, with the Vienna rectifier showing a slight edge in efficiency. Additionally, a tabular format was employed to provide a concise comparison of various AC-DC rectifier topologies for DC fast chargers. This comparison is detailed in Table 3.

5.2 | DC–DC Converter Stage

The DC–DC converter stage is essential in power electronic systems, enabling efficient and reliable conversion between different DC voltage levels. It plays a crucial role in a wide range of applications including power supplies, renewable energy systems, EVs, and telecommunications by employing diverse control techniques such as pulse width modulation (PWM) to regulate output voltage and ensure stability [78]. These converters offer versatility, compactness, cost-effectiveness, and high reliability, making them indispensable for maintaining the required voltage levels in various electronic devices and systems [79].

Emphasizing the pursuit of high efficiency, the design addresses power losses in converter components through methods like synchronous rectification and advanced control strategies. Moreover, protection mechanisms such as overvoltage and overcurrent protection are integrated for safe operation. Designing an effective converter stage involves meticulous consideration of factors like component selection, thermal

TABLE 3 | Comparison of AC–DC rectifier topologies [77].

Features	12-Pulse diode bridge	Vienna	PWM	NPC
Diodes	12	6	0 (switches)	6
Switches	0	6	6	12
Bidirectional flow	No	No	Yes	Yes
Harmonic distortion	Low	Very low	Low	Verylow
Control complexity	Low	Moderate	Low	High
Cost and size	Moderate	Moderate	Low	High
Efficiency	Low	High	Moderate	High
Power factor *F* range	Low	Limited	High	High

management, and voltage regulation accuracy, though specifics may vary depending on application requirements [80].

5.2.1 | Comparison of DC–DC Isolated Topologies

This comparison focuses on various isolated DC–DC converter topologies, outlining their features, advantages, and limitations. The LLC Resonant Converter is known for its high efficiency, minimal switching losses, and low electromagnetic interference (EMI). However, it demands intricate control mechanisms and a complex design [81]. The DAB converter offers a wide voltage conversion range, high efficiency, and low EMI but requires complex control and design for efficiency optimization [82]. The phase-shifted full-bridge (PSFB) converter ensures high efficiency, reduced switching losses, and wide voltage conversion range, also suitable for medium-to-high power applications [83]. The Flyback Converter is praised for its low component count and effectiveness in low-to-medium power applications, although it has limitations in efficiency and power capacity [84]. In contrast, the push-pull converter is better suited for medium-to-high power applications, offering improvements in efficiency and compactness, but requires complex circuitry [85]. The full-bridge converter excels in high-power applications, delivering exceptional performance over a wide voltage range, though its implementation involves complex circuitry [86]. The half-bridge converter is advantageous for medium-to-high power applications, enhancing efficiency with simpler circuitry, but it supports only unidirectional power flow and adds some complexity. Additionally, the Multi-Output Converter provides multiple outputs for varied applications [85]. Lastly, the Multi-Output Converter provides multiple isolated outputs with different voltage levels, offering flexibility but requiring more complex circuitry and incurring higher costs due to additional components and transformers [22].

5.2.1.1 | Comparison of DC–DC non-isolated topologies. This comparison outlines various non-isolated DC–DC converter topologies, highlighting their areas of improvement, salient features, advantages, and limitations. The Boost Converter, with its simplicity, ease of control, and compact size, offers efficiency improvement and higher output voltage but lacks electrical isolation [87]. Conversely, the buck-boost converter provides efficiency enhancement and step-up/step-down capabilities, suitable for wide input voltage range applications, albeit with drawbacks like voltage imbalance and high output ripples [88]. The SEPIC converter and Cuk converter offer input/output isolation and continuous input current, suitable for both voltage conversion directions, albeit with complexities and high costs [89]. The Zeta Converter, suitable for medium to high-power applications, provides efficiency improvement and continuous input current, though it suffers from unidirectional power flow and increased design complexity [90].

6 | Emerging Control Strategies for EV System

This section examines the control strategies employed in DC–DC converters for EV systems, highlighting their objectives, methodologies, and common challenges associated with various converter types. Both non-isolated and isolated DC–DC converters in EV charging systems utilize a variety of control techniques.

In non-isolated converters, voltage-mode control improves charging efficiency, delivers rapid response times, and maintains a stable output voltage [91, 92]. Concurrently, current-mode control boosts overall efficiency, safeguards against battery overcharging or undercharging, and enhances infrastructure reliability [93]. Peak current control preventing overloads, optimizing energy transfer, and keeping the charging current within specified thresholds, in the meanwhile, Average current control further reduces charging times while ensuring compatibility with existing infrastructure [6, 42, 64]. In isolated converters, voltage-mode control also guarantees a stable output voltage and maximizes energy transfer efficiency. Current-mode control in this context emphasizes efficient energy transfer and stable charging, while peak current control limits peak currents to enhance charging performance and avoid overcurrent issues [94, 95]. AI-Driven Charging Management, AI and machine learning algorithms are now employed to predict charging demands, optimize energy distribution, and enhance grid integration. Predictive control methods ensure efficient energy transfer and dynamic response to grid fluctuations [96, 97]. Advanced AI-based optimization enhances charger efficiency by dynamically adjusting charging rates based on demand and real-time grid conditions, reducing peak loads and operational costs. Thermal management and safety are vital in fast-charging infrastructure. Advanced thermal sensors and real-time monitoring systems prevent battery overheating during charging [25]. These systems enable dynamic adjustments to charge parameters, ensuring both safety and longevity of the battery. Efficient thermal management solutions, such as liquid cooling and phase-change materials, are increasingly integrated to manage high-power fast-charging stations and improve system reliability [98]. Recent studies have highlighted the growing importance of these control strategies in improving the performance and reliability of power converters in various applications.

7 | Research Contribution and Future Directions

Research in the EV domain has made significant strides in addressing emerging challenges and opportunities. Efforts are concentrated on enhancing charging infrastructure, especially in fast-charging technologies such as DC fast charging, to address the increasing demand for efficient and reliable EV charging solutions. Categorizing EV battery chargers, understanding DC–DC converter topologies, and optimizing control strategies contribute to enhancing charging efficiency and reliability. Generally, this research serves as a cornerstone for the ongoing development of EV technology and infrastructure. This research lays the foundation for the continuous advancement of EV technology and infrastructure. Future directions include the exploration of solid-state batteries for ultra-fast charging, grid-independent charging stations powered entirely by renewables, and the development of universal charging protocols.

8 | Practical and Policy Implications

The rapid adoption of EVs has prompted governments and policymakers to implement strategies for efficient fast-charging infrastructure deployment. Incentive programs, such as subsidies and tax credits for fast-charging stations, have accelerated the expansion of charging networks. The integration of renewable energy sources, such as solar and wind, into charging stations mitigates grid congestion and reduces reliance on fossil fuels. Additionally, the establishment of charging points in urban and rural areas ensures accessibility and convenience for EV users. Standardization efforts, such as IEC 61851 and CHAdeMO, are critical for ensuring interoperability among different charging networks and manufacturers. These standards help maintain safety, improve compatibility, and enhance user confidence in EV adoption. Furthermore, energy storage systems, such as battery-buffered charging stations, optimize energy consumption and alleviate peak demand stress on the grid. Future policies should focus on smart grid integration and intelligent charging solutions to enhance the efficiency and sustainability of EV infrastructure [16].

9 | Conclusions

This review provides an in-depth analysis of fast-charging techniques for EVs, focusing on infrastructure development, control strategies, and policy frameworks. The increasing adoption of EVs necessitates the expansion of efficient fast-charging networks, integrating AI-driven charging control strategies to enhance energy management and grid interaction. Additionally, the incorporation of renewable energy sources, such as solar and wind, can improve sustainability and reduce reliance on conventional power grids. Standardization efforts play a crucial role in ensuring seamless interoperability and safety within charging networks. Future research should address the challenges of battery degradation, high-power charging technologies, and energy storage integration to further advance EV fast-charging solutions. By considering these aspects, this study serves as a valuable resource for researchers, engineers, and policymakers working towards a more sustainable and efficient EV charging infrastructure.

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