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Review

A Comprehensive Review of Partial Power Converter Topologies and Control Methods for Fast Electric Vehicle Charging Applications

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Abstract: This paper provides a comprehensive review of Partial Power Converter (PPC) topologies and control methods for fast electric vehicle (EV) charging applications. Partial Power Converters are gaining traction to enhance converter efficiency, reduce power losses, and minimize component sizes by processing only a portion of the total power. This review covers key PPC topologies, including different partial power converters, and highlights their advantages and limitations in the context of EV charging. Various control methods that optimize the performance of these converters are also discussed. The paper presents a comparative analysis between partial power and full power converters. Finally, this review synthesizes the main findings and proposes guidelines for selecting appropriate PPC architectures for future fast EV charging stations.

Keywords: electric vehicle; fast charging; partial power converters; partial power processing

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1. Introduction

In recent years, society has increasingly focused on addressing environmental deterioration, prompting significant efforts to integrate renewable power systems and smart microgrids to mitigate greenhouse gas emissions that contribute to global warming. Fuel-powered vehicles brought convenience but also raised concerns about pollution and energy sustainability. The transportation sector contributes 30% to the overall total carbon emissions, with road transport contributing over 70% of this. Promoting electric vehicles (EVs) is essential for reducing energy use and achieving sustainability [1,2]. Also, the declining availability of fossil fuels has further highlighted the importance of electric vehicles (EVs) as a sustainable alternative to reduce dependency on non-renewable resources [3–6].

The EV sales are projected to rise rapidly over the next few years, Increasing from 3.1 million in 2020 to 14 million by 2025. Additionally, the global shift towards electric vehicles (EVs) is reflected in the significant growth of EV adoption, which has accelerated with an average annual growth rate of 24% expected from 2023 to 2035 [7]. This rapid expansion is projected to result in EVs making up 30% of the global vehicle fleet by 2035, showcasing the increasing integration of EVs into the market. Figure 1 illustrates this global growth trend highlighting several main regions. This growth supports global initiatives aimed at lowering greenhouse gas emissions and shifting toward sustainable energy sources.

Several factors have accelerated this transition, including heightened environmental concerns, the reduction in EV costs, governmental incentives, and significant improvements in battery technology, such as enhanced range and lifespan, which have collectively boosted consumer confidence in EVs [8]. Even with the increasing enthusiasm for electric vehicles (EVs), numerous obstacles still stand in the way of their mass adoption, including technical, economic, and policy challenges. Issues such as high battery costs, limited battery lifespan, reliability concerns, reduced driving range, lengthy charging times, and complex charging infrastructure hinder the advancement of EV technology [9,10]. Furthermore, developing appropriate power converter topologies and implementing advanced control strategies are crucial for achieving reliable, cost-efficient performance during high-power delivery and improved efficiency. Although EV adoption generally does not cause major disruptions to the electrical grid's distribution, transmission, and generation, unmanaged EV charging can lead to a sudden increase in load, potentially requiring utilities to modify existing infrastructure sooner than planned [11]. Additionally, EV chargers can generate undesirable harmonics that negatively affect the quality of power in the system, though this issue can be mitigated with harmonic compensation techniques in the rectifier stage of the EV charger [12,13].

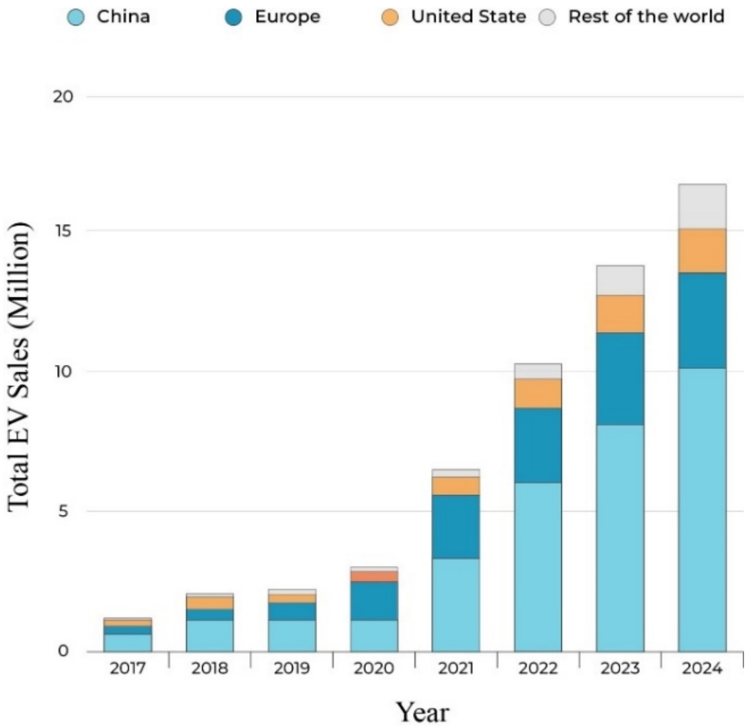


Figure 1. Total electric vehicle sales in the whole world (2017–2024).

With modern electric vehicles (EVs) featuring larger battery capacities and extended driving ranges than earlier models, the demand to support energy-efficient EV charging infrastructure capable of fast and ultra-fast charging is steadily increasing [14–17]. Since the battery lifespan and charging duration are closely linked to the performance of EV chargers, the design, development, and control strategies of these chargers play a critical role in building an effective fast-charging infrastructure. Different levels of charging have been developed, namely, Level-1, referred to as slow residential charging, Level-2 as commercial charging, and Level-3 DC fast charging and ultra-fast charging in accordance with the needs of the users and application requirements, from overnight home charging to quick refueling for longer distance traveled [18]. Among these, fast and ultra-fast charging systems are considered critical to speed up the charging time as well as minimize the energy lost and range anxiety resulting from the use of electric vehicles. Even with fast EV charging, an ideal EV charger is expected to offer high efficiency, elevated power density, and strong reliability while also maintaining low cost, minimal weight, and compact size. Partial-power conversion is an appropriate solution to reduce the size and weight of electronic components, which in turn lowers the costs and volume of the overall charger. A Partial Power DC–DC Converter processes only a fraction of the total power, regulating the system while the rest of the power is directly bypassed to the load [19–23].

In the existing literature, various review papers have explored different aspects of partial power converter (PPC) topologies and their power conversion techniques, each of which contributes unique insights into the field. Ref. [24] primarily focuses on the structural classification of isolated and non-isolated DC–DC converter topologies within Partial Power Processing (PPP). It discusses the theoretical operation limits and revisits component stress factors while exploring the energy efficiency improvements PPCs offer over traditional full-power converters. However, it emphasizes that the applicability of PPCs needs to be carefully assessed depending on specific operational scenarios, and further research is suggested in areas like fault tolerance and resonant converters. Ref. [25] shifts its attention to photovoltaic (PV) applications, evaluating power converter topologies based on cost and power loss factors. It provides a detailed comparative analysis for high-voltage gain applications, noting how different converter types perform in terms of these factors. Although not focused specifically on EV charging, it highlights the importance of efficiency and component selection in achieving optimal converter performance, especially in renewable energy systems. Ref. [19] offers a comprehensive review of PPP architectures and introduces a universal nomenclature to reduce confusion. It outlines three primary strategies: Differential Power Converters (DPC), Partial Power Converters (PPC), and Mixed Strategies—exploring how each strategy manages power flow and efficiency. While the focus is on PPP for PV, energy storage systems (ESS), and electric vehicle (EV) applications, it contributes to the field by formalizing a classification system for PPP architectures and evaluating their benefits and trade-offs in various applications. Ref. [21] delves deeper into series-connected partial power converters (S-PPCs), providing insights into the active and nonactive power processing within these converters. It evaluates the reduction of power processed by the converters, improving efficiency and component ratings for applications such as PV and EV charging. The paper provides a detailed analysis of how step-up/-down topologies can be optimized for power reduction and efficiency. Ref. [26] broadens the scope to multiport power converters (MPCs), which integrate multiple energy devices into a single hub. The review focuses on evaluating MPC topologies for distribution networks, analyzing their scalability, control complexity, and efficiency in decarbonizing power grids. Though its primary focus is on distribution networks, its findings on multiport topologies offer insights into the potential flexibility and high efficiency of converters for various applications, including EVs.

Ref. [27] presents a detailed overview of both AC–DC and DC–DC converter topologies used in off-board EV fast chargers, including Vienna, buck, boost, LLC, and Dual Active Bridge (DAB) converters. It also evaluates various control strategies such as power factor correction (PFC), constant current–constant voltage (CC–CV) charging, and soft-switching methods. Additionally, the paper discusses multiport converters for integrating PV, energy storage, and grid systems and highlights emerging trends like ultra-fast and wireless charging, grid-forming control, and smart grid integration, while Partial Power Converters (PPC) or Partial Power Processing (PPP) are only mentioned in the future directions section as a promising avenue for improving efficiency and reducing system cost. Therefore, this review specifically addresses this gap by providing a focused and comprehensive review of PPC topologies, control methods, and their advantages for high-power

EV fast charging applications. In ref. [28] authors provide a detailed review of various charging topologies and methodologies for EV battery charging. It covers conventional and advanced topologies, including unidirectional and bidirectional chargers and isolated and non-isolated DC–DC converters like boost, buck, resonant, and interleaved converters. The paper also evaluates control strategies such as constant current/constant voltage (CC/CV), power factor correction (PFC), and zero-voltage switching (ZVS) while exploring emerging charging methods like wireless and inductive charging. Additionally, it compares on-board and off-board charging architectures, discussing their challenges and trade-offs, and proposes future research directions, including ultra-fast charging and integration with renewables. However, the review centers on full power processing converters and does not discuss Partial Power Converters, while concepts like interleaving and modular converters are mentioned, which relate in principle to the goals of PPP (i.e., improved efficiency modularity). This gap highlights the unique contribution of the presented work on PPC.

Existing review papers have extensively examined the applications of Partial Power Converters (PPC) in photovoltaic (PV) systems, wind energy, and energy storage technologies, underscoring their role in improving efficiency and reliability. At the same time, the review of the potential of Partial Power Converters, specifically for EV charging applications, remains underexplored. The rapidly growing adoption of electric vehicles (EVs) presents unique challenges and opportunities for PPC applications, such as bidirectional power flow and more efficient EV chargers, by reducing component stress and enhancing efficiency [29]. Therefore, this review aims to provide a comprehensive analysis of the applications of Partial Power Converters in electric vehicle (EV) charging systems, focusing on their control methods and operational strategies. It seeks to offer insights into the current state of research and highlight the advancements, challenges, and potential of PPCs in EV charging applications while providing a roadmap for future developments.

Figure 2 illustrates the structured layout of the review, outlining its seven main sections. The structure of this paper is organized as follows: Section 2 provides a review of the state-of-the-art EV charging infrastructure, highlighting advancements in AC and DC system integration, as well as emerging trends in smart charging solutions. Section 3 introduces Partial Power Converters (PPC), explaining their fundamental principles, operational characteristics, and key applications in EV charging. Section 4 explores different PPC topologies, analyzing their impact on efficiency, power management, and overall system performance within charging infrastructures. Section 5 provides a detailed discussion of control strategies for PPCs, focusing on methods that enhance system reliability, dynamic response, and energy optimization. Section 6 examines the selection of converter topologies and system architectures, offering insights into optimal design approaches for high-performance EV charging stations. Finally, Section 7 summarizes the key findings, discusses technological challenges, and outlines future research directions.

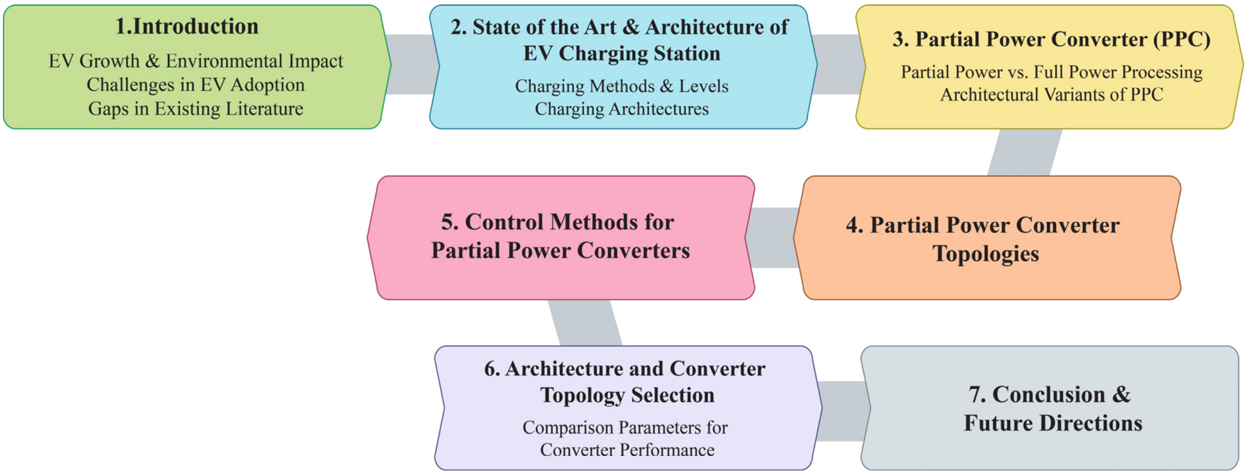


Figure 2. Structure diagram of the review.

2. State of the Art and Architecture of EV Charging Station

Current challenges in fast EV charging include charging speed, inefficient power conversion, and the need for robust grid integration. Additionally, the wear and tear on batteries from high charging currents, as well as the high cost of fast-charging infrastructure, pose significant obstacles to widespread adoption. While new technologies enable charging times as low as 10–15 min [30–32], such high-power demands strain local power grids, especially during peak hours. Additionally, repeated exposure to high-voltage charging can accelerate battery degradation. Advanced EV chargers with smart energy management can help mitigate these issues and support more sustainable scaling. Also, with the increasing global shift towards electric mobility, the demand for fast chargers that are not only efficient but also compact and cost-effective has become increasingly urgent. Fast EV chargers must deliver high power quickly without excessive energy losses, all while occupying minimal physical space and remaining economically viable for large-scale deployment. Developing such solutions is essential to support widespread adoption and ensure a practical, sustainable charging infrastructure.

This section provides a comprehensive overview of the state-of-the-art EV charging technologies and the evolving architecture of modern charging stations. The discussion begins by classifying various EV charging methods—such as conductive, inductive (wireless), and battery swapping—followed by a detailed breakdown of charging levels based on power output and application scenarios. This section also explores the structural design of EV charging systems, focusing on AC-connected and DC-connected configurations, their respective advantages and limitations, and the key components involved in power conversion. Explaining the emerging trends like the integration of renewable energy sources, energy storage systems, and vehicle-to-grid (V2G) capabilities.

Figures 3 and 4 illustrate the architecture of off-board electric vehicle (EV) charging systems. While Figure 3 presents a simplified block diagram, Figure 4 provides a more detailed structure incorporating an LF isolation transformer, AC-DC conversion, and an isolated DC-DC stage for enhanced safety and performance.

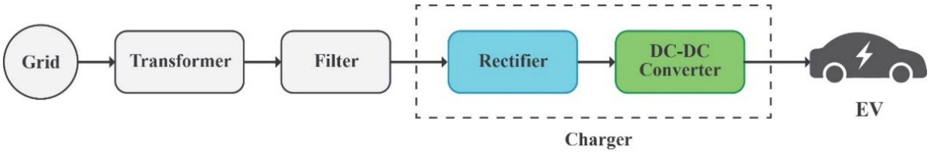


Figure 3. Block diagram of general off-board EV charging system.

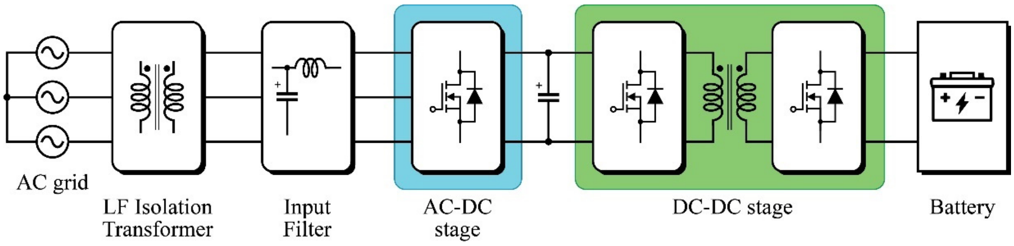


Figure 4. The general structure of an off-board EV charger with an isolated DC–DC stage.

The EV charging methods are divided into three main categories: conductive charging, wireless charging, and battery swapping, as illustrated in Figure 5. Conductive charging includes on-board AC charging—offering Level 1 (single-phase) and Level 2 (single or three-phase)—and off-board DC charging, which supports Level 3 fast and ultra-fast charging [33,34]. Battery swapping serves as a separate method where depleted batteries are quickly replaced with fully charged ones [35]. Wireless charging is further classified into inductive wireless charging, capacitive wireless charging, and resonant inductive wireless charging [36,37].

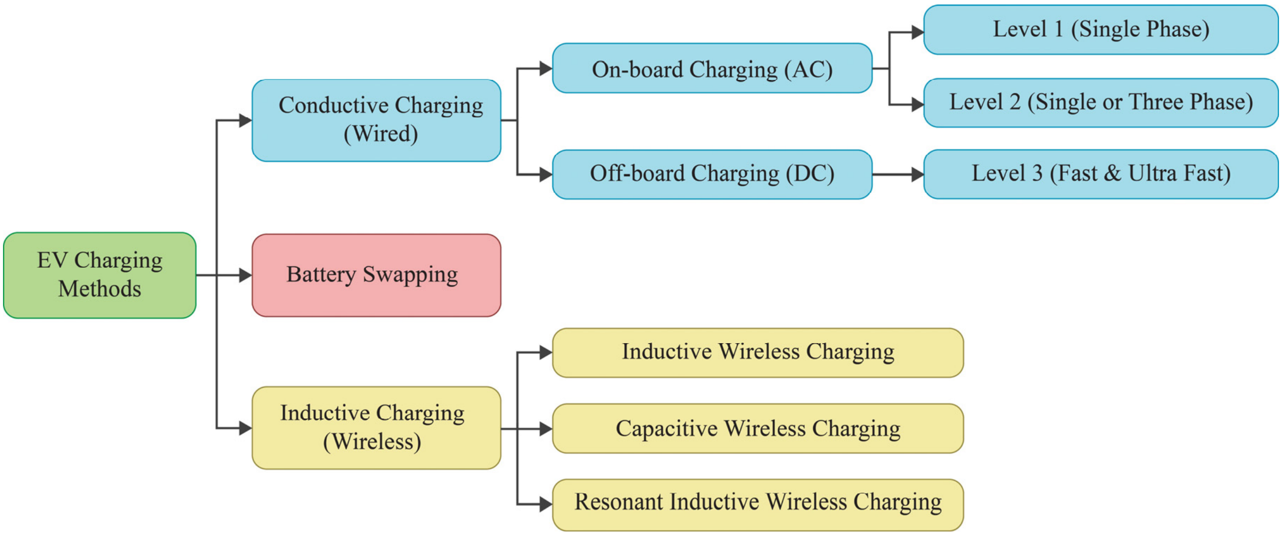


Figure 5. Categorization of EV Charging Methods.

The EV chargers are generally categorized into three main types based on their power levels: Level-1 (AC), Level-2 (AC), and a combined category for Level-3 (DC Fast and Ultra-Fast DC) [38,39], as illustrated in Figure 6. Each is designed to meet specific charging needs and infrastructure requirements, from residential to commercial and high-demand public spaces.

- Level-1 charging is the slowest form of EV charging, typically used in residential settings where overnight charging is sufficient. It operates on standard household voltage (120 V or 230 V) and delivers about 1.92 kW, making it ideal for users with short daily commutes or those who can afford longer charging times. It is most practical for vehicles to remain plugged in overnight to recharge fully. However, its low power output makes it unsuitable for long-distance travel [40,41].
- In contrast, Level-2 charging provides significantly faster speeds, with power levels up to 20 kW, making it suitable for both residential installations and commercial locations like malls and offices, using a higher input voltage of 208 V or 240 V. While it offers a practical solution for frequent users, the limitations of on-board chargers mean it can

still take several hours to fully recharge, making it ideal for settings where vehicles are parked for extended periods [42,43].

- Level-3, or DC fast charging, represents a significant leap in charging speed and efficiency, capable of delivering power between 50 kW and 300 kW, allowing EVs to charge up to 80% in as little as 30 min by providing direct current (DC) to the battery and bypassing the onboard charger [40,44,45], typically found in public charging stations along highways, using connectors like Tesla Supercharger.
- Ultra-fast DC charging, capable of delivering 400 kW or more, enables a full charge in just 10 min, reducing range anxiety for long trips. However, it presents challenges in managing large power flows, developing infrastructure, and maintaining battery health. Despite these issues, it is crucial to make electric vehicles competitive with traditional vehicles in terms of refueling convenience. Each charging level serves a vital role, offering solutions from slow, residential charging to fast charging for long-distance travel [40,46].

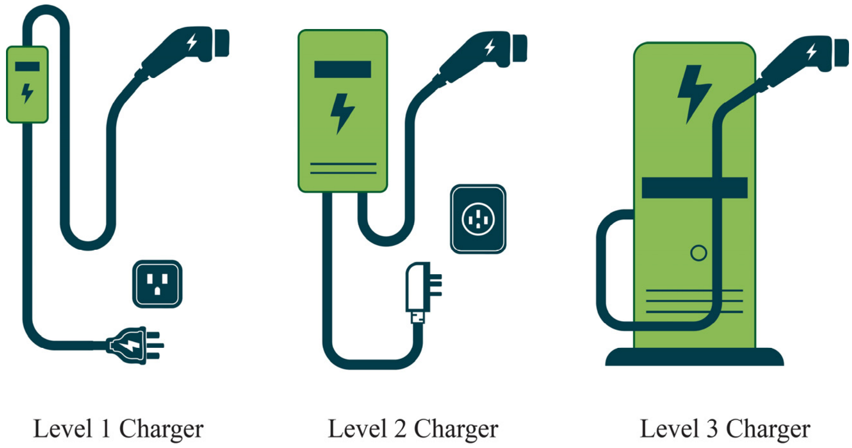


Figure 6. EV Charging: Level 1, Level 2 and Level 3.

Each charging level, supports EV adoption by offering tailored solutions—from home charging to high-speed options for long-distance travel—thereby providing convenient and flexible choices to meet diverse user needs. An overview of charging station classifications based on power level is presented in Table 1. The architecture of fast EV charging stations is designed to balance rapid charging demands with grid constraints and renewable energy integration. Key elements include battery energy storage systems (BESS) to stabilize grid impact and support operations in weaker grid areas.

Table 1. Charging station classification based on charging power level.

Charger Type	Charger Location	Power Supply	Power Level	Charging Time
Level 1 (AC)	On-board (Residential charging)	120/230 Vac; 12 A to 16 A	From 1.44 kW to 1.92 kW	11–36 h for EVs (16–50 kWh)
Level 2 (AC)	On-board (Charging at home or workplace)	208/240 Vac; 15 A to 80 A	From 3.1 kW to 19.2 kW	2–6 h for EVs (16–30 kWh)
Level 3 (DC Fast)	Off-board (Charging at public places)	300–600 Vdc (Maximum current 400 A)	From 50 kW to 350 kW	Less than 30 min for EVs (20–50 kWh)
DC Ultra-Fast Charging	Off-board (Charging at public places)	800 Vdc and higher; 400 A and higher	400 kW and higher	Approximately 10 min for EVs (20–50 kWh)

Generally, EV charging systems employ two primary architectures: AC-connected and DC-connected systems [18,47]. However, in recent years, there has been a growing trend toward the adoption of single-stage AC/DC EV chargers utilizing AC/DC converters. Unlike traditional two-stage architectures that separately handle power factor correction and DC conversion, single-stage EV chargers integrate both functions into a unified topology [48–50]. Examples include single-stage isolated topologies such as the resonant converter, matrix converter, and Dual Active Bridge (DAB) with direct AC interface, and non-isolated topologies such as interleaved boost and bridgeless PFC converters with direct battery interfacing. The unified control strategy used in these topologies enables simultaneous regulation of input current and output voltage, eliminating the need for intermediate DC buses and reducing the complexity of the system. The primary advantages of single-stage converters are reduced component count, minimized switching losses, higher power density, and improved overall system efficiency. Additionally, single-stage converters facilitate compact charger designs with lower thermal management requirements, making them suitable for onboard EV charging applications where space and weight constraints are critical. However, these benefits come with challenges, such as increased control complexity, higher sensitivity to input voltage variations, and reduced flexibility in isolating faults between stages [51].

2.1. AC Connected Fast Charging System

In an AC-connected fast charging system, the grid supplies three-phase AC power, typically operating within a voltage range of 250 V to 480 V line-to-line. Each charger unit consists of two key components: an AC–DC rectifier and a DC–DC converter. The AC–DC rectifier converts the grid's AC power to DC, while the DC–DC converter adjusts the rectified voltage to suit the specific charging needs of the EV battery. Due to this multi-stage power conversion process, AC-connected systems generally have a greater count of power processing stages, which increases both the system's complexity and the overall cost. Despite these drawbacks, AC-connected systems are widely adopted for fast and ultra-fast charging stations due to the maturity of the power electronics and AC power distribution technologies [52]. These systems benefit from a well-established infrastructure, making them a popular choice in many fast-charging applications. However, the increased number of power stages results in higher energy losses, which reduces overall efficiency and impacts the system's performance [50]. Figure 7 shows an AC-connected EV charging setup, with an EV charger having its own rectifier and DC–DC converter, with a common AC bus.

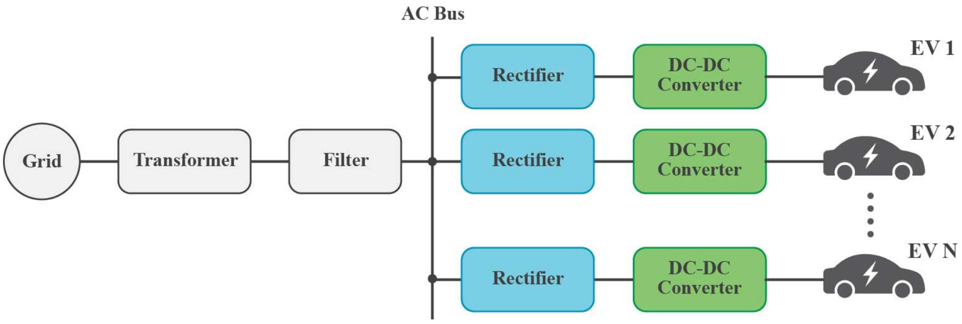


Figure 7. AC-connected, EV off-board charging station architecture.

2.2. DC Connected Fast Charging System

In contrast, DC-connected fast charging systems follow a more streamlined structure. A central AC–DC rectifier is used to convert grid AC power into DC, which is then distributed via a DC bus. Unlike AC systems, where each charging unit requires its own

AC–DC rectifier, DC bus systems centralize the rectification process. The DC bus connects various elements, such as EVs, renewable energy sources (RES), and energy storage devices, through DC–DC converters [53,54]. This configuration reduces the number of AC–DC rectifiers needed, thereby enhancing efficiency and simplifying the control system. DC bus systems offer significant flexibility by allowing the easy integration of PV sources and other distributed energy resources, improving the overall system's adaptability. Additionally, DC bus configurations are more robust in avoiding abnormalities or disruptions from the grid side, further enhancing their reliability. Figure 8 shows a DC-connected EV charging station where AC grid power is converted to DC through a rectifier. Multiple DC–DC converters then supply power to individual EVs via a common DC bus.

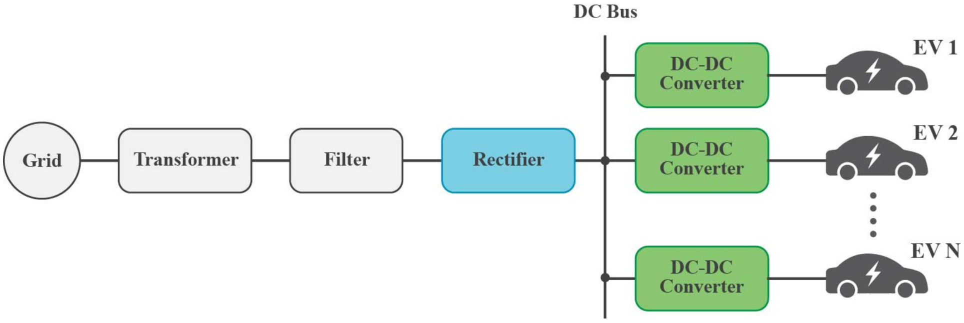


Figure 8. DC-connected, EV off-board charging station architecture.

However, while DC-connected systems are more efficient, the lack of well-established protection guidelines, especially during vehicle-to-grid (V2G) operations, poses a critical challenge. As V2G technology evolves, ensuring safe operation and avoiding system failures will be increasingly important. One of the key advantages of DC bus systems is the ability to use fewer AC–DC rectifiers, which directly translates into higher efficiency [55]. However, centralizing the rectification process requires more robust protection devices and control mechanisms, particularly to manage sudden changes in load conditions or potential failures.

The AC-connected fast charging system offers significant benefits due to its compatibility with existing electrical infrastructure, making it a widely adopted choice for fast charging stations. As outlined in Table 2, its modular design enables easier scalability, allowing for the addition of more charging units as demand grows. However, a key drawback of this system is the use of separate AC–DC rectifiers in each unit, which increases system complexity, overall cost, and energy losses due to the additional power conversion stages. This results in lower overall system efficiency compared to DC-connected systems. On the other hand, DC-connected fast charging systems, utilize a centralized rectifier and a common DC bus, leading to improved efficiency and simplified control as the power conversion is centralized. This configuration also offers better integration with renewable energy sources, making it a more sustainable option. However, DC-connected systems face certain challenges, such as the lack of established protection standards, particularly for Vehicle-to-Grid (V2G) applications, which may impact their long-term viability. Moreover, these systems require robust control mechanisms to efficiently manage the centralized operation of multiple charging stations. Despite these challenges, DC-connected systems remain an attractive option for high-performance, efficient, and scalable charging infrastructure [56].

AC-connected chargers cause higher grid disturbances and losses due to onboard rectifiers, while DC-connected chargers improve stability by handling conversion externally, reducing harmonics and transmission losses. In both AC and DC-connected systems, the final power conversion stage is the DC–DC back-end converter, which adjusts the rectified DC voltage to the appropriate level for the EV battery. This stage is crucial for providing constant current (CC) and constant voltage (CV) charging, ensuring safe and efficient charging. A high-performing DC–DC converter is characterized by high efficiency, high-frequency operation, power density, bidirectional power flow, and stable voltage regulation. Additionally, it should support soft-switching techniques to reduce losses and minimize voltage ripple, enhancing overall charging efficiency [46,56]. International standards regulate leakage currents in EV chargers to protect users from electric shock. Galvanic isolation, using either low or high-frequency transformers, minimizes leakage currents. Low-frequency transformers require larger equipment and increase installation costs, particularly in urban areas. High-frequency transformers are more cost-effective, increasing power density, though their operation and bidirectional control can be more complex. AC–DC rectifiers, used in both systems, convert grid AC voltage (250–480 V) to a stable DC voltage (~800 V) but may inject harmonics that reduce power quality [52,57]. Power factor correction (PFC) techniques are used to mitigate this issue, ensuring low total harmonic distortion (THD) and maintaining power quality.

Table 2. Comparison of AC and DC-Connected EV Charging System.

Criteria	AC Connected Charging System	DC Connected Charging System
Conversion Stages	Higher	Lower
Efficiency of System	Lower	Higher
Energy Sources Integration	Complex	Easier
Load Side Impact	High	Less
Control System	Complex	Simple
Cost of System	Higher	Lower

3. Partial Power Converter (PPC)

Traditional power conversion systems commonly employ full power converters due to their ability to offer precise voltage and current control, fast dynamic response, and flexibility across a wide range of applications. These converters are well-suited where full regulation is critical. However, processing the entire source power also leads to several drawbacks, including increased component count, higher conduction and switching losses, larger size, and more complex thermal management requirements [21]. To address these limitations, the concept of Partial Power Converters (PPCs) has emerged as a modern and efficient alternative. A modern concept of DC–DC converter is a Partial Power Converter (PPC) that utilizes Partial Power Processing (PPP), initially introduced in the spacecraft industry [58,59], with a primary focus on reducing the size of power converters connected to photovoltaic (PV) panels. A Partial Power DC–DC Converter regulates only a small portion of its total power, with the rest bypassing directly to the load. This method reduces conduction, switching, and magnetic losses, significantly boosting overall efficiency. This approach led to the development of more efficient converters with higher power density while maintaining system robustness. Over time, this concept has been extended to various renewable energy applications and EV fast charging. For DC applications, advanced architectures have been devised to minimize the power processed by the converter, each offering distinct advantages tailored to specific application characteristics.

In Figure 9a, the Full Power Processing converter processes 100% of the power, resulting in certain losses [60]. Conversely, Figure 9b depicts the Partial Power Processing concept, which aims to reduce the power processed by the converter. Essentially, a PPP-based converter handles only a fraction of the power flow, thereby reducing losses and overall size. This research focused on utilizing partial power converters for fast charging of electric vehicles (EVs). In the realm of energy conversion systems, several studies have contributed to enhancing performance and efficiency, particularly in the domain of electric vehicle (EV) charging infrastructure.

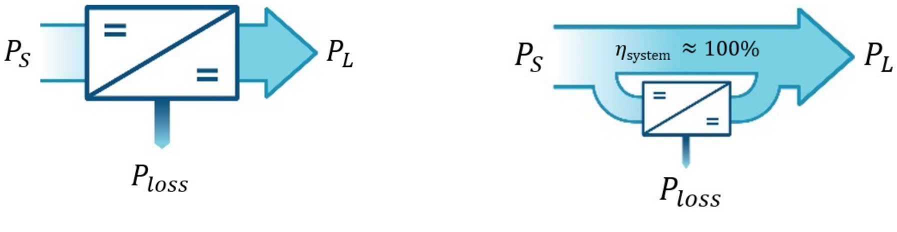


Figure 9. Power flow diagram of (**a**) Full Power Processing (FPP) and (**b**) Partial Power Processing (PPP).

Equations (1) and (2) detail how the converter's efficiency impacts the system efficiency differently depending on whether it is based on FPP or PPP.

$$\eta_{\text{system }FPP} = \frac{P_L}{P_S} = \eta_{\text{converter}} = \frac{P_{\text{out}}}{P_{\text{in}}} \tag{1}$$

$$\eta_{\text{system }PPP} = 1 - K_{pr} \cdot (1 - \eta_{\text{converter}}) \tag{2}$$

where, η_{system} and $\eta_{\text{converter}}$ refer to the efficiencies of both the system and the converter, respectively, and K_{pr} is the processed power ratio of the converter. A power converter operating on the PPP principle transfers only a fraction of the total power from the source to the load. Figure 9 compares the power flow between a converter utilizing the FPP approach and one based on PPP.

Figure 10 shows a Full Power Processing (FPP) fast EV charger, where all power flows through the power converter before reaching the EV battery. The blue color represents the power flow, while the red highlights indicate power losses. In the realm of Partial Power Converters (PPCs), the architectures shown in Figures 11 and 12 are referred to as Input Parallel Output Series (IPOS) and Input Series Output Parallel (ISOP), respectively. Figure 11 shows the IPOS configuration, also known as Type I PPC, connecting multiple input sources in parallel to deliver power in series to the output, making it suitable for applications requiring high voltage gain, such as electric vehicle charging. In contrast, Figure 12 presents the ISOP architecture, also known as Type II PPC, connecting input sources in series while delivering power in parallel, enhancing power density and efficiency.

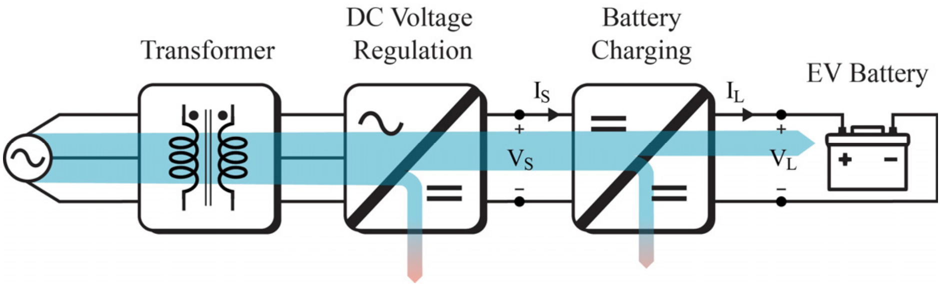


Figure 10. Structure of Full Power Processing based fast EV charger.

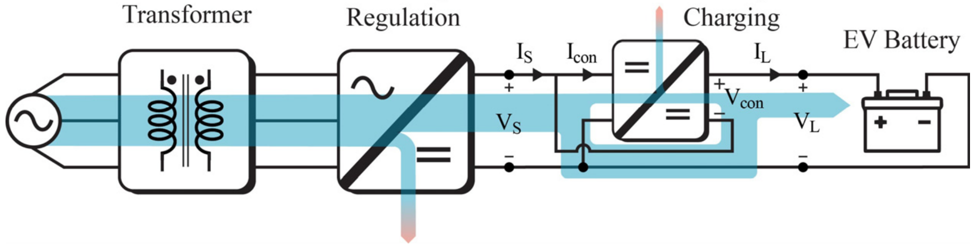


Figure 11. Structure of Partial Power (Type I) based fast EV charger.

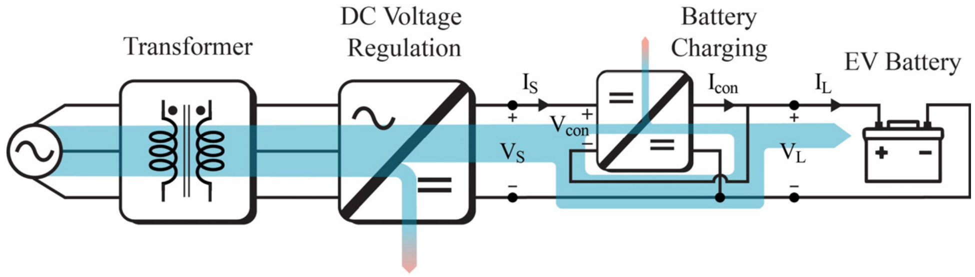


Figure 12. Structure of Partial Power (Type II) based fast EV charger.

Applying Kirchhoff's laws on architecture in Figure 11 leads to the derivation of Equations (3) and (4). Additionally, the system's efficiency is defined using Equation (5), which is essential for assessing the converter's performance.

$$V_S + V_{\text{con}} = V_L \tag{3}$$

$$I_S = I_{con} + I_L \tag{4}$$

$$\eta_{\text{system}} = \frac{V_L \cdot I_L}{V_S \cdot I_S} \tag{5}$$

The processed power ratio of the converter (K_{pr}) is defined as the ratio of the converter's processed power to the power provided by the source.

$$K_{pr} = \frac{P_{\text{con}}}{P_S} = \frac{V_{\text{con}} \cdot I_L}{V_S \cdot I_S} \tag{6}$$

Using Equations (3) and (5), Equation (6) above can be rewritten as:

$$K_{pr} = \eta_{\text{system}} - \frac{I_L}{I_S} \tag{7}$$

The static voltage gain (G_V) is the ratio of the load voltage to the source voltage, indicating how much the input voltage is amplified or reduced at a steady state.

$$G_V = \frac{V_L}{V_S} \tag{8}$$

Employing Equation (5), Equation (8) above can be expressed as:

$$\frac{I_L}{I_S} = \frac{\eta_{\text{system}}}{G_V} \tag{9}$$

Substituting Equation (9) into Equation (7), K_{pr} can be defined as in Equation (10).

$$K_{pr} = \eta_{\text{system}} - \frac{\eta_{\text{system}}}{G_V} \tag{10}$$

Similarly, for architecture, Figure 12, K_{pr} can be defined as in Equation (11).

$$K_{pr} = \eta_{\text{system}} - G_V \tag{11}$$

Each PPC architecture has a distinct K_{pr}. Step-up architectures yield K_{pr} values greater than 1, with the IPOS step-up having the lowest. In contrast, step-down architectures have K_{pr} values less than 1, with ISOP step-down showing the lowest ratio.

Figure 13 compares the processed power ratio $\left(K_{pr}\right)$ of FPC, ISOP, and IPOS architectures as a function of voltage gain $\left(G_V\right)$ for an ideal system having $\eta_{\text{system}} = 1$. The FPC maintains a constant K_{pr} of 1, indicating it processes 100% of the power. The ISOP shows a decreasing trend, meaning it processes less power as G_V increases, improving efficiency at higher voltage gains. The IPOS starts with a negative K_{pr} at $G_V = 0$ and gradually increases, showing a different power processing behavior. This comparison highlights the efficiency advantages of partial power converters over FPCs.

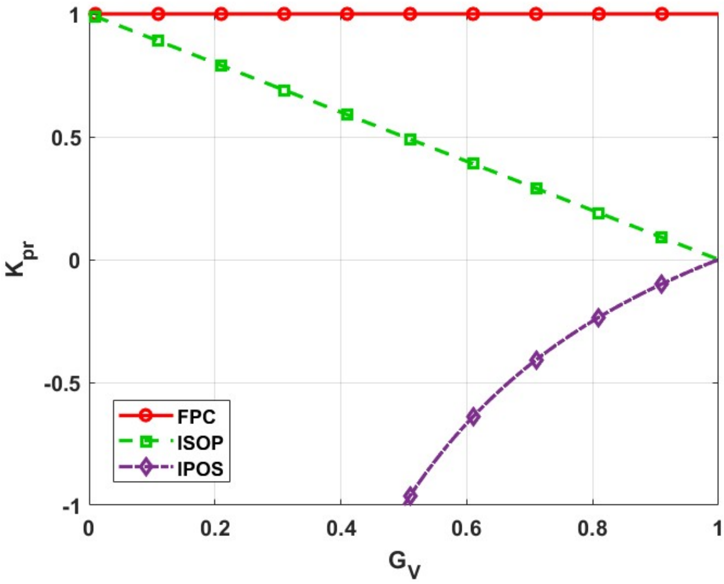


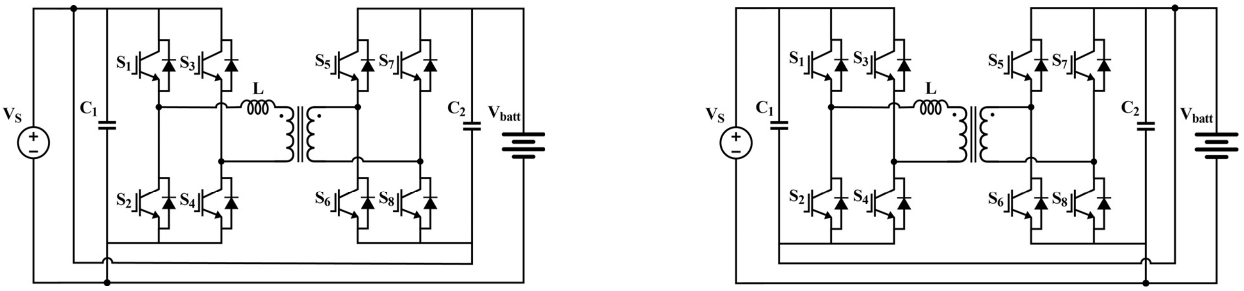
Figure 13. Processed Power Ratio of FPC, ISOP and IPOS architecture.

4. Partial Power Converter Topologies

This section covers different Partial Power Converter (PPC) topologies used in EV charging, including step-up (IPOS) and step-down (ISOP) converters, emphasizing their efficiency improvements and loss reduction.

4.1. Partial Power Dual Active Bridge Converter Topologies

The Partial Power Dual Active Bridge (PP-DAB) converter enhances the traditional DAB architecture by integrating a full-bridge design on both sides with a high-frequency transformer, enabling efficient power transfer in applications like electric vehicle (EV) charging. As illustrated in Figure 14, the PP-DAB can be implemented as Type I and Type II PPC, each offering unique advantages. This design enables high efficiency, greater power density, and bidirectional power flow by handling only a portion of the total power, thereby minimizing losses and reducing component stress.



(**a**) (**b**)

Figure 14. Structure of: (**a**) Type I and (**b**) Type II Partial Power Dual Active Bridge Converter.

Power transfer is managed through phase shift modulation techniques, such as Single-Phase Shift (SPS), Dual-Phase Shift (DPS), and Triple-Phase Shift (TPS), which ensure Zero Voltage Switching (ZVS). Although challenges related to reactive currents and transformer losses remain, advancements in multi-level and three-phase configurations improve voltage gain and reduce current ripple. Overall, the PP-DAB converter presents a promising solution for high-performance energy systems, enhancing efficiency and battery life in electric vehicle applications. In this context, ref. [61] introduces a Partial Power Configuration utilizing a DAB as a power interface for Hybrid Energy Storage Systems (HESS) in electric vehicle (EV) powertrains. Traditional battery systems face issues such as high current stress during transients, reduced battery lifespan, and limitations in regenerative braking. The proposed PPC mitigates these challenges, enhancing power density and validating its effectiveness through comprehensive efficiency analysis and transient dynamic results. Ref. [62] presents a battery emulator designed for AC/DC microgrids and electric vehicle powertrains. Conventional methods require multiple battery sets, increasing costs and safety risks. The proposed emulator employs a partial power processing approach with an input-parallel, output-series configuration and a DAB converter, achieving high efficiency and reduced control effort while minimizing downtime during testing.

Furthermore, ref. [59] proposes a power delivery scheme for Extreme Fast Charging (XFC) stations capable of charging multiple electric vehicles (EVs) simultaneously. This system utilizes a cascaded H-bridge converter connected to the medium-voltage grid, with dual-active-bridge solid-state transformers for galvanic isolation. The design allows independent charging control for each EV, resulting in efficiency improvements of 0.6% at full load and 1.6% at 50% load, validated through scaled-down tests. Ref. [63] addresses the growth of electromobility and the autonomy challenges of heavy-duty electric vehicle powertrains.

The study enhances an existing Bidirectional DAB Partial Power Converter topology by exploring modulation strategies to optimize efficiency. Findings indicate that strategic modulation can significantly improve efficiency, achieving a maximum of 99.41% at 6.526 kW. Advancements in DAB converter technology enhance efficiency and lower costs. Building on this, ref. [64] introduces a novel PPC design specifically engineered for EV fast charging, leveraging switching capacitors and interleaved power cells to enhance power density and reduce costs utilizing the H-bridge topology.

In ref. [65] authors implement a fixed-frequency Dual Active Bridge Series Resonant Converter (DAB-SRC) within a Partial Power Converter (PPC) architecture designed for electric vehicle (EV) fast charging stations. The DAB-SRC architecture, shown in Figure 15, is chosen due to its ability to provide soft-switching capabilities, specifically achieving Zero Voltage Switching (ZVS) on the secondary side and reduced voltage stress on the primary side, which minimizes switching losses and voltage overshoots. This resonant converter operates with phase-shift modulation (PSM) and benefits from a reduced power processing ratio, as only the differential voltage between the DC bus and the EV battery is processed. This significantly improves overall system efficiency, particularly during the early charging phase when the voltage difference is largest. By integrating a series resonant network into the DAB topology, the converter maintains high efficiency across varying load conditions, making it a compelling choice for fast and efficient EV charging in a PPC framework.

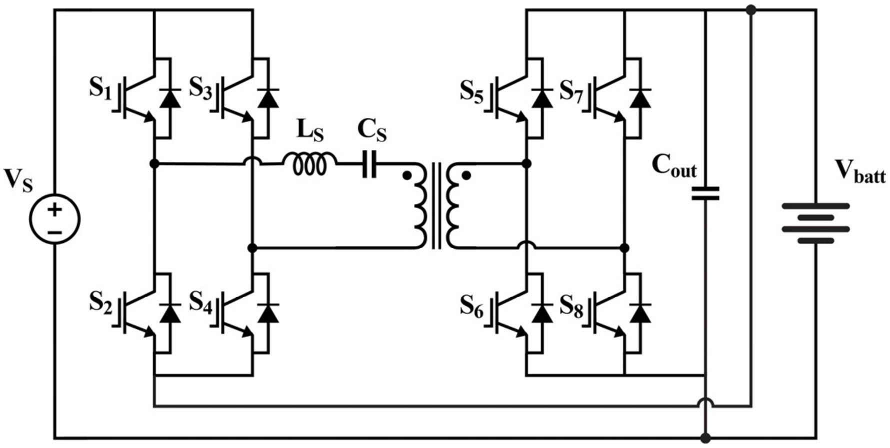


Figure 15. ISOP step-down DAB-SRC topology.

4.2. Partial Power Full-Bridge Converter Topologies

The Partial Power Phase-Shifted Full-Bridge (PSFB) converter, a variation of the DAB family, is well-suited for EV charging stations due to its soft switching, simple PWM control, scalability, and low EMI. Energy transfer is achieved by adjusting the phase on the input side, enabling soft switching in one direction. However, challenges arise during load operation, such as hard switching of secondary diodes and voltage spikes. To address these issues, improvements like using transformer leakage inductance for energy storage, turn-off snubbers, and center-tap clamp circuits enhance efficiency, resonant soft-switching, and power density. Combining the PSFB with the LLC converter further mitigates these limitations. Ref. [66] proposes a transformerless DC–DC Type I step-up partial power converter (PPC) using a full-bridge topology for electric vehicle (EV) fast charging stations. The design aims to increase power ratings, reduce charging times, and enhance efficiency and reliability. By replacing the traditional isolation transformer with an impedance network, the converter becomes more efficient, cost-effective, and simpler.

Validating the efficiency of such designs, ref. [67] validates a step-down Type II PPC for EV fast chargers using a phase-shifted full-bridge topology. Processing only part of the total power enhances efficiency, achieving 99.11% peak efficiency with a 7 kW demonstrator. Ref. [57] proposes an XFC station architecture with partial power-rated DC–DC converters and a full-bridge boost converter, improving efficiency and reducing redundant conversion. It supports independent EV charging while integrating renewables to ease grid impact. Scaled-down lab tests confirm its feasibility and cost-effectiveness. Expanding on this, ref. [68] introduces a novel three-port series partial-power converter for electric vehicle (EV) fast chargers, utilizing a full-bridge converter. The design handles a fraction of the power delivered to the battery and supports both step-up and step-down voltage, enabling compatibility with both legacy 400 V and modern 800 V EVs. Compared to existing partial power converters, the proposed structure operates over a wider range. Simulation results demonstrate its effectiveness, reaching a maximum efficiency of 98.65%.

The structural differences between Type I and Type II Partial Power Converters topologies are illustrated in Figures 16 and 17. Figure 16 focuses on Half Bridge Converter, while Figure 17 focuses on Full Bridge Converter.

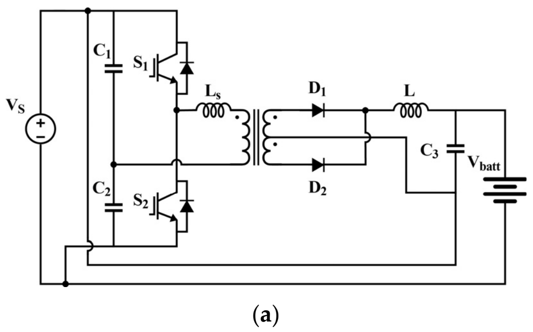


Figure 16. Structure of: (**a**) Type I and (**b**) Type II Partial Power Half Bridge Converter.

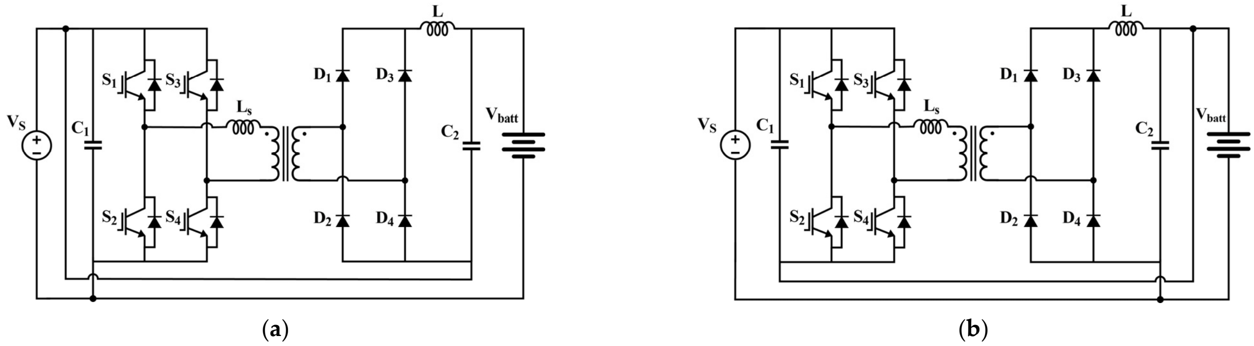


Figure 17. Structure of: (**a**) Type I and (**b**) Type II Partial Power Full Bridge Converter.

Ref. [42] examines the increasing demand for EV charging and the role of extreme fast charging (XFC) technology. It highlights the advantages of solid-state transformers (SSTs) over traditional ones in XFC stations. Using a cascaded H-bridge (CHB) converter and DAB-based SSTs, the proposed system enables simultaneous charging with reduced conversion losses. The paper suggests using a PSFB-based EV charger, with experiments indicating that a PPC handling 27% of the battery power increases efficiency by 0.6% at full load and 1.6% at half load.

4.3. Partial Power Flyback Converter Topologies

The partial power Flyback converter has emerged as a promising solution for improving the efficiency and power density of power conversion systems. Unlike conventional full-power converters, the partial power approach processes only a fraction of the total power, allowing the remaining power to bypass the converter, thereby reducing losses and stress on key components.

By boosting system efficiency and easing thermal management, this configuration is well-suited for high-power applications, including renewable energy systems, electric vehicles, and battery management. The Flyback topology, with its inherent simplicity and ability to provide galvanic isolation, is particularly effective in wide input voltage range scenarios. However, challenges such as managing voltage stress and optimizing the transformer design remain critical to fully realizing the benefits of this approach. Ref. [69] revisits the Partial Power Processing (PPP) concept, focusing on the design and performance evaluation of a highly efficient 5-kW flyback converter-based battery charger. The study analyzes different PPP architectures, specifically series and parallel configurations, highlighting how the series configuration outperforms in efficiency, achieving over 99% in power conversion. The structural implementations of the Flyback-based partial power converters are depicted in Figure 18, where (a) illustrates the Type I and (b) the Type II configurations.

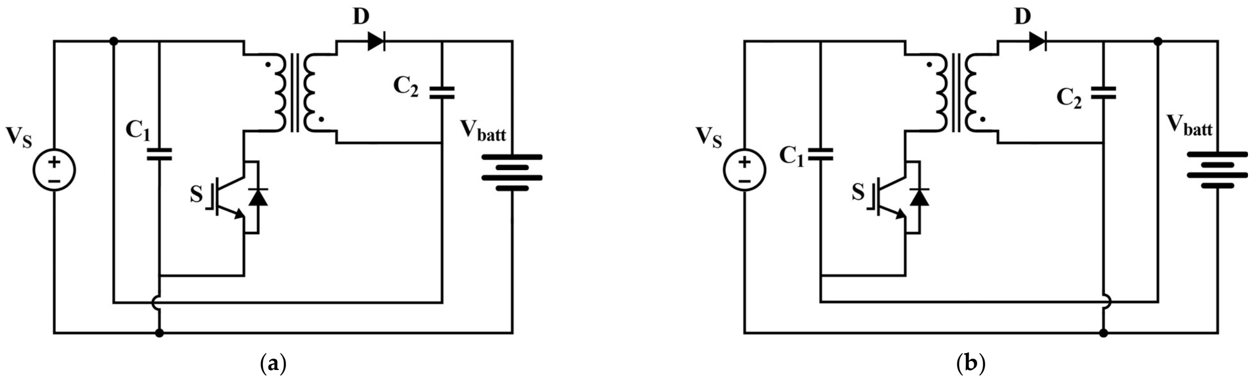


Figure 18. Structure of: (**a**) Type I and (**b**) Type II Partial Power Flyback Converter.

A bidirectional flyback converter was designed for use with a battery energy storage system (BESS) tied to a 700 V DC grid, demonstrating lower component stress and reduced filtering requirements due to partial power processing. The study presents a comprehensive analytical methodology, experimental validation, and design approach, verifying the proposed series PPP flyback converter's high efficiency, compactness, and suitability for modern battery charging applications. In [70], the authors propose a high step-up SEPIC-based partial-power converter that combines a Flyback circuit with a modified SEPIC configuration to achieve improved voltage gain over a wide input range. The approach reduces processed power, boosting efficiency and power density, with the Flyback converter handling voltage regulation and the SEPIC stage operating in a fixed state with zero-voltage soft switching.

4.4. Partial Power Interleaved Converter Topologies

A Partial Power Interleaved Converter (PPIC) improves efficiency and power density by processing only a portion of the total power, reducing stress on components. Its interleaved design minimizes current ripple, distributes thermal load, and reduces EMI, making it ideal for high-power applications like EV charging. By splitting power between the main path and converter, PPIC lowers losses and allows for smaller, more efficient components [71]. The modular nature of interleaving also enables easier scaling, making PPICs a compact, efficient solution for fast charging and renewable energy systems. Ref. [57] introduces an interleaved partial power converter (PPC) specifically designed for the DC–DC conversion stage in fast charging stations. By processing only a fraction of the total power, this design significantly boosts efficiency, as validated by simulation results showcasing a conversion efficiency increase from 95.1% to 98.3%.

Ref. [72] presents an interleaved single-ended primary inductor converter (SEPIC) partial power converter for fast EV charging stations, which processes only a fraction of the load's power. Unlike traditional partial power converter architectures that require isolated topologies, this design utilizes a non-isolated interleaved single-ended primary inductor converter. The proposed converter demonstrated significant advantages when compared to a conventional full-power converter. The findings conclude that the partial power architecture not only reduces the power processed by the converter but also enhances the overall efficiency, making it a compelling solution for fast-charging applications. Figure 19 illustrates a SEPIC-based Partial Power Converter (SEPIC-PPC), which combines the features of a SEPIC converter with partial power processing. The input voltage V_S supplies power through the inductor L_1 and switch S_1, which transfers energy to the coupling capacitor C_1. This energy is then passed to the second stage comprising inductor L_2, switch S_2, and output capacitor C_2, which helps regulate the output voltage. A diode provides a path for current when the switches are off. The battery V_{batt} is connected across the output to handle part of the total power directly.

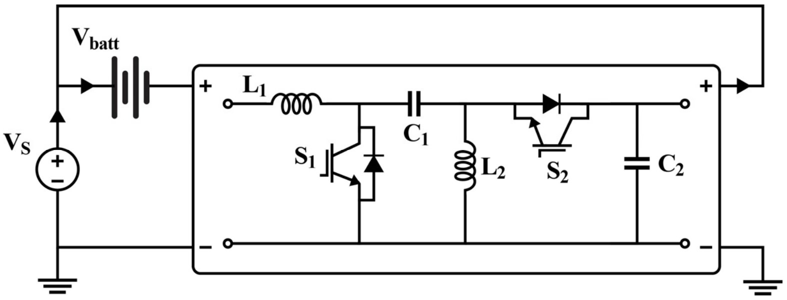


Figure 19. Simplified diagram of the SEPIC-PPC.

4.5. Multi-Port Partial Power Converters

Ref. [73] proposes a three-port partial power processing converter (3P-PPPC) for integrating battery storage systems (BSS) in fast charging stations (FCS). The design is based on a triple active bridge (TAB) converter and aims to reduce system losses, size, and cost by transferring less power from the BSS to the electric vehicle (EV) compared to conventional full power processing converters (FPPC). This leads to lower power losses and higher system efficiency. The paper investigates design trade-offs, dynamic behavior, and limitations and compares the round-trip efficiency of the 3P-PPPC with FPPC solutions, demonstrating its superiority. A prototype will also be built to validate the proposed design.

Figure 20 illustrates the circuit of a proposed Three-Port Partial Power Converter (3P-PPC) designed to manage energy flow between two input sources and a battery output. It consists of three converter stages: two input stages connected to separate capacitors and one output stage connected to a battery through a capacitor. Each input stage controls power flow from its respective source using switches and coupled inductors, transferring energy to the output stage via a high-frequency transformer. The output stage then regulates the combined power and delivers it to the battery.

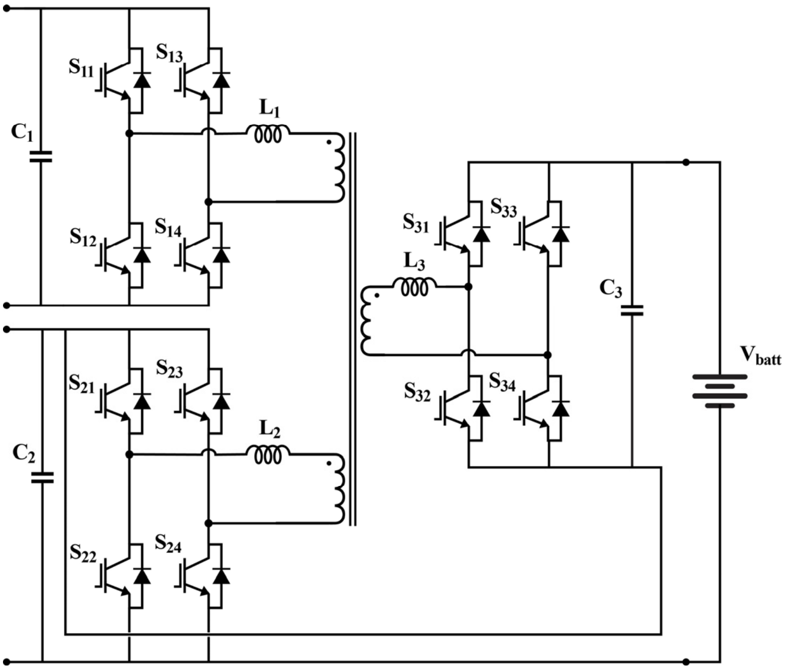


Figure 20. Circuit diagram of the 3P-PPC.

4.6. Inductive Power Transfer (IPT) Based Converters

Ref. [74] proposes a hybrid inductive power transfer (IPT) system with PPP to improve efficiency in CC-CV charging. The system is divided into main and auxiliary power channels with different topologies. The majority of the power is transmitted through the primary channel, while the auxiliary channel adjusts a small portion to maintain output, reducing power loss and device stress in the DC–DC converter. The system achieves CC and CV charging without relying on wireless communication between the primary and secondary sides utilizing commonly used boost converter topology. A prototype demonstrates 92.1% efficiency, a 2.1% improvement over traditional two-stage structures.

The inductive power transfer system, shown in Figure 21, uses a full-bridge inverter to convert DC input into high-frequency AC, which energizes the primary coil of a transformer. Through magnetic coupling, power is wirelessly transferred to the secondary coil, where it is resonated, rectified, and regulated using a DC–DC converter. The final output is a stable DC voltage suitable for charging a battery or powering a load.

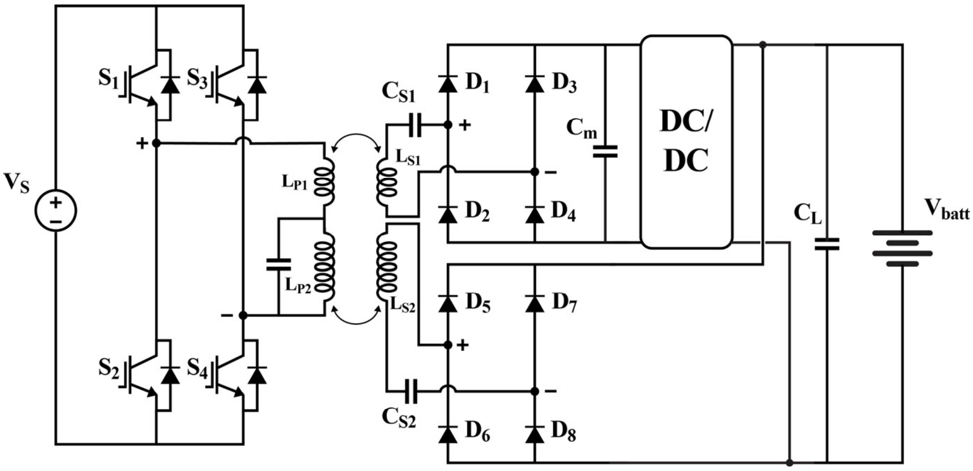


Figure 21. Circuit diagram of the IPT system.

4.7. Cascaded Conversion Topologies

Ref. [75] outlines the specifications for a modular, fast EV charging converter, proposing a 2-stage cascaded conversion approach with separate isolation and charging regulation stages for optimal design. The regulation stage features PPP to enhance efficiency. Two isolated topologies are introduced, using either 2 or 3 voltage levels and incorporating SiC or Si devices based on voltage stress. The study optimizes the converter's gain and transformer turns ratio to reduce RMS currents and inductor peak energy.

The 2-level topology, shown in Figure 22, consists of two isolated LLC converters, each connected to separate input capacitors. These converters operate independently to transfer power to the output while maintaining electrical isolation. Their outputs are combined and passed through output capacitors before entering a voltage balancer stage. This stage includes four switching devices that help regulate voltage and balance energy flow. The output from the voltage balancer is then processed by a partial power DC–DC converter, which can be a buck, boost, or buck-boost converter, depending on the battery charging requirements. Finally, an output capacitor smooths the voltage before delivering it to the battery or load.

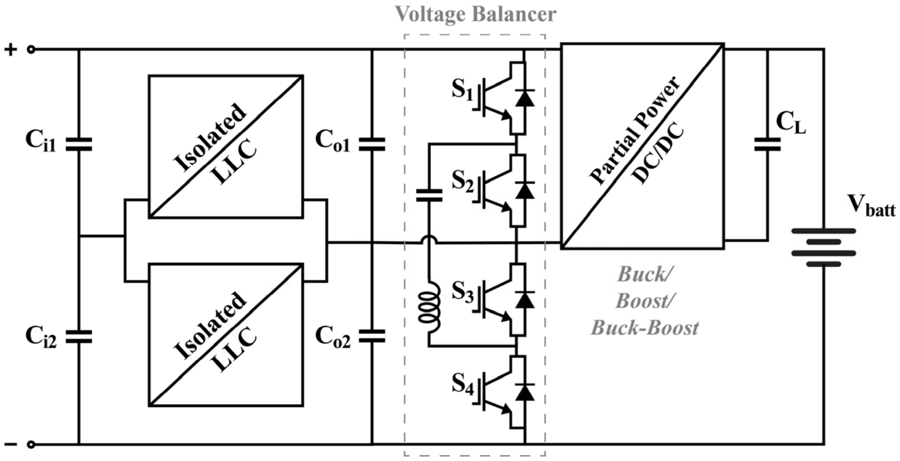


Figure 22. 2-level PPC topology.

4.8. Solid-State Transformer (SST) Based Converters

Ref. [76] introduces a multiport control strategy designed to facilitate partial power processing (PPP) within medium voltage multiport current-source solid-state transformers (SSTs). These SSTs allow the integration of low-voltage DC sources—like solar photovoltaic systems, energy storage units, and electric vehicles—into smart grids, eliminating the need for traditional bulky transformers. Figure 23 shows an isolated power transfer system where a DC source is converted to AC, transferred through a transformer, and then converted back to DC to charge a battery. It provides safe and efficient power transfer with electrical isolation.

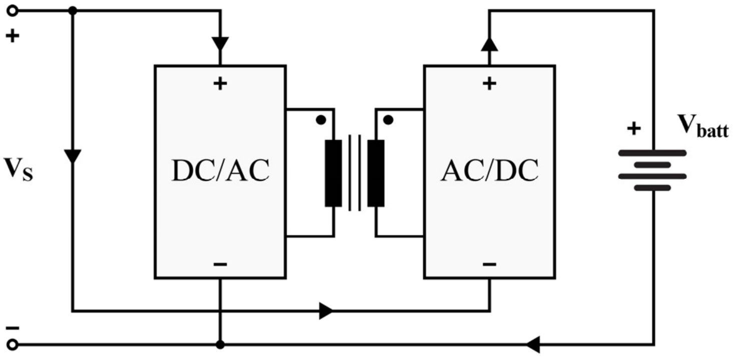


Figure 23. SST architecture.

4.9. Other Partial Power Converter Topologies

4.9.1. Modular Converters

Ref. [77] analyses the advantages of partial-power-processing (PPP) converters in fully electric maritime applications, focusing on modularity and scalability. Series-connected partial power converters are proposed, addressing overvoltage challenges in the event of a module failure. A reliability analysis is conducted using independent component failure probabilities, incorporating redundancy to enhance fault tolerance. Experimental validation on a 3 kW prototype confirms the system's robustness and efficiency across various battery charging points, achieving a peak efficiency of 99.36%. These results highlight the effectiveness of the proposed design in ensuring reliable and efficient EV charging.

4.9.2. Partial Processing Zeta Converter

Ref. [78] reviews recent advancements in electric vehicle chargers and charging infrastructure, focusing on partial processing converters. As electric vehicles gain popularity due to their environmental benefits, challenges such as limited travel range, charging station availability, and charging time persist. The active study aims to address these issues by developing new topologies. Partial processing converters transfer a significant amount of power directly to the load, while only a portion is managed for regulation. The paper illustrates various topologies utilizing these converters for EV charging and presents simulation results for battery charging using an isolated partial processing Zeta converter.

4.9.3. Buck-Boost Converters

Ref. [79] compares buck-boost partial power converters (PPC) for the DC–DC conversion stage of EV fast charging stations. The proposed DC–DC buck-boost structure enables operation across a wide output voltage range, suitable for charging both 400 V and 800 V batteries. By processing only a fraction of the total power, the PPC achieves high efficiency. Two different buck-boost PPC topologies are evaluated: one using two-quadrant switches for bipolar voltage and another employing an unfolding bridge to change voltage polarity. Results indicate that the two-quadrant switch solution offers superior efficiency. The proposed converter demonstrates high efficiency—up to 99%—for fast charging applications, making it an attractive option for EV charging.

4.9.4. Resonant-Type Converters

Ref. [80] presents a bidirectional soft-switching resonant-type PPC designed for high-efficiency, high-density battery chargers in energy storage systems, microgrids, and transportation electrification. The converter uses an IPOS topology, where only a fraction of power is processed to regulate the output voltage. To address the complexity of designing tightly coupled DC transformers (DCXs), a decoupled design method is proposed, allowing separate optimization of DCXs. The hardware design incorporates a two-direction flux cancellation method and an interleaving winding structure to enhance efficiency and power density. The design is validated with an 18 kW prototype operating at 500 kHz, achieving a peak efficiency of 98.8% and 142 W/in^3 power density.

Table 3 presents a comparative summary of the previously discussed Partial Power Converter (PPC) topologies, outlining their key features, operational benefits, and typical areas of application. This comparison helps to highlight the distinctions between each topology and supports the selection of an appropriate configuration based on specific system requirements.

In summary, Partial Power Converter (PPC) topologies offer a transformative solution for electric vehicle (EV) fast-charging applications, addressing the demand for efficient, high-power charging systems. Topologies like the Dual Active Bridge (DAB) and Phase-Shifted Full-Bridge (PSFB) enable bidirectional power flow and Zero Voltage Switching (ZVS), enhancing efficiency in EV powertrain and fast-charging applications. The incorporation of novel designs, including transformerless and resonant-type converters, further increases power density and reduces electromagnetic interference (EMI), making these systems more compact and cost-effective. The advancements in partial power processing technology thus provide a scalable, reliable foundation for meeting the rapid charging requirements in the evolving EV sector, promising significant benefits in efficiency and performance for sustainable electric mobility.

Table 3. Overview of Partial Power Converter Topologies.

PPC Topology	Ref. No.	Application	Advancement
Dual Active Bridge Converter Topologies	[61]	EV powertrains, Hybrid Energy Storage Systems (HESS)	Mitigates high current stress enhances power density, improves efficiency
	[62]	AC/DC microgrids, EV powertrains	Achieves high efficiency, reduces control effort, minimizes downtime
	[59]	Extreme Fast Charging (XFC) stations	Improves efficiency by 0.6% at full load, 1.6% at 50% load
	[63]	Heavy-duty EV powertrains	Strategic modulation improves efficiency to 99.41%
	[64]	EV fast charging	Enhances power density, reduces costs
Full-Bridge Converter Topologies	[66]	EV fast charging stations	Increases power ratings, reduces charging times, enhances reliability
	[67]	EV fast chargers	Improves efficiency, processes 13.32% of total power
	[57]	Extreme Fast Charging (XFC) stations	Improves efficiency, integrates renewable energy sources
	[68]	EV fast chargers	Supports both 400 V and 800 V batteries, reaches 98.65% efficiency
	[42]	Rapid charging stations	Increases conversion efficiency from 95.1% to 98.3%
Flyback Converter Topologies	[69]	Battery energy storage system (BESS) charging	99% efficiency in 5 kW charger with series configuration, less stress and filtering
	[70]	Renewable energy systems with a wide input voltage range	Enhanced voltage gain, better power density, and soft switching
Interleaved Converter Topologies	[71]	EV fast charging stations	Enhances efficiency, reduces processed power
	[72]	Medium-voltage multiport current-source (CS) solid-state transformers	Reduces DC-link current by 36%, improves efficiency
Multi-Port Converters	[73]	Electric maritime applications	Increases efficiency, enhances modularity and fault-tolerance
Inductive Power Transfer Systems	[74]	EV fast charging	Demonstrates 99% efficiency, suitable for fast charging
Cascaded Conversion Topologies	[75]	EV fast charging stations	Achieves high efficiency across a wide operating range
Solid-State Transformer based Converters	[76]	Constant current (CC) and constant voltage (CV) charging	Improves efficiency, reduces power loss and device stress
Modular Converters	[77]	EV charging stations	Achieves high efficiency in battery charging
Partial Processing Zeta Converter	[78]	EV fast charging stations	Optimizes gain and transformer turns ratio, reduces RMS currents
Buck-Boost Converters	[79]	High-efficiency, high-density battery chargers	Achieves 98.8% efficiency and high power density
Resonant-Type Converters	[80]	High-efficiency bidirectional battery charging	Ultra-high efficiency (98.8%) and power density (142 W/in^3)

However, despite their advantages, these converter topologies also present certain limitations. DAB converters face stability issues due to LC filters, conduction and switching losses, back-flow power with Single Phase-Shift (SPS) modulation, and higher device stresses in single-phase designs [81]. Full-bridge converters suffer from poor regulation and current sharing, a high component count, significant switching losses, large circulating currents, and a limited ZVS range [82]. Flyback converters encounter high voltage stress, limited component availability, complex control for Constant Current (CC)/Constant Voltage (CV) modes, power factor and harmonic challenges, and thermal management issues [83]. Interleaved converters experience poor current sharing, voltage stress, high switching losses, battery life reduction, and increased complexity and cost. Multi-port converters face challenges like complex mode analysis, switching losses, high control complexity, stability issues, and fault diagnosis concerns. Solid-State Transformer (SST)-based converters are hindered by high complexity and cost, efficiency challenges, voltage balancing issues, EMI, and large component sizes. Modular converters deal with increased harmonics, dependency on independent DC sources, circulating currents, thermal management difficulties, and larger footprints. Lastly, Zeta converters face drawbacks like bulkiness, lower efficiency compared to SEPIC, high resource consumption, power quality issues, and environmental dependency. Addressing these limitations through advanced control strategies, optimized modulation techniques, and innovative component integration will be essential to further enhance the performance, reliability, and scalability of PPC-based fast-charging solutions for EVs.

5. Control Methods for Partial Power Converters

In this section, the control strategies for the previously discussed Partial Power DC–DC converter topologies are reviewed. While these converters can be controlled using various methods across multiple applications, our focus here is limited to control techniques specific to EV chargers. Key control objectives involve maintaining stable battery voltage and effectively overseeing the charging and discharging operations.

5.1. Control of Partial Power Dual Active Bridge Converter

Dynamic control strategies are essential for ensuring high efficiency and smooth operation in Dual Active Bridge (DAB) converters. Typical control methods involve small-signal modeling and discrete-time averaging, especially when using multi-phase shift modulation to accurately reflect the system's dynamic behavior. These control strategies are generally classified into three categories: power calculation-based control, direct control of inductor current, and load current feedforward techniques. Power computation-based control relies on a mathematical model of power flow between the two bridges of the DAB converter [84]. Active power transfer P_o for Single Phase Shift (SPS) modulation can be expressed as:

$$P_o = \frac{V_{in} V_o D(1-D) T_s}{2nL} \tag{12}$$

where D is the phase shift ratio, L is the equivalent inductance, n is the transformer ratio, and V_{in}, V_o are the input and output voltages, respectively. A direct power control strategy can be implemented using a PI controller, where the control input D is regulated to maintain the desired output voltage. This approach proves advantageous in environments with significant input and output voltage fluctuations, providing robust voltage regulation.

- Direct inductance current control involves sensing the inductor current and using modulation schemes such as asymmetric double-side modulation. This approach is particularly effective in applications requiring a fast transient response, as the phase shift ratio D can vary dynamically, allowing the DAB converter to adapt quickly to load changes. The fast response time makes it suitable for scenarios with sudden load disturbances. Load current feed-forward control enhances the output transient response by directly accounting for load variations, eliminating the need for an inner current loop and simplifying the control system while maintaining high performance under varying load conditions [85].

- DPS and TPS modulation extend the ZVS range in DAB converters but lead to large turn-off currents. A combination of SPS, DPS, and TPS helps maintain ZVS across varying voltages while minimizing turn-off losses. Dead band adjustments further extend ZVS from 200 V to 450 V. Before connecting to an EV battery, the output capacitor must be pre-charged under no-load conditions by gradually increasing the reference voltage to match the battery voltage, preventing inrush currents. During pre-charging, the primary voltage appears as a narrow pulse, while the secondary resembles a square waveform, protecting switches from high leakage currents. After pre-charging, the DAB converter transitions through CC, CP, and CV charging modes, managed by PI controllers for smooth operation [86].

The control system in ref. [87] focuses on a new method called Additional Phase Shift (APS) Control. This approach provides more flexibility compared to the traditional Single Phase Shift (SPS) Control. By adding a phase shift between two low-voltage full-bridge units, the APS control extends the Zero Voltage Switching (ZVS) operation region and reduces the Root Mean Square (RMS) current of the inductor. This ultimately improves the efficiency of the converter, particularly in light-load conditions. The key advantage of APS control is that it allows the converter to operate more efficiently by adjusting the phase shifts between the full-bridge modules. Additionally, the Global Optimal Equation (GOE) helps calculate the optimal phase shift angles for improved performance. Simulations and experimental tests have shown that this control method can increase the converter's efficiency and reduce losses compared to the conventional SPS control system.

The control system in ref. [63] focuses on comparing modulation strategies to improve efficiency. The study analyzes Single Phase Shift (SPS), Extended Phase Shift (EPS), Dual Phase Shift (DPS), and Triple Phase Shift (TPS). SPS, though simple, generates high reactive currents. EPS, DPS, and TPS add internal phase shifts to reduce reactive power and RMS current, enhancing performance. The study found that SPS achieved the highest efficiency, 99.41% at 6.526 kW, making it ideal for high-power applications. EPS and DPS reduced losses at lower power levels but are more complex to implement.

Ref. [67] employs a cascade control system, as illustrated in Figure 24, for the Type II Partial Power Converter (PPC) used in the EV fast charger. This system consists of an inner current control loop, which regulates the charging current by adjusting the phase shift (φ) based on the reference from the Battery Management System (BMS), and an outer voltage control loop, which controls the battery voltage during the charging process. In Constant Current (CC) mode, the inner loop ensures the correct current is supplied, while in Constant Voltage (CV) mode, the outer loop takes priority to maintain the voltage. By modulating the phase shift between the converter legs, the system efficiently controls the power transfer to the battery, optimizing the charging process. The control system regulates the output voltage of the converter using phase-shift modulation. The voltage gain is controlled by adjusting the phase shift between the legs of the full-bridge converter. This phase shift (ϕ) determines the amount of power processed by the converter. The relationship between the output voltage V_o, the input voltage V_d, and the phase shift is captured by the following control equation, which also incorporates the transformer turn ratio n. Equation (11) ensures efficient power conversion by allowing dynamic control of the output voltage during the electric vehicle charging process.

$$Gv = \frac{V_o}{V_d} = \frac{n\phi}{\pi + n\phi} \tag{13}$$

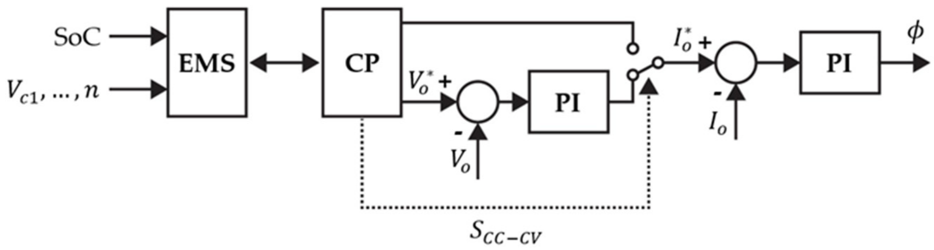


Figure 24. Proposed Cascade Control System for Type II PPC.

The control system used in ref. [65] is based on a fixed frequency dual active bridge series resonant converter (DAB-SRC). The modulation strategy employed is a conventional phase-shift modulation (PSM), which adjusts the phase difference between primary and secondary AC voltages. The phase shift (ϕ) controls the power transfer between the input and output, ensuring zero voltage switching (ZVS) for the secondary side semiconductors to minimize switching losses and improve efficiency. The system is designed to maintain efficient operation throughout the electric vehicle charging process by processing only a portion of the total power, reducing size, cost, and losses. The primary control equation is shown in Equation (12).

$$P_{pu} = \frac{8 \cdot M \cdot \sin(\phi)}{\pi^2 \cdot Q \cdot \left(F - \frac{1}{F}\right)} \tag{14}$$

This equation describes the transferred active power P_{pu}, where M is the voltage gain, Q is the quality factor, F is the normalized frequency, and ϕ is the phase shift. In ref. [88], the authors present a high-efficiency DAB converter for electric vehicle charging that leverages Partial Power Processing (PPP) to reduce the power handled by the converter, which in turn minimizes size, cost, and losses. The Extended Phase-Shift (EPS) control method is employed to ensure Zero Voltage Switching (ZVS) across the full load range, allowing for soft switching even at light loads. The EPS control also mitigates current stress and optimizes power flow, improving system efficiency. Experimental results from a 1 kW prototype showed an 80% reduction in the input voltage and power processed by the converter compared to full-power converters, resulting in a peak efficiency of 98.4%.

5.2. Control of Partial Power Phase-Shifted Full-Bridge Converter

The control system of a Phase-Shifted Full-Bridge converter operates similarly to that of a DAB converter. A common technique used for controlling the PSFB converter is Single-Phase Shift (SPS) modulation. In this system, output power and voltage are adjusted by slightly altering the phase shift angle. During constant current (CC) mode, the battery voltage increases as the phase shift angle decreases. Once the voltage hits a specific threshold, the system shifts to constant voltage (CV) mode, where the output voltage is regulated by gradually adjusting the phase shift angle. During both constant current (CC) and CV modes, soft switching is maintained through single-phase shift PWM (SPS-PWM), ensuring efficient performance [89].

However, at light loads, achieving soft switching becomes challenging, and the duty cycle reduces, leading to significant circulating and switching losses. A unified control method is often used to address this. It involves phase shift control for heavy loads, PWM switching control for light loads, and burst mode for no-load conditions. This approach reduces circulating and switching losses, enhancing efficiency, especially under light loads. Hybrid control methods have been proposed to improve efficiency in both heavy and light load conditions. These methods often decrease the transformer's turns ratio, which reduces circulating current using only phase shift control. Unbalanced PWM can also enhance stability, particularly when dealing with higher battery voltages. Additionally, adaptive dead time control is combined with these techniques to further minimize losses.

While Proportional-Integral (PI) controllers are commonly used in PSFB converters due to their simplicity, Model Predictive Control (MPC) has gained popularity for handling multiple physical constraints and optimizing the system. MPC techniques transform nonlinear constraints, such as peak inductor current, into dynamic linear constraints, enabling precise tracking of battery voltage while meeting system requirements. Studies show that MPC offers better performance than traditional PI controllers, particularly in disturbance rejection and error minimization [90].

For systems with multiple connected PSFB converters, a common duty ratio control ensures a balanced sharing of voltage and current among converters, minimizing circulating losses and power imbalances. This control uses a small signal average model and a steady-state DC model, with a Type II compensator employed as the voltage and current controller. In ref. [59], The proposed control system regulates battery charging. The control system's main goal is to control the output inductor current, ensuring that the charging rate is consistent and efficient. A proportional-integral (PI) controller is implemented to manage the output filter inductor current, ensuring smooth current regulation during the charging process. A key control equation for the effective duty cycle of the PSFB converter, considering leakage inductance, is given by:

$$Deff,i = Di - \Delta Di \tag{15}$$

$$\Delta Di = 4nL_{lk}\frac{V_{in,i}T_s}{I_{f,i}} \tag{16}$$

This control equation is essential for ensuring the stability and efficiency of the PSFB converter in the PPCU, enabling smooth and precise charging of electric vehicles.

5.3. Control of Partial Power Flyback Converter

A control system for a partial power flyback converter regulates the output by adjusting the switch duty cycle using feedback from the output voltage or current. It ensures stable, efficient operation, often using pulse-width modulation (PWM) to maintain desired output levels. In ref. [69] the control system for the Partial Power Flyback Converter (PPFC) is designed to manage bidirectional power flow between a battery energy storage system (BESS) and a DC grid with high efficiency. Using a Proportional-Integral (PI) controller, the system adjusts the duty cycle to regulate the power delivered during both charging (grid to battery) and discharging (battery to grid). Key control equations, such as those governing the primary and secondary currents and the voltage conversion ratio, ensure optimal power delivery while minimizing losses. The system processes only a fraction of the total power (partial power processing), achieving over 99% efficiency [69,91].

In conclusion, control methods for Partial Power Converters (PPCs) in electric vehicle (EV) charging applications are essential for achieving efficient, reliable, and flexible power management. The different converter topologies, such as Dual Active Bridge (DAB), Phase-Shifted Full-Bridge (PSFB), and Flyback converters, each employ distinct control strategies tailored to enhance performance in various EV charging scenarios. Techniques like phase shift modulation, Proportional-Integral (PI) control, Model Predictive Control (MPC), and adaptive modulation approaches allow for precise regulation of battery voltage and efficient power transfer while also addressing challenges like Zero Voltage Switching (ZVS), reactive current reduction, and transient response management. These control strategies not only ensure seamless charging and discharging processes but also optimize power efficiency, reduce component stress, and support advanced functionalities such as Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) transitions. As EV adoption grows, these control methods provide a robust foundation for high-performance charging solutions, enabling faster, safer, and more sustainable electric mobility [92].

5.4. Control of Multi-Port Partial Power Converter

In ref. [73] control system of the Three-Port Partial Power Processing Converter (3P-PPPC) is designed to regulate bidirectional power flow between the PV source, storage battery, and EV battery. It uses two phase shift angles—φ_{13} and φ_{23}—as control variables, making the system a two-input, two-output configuration where the outputs are the powers storage and EV load. The power transfer equations are nonlinear and depend on the port voltages and inductances. A simplified expression for power between two ports is:

$$P = \frac{V_i V_j}{2\pi f L_{ij}} \phi_{ij} \left(1 - \frac{\phi_{ij}}{\pi}\right) \tag{17}$$

where, V_i and V_j are the voltages at ports i and j, f is the switching frequency, L_{ij} is the coupling inductance between the ports and ϕ_{ij} is the phase shift angle used for control. To control the dynamic behavior, the nonlinear system is linearized around an operating point, resulting in a small-signal model:

$$\begin{bmatrix} \widetilde{P}_{S2} \\ \widetilde{P}_L \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} \widetilde{\phi}_{13} \\ \widetilde{\phi}_{23} \end{bmatrix} \tag{18}$$

where $\widetilde{P}_{S2}$ and $\widetilde{P}_L$ represents output powers; G_{11}, G_{12}, G_{21} and G_{22} is the gain matrix; and $\widetilde{\phi}_{13}$ and $\widetilde{\phi}_{23}$ are control phase shifts. To decouple the control of both power outputs, a decoupling matrix is derived from the inverse of the gain matrix, allowing φ_{13} and φ_{23} to be independently adjusted. A lookup table (LUT) is used for practical and efficient implementation. This LUT is precomputed using power equations and port parameters, mapping input conditions to optimal phase shifts [93]. The control loop includes PI controllers for each port current.

$$G_C(s) = \frac{K_C(\tau s + 1)}{\tau s} \tag{19}$$

Equation (17) represents a PI controller transfer function, where $G_C(s)$ is the controller output, K_C is the proportional gain, and τ is the time constant. A low-pass filter is used to suppress output current ripples due to minimal battery-side inductance. The system operates mainly in constant current (CC) mode for fast charging, with a switch to constant voltage (CV) mode based on the battery's state of charge. This ensures dynamic, decoupled, and stable power control across all three ports.

5.5. Control of Buck-Boost Partial Power Converter

The proposed buck-boost partial power converter (PPC) for EV fast charging in ref. [79] uses a control system to efficiently manage constant-current (CC) and constant-voltage (CV) charging profiles. As shown in Figure 25, classical PI controllers regulate battery voltage and current. The controllers are tuned with gains: $K_{pi} = 0.22$ and $K_{ii} = 2469$ for the current loop, and $K_{pv} = 4.12$ and $K_{iv} = 8064$ for the voltage loop, ensuring stable reference tracking.

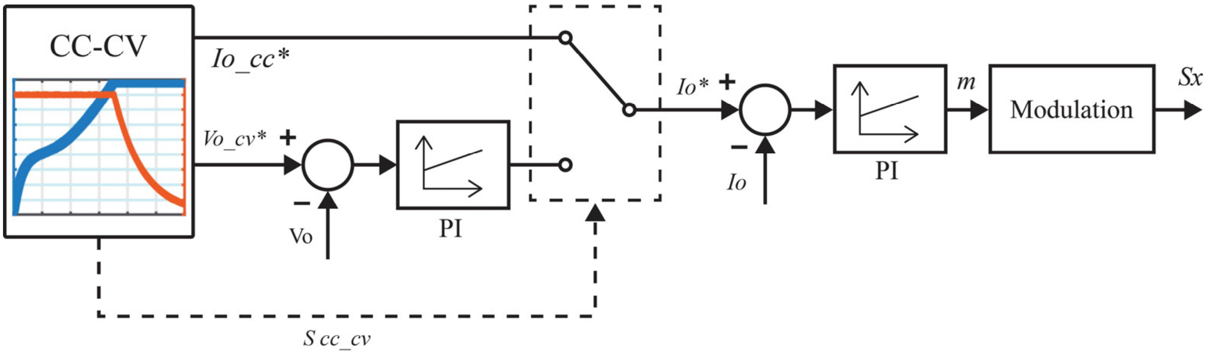


Figure 25. Control system for Buck-Boost PPC EV charging station. Reprinted with permission from Ref. [79]. Copyright 2021, IEEE.

The charging process begins with the CC mode using port 1, during which the current is maintained at a fixed level until the battery reaches its threshold state of charge—80% in this case. Here, the PI current controller adjusts the modulation index m to control the converter's duty cycle based on the error between the reference and measured current, as described by Equations (20) and (21) for boost and buck modes.

$$V_{pc\_\mathrm{boost}} = mNV_{in} \tag{20}$$

$$V_{pc\_buck} = -mNV_{in} \tag{21}$$

where N is the transformer turns ratio and V_{in} is the DC-link input voltage. When the battery state of charge reaches the set threshold, the system switches to the CV mode, by connecting to port 2. The voltage controller then maintains V_{bat} at the reference V_{ref} by adjusting the modulation index based on the voltage error. The output voltage V_o is defined by Equations (22) and (23).

$$V_{o\_boost} = (1 + mN)V_{in} \tag{22}$$

$$V_{o\_buck} = (1 - mN)V_{in} \tag{23}$$

The battery's state of charge (SOC) is modeled using Equation (24), incorporating open-circuit voltage and internal resistance. Here, E is the battery voltage, i_t the accumulated current, and E_0, K, Q, A, and B are battery-specific parameters.

$$E = E_0 - K\frac{Q}{it - 0.1Q} + Ae^{-Bi_t} \tag{24}$$

This model ensures accurate simulation and control response during charging. Simulation results for 400 V and 800 V batteries confirm the control system's efficiency and smooth CC–CV transitions.

6. Architecture and Converter Topology Selection

A proposed method for power delivery to a specific EV battery can be based on Partial Power Processing (PPP) using an appropriate Partial Power Converter (PPC) strategy. Given the voltage requirements, either a step-up or step-down architecture can be selected. The ISOP step-down architecture, which exhibits a lower K_{pr} curve and can be considered the most suitable choice for most fast EV charging applications. Once the PPC architecture is selected, the next step would be to choose a converter topology. Since the ISOP step-down architecture requires isolation and the application involves high power levels, a Dual Active Bridge (DAB) converter could be a good choice for it. To ensure simplicity, phase shift modulation (PSM) can be used to control the power flow between the source and the load. The circuit parameters can be defined primarily by the input/output voltage and the maximum power the converter must process. The main difference between the systems would lie in these factors. As a result, the PPC would process less power and require lower-rated devices, leading to increased efficiency and reduced overall system cost.

6.1. Comparison Parameters

To compare the designed Partial Power Converter (PPC) with a conventional converter or other possible PPC designs, the following parameters can be considered: processed active power, component stress factor (CSF), and the efficiency of both the system and the converter. These factors can help evaluate the impact of various design aspects on the converter's performance.

6.1.1. Processed Active Power

A proposed method for comparing the processed power ratio of different converters can be based on the ratio derived from the relevant equation. In this context, the Dual Active Bridge-Full Power Converter (DAB-FPC) can process 100% of the power flowing from the source to the battery, regardless of the charging point. In contrast, the DAB-Partial Power Converter (DAB-PPC) processes a maximum of 60% of the source power. This value may change throughout the charging period [94].

6.1.2. Semiconductor Stress Analysis

When evaluating the performance of different power converters, an important factor to consider is the Component Stress Factor (CSF), which measures the stress on the components within the converter. This parameter helps in assessing how the converter operates [95]. The CSF for semiconductors can be expressed as:

$$SCSFi = \frac{Wi}{\sum_{j} Wj} \cdot \frac{V_{max}^2 \cdot I_{rms}^2}{P_S^2} \tag{25}$$

where, $\sum_{j} Wj$ represents the total number of components, Wj is the quantity of the specific component, V_{max} is the maximum voltage the semiconductor can withstand in a steady-state, and P_S is the power source.

By using this approach, the SCSF for both FPC and PPC can be compared. From the literature, it is found that due to the reduced power processed by the PPC, the semiconductors inside it experience less stress throughout the entire charging process.

6.1.3. Efficiency

An appropriate method for evaluating system and converter efficiency involves calculating both terms, wherein a Full Power Converter (FPC) is the same. In a Partial Power Converter (PPC), they are influenced by the K_{pr} value. While the application may not need step-up and step-down functions, all architectures can achieve this. For instance, an IPOS step-up architecture can be adapted for step-down applications by inverting the output voltage and managing the power flow accordingly. This behavior can be applied to other architectures, where adding extra switches enables both buck and boost capabilities [19].

7. Conclusions and Future Directions

This paper presents an in-depth review of Partial Power Converter (PPC) topologies and control methods specifically for fast electric vehicle (EV) charging applications. PPCs are increasingly recognized as a promising solution due to their ability to process only a portion of the total power, leading to improved efficiency, reduced losses, and smaller, lighter components. By reviewing existing PPC topologies such as the Dual Active Bridge, Phase-Shifted Full-Bridge, Flyback, and Interleaved topologies, this paper has outlined how these converters can be utilized in fast EV charging stations to achieve significant performance improvements over traditional full-power converters. Selecting appropriate Partial Power Converter (PPC) architectures depends on the application's voltage gain requirements, isolation needs, and thermal performance. IPOS step-up is ideal for boost applications $(G_V > 1)$, while ISOP step-down suits buck needs $(G_V < 1)$. For high-power systems, DAB-PPCs offer efficiency and thermal advantages, particularly in EV fast charging. Without a doubt, PPC offers significant advantages over FPP; however, in isolated converters, maintaining effective isolation can pose a challenge. Control methods tailored to PPCs, including phase-shift modulation and power computation-based control, have been explored, showcasing their potential to regulate power flow effectively and ensure reliable, fast charging under varying load conditions. Although this review focused on explaining the operational principles and advantages of each PPC topology, it has become evident that PPCs offer a promising avenue for the future of EV charging infrastructure, particularly in improving power density, minimizing losses, and fast EV charging applications.

Future work could explore the experimental validation of PPCs in real-world EV charging scenarios to further demonstrate their advantages. Additionally, improving fault tolerance, fault detection, converter isolation and control methods, as well as exploring new technologies such as wide-bandgap semiconductors, may lead to even higher efficiency and performance. Furthermore, optimizing PPC solutions for multi-domain applications, such as vehicle-to-grid systems and hybrid energy storage systems, could expand their versatility. Finally, developing robust standards, protection mechanisms, and fault-tolerant designs for large-scale deployment of PPC-based EV fast-charging stations would be a key step toward widespread adoption.

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Abbreviations

The following abbreviations are used in this manuscript:

PPC	Partial Power Converter
EV	Electric Vehicle
AC	Alternating Current
DC	Direct Current
PPP	Partial Power Processing
FPP	Full Power Processing
FPPC	Full Power Processing Converter
DPC	Differential Power Converters
ESS	Energy Storage Systems
MPC	Multiport Power Converters

PV	Photovoltaic
BESS	Battery Energy Storage System
CSS	Combined Charging System
IPOS	Input-Parallel-Output-Series
ISOP	Input-Series-Output-Parallel
DAB	Dual Active Bridge
HESS	Hybrid Energy Storage System
XFC	Extreme Fast Charging
SST	Solid-State Transformer
PSFB	Phase-Shifted Full-Bridge
EMI	Electromagnetic Interference
LLC	Inductor-Inductor-Capacitor
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
CC	Constant Current
CV	Constant Voltage
SPS	Single Phase-Shift
MPC	Model Predictive Control
PWM	Pulse Width Modulation
PI	Proportional-Integral

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