A Comprehensive Review on Charging Topologies and Power Electronic Converter Solutions for Electric Vehicles

Abdelfatah Ali, Hossam H. H. Mousa, Mostafa F. Shaaban, Maher A. Azzouz, and Ahmed S. A. Awad

***Abstract*—Electric vehicles (EVs) are becoming more popular worldwide due to environmental concerns, fuel security, and price volatility. The performance of EVs relies on the energy stored in their batteries, which can be charged using either AC (slow) or DC (fast) chargers. Additionally, EVs can also be used as mobile power storage devices using vehicle-to-grid (V2G) technology. Power electronic converters (PECs) have a constructive role in EV applications, both in charging EVs and in V2G. Hence, this paper comprehensively investigates the state of the art of EV charging topologies and PEC solutions for EV applications. It examines PECs from the point of view of their classifications, configurations, control approaches, and future research prospects and their impacts on power quality. These can be classified into various topologies: DC-DC converters, AC-DC converters, DC-AC converters, and AC-AC converters. To address the limitations of traditional DC-DC converters such as switching losses, size, and high-electromagnetic interference (EMI), resonant converters and multiport converters are being used in high-voltage EV applications. Additionally, power-train converters have been modified for high-efficiency and reliability in EV applications. This paper offers an overview of charging topologies, PECs, challenges with solutions, and future trends in the field of the EV charging station applications.**

***Index Terms*—Charging station, charging topology, electric vehicle, power electronic converter, vehicle-to-grid.**

I. Introduction

USING fossil fuels for power generation, heat generation, and transportation results in high CO_2 and industrial emissions. Figure 1 shows total emissions in United States in 2020. The transportation sector generates the largest share of greenhouse gas emissions in United States [1]. Emissions of greenhouse gas from transportation are primarily generated through burning fossil fuels in cars, trucks, ships, trains, and planes. Low- or zero-emission vehicles are essential to reduce the emissions that are generated by the transportation sector and enhance the sustainability of the transportation systems. Since electric power systems are almost available everywhere, electric vehicles (EVs) are considered to be one of the best options for reducing emissions. EVs have been encouraged by governments in many countries all over the world. Figure 2 shows the expected EV market share of light-duty vehicles. In 2030, EVs are expected to represent about 42%, 27%, and 48% of light-duty vehicles in Europe, United States, and China, respectively [2]. This high penetration of EVs will cause severe issues for the electric power systems such as upgrading the transmission lines, transformers being overloaded, and power quality problems. Most of these challenges are directly connected to the charging method and the characteristics of EV chargers.

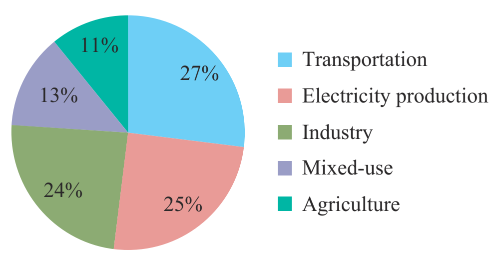

Fig. 1. Total emissions in United States in 2020.

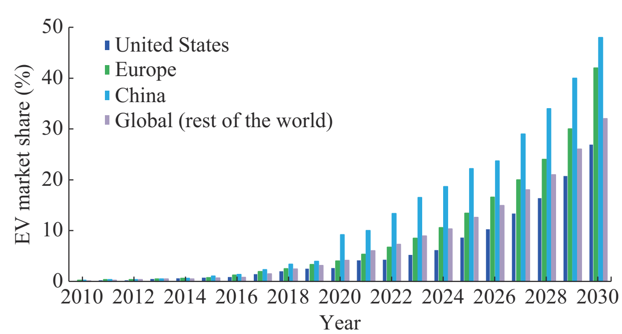

Fig. 2. Expected EV market share of light-duty vehicles.

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With the recent expansion of EV driving ranges, there remains a need for further investigation into the charging process for several reasons. One is that the driving ranges of most available EVs on the market are lower than those of their gasoline counterparts. For instance, the battery of the Nissan Leaf, with a range of 240 km, would require recharging after a few hours of continuous operation. Also, the duration of EV charging is still way higher than the refueling time for conventional vehicles. For instance, charging a Nissan Leaf's battery from 0 to 100 using a 50-kW fast charger requires approximately one hour [3]. Moreover, although the EV driving ranges will continue to expand in the coming years, the modeling of innovative charging technologies is still significant for several applications. For example, EV charging can be synchronized with smart grid control systems to provide ancillary services [4], which will be helpful for the electrical power grid and ride-hailing service providers.

To regulate the power flow for several electrical applications such as EVs [5], [6], uninterruptable power supplies (UPSs) [7], and renewable energy sources (RESs) and energy storage systems like solar photovoltaic (PV) systems [8], fuel cells (FCs) [9], and wind energy conversion systems [10], power electronic converters (PECs) are widely utilized [11]-[14]. Hence, several recent review papers have investigated PEC categorizations, structures, control schemes, applications, design comparisons, and their influences on the power quality of utility grids [15]. Furthermore, the discussion extends to various important features related to the various topologies of the PECs in the EV applications such as research trends and evaluation. Brief literature survey of recent review papers for PECs [6] is illustrated in Table I.

TABLE I
BRIEF LITERATURE SURVEY OF RECENT REVIEW PAPERS FOR PECS

Ref.	Year	Remarks and contributions
[11]	2019	Consider DC-DC converters for EVs concerning their topologies and applications, especially paying special attention to charging stations without investigating control schemes or their optimization methods
[16], [17]	2020 2021	Discuss various topologies of non-isolated unidirectional DC-DC converters in FC EVs; however, the control and energy management systems, challenges, and future aspects of DC-DC converters are not discussed in addition to other topologies of PECs
[18], [19]	2021	Investigate only state-of-the-art multiport DC-DC converters based on EV applications
[20]	2021	Deliberate briefly challenges and solutions of PECs, configurations of EVs and applied control schemes
[13], [21] [12], [22]	2021 2022	Review only bidirectional, resonant, and multilevel DC-DC converters in terms of various aspects without considering other topologies of PECs
[6]	2022	Analyze and assess current research trends of multidisciplinary technologies in EV applications including various configurations of PECs, energy storage systems, control methods, optimization techniques, and energy efficiency, transfer, and management aspects; declare the research gap and focus on the latest industrial applications and their practical issues
This work		Study in detail state-of-the-art EV charging topologies and PEC solutions for EV applications from the point of view of their groupings, configurations, control methods, and future research projections and their impacts on the power quality of the utility grids based on recent review papers

The PECs can be classified into various topologies: DC-DC converters, AC-DC converters, DC-AC converters, and AC-AC converters for high-voltage and low-voltage applications, mainly for EV charging stations [13], [23]. Bidirectional DC-DC converters represent the major research field in the PEC topologies instead of conventional unidirectional converters to interface different energy sources and energy storage elements [24]-[26]. The PEC topologies possess various features, such as minimizing electrical and thermal stresses related to switching patterns [27], enhancing overall efficiency, achieving high power density, and preserving battery state of charge (SOC) for EV applications [28]-[30].

To cope with the restrictions of the DC-DC converters such as switching losses, size, and electromagnetic interference (EMI), resonant converters and multiport converters (MPCs) have been extensively implemented in high-voltage EV applications depending on the number of reactive elements and independent voltage sources [22], [31], [32].

Soft-switching converters also recognized as resonant converters, have been implemented in both low- and high-voltage EV applications to get rid of hard switching problems either in zero current switching (ZCS) or zero voltage switching (ZVS) modes [12], [33].

Resonant DC-DC converters can be classified according to the number of reactive elements and their connections into several topologies such as series, parallel, and hybrid resonant DC-DC converters [34]-[39]. In contrast, multilevel converters are employed to diminish the drawbacks of the two-level converters. Multilevel converters sustain low-voltage ratings, switching losses, and switching frequency below the same output voltage compared with the conventional two-level converters, with high efficiency [40]-[42]. Moreover, MPCs contribute to increasing the demand for multi-input multi-output (MIMO) applications that are appropriate for the integration of independent voltage sources in EVs relative to their merits such as the economic operation, compact size, cost effectiveness, high efficiency and reliability, and power-train performance improvements [19], [43]-[46]. Regarding the complete configuration of the power-train in EV applications and charging systems, the deployment of AC-DC converters, DC-AC converters, and AC-AC converters are required to be implemented to sustain high efficiency, reliability, and operational performance [37], [38], [40], [47]. Focusing on DC-AC converters, they achieve high power density without excessive switching losses. However, the complexity of control scheme and fabrication is a problem [48]. Therefore, innovative circuit constructions have emerged, combining various topologies such as multilevel converters, MPCs, and resonant converters, with novel modulation techniques and control methods [8], [42], [49], [50].

In [51], the AC-DC converters are divided into two main groups: single-phase and three-phase conversion stages. Different control schemes are adopted to accomplish DC fast-charging stations, EV power conversion, and enhancing the performance index of power exchange flow in vehicle-to-grid (V2G) applications. Also, these converters enhance the power quality at AC inputs of distribution systems by reducing the switch voltage stress, total harmonic distortion (THD), and EMI noise. Furthermore, AC-DC converters achieve a high-power factor and maintain a ripple-free DC output voltage under both load and supply interruptions [52]-[55]. Additionally, the AC-AC converters are utilized in the power-train for EV applications such as cyclo or matrix converters combined with resonant and MPCs without using the DC-link capacitor [56], [57]. However, these converters have some challenges and influences on vehicular system or power system operating performance such as control loop complexity in which future research aspects are involved.

According to the above-mentioned discussion, the main contributions of this paper can be summarized as follows.

1) Investigating the EV charging topologies in terms of charger placement, power rating, physical contact, and power flow direction.

2) Presenting a comprehensive review of the PEC solutions to the EV applications in terms of their classifications, configurations, and control methods related to recently published paper reviews.

3) Discussing the role of soft-switching converters, multilevel converters, and MPCs as current solutions to the power-train challenges in EV applications.

4) Exposing the future research prospects, challenges, and impacts of the PECs on the vehicular system and power quality of the utility grids based on recent review papers.

II. EV Charging Topologies

The charging station is one of the main parts of the grid infrastructure, which can be installed along the roads, public garages, home garages, and parking lots. The main target of the charging station is to supply power to EVs to charge their batteries. Many topologies can be used for EV charging such as AC single-phase charging, AC three-phase charging, DC charging with rectification, and bidirectional charging (grid-to-vehicle (G2V) and V2G) [58]. The AC single-phase charging topology utilizes a single-phase AC power supply for EV charging. It is commonly used for low-power charging, typically found in residential or slow-charging scenarios. Single-phase charging is typically constrained by power level limitations. In addition, the topology of AC three-phase charging involves using a three-phase AC power supply, which allows for higher-power delivery compared with single-phase charging. This topology is commonly used in commercial and public charging stations, enabling fast-charging rates. In the DC charging topology, AC power is converted into DC power by using an external rectifier, which is then directly supplied to the EV battery. Compared with AC charging, DC charging is well-suited for public fast-charging stations and long-distance travel due to its ability to offer fast-charging rates. This topology often utilizes high-power chargers capable of delivering power level ranging from tens to hundreds of kilowatts. Furthermore, bidirectional charging enables power flow in both directions, allowing the EV to not only receive power but also supply power back to the grid or other devices. This topology is useful for V2G integration, where EVs can act as energy storage units and provide power to the grid during peak demand or support local energy demands. Bidirectional charging typically requires additional hardware and control systems within the charging infrastructure.

The EV chargers can be classified based on their placement and power rating [59]. Regarding the placement of the EV chargers, they are classified as offboard and onboard with unidirectional or bidirectional power flow. The unidirectional power flow charger enhances battery degradation, reduces hardware requirements, and simplifies interconnection issues. In addition, the bidirectional power flow charger can be employed for both G2V and V2G functionalities. The onboard charger is installed inside the EV, while the offboard charger is installed outside the EV. The onboard chargers are commonly employed for slow-charging systems, while the offboard chargers can be employed for fast-charging systems. Figure 3 shows EV infrastructure with onboard and offboard charging topologies and charging power level.

The power level of the charger indicates the charging rate, location, charging time, cost, equipment, and effect on the power grid. Characteristics of different levels of chargers are shown in Table II. Level 1 EV chargers do not require special installation as they receive the electrical supply from a conventional power plug. Level 2 EV chargers are the typical ones to be installed in households but require special installation. Level 3 EV chargers are known as the DC fast-charging ones as they have high-power delivery capabilities. DC fast chargers are typical commercial ones [21], [59], [60]. Figure 4 shows the organization of level 1, 2, and 3 EV chargers. This figure illustrates that the AC charger charges the EV battery through the onboard charging of the EVs, whereas the EV battery can be directly charged by the DC charger bypassing the onboard charger. Moreover, in the DC charger, modular converters that can be stacked are utilized to achieve high power level (120 kW-240 kW). However, the stacking of the converters inside the EV makes it bulky. Therefore, these converters are stacked and placed outside the vehicle and represent the charging station of the EVs [61], [62].

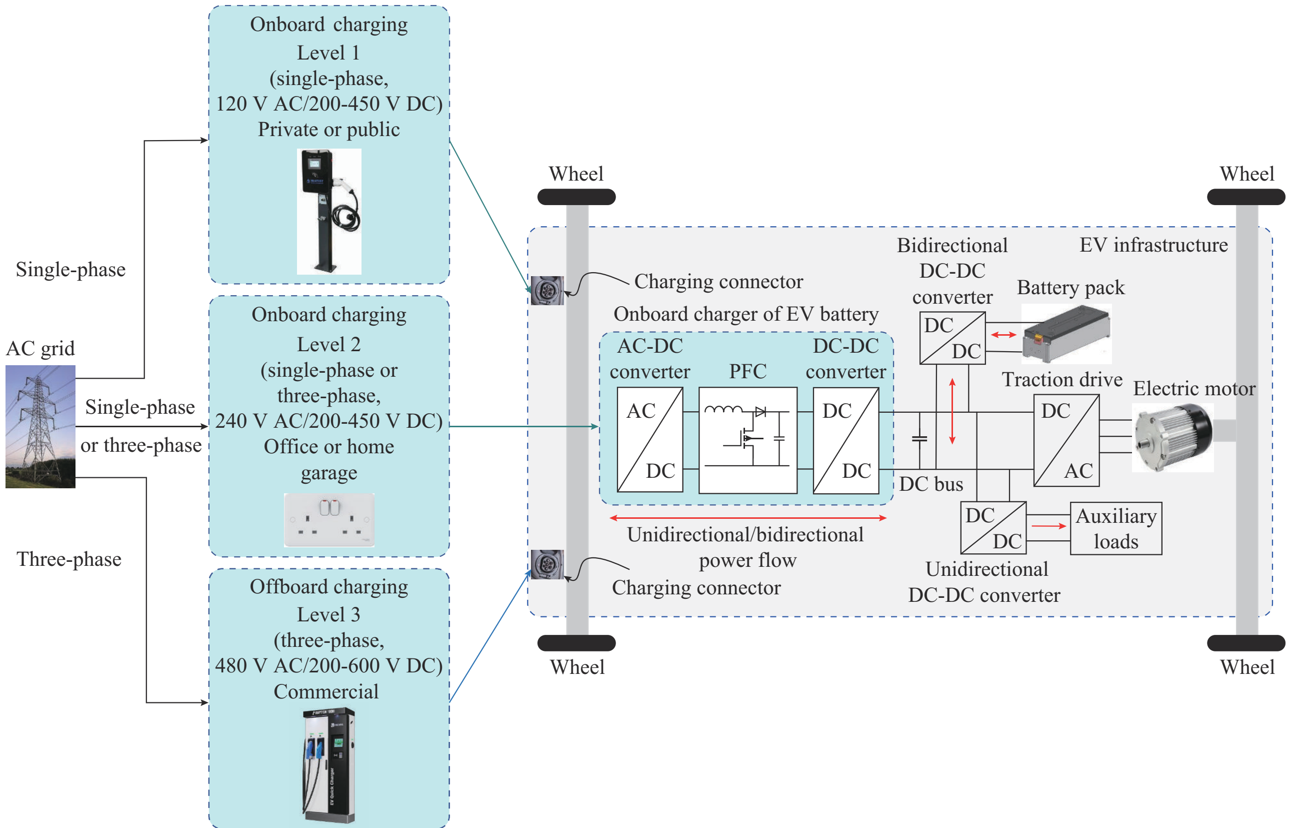
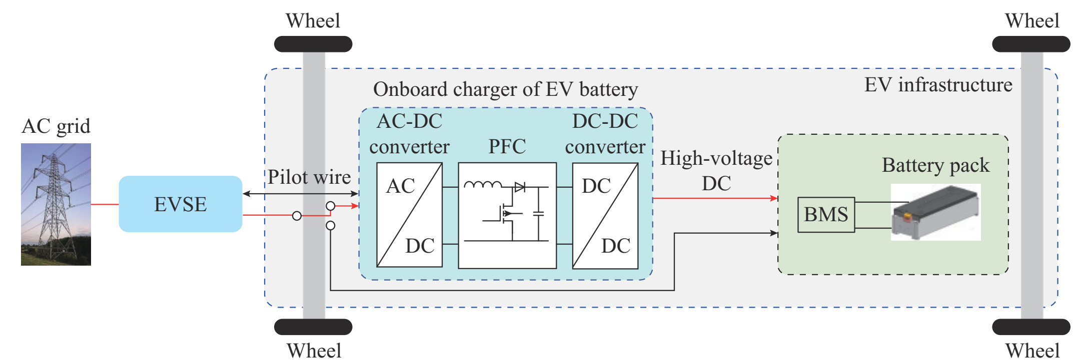


Fig. 3. EV infrastructure with onboard and offboard charging systems and charging power level.

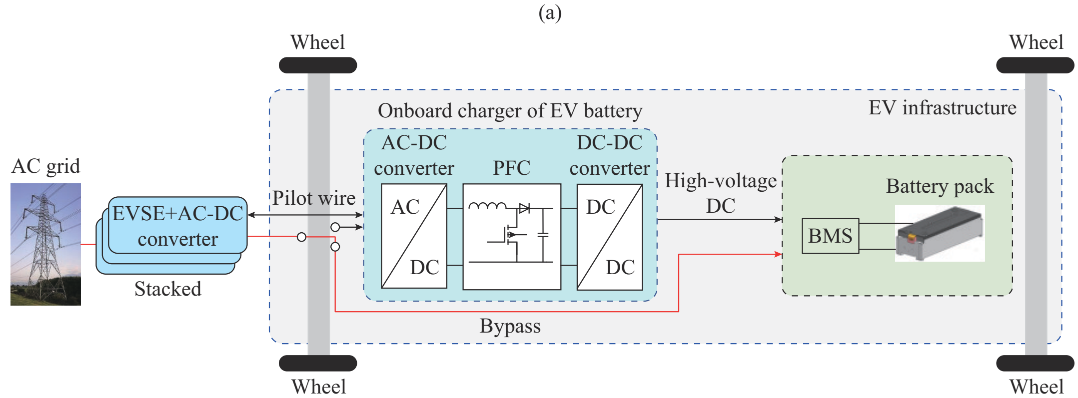
TABLE II
CHARACTERISTICS OF DIFFERENT LEVELS OF CHARGERS

Classification	Level 1 (AC slow charging)	Level 2 (AC accelerated charging)	Level 3 (DC fast charging)
Electrical characteristic	120 V, 1.4 kW (12 A), 120 V, 1.9 kW (16 A) 200-450 V DC, up to 36 kW (80 A)	240 V, up to 182 kW (80 A) 200-450 V DC, up to 90 kW (200 A)	480 V, 20 kW (150 A) 200-600 V DC up to 240 kW (400 A)
Onboard/ offboard	Onboard (single-phase)	Onboard (single-phase or three-phase)	Offboard (three-phase)
Location of installation	Parking lots for employees, long-term customers, visitors, etc.	Municipalities, private parking lots, shopping centers, etc.	Close to high-capacity roadways
Typical useage	Charging at home or office during the workday, long-term parking (more than 8 hours)	Charging at home with fast-charging or commercial charging places (e.g., public garages)	Fast-charging during a long journey to either reach a destination or prolong the duration of the trip, (analogous to fueling stations)
Energy supply interface	Suitable outlet	Dedicated EV supply equipment (EVSE)	Dedicated EVSE
Socket	Household/domestic socket	Dedicated socket	DC connection socket
Charging time	6-10 hours	1-3 hours	0.5 hours
Range per hour/mile	5	10-20	More than 75
Safety	Basic protection (e.g., circuit breaker, earth leakage protection, and earthing system) with an in-cable protection device	Basic protection (e. g., circuit breaker, earth leakage protection, and earthing system) with a control system	Basic protection (e.g., circuit breaker, earth leakage protection, and earthing system) with a control system
Desirable characteristics	Amenities at charging location	Facilities for pedestrians, lighting, a secure location, and other things	Facilities for pedestrians, lighting, a secure location, and other things

Furthermore, EV chargers can be classified based on their physical contact into conductive and inductive chargers. The conductive charging method involves transferring power by making direct contact with the vehicles, whereas the inductive charging method relies on an electromagnetic field to transfer power to the vehicles (i.e., wireless charging method (WLC)). However, the conductive charging method is more efficient than the WLC [63]. The wireless power transfer (WPT) technology makes power transfer very easy for the charging process. The main idea of WPT technology is to convert AC energy into DC energy and then invert it again to AC energy with high frequency to generate magnetic fields [64].



(a)



(b)

Fig. 4. Organization of level 1, 2, and 3 EV chargers. (a) AC charging system. (b) DC charging system.

Electrical energy can be transferred from the sender to the receiver based on near-field and far-field transmissions [65]. Far-field transmission can utilize some mediums such as microwave, acoustic, or optical while typically involves inductive coupling or capacitive techniques that create nonradiatively electric, magnetic, or electromagnetic fields. Optical methods can be employed to transfer the energy by a laser beam [66], while the energy can be transferred by microwaves using frequencies in the range of 1 GHz to 1000 GHz [67]. Electric power can be transferred over long distances by employing microwaves and optical methods. Nevertheless, when employing these methods for WPT, a clear line of sight between the transmitter and the receiver is required. Moreover, these methods can have harmful effects on human and biological life. However, researchers have proposed methods for EV charging using the laser [68] and microwave [69], [70], but as of now, none of these methods have seen commercial adoption [71]. Another WPT technology is the magnetic gear [72], which compromises two synchronized permanent magnets placed side by side in a different way from other WLCs based on coaxial cable.

The most effective technology of WPT is the mutual coupling technology [73], which can be capacitive coupling or inductive coupling. In the capacitive WPT (CPT) technology, the power is transferred through coupled capacitors that are realized by metal plates [74]. In addition, the power can be transferred using the magnetic field coupling between primary and secondary coils, which is called inductive power transfer (IPT). To mitigate the leakage flux because of the large air gap, capacitors are utilized and connected to transmitting and receiving coils, in which the transmitter and receiver circuits compromise an inductor and a capacitor. In each circuit, the inductor and capacitor are adjusted to work and resonance. The IPT utilizing the capacitors is called inductively CPT (ICPT) [73] or resonant inductive coupling (RIC). Table III shows a comprehensive comparison of different WPT technologies.

TABLE III
A COMPREHENSIVE COMPARISON OF DIFFERENT WPT TECHNOLOGIES

WPT technology	Cost	Efficiency (%)	Power level (kW)	Air gap (m)	Frequency range (kHz)	Biological effect
Microwave	High	76	1.4	0.10	$1\text{-}10^8$	Damage living tissue
Laser	High	1-30	0-0.5	0-200	More than 10^9	Damage living tissue
CPT	Low	83-90	3	0.15-0.3	100-150	No harmful effects
Magnetic gear	High	81	1600	0.15	0.05-0.50	No harmful effects
IPT	Medium/high	95	3-50	0.15	10-50	No harmful effects
ICPT	Low	71-96	Up to 250	0.075-0.5	10-150	No harmful effects

The wireless charging system can be categorized into three main modes: ① static wireless charging (SWC), ② dynamic wireless charging (DWC), and ③ quasi-dynamic wireless charging (QWC) [75]. SWC has high power transfer efficiency due to enhanced alignment. Moreover, it offers the benefit of suitable charging locations such as parking lots, home garages, traffic lights. However, this charging method cannot address the issues faced by EVs on highways.

In the DWC, EVs can charge while in motion by traversing along specially constructed charging roads. DWC effectively addresses numerous challenges associated with EVs, including battery size, range anxiety, and battery cost. The majority of current DWC models rely on the inductive WPT method. QWC is employed during brief stops such as at traffic lights. Consequently, when both SWC and DWC infrastructures are ubiquitously accessible, QWC becomes a viable option. This charging mode significantly enhances the driving range of EVs. Inductive wireless charging possesses certain desirable attributes such as reliability and user-friendliness. However, it faces some technical challenges such as short-range, low-efficiency, cost effectiveness, and bulkiness. As the active charging methods are more efficient than the WLC, they are more common and established. Figure 5 shows classifications of EV charging topologies [76]-[83].

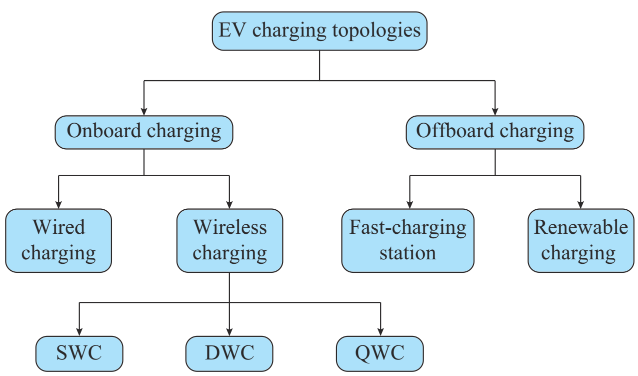


Fig. 5. Classifications of EV charging topologies.

The power flow direction between the EVs and the power grid can be unidirectional, where the power flows from G2V and resulting in what is known as a unidirectional charger. Conversely, the power can flow from V2G. Therefore, V2G is termed a bidirectional charger. This type of charger can facilitate several demand-side management planning applications for both G2V and V2G scenarios [84]. Moreover, it enhances the reliability of the electrical system, e.g., the load curve can be flattened under unexpected system failures. Furthermore, the penetration of the V2G functionality can reduce the investment in new power generation units [85]-[87]. Therefore, the selection of the appropriate charging technology is of paramount importance when choosing a charger. The selected charger must have some important characteristics such as high-efficiency, high power density, and low cost. The operation of the charger depends on the converter used with it. Hence, in the following sections, a comprehensive review of PEC technologies used in EV chargers is conducted.

III. PECs FOR EVs

PECs exhibit a prominent role in EV applications as employed to interface the various types of EVs with energy storage devices and charging stations especially based on RESs as energy inputs [11]-[14]. Therefore, various review papers elaborate on PEC classifications, configurations, applied control strategies, applications, specification comparisons, and their impacts on the power quality of the utility grids [15]. In addition to investigating various significant aspects associated with various topologies of PECs in the EV applications, other aspects such as developing trends, assessment, and future research prospects are also studied by many scholars [6]. Hence, Table IV discusses recent review papers on PEC technologies for EV applications, where A means configuration, B means control strategies, C means power quality, D means challenges, E means optimization methods, F means applications, and G means comparative analysis.

To provide a broad overview of authors' concerns in this field, Fig. 6 shows VOS viewer visualization for analysis of co-occurrence keywords based on Scopus database. The most utilized PEC topology for EV applications is various topologies based on DC-DC converters for charging batteries, energy storage devices, and EV charging stations. PEC topologies can be classified into various technical topologies, including DC-DC converters, AC-DC converters, DC-AC converters, and AC-AC converters, suitable for both high-voltage and low-voltage applications [21], [88]. To declare the significant specifications of various configurations of PECs, several paper comparative analysis are revealed in [6], [89], [90] among the topologies and their roles in the power quality improvement. And several papers revealed perceptive challenges and other aspects in [11], [14], [19]-[21], [90]-[94].

Furthermore, a comparison of various switching devices used in PECs, with different material composites such as Si, SiC, or GaN, is presented in [21], [95]. This comparison considers material properties, weight, volume, and peak efficiency, focusing on their extensive application in EVs. The papers demonstrate the superiority of SiC or GaN-based switching devices in achieving low switching losses, higher thermal capabilities, and improved configuration stability, making them well-suited for low- or high-power EV applications [21], [95]. Additionally, Table V shows the summary of performance parameters of SiC-based converters [88]. In the coming section, the various topologies of PECs and their applications for EVs will be studied and conclusions for the recent research trends will be drawn.

TABLE IV
RECENT REVIEW PAPERS ON PEC TECHNOLOGIES FOR EV APPLICATIONS

Ref.	Year	Objectives and keywords							Remarks and contributions
		A	B	C	D	E	F	G	
[96]	2017	√	×	×	×	×	√	√	Deliberate role of PECs in charging EV battery interfacing with RESs and choosing suitable topology in grid on/off operational modes
[97]	2018	√	×	×	√	×	×	√	Survey applications of energy storage systems on EV technologies integrated into various types of multi-input DC-DC converters to enhance EV's efficiency and reliability
[92]	2019	√	×	×	√	×	×	√	Evaluate bidirectional converters for V2G and G2V systems based on active power flows and power factor correction
[25]	2019	√	√	×	×	×	×	√	Highlight various topologies of bidirectional DC-DC converters and their associated control schemes for several applications among EV applications
[11]	2019	√	×	×	√	×	×	√	Outline various configurations of DC-DC converters and their applications on EV charging stations
[98]	2020	√	√	×	√	×	×	√	Realize control schemes of DC-DC converters and their configurations concerning active battery charge balancing method
[22]	2020	√	×	×	√	×	√	√	Investigate multi-input DC-DC converters and their configurations with detailed comparisons to cope with multiple energy sources as inputs to be interfaced with battery charging in EVs. In [31], non-isolated multi-input high-step-up DC-DC converter configurations and assessments are studied
[19]	2021	√	×	×	√	×	√	√	
[99]	2021	√	×	×	√	×	√	√	
[16]	2020	√	×	×	√	√	√	√	Study the non-isolated unidirectional DC-DC converters in FC EVs concerning their topologies, applications, and challenges. While in [100], control and energy management techniques, obstacles, marketing, and future aspects of DC-DC converters are highlighted for FC EVs
[100]	2021	√	×	×	√	√	√	√	
[101]	2021	√	√	×	√	×	×	√	Study the bidirectional DC-DC converters concerning multilevel battery storage systems for EV and utility grid applications in terms of topologies and trends
[93]	2021	√	×	√	√	×	√	√	Present power quality improvement challenges of utility grid during the interactions of multi-input power electronic technologies applied to EV charging stations
[18]	2021	√	×	×	√	×	√	√	Review latest developments for multiport DC-DC converters based on EV applications in terms of various aspects
[20]	2021	√	√	×	√	√	√	√	Discuss obstacles and solutions of EVs' PEC configurations and applied control schemes
[13], [21]	2021	√	×	×	√	×	√	√	Review bidirectional, resonant, multilevel DC-DC converters in terms of their configurations, evaluations, applications, and challenges
[102]	2022	√	×	×	√	×	√	√	Investigate various topologies of PECs integrated into renewable energy systems, energy storage systems, and EVs. Moreover, their influence on the utility grid's stability is highlighted with advanced control strategies to improve overall stability
[32]	2022	√	×	×	√	×	√	√	Study with a detailed comparison of the topologies of DC-DC converters with multiple outputs in different fields, especially several types of EVs
[48], [103]	2022	√	×	×	√	×	√	√	State reviews of PECs including their characteristics, performance, merits and demerits, challenges, and economic aspects
[15]	2022	√	×	√	√	×	√	√	Highlight significant role of PECs and their convenient location in EV charging systems through single- or multi-energy sources and declare importance of energy storage systems, and energy management strategies to cope with on-/off-grid charging modes
[91]	2022	√	×	√	√	×	√	√	Indicate fast-charging station's infrastructure using various topologies of PECs and study their significant influence on utility grid performance supported by perspectives for future research trends
[104]	2022	√	×	√	√	×	√	√	Declare current topologies of PECs used for PV systems and utility grid interfaces and their impacts during charging EVs
[90]	2022	√	×	×	√	×	√	√	Discuss briefly the interfaced DC-DC converters with energy storage devices to boost EV efficiency
[14], [88]	2022	√	×	×	√	×	√	√	Introduce a concentrated review of PEC topologies and their applications in EV charging stations, besides discussing the current research gaps to fulfill the required aims of the energy management strategies applied in EV technologies
[31]	2022	√	√	×	√	×	√	√	Discuss the state-of-the-art resonant converters in terms of topologies, challenges, and control methods for renewable energy applications supported with a comprehensive comparison
[12]	2022	√	√	√	√	×	√	√	Debate a comprehensive review of the resonant converters for EV chargers in terms of topologies, modulation methods, control schemes, commercial applications, obstacles, and development trends
[6]	2022	√	√	√	√	√	√	√	Elaborate and evaluate current status of multidisciplinary technologies in EV applications including various configurations of PECs, energy storage systems, control methods, optimization techniques, energy efficiency, transfer, and management aspects. Additionally, declare research gap and focuses on latest industrial applications and their practical issues

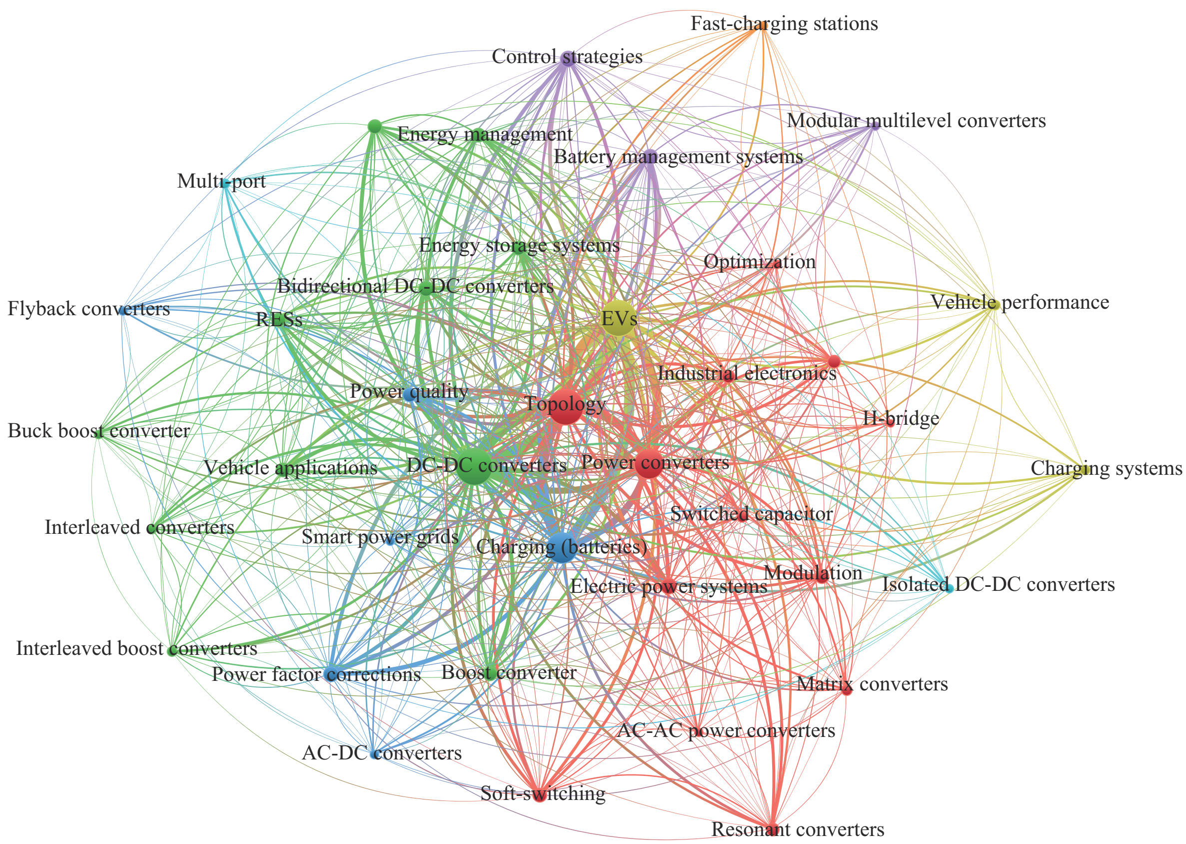


Fig. 6. VOS viewer visualization for analysis of co-occurrence keywords based on Scopus database.

TABLE V
SUMMARY OF PERFORMANCE PARAMETERS OF SIC-BASED CONVERTERS

Converter	Voltage level (V)	Power rating (kW)	Power density (kW/L)	Switching frequency (kHz)	Efficiency (%)
DC-DC converter	300-2500 to 22-34/520-830	1-100	2.2-42.0	10-1000	87.00-99.30
DC-AC converter	1000	300	4.0-35.0	15-50	95.00-99.50
AC-DC converter	600-800 DC	350	4.0-18.2	10-1000	95.00-98.86

IV. PEC TECHNOLOGIES

A. DC-DC Converters

According to the significant utilization of DC-DC converters, it is essential to state the number of circuit elements, power rating and voltage gain, electrical isolation, and overall efficiency to specify their appropriate type [90]. Hence, the DC-DC converters can be grouped associated with the active balancing topologies, which can be determined using the energy flow (bidirectional or unidirectional) or the applied topology, especially those applied for battery balancing control, as discussed in [98]. In this subsection, different configurations of DC-DC converters are examined and discussed in detail relative to the review papers. The assessment of DC-DC converters involving infrastructure and charging power level is investigated, with an adequate comparison presented in [84]. Additionally, the review papers have deliberated the control strategies for DC-DC converters in terms of parameters, control variables (terminal cell voltage, capacity, SOC), and control algorithms (high-level or low-level). These discussions are supported by the comparison with relevant studies [13], [21], [22], [88], [90], [98], [105]-[107].

These converters can be classified according to the power exchange methodology into three main types: unidirectional, bidirectional, and special converters. Bidirectional converters regulate the power in both directions, while unidirectional converters have a unique power flow direction [13], [25]. In contrast, special converters include multi-port and soft-switching converters for specific industrial technologies [12], [13], [32], [97], [108]-[112]. Looking specifically at the unidirectional and bidirectional converters, they can be classified into isolated converters and non-isolated converters depending on the existence of the transformer in the power circuit [11].

1) Unidirectional DC-DC Converters

Using high frequency transformers, isolated DC-DC converters provide galvanic isolation between input and output such as full-bridge converter, flyback converter, and push-pull converter [113] which are applied extensively in active balancing technologies. In non-isolated types, the construct classification depends on the presence of magnetic coupling for medium- and high-power EV applications [107]. Without magnetic coupling, the design complexity is reduced; however, the prominent shortcomings such as high voltage stress and expanded size due to more switching devices with high-cost effectiveness are more challenging. For low-voltage-gain applications in non-isolated topology, buck, boost, buck-boost, Cuk, single-ended primary-inductance converter(SEPIC), and Zeta converter are suggested [114]. Conversely, various converter types are designed for high-voltage-gain applications [107], [114], including modified and cascaded boost converters, switched inductors/capacitors family, multi-stage dual-active bridges (DABs) [107], modified Cuk and SEPIC, multi-phase buck and boost [115], and multi-stage converters. A detailed description of these types in terms of their application, design, parameters, and comprehensive comparison, is provided in [107], [116], and [117].

2) Bidirectional DC-DC Converters

In low-voltage EV applications of non-isolated bidirectional converters, several types are used such as single-stage, half-full-bridge, bidirectional boost, and bidirectional buck-boost converters [118], [119]. Multi-stage converters, interleaved or combined converters, and switched capacitor converters are proposed in high-voltage applications of non-isolated bidirectional converters [14], [25], [90], [107]. To accomplish both high voltage gain and low current ripples, the interleaved coupled-inductor converter is employed connecting the interleaved bidirectional buck-boost converter with a dual-active half-bridge converter [110]. The buck-boost bidirectional (single- or multi-stage) converters are applied to reduce the electrical and thermal stresses associated with the modes of the switching patterns [27], increase the overall efficiency, and maintain the battery SOC for EV applications [28] - [30]. However, they still suffer from high-ripple currents which directly impact the working life of the battery and increase the number of elements compared with conventional ones. Concerning the isolated topologies, the phase-shift full-bridge strategy using zero voltage conduction (ZVC) of power switches is discussed in [111] for high-power applications with reduced voltage stress on switches. Hence, DAB, push-pull, flyback, and other DC-DC converters can be considered as vital solutions for charging limitations in EV applications, as discussed in [44], [120] - [128]. Further, various review papers have presented detailed explanations of the various configurations, control schemes, challenges, and future trends of the DC-DC converters in [14], [25], [90].

3) Multi-port DC-DC Converters

To deal with the MIMO applications, MPCs are extensively implemented in EV charging stations, especially those that depend on the integration of different types of RESs. MPCs are applied to interface different energy resources for EV applications, grid-connected systems, and RESs. Compared with other DC-DC converter topologies, MPCs provide fewer circuit elements and reduction in both complexity and cost, and ensure higher power density [129] - [134]. MPCs can be classified into MIMO converters [43], [46], [135], [136], multi-input single-output (MISO) converters [137] - [144], and single-input multi-output (SIMO) converters [19], [145]-[149]. MISO converters can be used for combining different voltage sources for EV applications while SIMO converters are used for portable applications. Several studies present a comprehensive review related to the MPCs in various aspects such as types, design, and detailed comparison [31], [32], [18] - [19], [97], [131] - [134]. Most research trends associated with the MPCs for EV applications can be found in [32] and [18] supported by the current challenges.

4) Soft-switching DC-DC Converters

To cope with a wide range of voltage gain in the presence of the hybrid energy sources, the modified bidirectional DC-DC converter using both switched-capacitor/switched-quasi-z-source topologies is applied to control the energy flow with low voltage stresses in [150]. Soft-switching DC-DC converters are extensively utilized in industrial applications, especially in high voltage applications, due to their merits such as high efficiency, low switching losses, low stresses, and high power density, as investigated in [12], [22], [151] - [154]. They can be classified according to their structure and the number of reactive components, as discussed in [12], [22]. Regarding the structure, they contain different cascaded stages: control switching network (CSN), resonant tank network (RTN), and rectifier network with low-pass filter, as studied in [12], [25], [155] - [158]. In addition, according to the number of reactive components, the soft-switching PEC's family involves the quasi-multi-resonant converter, zero transition converter (ZTC), and resonant power converter (RPC) groups [12], [22].

Soft-switching DC-DC converters are implemented for EV applications, as deliberated recently in [12], [31]. To boost the efficiency and power density for EV applications, bidirectional half-bridge capacitor-inductor-inductor-capacitor (CLLC) resonant converters have been applied [112]. For wireless charging modules, a full-bridge three-element LLC converter with a hybrid modulation method is proposed in [159]. Additionally, a half-bridge LLC converter by integrating two various storage devices is applied for fast-charging purposes [33], [160], [161]. For power factor correction, a modified Cuk converter fed isolated LLC resonant converter is performed [109]. Several recent research works have discussed the control schemes for soft-switching DC-DC converters for maximizing the transferred power to the EV battery with the minimum switching losses and providing fast-charging without fluctuations [5], [162] - [165]. Other research studies have stated a comprehensive comparison among various topologies and given the solutions to current challenges with predicted future trends in [12], [22], [156], [158], [166]-[168].

B. AC-DC Converters

AC-DC converters are mainly utilized for DC fast-charging stations and EV power conversion, thus enhancing the performance indices of power exchange flow in V2G applications. These converters can operate as single-phase or three-phase conversion units, featuring various types such as the buck-boost converter (SEPIC converter) for low-power applications, and the diode bridge (half-full) rectifier with boost or buck-boost power factor correction (PFC). Figure 7 shows classifications of various PEC topologies, which are costly with compact size [21], [96], [169]. Several studies present their design and control schemes and check the modeling stability using the Lyapunov-based function [170] - [172]. For improving the power factor with high power quality, several research works study the novel implementation design of the AC-DC converters in terms of operation modes [173], [174], soft-switching technologies and band-gap devices [173]-[183], harmonics [184]-[187], control scheme [188]-[191], and size [192]-[195], supported by a comprehensive comparison [21], [96].

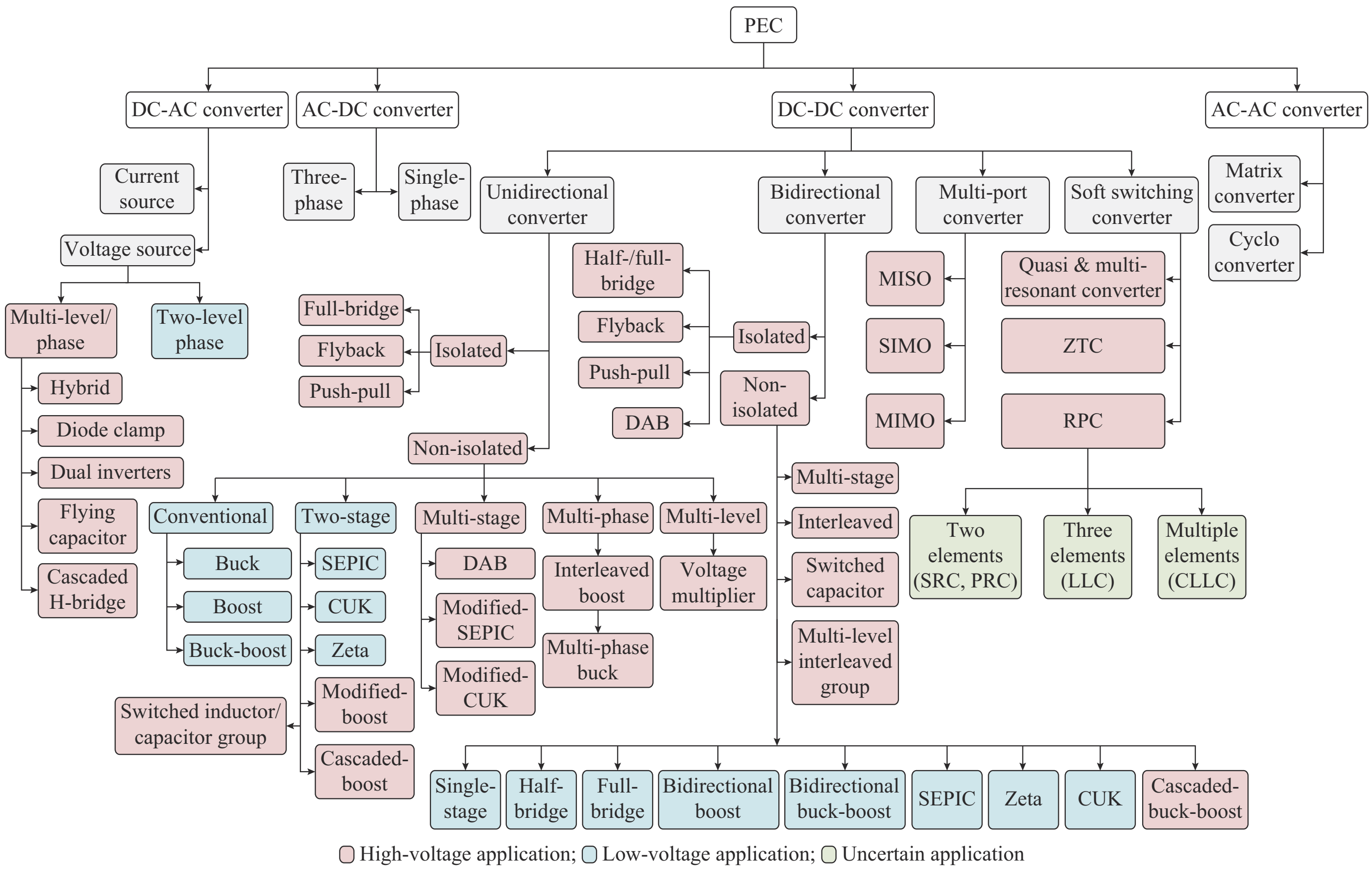


Fig. 7. Classifications of various PEC topologies.

C. DC-AC Converters

In this subsection, various types of DC-AC converters applied in both low- and high-voltage applications are highlighted, as stated in [48]. In EV applications, the power-train employs three PECs: AC-DC converters, DC-DC converters, and DC-AC converters. Also, some auxiliary components need converters at a lower power rating. Hence, the DC-AC converters convert the DC input voltage to AC output voltage with specified magnitude and frequency because using AC power is more efficient and reliable, especially in industrial applications related to the EV technologies [196], [197]. The DC-AC inverters can be classified into two-level pulse width modulation (PWM) DC-AC inverters (TLIs) and multilevel PWM inverters (MLIs). The MLI topologies have some merits compared with TLI topologies such as low current distortion, reduced voltage harmonic distortion, using compact filter size, requiring low switching frequencies, and low switching losses. However, the MLIs require a large number of switching components with complicated control schemes causing high implementation costs. As mentioned in several review research studies, various topologies with different control schemes and challenges have been proposed in [42], [50], [51], [196], [198]-[201] for EV applications.

D. AC-AC Converters

The AC-AC converters can be applied in the power-train for EV applications which can be cyclo or matrix converters. By using the matrix converters, direct power conversion is attained without using the DC-link capacitor [56], [57]. This is achieved by converting the constant AC input voltage into variable voltage or frequency output using nine bidirectional switches. However, the output voltage has limited capacity, and filters are required for the decline of the harmonics. These limitations cause the implementation to be complicated and costly with low reliability [202]. In [203], the bidirectional matrix-type AC-DC converter with a flyback-based clamp circuit is proposed for enhancing the operation of EV battery charging. In [204], the matrix converter is implemented based on the resonant DABs as a single-power conversion stage which is costly and suitable for single or multiple EVs or V2G applications during charging and discharging modes. For enhancing the battery charging technology, the cyclo converters can be used in EV applications, as investigated in [205]-[207].

E. PEC Topologies for V2G Applications

Regarding its significance in EV applications, V2G technology has been widely utilized to enable energy exchange between EV batteries and the utility grid or RESs. Various PEC topologies have been discussed in several review research works, including [58], [83], [92], [208], [209], and can be used for V2G technology. In EV charging systems employing V2G technology, bidirectional converters are commonly used for power flow control and power factor correction. These converters aim to achieve lower THD and address power quality issues. They can be implemented with different conversion stages and voltage levels. Previous discussions have outlined different types of bidirectional PECs, categorized as bidirectional AC-DC converters and bidirectional DC-DC converters.

In bidirectional AC-DC converters used for V2G applications, the full bridge topology is commonly employed due to its simplicity in control and structure, as discussed in [210]-[212]. Another implementation is the eight-switch topology, which utilizes a non-isolated half-bridge converter with the assistance of optimization algorithms [213]. To facilitate power exchange among multiple sources with varying voltage levels and pulse widths, the three-level topology is applied [214], [215]. Additionally, the single-stage topology is utilized with different system configurations [216], [217]. The matrix converter-based topology offers system compactness, cost reduction, and reliable operation, as demonstrated in [219], [220].

Regarding bidirectional DC-DC converters, isolated topologies are widely utilized due to their ability to handle a wide voltage range such as the DAB topology discussed in [220] - [222]. Additionally, non-isolated topologies are employed, offering the features like soft-switching capability, control simplicity, and a narrow voltage range. Examples include buck-boost converters with varying numbers of implemented switches [223], [224], and multi-phase interleaved converters [225]. Recently, resonant and multi-port DC-DC converters have emerged as promising technologies for wide-voltage-range applications, offering benefits such as low EMI, high efficiency, frequent operation, and compact size [112], [226]-[229]. To provide a comprehensive study of various topologies for V2G applications, comparisons among these topologies are presented in [58], [92], [209], supported by their prospects.

V. Perspectives for Prominent Challenges and Current Status

Several review research works have investigated the most prominent challenges and the future research trends for PECs utilized in EV applications in [2], [3], [4] - [7], [8], [12], [13], [15], [23] - [25], [29], [31], [33], [38] - [41], [48], [72], [73], [80], [97], [98]. To provide an overview of the research trends of published research works related to PECs based on EV applications, Fig. 8 shows published research works in field of PEC-based EV applications between 2010 and 2023, which depicts an upward trend from 2010 to 2023 except in 2020 which records a slightly low number of publications due to coronavirus pandemics. The data of 2785 published research works are extracted from the Scopus database with the keyword of PECs of EVs. Figure 9 shows prominent challenges and future research opportunities of PEC-based EV applications. In this section, the prominent challenges can be summarized in terms of the current challenges for PEC configurations and influences on the vehicular system or power system operating performance. The PEC challenges in EV applications can be described as follows.

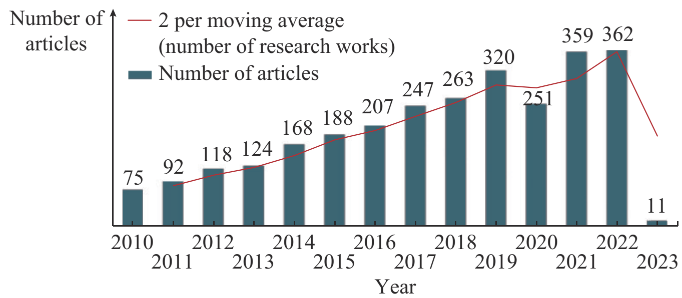


Fig. 8. Published research works in field of PEC-based EV applications between 2010 and 2023.

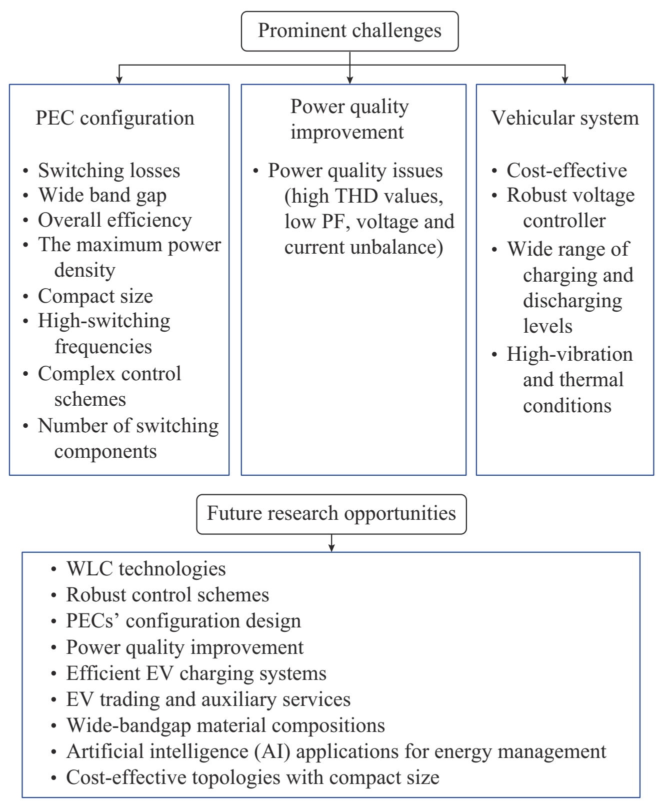


Fig. 9. Prominent challenges and future research opportunities of PEC-based EV applications.

A. Challenges Related to PEC Configurations

Bidirectional converters have more advantages compared with unidirectional ones such as various operating modes and ancillary services. However, they consist of many switches which increase the switching losses, maximize the implementation cost, and decline the overall efficiency and power density. Some topologies have a low number of switching components such as flyback and forward converters compared with buck-boost and Cuk converters based on the active balancing circuits. Thus, these converters are suitable for soft-switching topologies that ensure low switching losses during high switching frequencies. For MPCs, various challenges come into the picture, e.g., cross-regulation problems, regulated output voltage, duty ratio constraints, large output ripples, controller complexity, and cost based on the EV applications. The challenges of RPCs can be highlighted in several aspects such as high-frequency operation, soft-switching range, boosting the power rating, wide band gap, and compensation networks. In [12] and [22], the possible solutions to these challenges are discussed.

As the wide implementation of AC-DC converters to enhance the power quality, they still suffer from harmonics, switching losses, size, and power factor deterioration issues, as discussed in [21]. For developing the DC-AC converters, it is essential to specify the required application first. After that, the parameter selection and design with soft-switching operation are the challenging aspects, especially in MLI topologies [48]. The implementation of AC-AC converters for improving the operation of EV battery charging is a costly and complex control scheme.

B. Influences on Vehicular Systems

In the context of PECs' influence on vehicular systems, it is essential to select the suitable PEC depending on the switching methods, control strategies, type of input supply, and load demand. This selection aims to increase PEC efficiency and reduce switching losses. Moreover, robust control strategies play a vital role in accomplishing high-performance EV applications by using digital signal processing (DSP) coupled with PECs. In terms of EV durability, the lifespan of a PEC is associated with power electronic device longevity. Therefore, it is a challenging aspect to specify a suitable PEC to cope with the EV charging and discharging levels of batteries using a robust voltage controller, resist high vibration and thermal conditions, and achieve high efficiency, low cost, and small size constraints. According to the luxury features, a multiport DC-DC converter appears as a significant solution to handling various voltage ratings and sources in charging stations. Another aspect is safety improvement, where the selection of a suitable PEC, along with DSP technique, participates in the detection and mitigation of failures in the vehicular system. Besides these challenges, reducing the overall cost of EVs should be taken into account depending on the PEC components and luxurious loads.

C. Power Quality Improvement

In [91] and [93], the effects and challenges of PECs are discussed for various applications, especially EV applications. Also, the approaches to enhancing the power quality with future research trends are investigated. The most challenging aspects of EV applications involve high THD values of currents, voltages, low power factor, and current unbalance due to the presence of EV battery charging stations [230]. To cope with adverse consequences, new power transformers can be installed near the EV charging stations [231], [232] as well as improving the design of PECs to operate with balanced currents and low THD with unity power factor, independently of the operating power [233].

Regarding future research directions aimed at enhancing power quality in EV charging stations, it is worth exploring novel configurations of PECs such as multi-level and interleaved topologies. Additionally, conducting investigations into advancements in the fabrication of switching components and elements such as SiC and GaN holds significant potential.

VI. Analysis of Global EV Market

Recently, real-world EV applications have rapidly developed across various industrial technologies, encompassing several EV components such as battery technology, charger technology, and charging stations. In [21], [90], and [234], advancements in both wired and wireless charging techniques are discussed, considering the characteristics such as battery type, DC voltage, power level, and charging speed, and highlighting prominent companies in the field. Furthermore, the characteristics of EV batteries and the EV market share in various countries over the past five years have been examined. Several companies, including Pod Point, ABB, and Tesla, have made significant contributions to global EV sales in 2021. Figure 10 shows share percentage of prominent companies in global EV sales in 2021. In terms of the highest percentages of total new sales in 2020, Norway leads with 55.90%, followed by both the UK and Iceland with 45%. Additionally, plug-in hybrid EV unit sales reached 6.6 million in 2021, compared with just 3 million in 2020, and are predicted to reach 16.21 million by 2027.

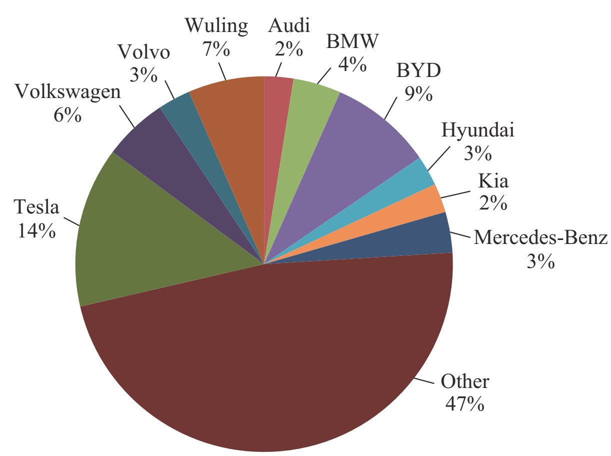


Fig. 10. Share percentage of prominent companies in global EV sales in 2021.

In [90], [235], the implementation of real-world V2G projects has been summarized, encompassing both pilot and commercial projects. Among the pilot projects, the Parker project in Denmark [236] has been implemented, providing frequency containment reserve services and involving four EV models: Nissan Evalia, Nissan Leaf, Peugeot iOn, and Mitsubishi Outlander plug-in hybrid EVs. Another pilot project [237] involves 30 EVs owned by the Los Angeles Air Force Base, aiming to enhance regulation capacity bids and minimize charging costs. The Power Plant Project, located at the Green Village in the Netherlands [238], focused on investigating both mobility and power generation aspects. In terms of commercial real-world applications, frequency regulation, arbitrage services, and load shifting services have been considered in various projects, including the Frederiksberg Forsyning EV fleet in Denmark, the Clinton Global Initiative School Bus Demo in the United States, the Domestic V2G Demonstrator Project in the UK, and other projects in the Netherlands, Namibia, New Zealand, and Germany [235], [239], [240].

VII. Future Research Opportunities

In the future, EVs will primarily be charged at home or at lower-level public charging stations due to the cost effectiveness and convenience of electricity at these levels. However, as sizes and ranges of EV battery continue to improve, and some EVs may need higher levels of charging to extend their driving range, there will be a greater demand for fast-charging infrastructure. Despite the high cost of building this type of infrastructure and the difficulty in drawing large amounts of energy from the power grid, most people will still charge their EVs overnight at home or normal charging stations. To reach a wider market, it will be important to make charging options available in public places and along highways, ideally with fast-charging options. Therefore, the selection of PECs for various charging topologies will majorly affect the reliability, safety, and durability, which leads to consumer approval of EVs.

From recent studies, it is clear that isolated converters are more reliable than non-isolated converters for the DC-DC converters between the utility grid and battery. Thus, the DAB converter is considered as the most favorable converter for EV charging stations because of achieving high power density, high efficiency, and small size of filter components. Moreover, the MPCs have gained prominence for their capability to interface various energy resources in EV applications, grid-connected systems, and RESs. These converters are characterized by fewer circuit elements, reduced complexity, lower cost, and superior power density compared with other DC-DC converter topologies. Relative to the RPCs, recent research works have been done to enhance the operation of the EV chargers to acquire essential objectives such as high power density, reliability, and efficiency with economical implementation and compact size. New modulation and control schemes have been proposed for developing EV chargers and enhancing the charging time. These systems can reduce the switching losses, the voltage stress on switches, and the size of the components. Several research works have developed the RPCs to overcome the above-mentioned limitations.

To deal with the challenges of the AC-DC converters, several studies have analyzed the future aspects in terms of cost effectiveness, number of controlled switches, filter design, and harmonics for EV applications, especially for DC fast-charging technologies. Thus, the Vienna rectifier is considered as the most promising converter type for the AC-DC conversion stage in high-power EV applications as it achieves less input current THD with the highest power density compared with other AC-DC converters. In DC-AC converters, recent technologies for EV applications are proposed to specify accurately the parameters during the implementation for reducing the switching losses and maintaining the compact size with an economical design. Moreover, some topologies have been employed for providing soft-switching without using complex control algorithms. In AC-AC converters, several research works work to propose a new design to reduce the cost and simplify the applied control schemes.

Thus, prominent challenges and future research opportunities of PEC-based EV applications can be highlighted briefly as follows.

1) Developing more efficient and cost-effectiveness charging topologies by reducing the number of power conversion stages and switching devices with a better economical design. Moreover, various metaheuristic optimization algorithms (such as genetic algorithm and particle swarm optimization) can be applied in EV applications to enhance their implementation by minimizing the switching loss, number of converter components, and overall cost.

2) Ensuring that all stakeholders, including EV users, building operators, and power grids, benefit economically from co-management initiatives. This necessitates the establishment of efficient and effective electricity pricing plans.

3) Investigating the use of artificial intelligence and machine learning for optimizing the performance and energy efficiency of EVs. Additionally, they can aid by analyzing and expecting the actual dataset of the faults which can extensively occur in PECs, for instance, open-circuit or short-circuit faults. Hence, the hazardous incidences of PECs can be prevented in industrial technologies in the implementation of EV applications.

4) Exploring the application of WLC technologies. EVs equipped with wireless charging technology can simply park over a charging pad or use dynamic wireless charging systems embedded in roads, allowing for convenient and seamless charging. As the interest in using WLC technologies for EVs is increasing, future research may focus on developing and testing new WLC technologies and their potential applications in different settings.

5) Enhancing the integration of EV charging with the grid is crucial as the number of EVs on the road increases. It will be important to ensure that the charging infrastructure can integrate seamlessly with the grid. Hence, optimizing the connection between charging stations and the grid, and developing new approaches to managing the power flow between them are very important.

6) Fast-charging systems capable of delivering high power at strategic locations will give consumers more options and flexibility. This involves the development of charging systems that can deliver extremely high power level, enabling rapid charging sessions of just a few minutes.

7) For delivering high power density with lower losses and heat in passive components, new compositions of wide-bandgap materials such as SiC and GaN, can be used for

PECs. As a result, the converter utilization by SiC or GaN semiconductor materials will attain low switching loss, higher operating thermal capability, and better configuration stability and reliability, which make the converter suitable for low-power or high-power EV applications.

8) Choosing suitable material composition for developing new topologies of the PECs for EV applications, providing improved reliability, cost effectiveness, and a high switching frequency. Moreover, enhancing the electrical design characteristics to accomplish the high frequency with low losses. Furthermore, mechanical design optimization should be considered to achieve a compact size with better reliability and accuracy, and costly.

9) The control schemes should be improved to address challenges related to high harmonics in output current and voltage stress. Further, for better energy management with high efficiency, intelligent control schemes should be applied without any complexity through the training process and choose the hyperparameters. As a result, various metaheuristic optimization techniques and machine learning methods can be employed to determine controller parameters, reduce the number of components, and minimize the cost of PECs.

10) New topologies can be improved such as multi-level multi-phase bidirectional converters, DAB, and matrix converters, to overcome the PEC limitations and problems because of their low current stress on switching devices, simple control schemes, high efficiency and reliability, which directly influence the overall operational performance.

VIII. Conclusion

The EVs can modernize transportation and help combat global warming by providing a sustainable alternative to fossil fuel-dependent vehicles. The adoption of EVs can reduce our reliance on finite fossil fuel resources and play a crucial role in mitigating the adverse effects of global warming. The EV charging topologies in terms of their placement, power rating, physical contact, and power flow direction have been investigated in this paper. Furthermore, a comprehensive review has been conducted on PEC solutions for EV applications relative to their circuit arrangements, switching patterns, structure, and control approaches related to recently published review papers. Moreover, various PEC topologies that involve DC-DC converters, AC-DC converters, DC-AC converters and AC-AC converters in terms of their construction, types, modulation techniques, and control schemes for high-voltage and low-voltage applications mainly for EV charging stations have been investigated in detail. In addition to presenting the soft-switching converters, multi-level converters and MPCs are introduced as current solutions to power-train challenges in EV applications. Based on recent review papers, this paper offers an overview of major future research predictions, challenges, and impacts of PECs on vehicular systems and power quality in utility grids.

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