A comprehensive review on EV power converter topologies charger types infrastructure and communication techniques

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The energy transition is a crucial effort from many sectors and levels to create a more integrated, carbon-neutral society. More than 20% of all greenhouse gas emissions are attributed to the transportation sector, predominantly concentrated in metropolitan areas. As a result, various technological hurdles are encountered and overcome. It facilitates the adoption of electric vehicles (EVs) run on renewable energy, making them a practical option in the fight against climate change and the completion of the energy revolution. Recent developments suggest that EVs will replace internal combustion engine (ICE) during the next few months. The EV either gets all of its power from batteries and ultra capacitors or some of it from both. In a plug-in electric vehicle, the battery or ultra-capacitor is charged by an AC supply connected to a grid line. In a hybrid electric vehicle, the ICE charges the battery or ultra-capacitor. Regenerative braking is another way to charge the battery from the traction motor. In a plug-in electric vehicle, the energy from of the battery or ultra-capacitor is put back into the AC grid line. Electronic converters are essential to converting power from the grid line to the traction motor and back again. This paper examines the current state of the electric vehicle market throughout the world and its potential future developments. Power electronics converters (PEC) and energy storage devices significantly impact electric vehicles' efficiency. Furthermore, general opinions about EVs are soon in this sector, as well as research topics that are still open to industry and University researchers.

KEYWORDS

electric vehicle, DC-DC converter, DC-AC converter, bidirectional converter, electric market, on-boarding charging, off-board charging

1 Introduction

Recently, there has been significant growth in the number of initiatives aimed at increasing, establishing, and managing RES. Polluting, degrading, and adding to the greenhouse effect are all side effects of using conventional energy sources. Conventional vehicle significantly contributes to the transportation sector's air pollution and greenhouse gas emissions. Carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen oxide (NO_2) are released when gasoline, coal, or natural gas are burned in these automobiles, making them hazardous combustion vehicles. An internal combustion engine (ICE) loss is caused by friction and heat loss in the transferring section (Sharma and Sharma, 2019).

The replacement of ICE highlights the importance of EVs as the most incredible alternative for lowering emissions (Gryparis et al., 2020). Heavy-duty vehicle (HDV) energy efficiency is crucial due to its link to other policy instruments. Hence, this is critical because some HDVs, such as city buses and refuse trucks, are purchased in significant quantities by government organizations. Despite this, no technical comparison of the CO_2 emissions or fuel consumption of vehicles in the same class. Battery-powered EV propulsion demands a massive battery pack with a restricted range (Fontaras et al., 2016). Power electronic converters of various types are connected to energy storage systems (ESSs) in electric vehicles in various ways (Khalid et al., 2019). An EV's energy storage and control optimization are detailed (Islam and Pota, 2013).

Power management control (PMC) based on a fuzzy inference system has improved due to genetic algorithm (GA) assistance. To decrease the total size of the hybrid energy storage system and increase the EV range, the GA is used offline to optimise the lower and upper membership limitations. An accurate model for estimating the energy needs of EVs was created by Miri et al. Since the amount of power required to operate a vehicle's accessories varies widely, this estimation is included in the EV's design. Energy storage systems (ESSs) are charged by connecting them to an AC power source, such as the utility grid or a dedicated charging station (Wu et al., 2017). DC-DC converters are necessary to regulate the power flow in the EV (Elsayad et al., 2020).

An energy-harvesting and power-demanding bidirectional non-isolated DC-DC converter is designed (Navarro et al., 2020). It is challenging since it depends on the load characteristics, source voltage, and duty cycle (Fardahar and Sabahi, 2020). Kanamarlapudi et al. developed a novel full-bridge isolated DC-DC converter with a passive auxiliary circuit that offers zero voltage switching (ZVS) for every significant switch across the battery charging range (Kanamarlapudi et al., 2018). The creation of diverse energy sources reduces vehicle running costs and enhances efficiency. The hybrid electric vehicle (HEV) has developed as an effective alternative for minimizing greenhouse emissions due to transport. Compared to ICE vehicles, HEVs claim superior fuel economy by maintaining the state of charge (SOC) (Kumar and Jain, 2014). By using renewable energy to power EVs, green charging systems (GCSs) with lower CO_2 emissions and promote the use of RES in the energy sector (Najafi et al., 2021a).

Grid is the primary source for charging EVs, but in practice, they also use renewable energy sources and coal for their energy needs (Mamun et al., 2022). The main problems with HEVs seem to be the fuel tank and regenerative braking. Plug-in hybrid electric vehicles (PHEVs) with externally charged batteries can solve the above-said problem (Shakeri et al., 2018). The most recent technology has developed a carbon-free EV charging station utilizing solar energy, drastically reducing pollutants and the effect of EVs on the electrical network. The expansion of renewable energy will significantly accelerate the use of maximum power converters with much more efficient and reliable conversion of boundless energies into an electricity network. PHEVs address the issue of restricted driving range by providing vehicle-to-grid (V2G) functionality (Islam and Cirrincione, 2016).

Multiple communication connection qualities are necessary to suit the demands of various charging mechanisms. A component powered by multiple wireless connections is necessary for a large-scale EV charging system with static, dynamic, and quasi-dynamic charging to enable effective interaction among numerous network elements (Yu et al., 2019). Consequently, to maintain their economic performance in the coming years, several firms are doing more thorough research into BEV charging options (Verma and Singh, 2019). The battery management system (BMS) is notable in light of the challenging-to-attain safety and dependability standards (Momete, 2018). The new distribution network, driven by EVs and energy markets, is expected to play a significant role in autonomous charging stations at a port, public parking lots, and quick charging infrastructure (Nunes et al., 2016). This article put forth a comprehensive review of EV technology, which includes selection of motors, battery requirements, power electronic converters, charging technologies, different charging methods, EV market and charging infra structure, with future directions. This article will help the kindle researchers who wish to work in EV technologies.

The course of the paper is organised as follows. The details of electric motors for EV applications are explained in Section 2, whereas in Section 3, the battery requirement for EVs is briefed. Power converters and charging communication technologies are elucidated in Sections 4, 5, respectively. Sections 6, 7 briefs about the conductive and inductive charging respectively. The electric vehicle market and Repercussions of electric vehicle charging infrastructure are briefed in Section 8, 9, respectively. The future direction of the research area is explained in Section 10, birds view. The conclusion of the paper is drafted in Section 10.

2 Electric motors for EV

An integral component of the EV is the electric motor, which includes power electronics and batteries. In EVs, where weight and space are constrained, more power and torque density enable improved driving characteristics in a small, straightforward design. The other factor, efficiency, is improved. Whenever the vehicle is in motion, the energy stored in the battery is wasted, resulting in a more excellent range despite the same storage space. According to multiple unique problems in motor design, the EV industry has applied a range of distinct options, comprising wound rotor, permanent magnet and induction. The rare metals used in permanent magnet motors are subject to price fluctuations, have a restricted geographical distribution system, and come with a unique mix of benefits and drawbacks in terms of development costs, dependability, and accessibility. DC motors offer a

TABLE 1 Performance comparison of different motors.

Types of motor/ parameters	Torque density (Nm/kg)	Power density (kW/kg)	Loading capacity factor	Remarks
IM	4	1.5	1.6–3.2	• Less cost • Simple construction • Established technology • Expensive controller • At constant power operation due to breakdown operation
PMSM	5	1.5	2 (approx.)	• Better efficiency • Compact size • Lesser weight • Demagnetisation issue • Costlier
SRM	4	1	High	• Less cost • Torque ripple is high • more acoustic noise • Suffers from mechanical losses
BLDC	3.5	1	1.8	• High operating speed • Maintenance free • High reliable • High costly • Rugged mechanical strength

straightforward monitoring system compared to AC motors. Again, contrasted to DC motor drives, there are several significant benefits of using AC motors, such as increased efficiency through less motor frictional loss, fewer maintenance requirements, robustness, and maximum power density.

Motors preferred for EV applications are induction motor (IM), permanent magnet (PM), switched reluctance motor (SRM) and brushless DC motor (BLDC). Though challenging, evaluating various versions of these machines is non-etheless a task. IM has a simplified construction, requires minimal, is less costly, and has better overloading performance than PM-based motors (Hannan et al., 2018). On the other hand, PM motors outperform IM in terms of effectiveness and portability. Its tiny size, high power densities, and efficiency make it superior to IM (Barkas et al., 2020).

However, its torque decreases with increasing speed when subjected to a load. Therefore, it can only be used to a certain extent. As the torque changes, there is an audible noise produced. Compared to the other types of motors discussed, the permanent magnet synchronous motor (PMSM) stands out well. It operates across a wide range of speeds, is extremely powerful and efficient, causes no harmonic distortion, and is simple to operate (Sun et al., 2019a). However, the cost of PMSM-based drives exceeds that of both BLDC and IM-based systems. The switched reluctance motor (SRM) has several benefits over the IM and PMSM, including a magnet-free and sturdy rotor design that enables incredible

velocities and is highly reliable by construction. Ripple torque reduction is among the most important and challenging SRM design elements to handle whenever it relates to vehicle applications. The SRMs for significantly higher torque in EV with reduced ripple torque, disturbance, and auditory concerns (Lan et al., 2021). The performance comparison of different motors used for EV applications is given in Table 1.

3 Requirements of battery for EVs

Electric vehicles (EVs) charge their batteries, super capacitors, fuel cells, or internal combustion engine (ICE) to power internal electrical and electronic load functions (Chan and Chau, 1997; Amjadi and Williamson, 2010a; Naghizadeh and Williamson, 2013; OnarKobayashi and Khaligh, 2013; Cabezuelo et al., 2017). The automobile cannot be powered in fuel mode by the fuel cell's electricity. Consequently, the unidirectional boost converter boosts it (Jafri and Gupta, 2016). Several electrical and technological loads are placed on the car, enhancing its opulent characteristics and convenience.

A power converter supplies energy to specific electrical loads requiring higher AC voltage, such as air conditioners and automatic headlights. A DC motor-fed mirror and driving seat adjustments receive electricity from a battery or fuel cell through a DC-DC
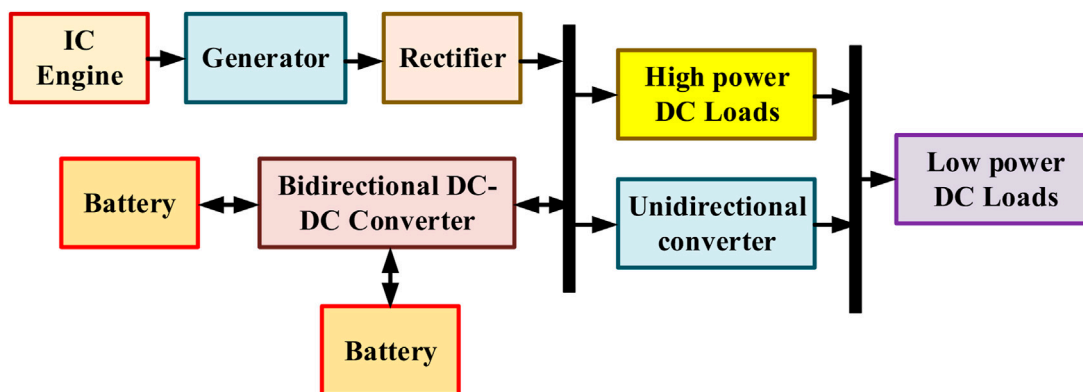
FIGURE 1
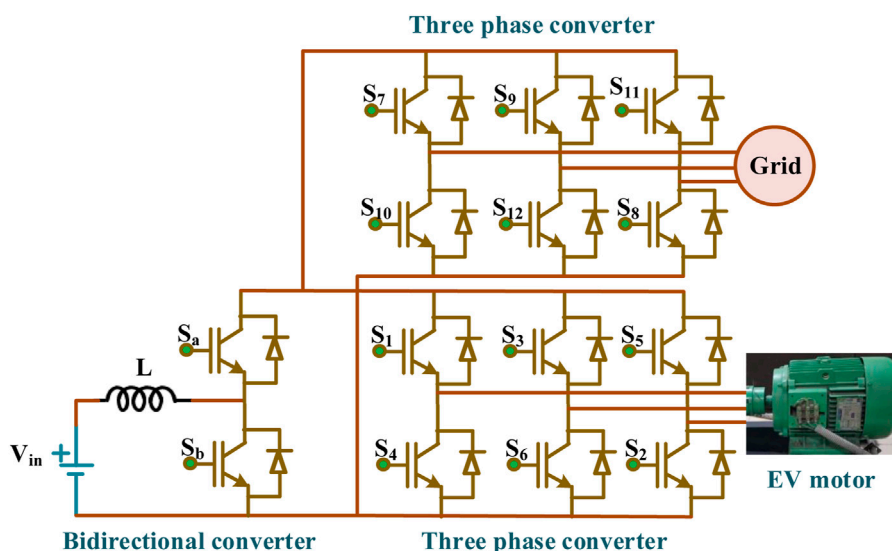Block diagram of battery with the power converter.

FIGURE 2
Overview of EV system with power electronic interface.

converter, which requires various voltage levels. The projection lamp needs 42 V, and the internal lighting needs 12 V to operate. Low voltage is required to function electronics components such as sensors, telecommunication networks, and tachometers. As the electrical/electronic load on the car rises, separate voltage output feeds are required, which are not achievable with a unified battery. The effectiveness of a vehicle powered by a single charge decreases as the quantity of DC-DC converters grows with rising diverse rating loads. The combination automotive system uses two forms of design (AdamsKlobodu and Apio, 2018). The other is a solitary, ICE- or fuel-cell-powered vehicle system (36 V). A different type is an ICE, or fuel cell, that uses two batteries (14 V and 42 V).

Figure 1 illustrates the block diagram of the battery with the power converter. This scheme uses a dual battery to deliver power to

low-voltage electrical equipment (Cabezuelo et al., 2017). 12 V and 36 V batteries are used for low and mid-voltage applications. Nevertheless, for the driving and high voltage applications, the 36 V from the battery is raised to 42 V. Overview of the EV system with the power electronic interface is illustrated in Figure 2. The voltage from the grid/generator charges the battery through the rectifier and DC-DC converter (Elnozahy and Salama, 2014), (Yong et al., 2015). The bidirectional DC-DC converter boosts the battery voltage and feeds to high-voltage DC loads. Then it is inverted using a three-phase inverter to get variable voltage and frequency supply for feeding to motors. Modern electric vehicles can recharge batteries using the energy lost during braking and de-acceleration. During that mode, the converter acts as a rectifier and the battery charges with the
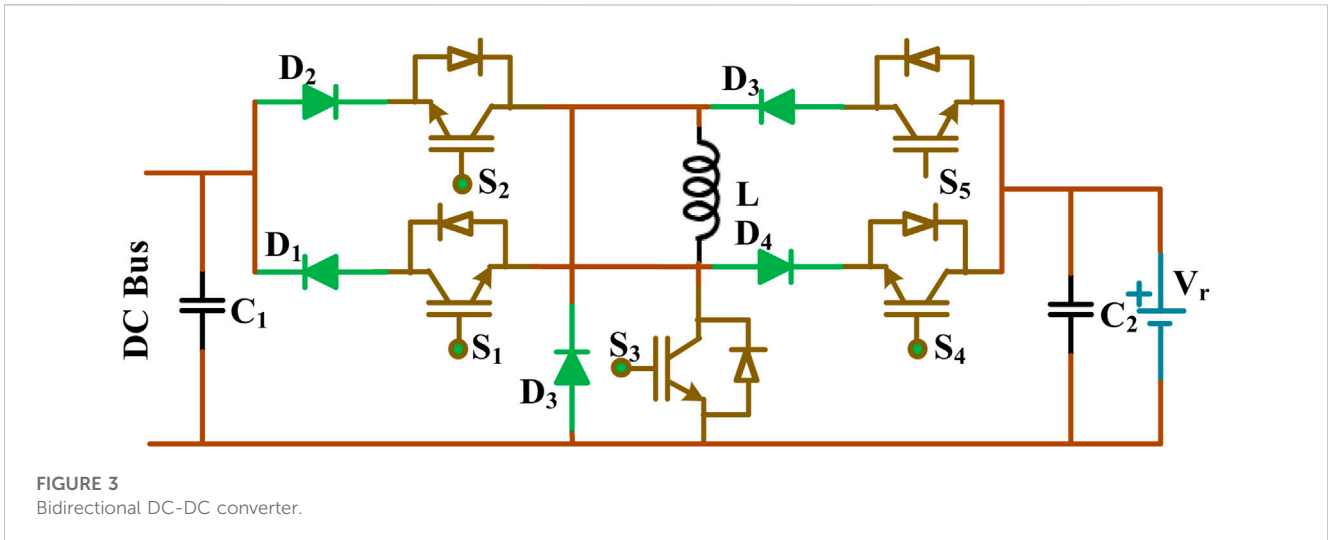
FIGURE 3
Bidirectional DC-DC converter.

TABLE 2 Modes of the operation.

Switches/modes	Source to Load		Load to source	
	Buck	Boost	Buck	Boost
S_1	Control	ON	OFF	OFF
S_2	OFF	OFF	ON	ON
S_3	OFF	OFF	Control	ON
S_4	ON	ON	OFF	OFF
S_5	OFF	Control	OFF	Control

bidirectional converter (Amjadi and Williamson, 2010a), (Chung et al., 2000; Di Napoli et al., 2002; KhanAhmedHusain et al., 2015; Lulhe and Date, 2015; Choubey and Lopes, 2017).

In the current EV system, the converter act as an inverter at the normal operating condition and a rectifier during the braking period. The controller fixes the operating mode upon the operation of the motor and produces the triggering pulses for the converter. The produced signal decides the operation of the converter, either in rectifier or inverter mode. The controller maintains the state of the charge (SOC) of the battery by monitoring it continuously. DC-DC converter regulates the output voltage by comparing the actual battery voltage with the reference voltage set by the user. Thus, the closed system maintains the battery voltage and speed of the motor.
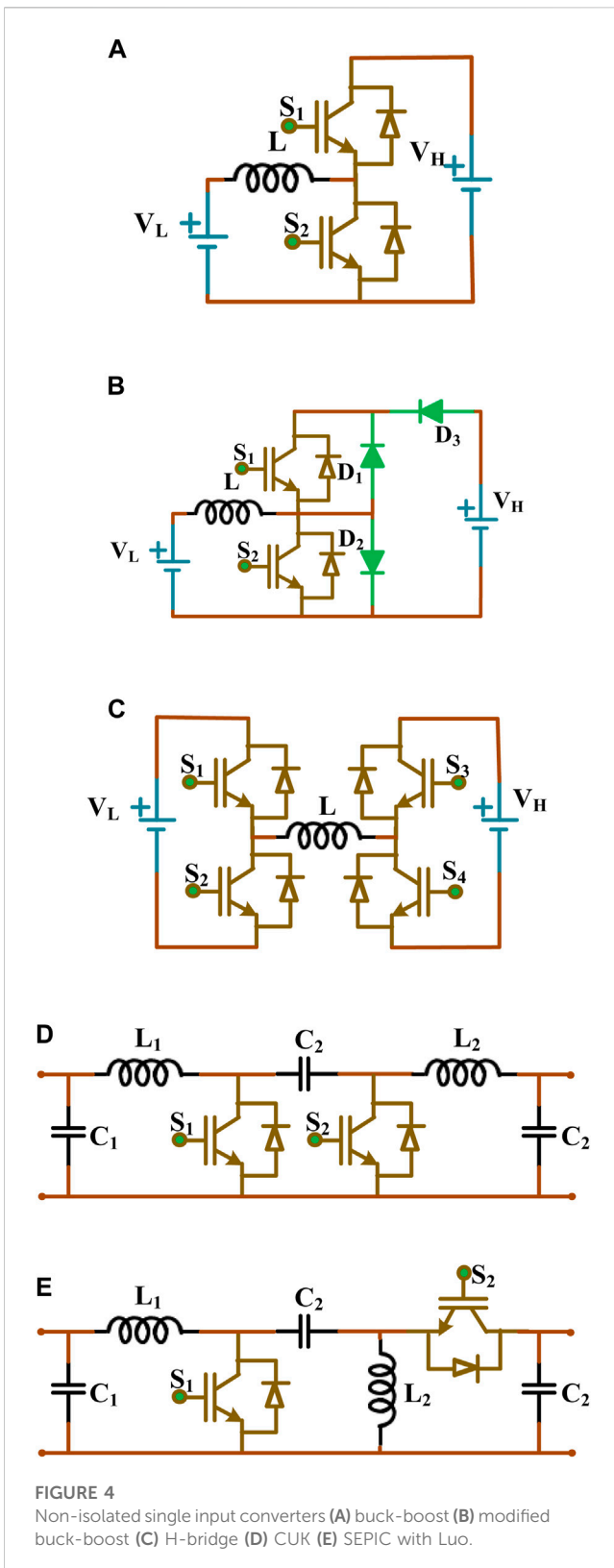
4 Power converters for EV applications

The power converter plays a vital role in EV applications. As discussed in the previous section, Bi-directional DC-DC converters with boost and buck modes are preferred. In boost mode, the input voltage is boosted and fed to the motor, whereas the generated voltage from the motor during regenerative braking is bucked and fed to the battery. One of the well-known bidirectional DC-DC converter is illustrated in Figure 3, and the modes of operation are included in Table 2 (OnarKobayashi and Khaligh, 2013). The converter can operate in buck and boost modes upon selecting the proper switching pattern. Besides the basic topologies, several bi-directional converters are developed with single/multi-input, single/multistage and non-isolated multiphase converters.

In (Amjadi and Williamson, 2010b), Authors have developed a novel single-input bi-directional buck-boost converter, as shown in Figure 4A. The developed topology can be operated in both buck and boost modes by selecting the proper switching pattern. The topology includes two controlled switches and three passive elements. In this topology, the output current ripple is high, which may damage the battery and discontinuous operation in boost mode results in the increased size of the filter capacitor. Emadi proposed a modified buck-boost converter with an anti-parallel diode as shown in Figure 4B (Emadi, 2005). The diode connected in parallel with the power switches decreases the voltage stress across the switches, increasing system efficiency. The circuit diagram of the H-bridge converter is shown in Figure 4C. They maintain the SOC as the desired value and charge the battery during the regenerative braking (Waffler and Kolar, 2009; WuLuShi and Xing, 2012; Choubey and Lopes, 2017; Bharathidasan et al., 2022). This topology results in more semiconductor switches. The circuit diagram of DC-DC CUK and SEPIC with Luo converter is illustrated in Figures 4D, E, respectively (Amjadi and Williamson, 2010a). The developed topology can buck and boost the output voltage, and a bidirectional current flow is also possible. The input and output current ripple is minimum. But the output current is discontinuous in the Luo converter, which requires a bulky output capacitor. Elements in non-isolated single-input converters are summarised in Table 3.

The multiple-input fed bidirectional converter and single-input converters are developed for EV applications. The circuit diagram of the developed topology is illustrated in Figure 5. The input fed to the converter may be a battery, super capacitor or fuel cell in which battery-operated EV yield better response when compared with others (KhanAhmedHusain et al., 2015). A DC bus is maintained using a buck-boost converter with the battery and ultra-capacitor, as shown in Figure 5A. As two sources are used, voltage control is essential to maintain the value and to avoid circulating currents. A DC-DC converter with multiple sources is illustrated in Figure 5B

FIGURE 4
Non-isolated single input converters **(A)** buck-boost **(B)** modified buck-boost **(C)** H-bridge **(D)** CUK **(E)** SEPIC with Luo.

(Khaligh, 2008). The converter can handle multiple different sources that possess different VI characteristics. Figure 5C illustrates the cascaded bidirectional converter for fuel cell-operated EVs. The converter can boost the input voltage with high gain (Marchesoni and Vacca, 2007). The prime disadvantage of this topology is that

DC link voltage should be maintained more significant than the sum of source voltage to avoid circulating current. They possess higher efficiency if the sources are connected in the same direction. Figure 5D shows the circuit diagram of the multi-level power electronic converter (Di Napoli et al., 2002; Onwuchekwa and Kwasinski, 2011; Dusmez, 2012). The converters can operate buck and boost modes to maintain the DC bus voltage constant. Elements in non-isolated multiple-input converters are summarised in Table 4.

Figure 6 depicts the non-isolated multiphase DC-DC converters used for electric vehicle applications. Figure 6A depicts the circuit diagram of interleaved boost three-phase converter (Khaligh and Li, 2010)- (YangGuanZhangJiang and Huang, 2018). The interleaved converter minimizes the input-output current ripples, significantly improving over the traditional bidirectional DC-DC converter. When there are multiple phases, the current ripple will decrease. Still ultimately, this will result in a fall in efficiency due to the increased number of passive and active elements required for each phase. Figure 6B illustrates the several structures in an interleaved converter (Ni et al., 2012). As the number of stages grows, the input/output filter gets smaller. This structure includes more active and passive elements than Figure 6A.

Figure 7 depicts electric vehicles' various switched capacitor (SC) circuit configurations. Figure 7A depicts the circuit diagram of SC converter (Amjadi and Williamson, 2010a), (Ni et al., 2012), (Chung et al., 2000). The SC structure possesses the capabilities of buck, boost, and buck-boost power flow operation in either direction. The topology supports both mode A (buck operation) and mode B (boost operation) of operation. Mode-efficiency A's of the illustrated topology is 85%, whereas mode-efficiency B's is 80%. Figure 7B, C demonstrate quasi-resonant converter of single-level and two-level topologies (Lee and Chiu, 2005). By utilizing an SC structure and a single inductor, the topology helps to alleviate the issue of current stress. The converter can achieve soft switching with the assistance of L and C, which decreases the losses. As a result, the MOSFET semiconductor device being switched ON and OFF in a condition with zero current, the EMI issue is significantly mitigated. The efficacy of the topology is 93%. Higher voltage conversion ratios require more SC stages. Table 5 lists the summary of various converter topologies for EV applications.

5 Charging communication technologies

Dynamic wireless charging necessitates a distinct communication network with an exceptionally low delay and high dependability to enable effective connection with the fast charging arrangement through the car's on-road capabilities (Abboud et al., 2016). The ability of the communications network is an essential factor that is determined by the amount of data that has to be sent and is reliant on this factor. Methods of good communication, whereby a network connection is built between the charging station and EV, are necessary to accomplish and control efficient synchronization of EVs on the internet of electric cars. It has been the impetus for developing 5G V2X innovation, which builds upon existing LTE, LTE-advanced (LTE-A), and LTE C-V2X networks. It also solves certification

TABLE 3 Elements in non-isolated single-input converters.

Ref. no	Converter topology	Active switch	Diode	Inductor	Capacitor
Amjadi and Williamson, (2010b)	Buck-boost	2	-	1	-
Emadi, (2005)	Modified buck-boost	2	3	1	-
Choubey and Lopes, (2017)	H-bridge	4	-	1	-
Amjadi and Williamson, (2010a)	CUK	2	-	2	3
Amjadi and Williamson, (2010a)	SEPIC with Luo	2	-	2	3

requirements such as super reliability, better portability, lower energy consumption, and more extensive density interconnections (Dai et al., 2018). Millimetre-wave (mmWave) technology is used to investigate the massive multiple-input multiple-output (MMIMO) technique (Busari et al., 2019). Several communication technologies, such as mmWave, D2D, MMIMO, and software-defined networks (SDN), are used for communications (Chen et al., 2017; Ahmed et al., 2019; Dagdougui et al., 2019; Zhang et al., 2020).

Static synchronization is concerned chiefly with task scheduling of driven automobiles at access points or in commercial parking areas (Zhang et al., 2020). Consequently, the vehicle's manoeuvrability is disregarded. The coordination that takes mobility into account considers not only the packages that need to be delivered but also where they need to be sent, how far they need to go, and how much energy they need before they get charged (Wang et al., 2019). Assessed is the best battery charging plan that may be used for EBs within a BSS (You et al., 2016). Several approaches to charging synchronization and routing management have been discussed in the research that has been published. The most current developments in 802.11bd and NR V2X standards have been analyzed (Kosmanos et al., 2018), (Naik et al., 2019). The United States National Institute of Standards and Technology (NIST) created a cyber-security structure that offers businesses recommendations on avoiding, detecting, and preventing cybersecurity risks. Recent years have seen a rapid increase in the purchase of electric vehicles, even though the overall cost of owning an EV is more than owning an internal combustion engine version of the same vehicle type (Forocoches Electricos, 2017).

DSRC's dependability quickly crumbles in highly congested systems due to severe network problems in inter-cluster communication (Framework Convention on Climate Change, 2015). Consequently, problems with quasi-dynamic charger synchronization develop, particularly in situations where electric vehicles benefit from high vehicle concentrations to increase their efficient charging duration and enhance the amount of electricity collected. Standards committee recommendation for IEEE 802.11bd, the problems of interference and non-line of sight (NLOS) functioning that plague DSRC based on IEEE 802.11p are addressed in the DSRC technique known as DSRC. To improve channel estimates with the rapidly changing channels seen in a moving vehicle, the latest revision of IEEE 802.11bd includes a new feature called midambles, which function similarly to opening paragraphs but are put amid the frame (Forocoches Electricos, 2017). In addition, unlike IEEE 802.11p, IEEE 802.11bd allows for many packet forwarding to ensure a steady
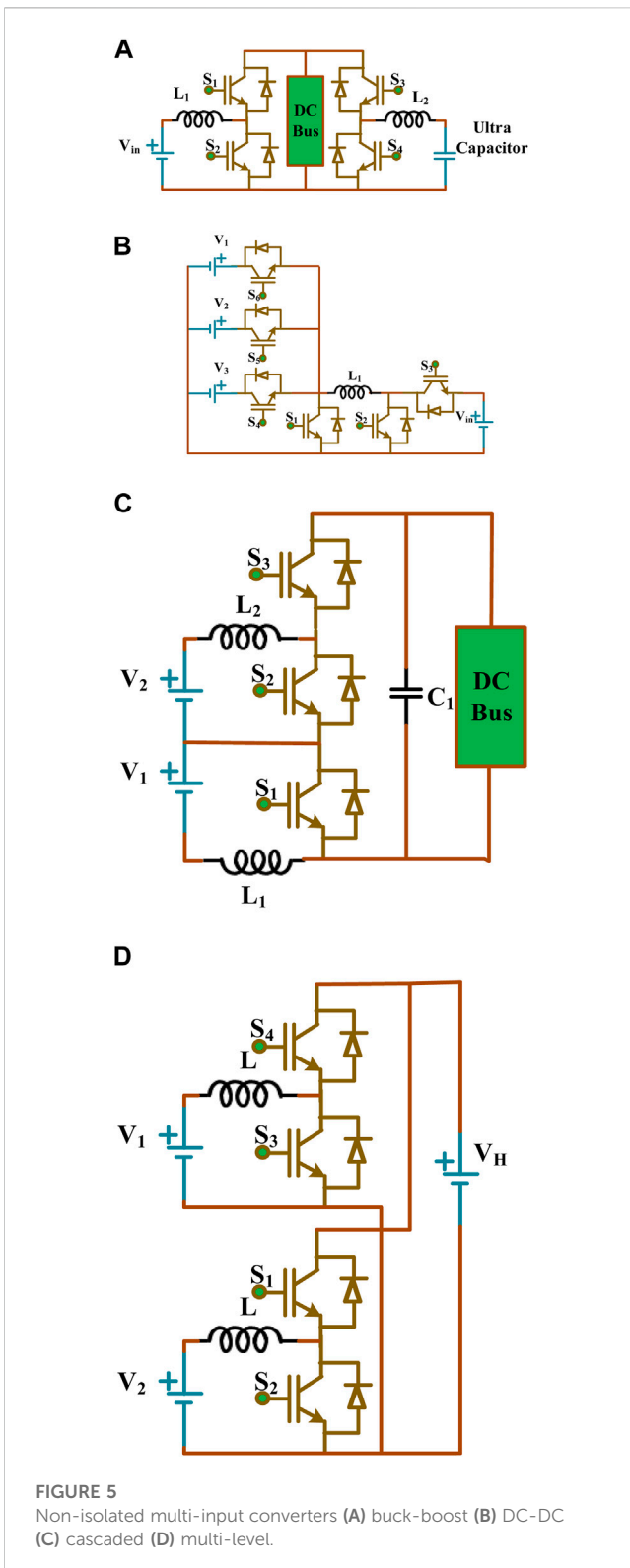
connection. On the other hand, the physical layer delay also referred to as issues that limit inside the wireless medium, is shorter for IEEE 802.11bd than for IEEE 802.11p.

6 Conductive charging technologies

The electricity is transferred to an electric vehicle by conductive charging by a direct copper connection between the grid system and the EV. This charging technique is very reliable and has a high-efficiency level. There are two main types of conductive charging infrastructure: on-boarding and off-boarding. Slow charging is often performed using onboard charging infrastructures, wherein the charger facilities and battery storage system are housed within the electric vehicle's chassis. On the other hand, off-board charging infrastructures are made to charge electric cars quickly. Parking garages, shopping malls, hospitals, universities, and interstates are familiar places to find off-board charging infrastructures. Electrified automobiles use a conductive charging method, such as the Tesla Roadster, Nissan Leaf, and Chevrolet Volt. Figure 8 displays on-board and off-board charging facilities. The Society of Automatic Engineers (SAE) has established various charging levels for electric vehicles, outlined in Table 6.

As previously established, power quality measurements for EV chargers are crucial. One such indication is the total harmonic distortion (THD), which quantifies the amount of harmonic distortion delivered into the AC input by the charger (PF). For recharging electric vehicles, (Bai and Lukic, 2013), presents a 12-pulse rectifier and two buck-boost converters. To lessen the input current's harmonics, the virtual impedance injection technique is explained. Improved input power factor and 3.34 percent total harmonic distortion of the input line current are the results of this modification. The authors propose (Rivera et al., 2015; Rivera and Wu, 2017) that a bipolar dc structure be formed at the output of a grid-tied neutral point-clamped converter in order to charge electric vehicles. Because of its bidirectional energy conversion capabilities, it is well suited for use in linking electric vehicle power to the utility grid. Under balanced load conditions, the THD was found to be 5.8 percent, whereas under unbalanced load conditions, it was found to be 7.3 percent.

The development of the two-stage, bidirectional dc rapid charging facilities in MATLAB/Simulink (Arancibia and Strunz, 2012; Reed et al., 2012; Gjelaj et al., 2017). On the other hand, the efficacy of the chargers in addressing the problems with the power quality is not present. The two-stage energy conversion procedure is proposed to facilitate the integration of a flywheel energy storage

FIGURE 5
Non-isolated multi-input converters **(A)** buck-boost **(B)** DC-DC **(C)** cascaded **(D)** multi-level.

system with a charging system for electric vehicles (Sun et al., 2016). On the other hand, none of the power-quality concerns raised by the suggested charging scheme is addressed. Several distinct designs for EV chargers are explored, each involving low-frequency or high-frequency (LF or HF) transformers for electrical isolation (Aggeler et al., 2010). For charging electric vehicles during peak demand on

the electric grid, a two-stage, bidirectional charging structure is considered together with a dynamic load control approach (Ahmadi et al., 2015).

For electric vehicle charging stations, Bai. et al. have proposed ac-to-dc converters with 6, 12, or 18 pulses and the difficulty of constructing the necessary specialized transformers to get that many pulses (Bai et al., 2010). The THD in the input line current for a 12-pulse converter is 11.5%. A dc-active power filter (dc-APF) circuit is developed using a 12-pulse rectifier for recharging electric vehicles (Bai and Lukic, 2011). When looking at the power quality of the input line current, the stated findings were highly promising. However, a significant heating issue is introduced by high-frequency switching in dc-APF to transform the input current into a sinusoidal waveform. In (Joy et al., 2013), it is detailed how a two-step, two-way charging setup for electric vehicles may work. High-frequency switching is a part of this design. However, it doesn't appear appropriate for a charging setup for electric vehicles that requires a lot of energy (in the MW range).

A bidirectional, multilayer cascaded converter with a medium switching frequency of 2880 Hz is proposed (Crosier et al., 2012) for use in EV charging stations. The authors propose a two-stage charging process for EVs. Because the dc/dc converter provides isolation in this charger, the isolation transformer may be smaller (Vasiladiotis et al., 2012), (Prakash et al., 2022). The switching frequency of this design is 10 kHz, and the circuit uses thirteen DC-DC converters linked in parallel. It is proposed to build a high-power bidirectional EV charger using a matrix converter and two inverters (Waltrich et al., 2012). On the other hand, this design uses many power electronics switches operating at high frequencies.

Slow charging uses a typical 120 V AC single-phase outlet with a 15 A–20 A current capability. One end of a typical electric socket is NEMA5-15R/20R, while the other is a standard SAEJ1772 connection. This level's power consumption ranges between 1.4 and 1.9 kW, depending on the current drawn from the grid. Typically, it takes 8–16 h to charge the battery altogether (Introduction, 2014). The price range for facilities at this degree of charge ranges from $500 to $880 (Morrow, 2008).
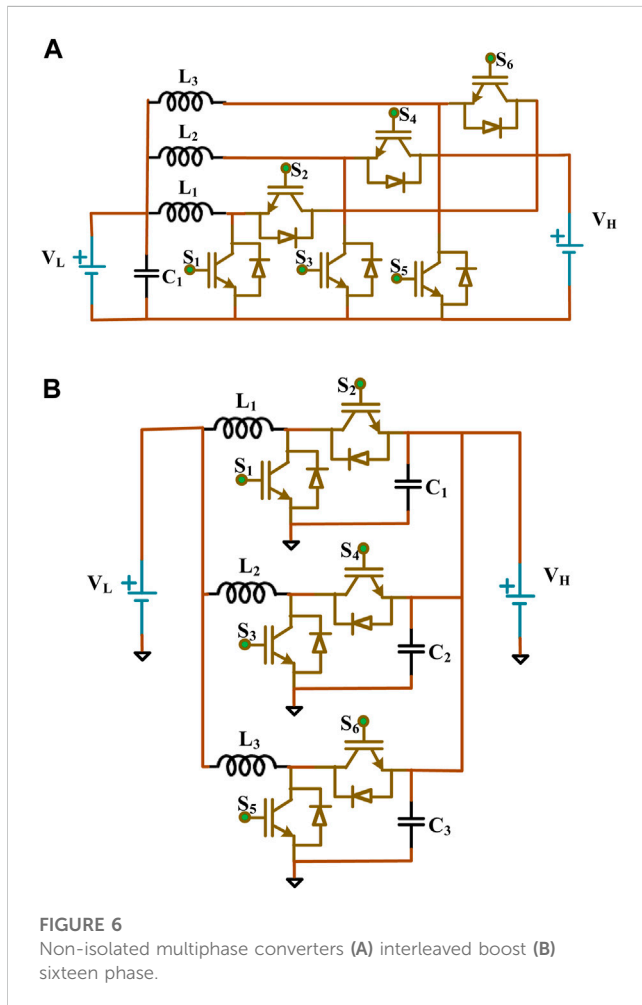
The semi-fast charging technique is typically implemented in private and public institutions, including hospitals, universities, and retail malls. Private equipment utilizes 1 ϕ 230 V_{AC} plug with a 40 A current size, whereas public facilities utilize a three-phase 400 V_{AC} output having an 80 A existing size (Bai and Lukic, 2013). This charging level uses SAEJ1772 (Plug-in electric vehicle, 2013). This charge level has a power rating of 7.7–25.6 kW, and it typically takes 4–8 h to fully charge the battery of an electric vehicle (Introduction, 2014). Costs associated with semi-charging construction are significant, anywhere between $2150 and $2300 on average (Morrow, 2008).

Public and private charging stations alike must adhere to the rapid charging requirement. This charging protocol mimics ICE fueling stations that use fossil fuels. The longest time an EV may spend charging at this rate is 10–15 min, at which point it will have been charged to 80% of its theoretical capacity. Only up to 80% of the entire capacity of an EV battery is considered to be charged using this approach (Braunl, 2012). Charging the remaining 20% needs charging at constant voltage, which takes time. A three-phase power supply between 208 V and 600 V alternating current and a maximum current capacity of 200 A is required for this level of

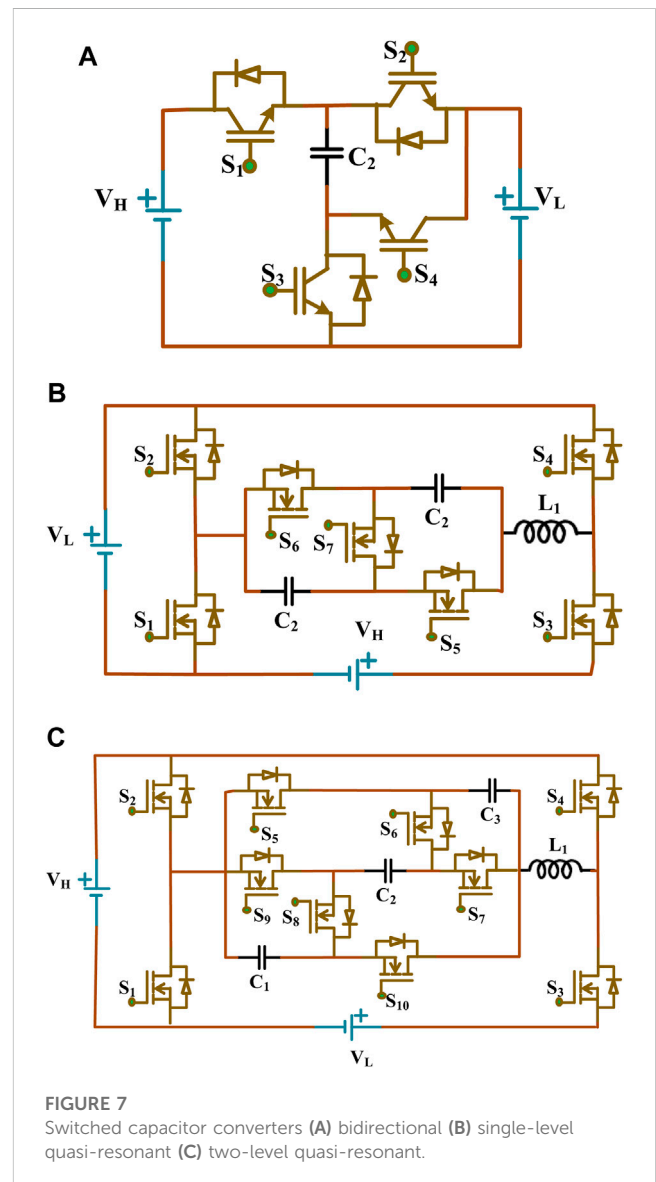**TABLE 4 Elements in non-isolated multiple-input converters.**

Ref. no	Converter topology	Active switch	Inductor	Capacitor
KhanAhmedHusain et al. (2015)	Buck-boost	4	2	1
Khaligh, (2008)	DC-DC	6	1	-
Marchesoni and Vacca, (2007)	Cascaded	3	2	1
Onwuchekwa and Kwasinski, (2011)	Multi-level	4	2	-

FIGURE 6
Non-isolated multiphase converters **(A)** interleaved boost **(B)** sixteen phase.

FIGURE 7
Switched capacitor converters **(A)** bidirectional **(B)** single-level quasi-resonant **(C)** two-level quasi-resonant.

charging. Due to the lighter weight of an electric vehicle, batteries with a higher energy density may be employed (Rawson, 1999). Only the SAE J1772 Combo standard and the Japanese CHAdeMO benchmark are in use for rapid charging of electric vehicles throughout the world (Braunl, 2012). It is estimated that between $50,000 and $160,000 would be needed to set up rapid charging infrastructure.

7 Inductive charging technologies

The concept of mutual induction is utilised by inductive charging infrastructures to carry power from the utility grid to the EV. There is no physical connection between the EV and the utility grid. In addition, unlike conductive chargers, they might not need bulky isolation transformers for further safety (Bryan et al., 2015). While convenient, inductive charging infrastructure suffers inefficiency because of power transmission coil mismatch. Infrastructure for inductive charging is categorized into three groups. a) Static inductive charging, b) Dynamic inductive

**TABLE 5 Summary of various converter topologies for EV applications.**

Ref	Topologies	Objective	Voltage gain	Advantage	Disadvantage	Remarks
MartmezMartinez-Salamero et al. (1998)	CUK	• To improve the efficiency	$\frac{-D}{1-D}$	• Minimum inductor ripple • Continuous conduction operation	• Unstable • underdamped oscillation	• Ripple free output
Zhang et al. (2019)	Switched Capacitor Bidirectional Converter	• To increase the gain and efficiency	$\frac{2}{1-D}$	• Minimum cost • Compact size • Reduced output current	• High current ripple • Less efficiency for wide range input variations	• Efficacy is greater than 90%
Babaei et al. (2019)	Couple Inductor Bidirectional Converter	• To minimize the inductor and load current ripple	$\frac{2+N-D}{1-D}$	• Reduced sie • Low cost • Minimum ripple	• Output voltage ripple	• Improved efficiency due to enhanced coupling coefficient
Wu et al. (2019)	Quasi-Z-source Converter	• To get high voltage gain with common ground	$\frac{1+D}{1-D}$	• Minimize the switching stress • Reduced components	• Discontinuous source current • High voltage stress in capacitor	• Efficiency varies between 88.17% and 96.44%
Mirzaei et al. (2010)	Multi-Device Interleaved Bidirectional Converter	• To minimize the circuit components • To minimize the inductor and load current ripple • Better transient response	$\frac{1}{1-ND}$	• Minimum current stress • Easy design • Compact size	• Complex to control • More sensitive to the duty cycle	• Minimum electromagnetic interference • Reduced voltage and current ripple
Lee et al. (2019)	Flyback Converter	• To handle the wide variations in input voltage	$\frac{ND}{1-D}$	• Primary and secondary is isolated • Regulated multiple outputs	• High current ripple • More losses • Requires bulky filters • Converter is unstable	• Leakage inductance is within allowable limits
Lee and Chiu (2005)	Zero Voltage Switching Converter	• To develop the adaptive load controller • To achieve zero voltage switching • To reduce the circuit components	$\frac{2}{\pi}D(1-D)$	• Minimum electromagnetic interference • Minimum switching losses • A clamping circuit is not required	• Requires bulky capacitor • Less fault-tolerant capacity	• Wide range of soft switching
			D- Duty ratio, N- Turns ratio			

charging, and c) Quasi- Dynamic inductive charging (Miller et al., 2015; Chen et al., 2016; Li et al., 2016; Vu et al., 2018).

Figure 9 depicts the concept of electric car static and roadbed inductive charging. For static charging, one coil is located in an external charger, while the other is built within the electric vehicle itself. Both coils need to be positioned correctly for maximum efficiency (Khaligh and Dusmez, 2012). As the EV drives, inductive charging pads embedded in the road surface top up its battery. With this charging, dedicated charging tracks are set out on the roadways, most commonly on highways. As a result, the electric vehicle's driving range is improved, and the size of the battery pack is decreased (Budhia and Covic, 2487). In

FIGURE 8
On-board and off-board charging facilities.
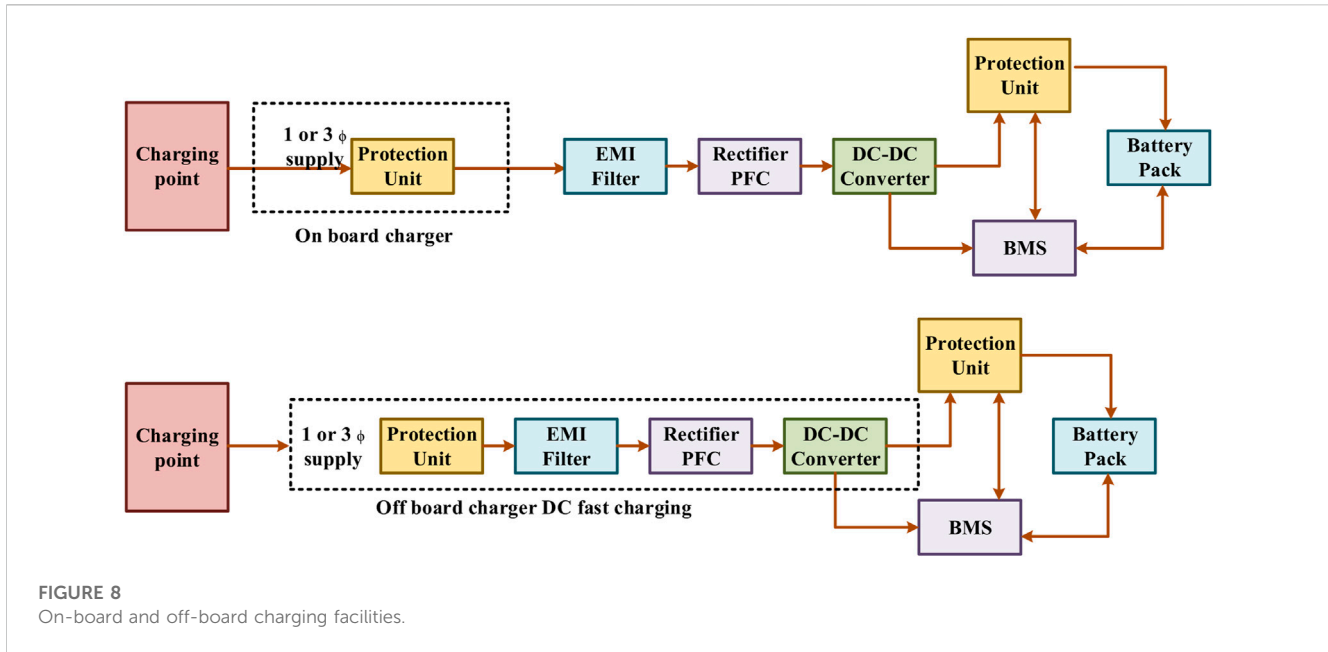
TABLE 6 Various charging levels for electric vehicles.

Charging	Slow	Semi fast	Fast
Typical voltage (V)	120	240	208–600
Typical current (A)	16	80	400
Duration (h)	4–12	2–6	0.2–1
Type	On-board	On-board	Off-board
Location	Home	Home/Commercial	Commercial

the process known as quasi-dynamic inductive charging, the electric vehicle obtains a charge anytime it comes to a halt for a brief period, such as at a traffic light (Honda accord plug-in hybrid, 2017).

8 Electric vehicle market

Five primary research issues are evaluated and correspond to the findings from the existing studies: 1) estimating the percentage of plug-in electric vehicles (PEVs) sold in a specific region; 2) identifying the inputs, 3) promising policies, 4) expected outcomes effects of widespread PEV market penetration 5) a new modelling strategy. Research questions about the above scenario are displayed in Figure 10 in chronological order, beginning with the most recently published. Most publications seek to identify the factors contributing to spreading PEVs in a specific market or geographic region. Research questions about adopting a new technique, with an emphasis on the methodology instead of the predicted market proliferation, often play a role. In recent years, interest has been raised in determining crucial policies and

the influence of the PEV market's spread (for instance, on the power grid). The maturation of modelling tools or the need to incorporate policy initiatives to expedite markets may account for the current emphasis on examining effects and strategies.

A straightforward classification is utilized when comparing models because the above-mentioned categories do not adequately describe most models. To show model detail, they are categorized by aggregation: 1) Very consolidated models that analyze simply the vehicle stock; 2) more differentiated methods that predict vehicle sales and distinguish several markets or customer categories; 3) the most differentiated techniques model people and integrate them for vehicle sales. Every analysis has found that by 2020, PHEVs will have captured a more significant percentage of the market than BEVs. This indicates the state of affairs in the world's largest auto markets, where PHEVs are selling at a premium due to their more excellent range. But as battery prices continue to drop, more powerful batteries could be within reach (Nykvist and Nilsson, 2015)- (Gallagher et al., 2014). In light of this shift, several analyses (Gnann, 2015; Liu and Lin, 2017) suggest that between 2030 and 2050, BEVs will have a more significant percentage of the market than PHEVs. However, this shift in finest has to coincide with either consumers' diminishing range concern or the capacity to recharge during long-distance travels.

As seen below, only two scenarios that project 2050 seriously consider the problems mentioned above. Both Pasaoglu et al. and Shepherd et al. omit to charge infrastructure from their model. Therefore, it cannot account for "restricted range variables" (Pasaoglu et al., 2016)- (Shepherd et al., 2012). Both studies have strong models, but these two elements will determine how quickly the BEV industry expands in the future. The emphasis on the most cost-effective option for the foreseeable is one criticism levelled at the fourth research out to 2050 (Yabe et al., 2012). It may be inaccurate to focus on price until 2050, as virtually all research
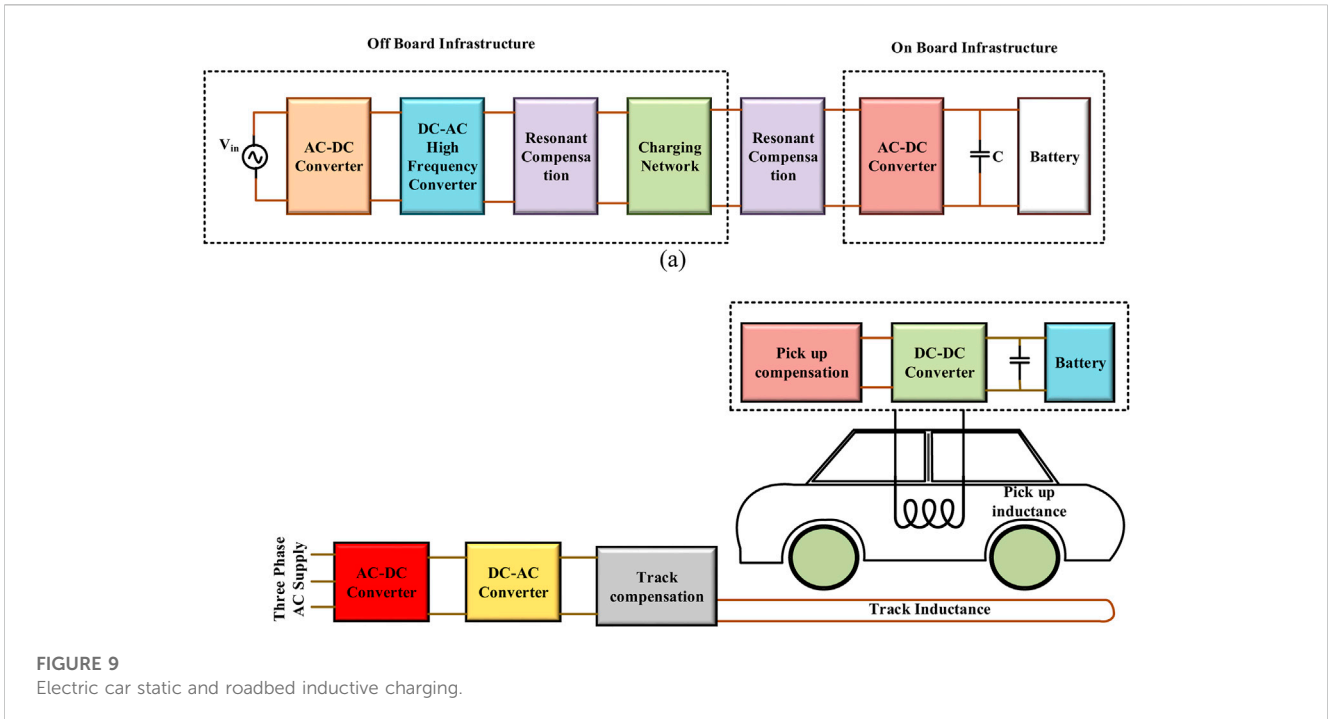
FIGURE 9
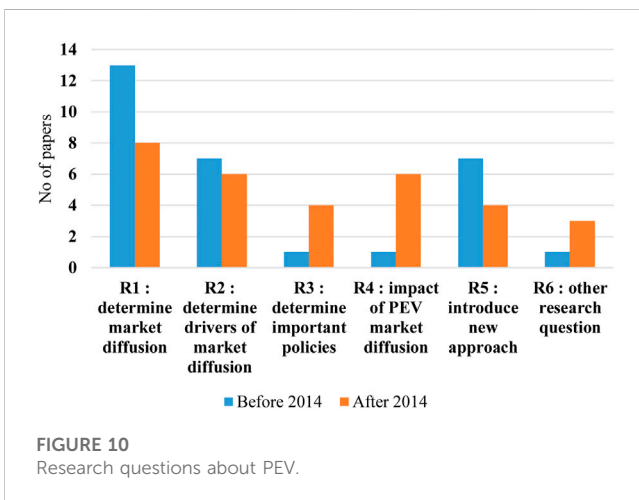Electric car static and roadbed inductive charging.

FIGURE 10
Research questions about PEV.

9 Repercussions of electric vehicle charging infrastructure

This section investigates the various electric grid components affected by EV chargers and discusses efforts to mitigate these effects.

9.1 Effects of utilizing alternative energy sources

Renewable energy sources are challenging for utilities to incorporate because of their intermittent nature. Still, advances in PEC and high-energy-density storage systems have resolved the problem of inconsistent power and made it less complicated to link EV chargers (Yabe et al., 2012). Wind energy resources that are linked to the utility grid are susceptible to being dispatched. It regulates the flow of energy when an electric vehicle is being charged or discharged. This approach is provided as an alternative. A similar strategy may be found in (FraukeHeider, 2009), which details an investigation into how to keep the power constant at the feeder while linking it to both electric vehicles and renewable sources (El Chehaly et al., 2009). The successful functioning of an isolated grid is demonstrated (Pecas Lopes et al., 2009). About 59% of the total utility grid generation capacity is accounted for by wind energy in this analysis, which involves 323 EVs (Xin et al., 2009; Bedir et al., 2010; Gamboa et al., 2010). Research demonstrating the viability of solar-powered EV charging is reported (Xin et al., 2009). This research accounts for the typical 40-mile commute that North Americans do in their SUVs daily.

on PEV market spread includes combating climate change and reducing GHG emissions as critical drivers of PEV industry diffusion. Although BEV market shares may rise significantly in the long run, projections beyond the next few years are highly dependent on several factors. Four groupings of qualities are included in the simulations to look at the specific characteristics more carefully and to develop recommendations for future modelling attempts: Considerations unique to PEVs include, but are not limited to, the following: (1) elements directly connected to the purchasing decision; (2) vehicle qualities that are included in the models; (3) characteristics to define customer traits; and (4) aspects specifically relevant for PEVs.

9.2 Effects on the reliability of the power system

Since many power grids are already suffering on the edge of instability, a stability study must be performed before increasing the electric vehicles. The EV demand is must be modelled as a continuous power demand, with the resistive load to identify the utility grid's reliability. The research concludes that modelling Electric vehicle charging stations as the constant resistance load since the integral to maintaining is higher, when the EV is treated as a continuous power load (Das and Aliprantis, 2008). Also, modelling EV chargers as the steady impedance load is preferable with artificial intelligence algorithms because the firm reliance is increased (Jingyu et al., 2010). The stability of the IEEE-24 bus system is analyzed with the aid of EVs employed as a power source (V2G mode), and it is observed that the usage of EVs as a power source assists in increasing the system's stability. So, it follows that EVs are better for the utility system's stability while they're the power supply, but they can cause significant problems when they're the load (El Chehaly et al., 2009).

9.3 Effects of source harmonics on the power system

The power electronics that are a part of the electric vehicle charger directly influence the harmonics that are produced by the charger. An elementary investigation has revealed that the design of the electric vehicle chargers is to blame for introducing a particular harmonic order into the electrical grid. The electric grid has demonstrated that it typically incorporates odd-order harmonics into its operations (Bradley, 1981). An investigation describes the design of electric vehicle chargers, which include regulated rectifiers and flattening line current inductors (Orr et al., 1982). Adjusting the control angle of the rectifiers demonstrates that it is possible to diminish or even eliminate the presence of the third harmonic in the line current. The architecture of the chargers at each of the 26 distinct charging stations is analyzed. The results demonstrate that the total harmonic distortion (THD) in the line current can range from 10% to 100%, depending on the architecture of the charger (Karady et al., 1994). Harmonics are introduced into the line current by electric vehicle chargers that are available for purchase, and the range of these harmonics is around 7%–99%. In addition, the results of this study indicate that it is possible to incorporate approximately fifty percent of EVs into the system without going over the voltage harmonics limit if capacitor banks are utilized. However, if capacitor banks are not utilized, it is only possible to incorporate thirty percent of EVs into the system (Staats, 1997). The dropout voltage of a transformer occurs primarily due to a decrease in its original current. It mainly relies on the amount of time the charging process is allowed to take. The total harmonic distortion of the line current has a quadratic relationship with the transformer's lifespan. The lifespan of a transformer is not significantly impacted when the THD is maintained between 25 and 30 percent of the total output.

9.4 Effects of losses on the power system

When electric vehicle load is incorporated into the existing distribution system, the losses in the power system are another significant factor to consider. During the off-peak charging time, the system experiences losses of around 40% when there is a penetration of EV load of 62%. It has also been demonstrated that the system's losses are proportional to the amount of EV demand and are not contingent on the geographic location (Bradley, 1981). The higher the load from electric vehicles, the higher the current in the system. As a result, the system sufferes from higher the losses across all utility system components, including transmission lines, transformers, etc.

10 Birds view

Initially, a motor provides propulsion in EVs rather than a mechanical or hydraulic shaft. Increasing the efficiency of a hybrid electric vehicle (HEV) can be achieved by carefully considering the optimal ICE and fuel cell or battery combination. PECs play an essential role in maximizing efficiency in the battery or fuel mode by making the right power converter choice. The input power and load requirements determine which converters are used. The number of components, control methods, and EMI effects all affect how well PEC works.

A critical factor in EVs' reliability is their electrical system's longevity. Consistently regulating the charging and discharging level with the aid of the voltage controller boosts the battery's lifetime. Semiconductor components determine how long PEC will last. The converter must be able to withstand excessive vibration and temperature. The difficulties arise when deciding on a converter that meets all your needs simultaneously: it must be very efficient, highly rigid, cheap, and compact.

One of the most challenging trends in today's vehicle system is the need for rapid and highly effective industrial motion control. High performance in EVs is accomplished by combining the PE method with digital signal processing.

Modern electric vehicles place greater emphasis on passenger conveniences. There is a specific minimum voltage requirement for each use case. Whether a multistage or multioutput DC-DC converter, it is a power source for DC appliances with varying ratings. The 3-ϕ inverter supplies energy to the AC load.

Traction motor health monitoring is as important as power conversion and propulsion regulation for spotting problems like faulty stators, rotors, and bearings. There is a need for robust actuators in advanced EVs to power systems like ABS and airbags. Future EVs may have better built-in safety measures thanks to the PEC with the DSP method.

The expense of the electrical system in EVs is defined by the number of inverter units and components used. The higher the luxury load, the more PEC is required to propel the car. The difficulty is reducing the vehicle's price by deciding on fewer power conversion units to handle more opulent loads.

11 Conclusion

The purpose of this concise study is to supply readers with more recent data on studies involving EV adoption with RE systems. Electric vehicles (EVs) have a lot of potentials to be the future of transportation and a saviour from the looming tragedies caused by global warming. The following recommendations are also provided for resolving the issues highlighted by this analysis.

- V2G is a prospective method that allows idle or parked EVs to act as dispersed resources that may store or generate power at suitable periods, allowing the grid and EV to interchange power.
- Improving asymmetric estimating methods and variable extraction approaches is essential for their usefulness in practice, accountability, and computing performance.
- To ensure long-term profitability and environmentally benign transportation, governments in practically all industrialized countries continually create new legislation to promote EV use.
- Battery life may be improved for many uses by developing estimation algorithms.
- The pace at which the EV battery may be charged or discharged is slow because of the power constraint of traditional silicon devices.
- The demand for faster and more powerful charging methods and more advanced inductive charging technology will increase as battery capacities increase.

This study addresses the currently available and commonly used architectures with back-to-back ac/dc/dc converters, constructions with multiple dc ports and a shared ac connection, and constructions without an isolation transformer. These buildings may be further classified by whether they use conductive or inductive charging. In addition, several forms of energy used by these structures are extensively outlined. This study delves deeply into several essential topics, including their adverse effects on renewable energy resources, the stability of the utility grid, the supply and demand balance, the assets of the utility system, voltage and phase, the current harmonics of the utility grid, and the utility system losses.

Data availability statement

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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