A review on unidirectional converters for on-board chargers in electric vehicle

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Transport is a vital sector for achieving sustainable development. The evolution of the electric vehicle is subject to the charging time, accessibility, and facility. On-board chargers are broadly used in the battery-electric and plug-in-electric fleets due to their easy installation and low cost. Also, it must be powerful and extremely efficient because of the constrained interior area and quick charging times. The minimization of hardware requirements and ease of interconnection problems are benefits of unidirectional charging. This review article presents an overview of charging levels, standards of chargers, and various topologies. On-board chargers pose a higher-power rating that reduces the anxiety of charging time and improves the charging facility on level-1 and level-2 grid supply. Unidirectional chargers reduce the charger size while other two-stage chargers pose a higher charging rate with various topologies. Finally, emerging charging trends in off-board charging, inductive charging, technology about vehicle-to-grid, wide-bandgap devices, and application of renewable energy uses are addressed.

KEYWORDS

solar energy, on-board charger, electric vehicle, battery charging, DC—DC converter

Highlights

- The electric vehicle charger type and the charging level are reviewed.
- The single-stage and two-stage on-board electric vehicle chargers of different converter topologies are described and compared.
- Charging and safety standards are briefly explained as also the future charging trends.
- Various commercial on-board chargers are listed and compared.

1 Introduction

Global warming is a big crisis in climate change and is hazardous to the environment. One of the reasons for global warming is exhaust gas from the IC engine vehicle and the air pollution in transportation. Also, the fuel shortage for vehicles, price, and demand for fuel are of great concern (Wirasingha et al., 2008; Ahourai et al., 2013). Green vehicles are solar-powered, electric vehicles, fuel cell vehicles, and hybrid vehicles help to mitigate air

TABLE 1 Electric vehicle charging level.

Power level	I/P Amps	I/P volts (V)	O/P power	Charging time	Place of use	Device	Charger connector standard
Level-1	12–16 A	120	1.3–1.9 W	4–11 h	Residential and workplace charging	On-board	SAE J1772
Level-2	80 A	240	Up to 19.2 kW	2–6 h	Residential, workplace, and public charging	On-board	SAE J1772
Fast charging	200 A	480	24–150 kW	20 Mins	Public charging	Off-board	SAE J1772 CCS CHAdeMO Tesla Supercharger

pollution and global warming (Cheng et al., 2014). The electric vehicle is one of the significant technologies for fossil fuels to save the environment and achieve energy sustainability (Pan and Zhang, 2015).

An electric vehicle consists of a battery, a powerful electronic device, and an electric motor for the propulsion system. A battery charging device is the most important subsystem of an electric vehicle (Vankayalapati et al., 2018). Electric vehicle charging technologies are categorized into battery swapping methods, conductive charging, and inductive charging. Battery swapping technologies are replaced once in a particular driving range but it needs a specific place. In the battery swapping technology, TESLA can charge the battery in 90 s (Tesla unveils, 2013). Currently, China is the leading country in battery swapping points (Chen et al., 2012). In conductive charging, an electric vehicle is charged at the charging station by connecting the vehicle to the power supply through the cable. The conductive charger is divided into on-board and off-board chargers. An on-board charger is a device that is mounted in the vehicle for charging the battery when it is in an idle condition. By considering the limitations of space and weight in the electric vehicle, a high-efficiency DC–DC converter with low cost is suggested. An on-board charger accomplishes the needs and yields attention due to the deficiency of a fast-charging station (Haghbin et al., 2011; Kim and Kang, 2014). An on-board charger enables the vehicle to charge at home, parking area, and charging station (Patil et al., 2012). It can charge the battery with wide variations of the voltage on the state of charge of the battery.

An on-board charger is used in battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) (Chae et al., 2010; Grenier et al., 2010). So, the on-board charger rating is 3–6 kW which belongs to a single-phase supply that is generally installed and it can be unidirectional or bidirectional (Gautam et al., 2012). This technology enables the EV to charge the battery from any available AC power source (Whitaker et al., 2014). A level-2 on-board charger needs an electric vehicle supply equipment device to provide a 240 V supply which is mounted on the wall (Li et al., 2014). On-board charger technology is also used in inductive power transfer while it acts as the receiver side and is mounted in the vehicle. Off-

board charging is called fast charging, and it charges the vehicle in a few hours. In an off-board charging method, a DC–DC converter is placed in a charging station that provides DC power to the vehicles through cables (Tao et al., 2019). It is not limited in size and weight but it needs added cost for infrastructure to implement the number of charging station (Ghorbal et al., 2012). The fast-charging station is available with high EV mobility (Berjoza and Jurgena, 2015). Off-board chargers decrease the lifespan of battery life when compared to an on-board charger (Yilmaz and Krein, 2013). The grid to vehicle (G2V) and vehicle-to-grid (V2G) technologies are popular in electric vehicle charging that electric vehicle can charge the battery from the grid as well as discharge to the grid during peak demand on the grid by the bidirectional charger (Tuttle and Baldick, 2012). Battery chargers can make harmful harmonic effects such as low power quality, poor power factor, and voltage distortion on the grid system (Sul and Lee, 1995; Bojrup et al., 2002) but it is mitigated by an active front-end rectifier in the chargers (Masoum et al., 2010; Lee et al., 2011). The solar-powered electric vehicle has been intended by car manufacturers, such as Tesla, Audi, and Toyota, and a solar-powered EV developed by NEDO, Sharp, and Toyota companies has been publicly tested since July 2019.

2 On-board charger-based electric vehicles

Level-1 and level-2 charging standards use single phase and three phases of AC grid supply. Level-2 needs dedicated private and public facilities with dedicated equipment for home or public charging whereas level-1 did not need dedicated equipment. Level 3 is the DC charging method and it is used for commercial applications. Different power levels (Yilmaz and Krein, 2013; Jain and Kumar, 2018) of electric vehicle charging are shown in Table.1.

The EV is classified into FCV, PHEV, and BEV in Figure 1, (Khaligh and Li, 2010). Among these, the BEV and PHEV are charged by the battery from the AC and DC outlets. A BEV may be an automobile or a truck that derives all motive force from the battery itself without the assistance of another engine. Such as a

FIGURE 1
Classification of electric vehicles.

FIGURE 2
Plug-in hybrid electric vehicles (Ahourai et al., 2013).
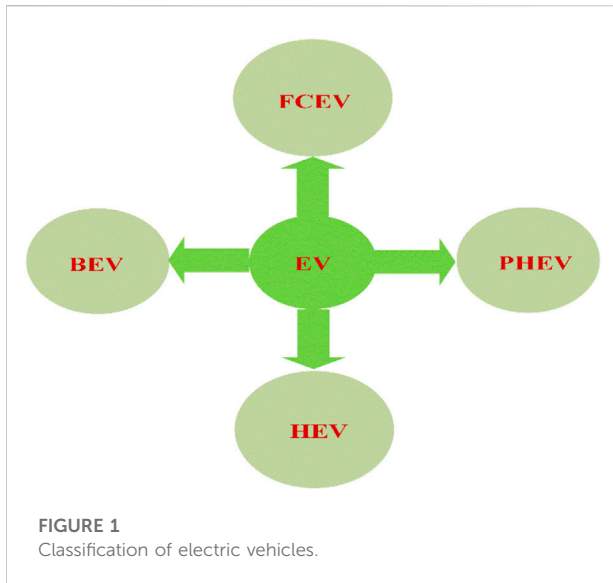
fuel cell or IC engine charging of the battery needs an external power source terminal (Dell et al., 2014). Typically, they can cover 100–250 km on a charge whereas top-tier models can go a lot further from 300 to 500 km (Grunditz and Thiringer, 2016). All of Tesla's models are Nissan Leaf, Chevy Bolt, and Jaguar I-Pace.

A plug-in hybrid electric vehicle, Figure 2, (Jain and Kumar, 2018), uses both an internal combustion engine (ICE) and an electrical power train such as an HEV. But the difference between them is that the PHEV uses electric propulsion as the main driving force, so this vehicle requires a bigger battery capacity than HEVs (Un-Noor et al., 2017). PHEVs offer higher fuel economy than HEVs and ICEVs, up to 133 miles per gallon of gasoline equivalent (Diaz, 2021). PHEV batteries can charge by plug-in at an AC outlet and by regenerative braking in an ICE engine (Blau, 1998). A plug-in hybrid electric car emits less than an average global ICE vehicle using gasoline on a life-cycle basis (IEA, 2019).

3 Types of electric vehicle chargers

Electric vehicle chargers are categorized into the on-board charger, off-board chargers or fast chargers, and inductive chargers in Figure 3.

3.1 On-board chargers

The OBC charger classifies into two stages, that is, topology and single-stage topology. The two-stage charger consists of a PFC rectifier to get a good power factor and a DC–-DC converter to control the output voltage and provide galvanic isolation (Choi
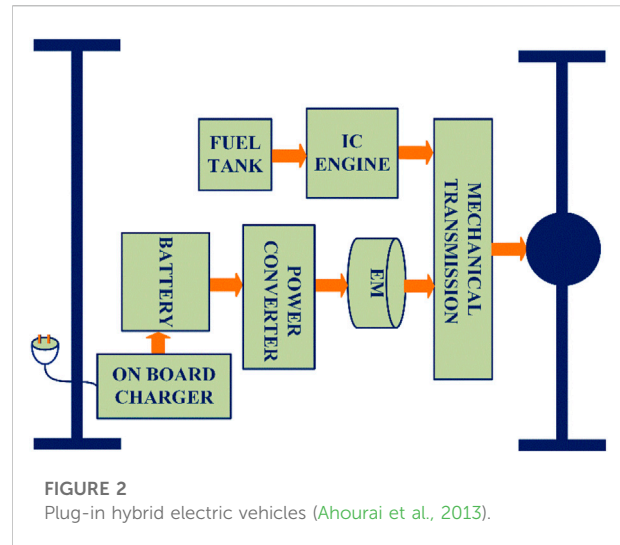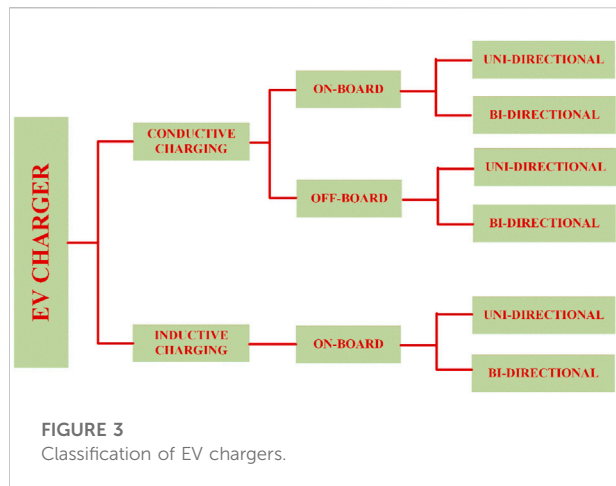
et al., 2014; Lee and Chae, 2014; Wang et al., 2014). The on-board charger for AC supply is level-1 and level-2 as defined in SAE J1772 (Ucer et al., 2019). Level-1 and level-2 on-board chargers utilize the supply range of (120–240 V AC) and provide a high power of 1.9 and 19.2 kW (IEC 61851-23:2014, 2014) and this range of power supply is available in residential and public. When the OBC connects to a single-phase supply, a larger power oscillation at a double-line frequency (Li et al., 2013a) generates at the diode bridge rectifier, which would disappear when connecting to a three-phase power supply. The on-board charger should meet the harmonic regulations and standards of IEC 6100-3-2 and IEEE 519 for high-power quality (IEC 61000-3-2:2018+AMD1:2020, 2020).

3.1.1 Multifunctional on-board charger

A multifunctional single-phase on-board EV charger with a new unified control system supports the main functions of V2G/G2V and ancillary functions such as reactive power support, harmonic reduction, and voltage regulation simultaneously in a residential power system (Taghizadeh et al., 2018). In study of Taghizadeh et al. (2020), they proposed an on-board charger design for an EV that can charge the EV from another vehicle using the vehicle to vehicle charging method (Verma et al., 2020a). Solar PV is connected with grid to meet the domestic load, G2V, G2H in islanded mode, and V2G operation.

3.1.2 On-board integrated chargers

Integrated OBCs use driving circuit components such as the electric motor, and the inverter, for battery charging instead of a dedicated charging circuit with large passive components (Shi et al., 2017a). The motor windings are utilized as the propulsion inverter filters, galvanic isolation, and bidirectional DC/AC converter cum inverter. This technique has developed as an optimum dealing between on-board and off-board battery

FIGURE 3
Classification of EV chargers.

FIGURE 4
On-board charger block diagram.

that induces the power in the transmitting coil which charges the battery. To maximize the transferred energy, both coils should be near and well-aligned (Miller et al., 2015). IPT consists of a transmitter converter on the primary side, magnetic coupling coils, and a receiver converter on the secondary side with the on-board charger facility (Hasan et al., 2015; Shi et al., 2017b). Dynamic inductive charging is quickly becoming trending research on EV charging (Shin et al., 2014) and has been implemented in Nissan Magnite, Renault Kiger, and Hyundai Aura cars. Inductive chargers are categorized into three types that are microwave radiation, electric field couple, and magnetic field couple (Mayordomo et al., 2013; Sasaki et al., 2013; Dai and Ludois, 2015). It has advantages of safety, convenience, flexibility, weather immunity, and the possibility of range extensions (Wang et al., 2005; Khaligh and Dusmez, 2012).
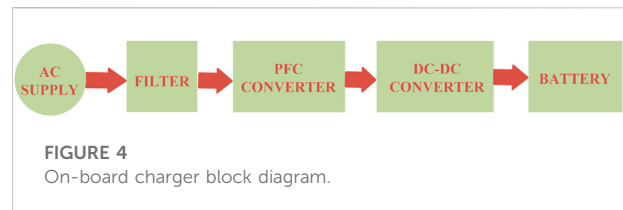
chargers. The efficacy of this technique includes various technical criteria, namely, limited and no winding reconfiguration with zero average torque and torque ripple production throughout the charging process. The aforementioned characteristics will be heavily influenced by the motor type, number of phases, and power converter used (Xiao et al., 2019).

3.2 Off-board charger

It delivers DC power to the EV battery through the cable from an isolated power converter located outside (Tu et al., 2019). Off-board chargers consist of two stages, the first stage is an AC–DC converter and the second stage is a DC–DC converter (Seth and Singh, 2021). Off-board charger offers more power than an on-board charger in the range of 50 kW (Celli et al., 2014). The SAE International has drafted the fast charger configurations with DC voltage of up to 600 V and a current of up to 550 A to charge EVs within the acceptable time (Tan et al., 2016a). The most popular converter topologies are Vienna rectifier (Channegowda et al., 2015), multilevel neutral point clamp chopper (Rivera et al., 2015), and interleaved converters (Abusara and Sharkh, 2013). The aforementioned converters can be made in either unidirectional topology (G2V) or bidirectional topology (G2V and V2G) (Chaurasiya and Singh, 2019). According to the study of Nachinarkiniyan and Subramanian (2020), solar PV enabled a fast-charging station, steadily charging the battery irrespective of the radiation.

3.3 Inductive chargers

An inductive charger is a choice for both on-board and off-board chargers in present days (Feng et al., 2020).The inductive charger works on electromagnetic induction between two coils kept nearby. Receiving coil produces the varying magnetic field

3.4 Hybrid chargers

Charging the electric vehicle through the grid with a solar PV energy source is credible for battery charging and saving time (Guru Kumar et al., 2019). The algorithm is used to monitor the battery parameters with solar PV panels to ensure battery health and efficiency while charging under CC–CV (Padmagirisan and Sankaranarayanan, 2019). Inductive and PV combinedly charge the battery using a dual input boost converter (Kamalapathi et al., 2021). In the study of Kumaravel et al. (2019), dual input and dual output converters operate in multiple energy storage sources to charge the battery as well as power the grid.

4 On-board charger topologies

On-board chargers are classified into unidirectional and bidirectional chargers. The unidirectional chargers permit the G2V technology; bidirectional chargers support both the G2V and V2G technology. The on-board unidirectional EV charger block diagram is shown in Figure 4.

4.1 Single-stage unidirectional chargers

The DC–DC converter followed by an AC–DC diode rectifier is called a single-stage charger and its details are shown in Table 2. The single-stage charger is used for the need of lower

TABLE 2 Single-stage unidirectional converter summary.

| Input volt	Output power	p.f	Switch	Diode	Inductor	Capacitor	Efficiency	T.H.D	Switching frequency	Battery capacity	Charging mode	Charging type
55–85 V (Mishra et al., 2020)	120 W	0.99	3	5	2	3	97.2%	4.5	20 kHz	26 Ah	PIC, RB	CC
200 V (Jeong et al., 2016)	2 kW	0.99	2	2	2	4	96.2%	—	50 kHz	—	PIC	—
240 V (Patil and Agarwal, 2016)	1 kw	0.99	4	5	2	4	91%	—	50 kHz	—	PIC	CC
240 V (Gupta et al., 2020)	3.2 kW	0.99	2	6	5	2	97%	4.4	5 kHz	48 Ah	PIC	CC, CV
85–65 V (Praneeth and Williamson, 2019)	1 kW	0.99	2	6	2	2	96%	4.3	—	—	PIC	—
220 V (Verma et al., 2020b)	100 W	0.99	4	4	2	3	—	—	70 kHz	22 Ah	PIC, RB	CC, CV
220–60 V (Gupta et al., 2021)	850 W	0.98	2	4	2	1	87%	2.7	20 kHz	100 Ah	PIC	CC, CV
200–260 V (Dusmez and Khaligh, 2013)	8.4 kW	0.99	4	4	1	1	91.6%	—	20 kHz	—	PIC, RB	CC, CV
110–150 V (Singh et al., 2020)	800 W	0.99	3	4	3	3	95%	4.4	20 kHz	26 A h	PIC, RB, PV	CC
40–70 V (Singh and Pathak, 2018)	115 W	0.99	3	4	2	3	96%	7.2	20 kHz	26 A h	PIC, RB	CV
207–253 V (Zinchenko et al., 2021)	3 kW	0.99	10	4	1	1	95%	4.1	50 kHz	—	PIC	CV-CP
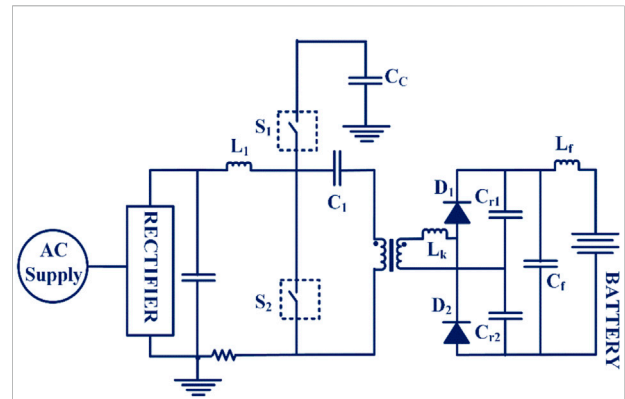
FIGURE 5
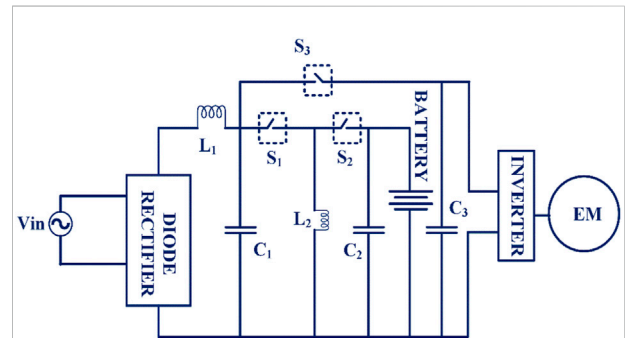Single-stage resonant converter charger.

FIGURE 6
Single-stage non-isolated PEV charger.

cost and in size (Lee et al., 2019). It permits the removal of huge components and costly components such as inductors and DC-link capacitors (Mishra et al., 2020) used in two-stage chargers. For the power factor correction, many diodes and active switches are needed and cause circuit complexity. But the single-stage charger is too simple and lower cost (Egan et al., 2007; Lu et al., 2008). The single-stage battery chargers with non-isolated converters are affected by a limited conversion ratio, which limits their application for the wide range of output voltage. The lower frequency component is generated by the rectification stage (Kim et al., 2016) and causes the larger magnetizing current in the high-frequency transformer. The single-stage battery charger is based on a diode-clamped series-resonant converter proposed in Yoon et al. (2013) and it achieves high power with a good power factor but low efficiency. The electrolytic capacitor-less in Jeong et al. (2016) overcomes the single-power-conversion OBC comprises a step-up AC–DC converter with an active-clamp circuit and a series-resonant circuit Figure 5. For power factor correction, an active-clamp circuit recycles the transformer stored energy. The series resonant circuit enables fast turn on and

off time of the output diode and the output power level-1 (i.e.,) 350 V.

The single-stage non-isolated buck–boost charger Figure 6 is used for light electric vehicles to charge the battery from the grid supply during plug-in and regenerative braking. By using non-linear carrier control (NLCC) techniques, circuit size is reduced as well as feedback circuit complexity with the improvement of PFC at the gird side (Mishra et al., 2020). A single-stage resonant converter (Li et al., 2013b) transfers the input supply to the battery along with leakage inductance energy. Since charging a battery in a sinusoidal-like direct current (Youn and Lee, 2011; Yoo et al., 2013), input AC power goes to the battery side directly, without an energy buffer such as a DC-link capacitor. PFC is realized by keeping the switching frequency constant while switches obey zero current switching conditions. In this topology, a bulky inductor and DC-link capacitor are not used. A compensator proposed in Patil and Agarwal (2016) reduces the battery ripple current without bulk filter components and complicated control. A current ripple compensator, that is, CUK converter connects the series with the battery to reduce the battery ripple current. Boost and zeta converters are connected in a cascaded form, and a capacitor is connected between them. That capacitor stores the energy when ripple current is more than the average output and delivers the stored energy when the ripple current is less than average. Both converters operate in CCM mode which reduces current and voltage stress across devices. The three-level SEPIC-derived DC–DC converter provides better PQ features for battery charging and lowers the reverse recovery losses of the output diode with less voltage stress (Gupta et al., 2020). The conventional current control scheme with an additional duty ratio makes the input impedance of resistive nature so that the power factor is near to unity with less total harmonic distortion (THD) at the input supply.

In the study of Praneeth and Williamson (2019), they proposed non-isolated OBC-operated independent PWM for buck and boost mode to retain good input power quality. A two-mode average current-mode control is designed to operate in a wide output voltage range with high input power quality. The control logic block enables the independent control of PWM for boost and buck switches that consists of a comparator, switch block, and logical gates. The transition of the boost to buck mode and vice versa depends on the demand for output voltage. When low input voltage losses are high and high total harmonic distortion at the input, in this context, charging the battery through not only in the plug-in mode but also through regenerative braking and PV charging which are both conducted in on-board chargers. For regenerative braking to charge the battery in a single-stage unidirectional charger with fewer switches, an effective control technique is given.

Though the single-stage chargers have high input power quality, it contains the low-frequency ripples that worsen the battery performance and decoupling circuits are required to
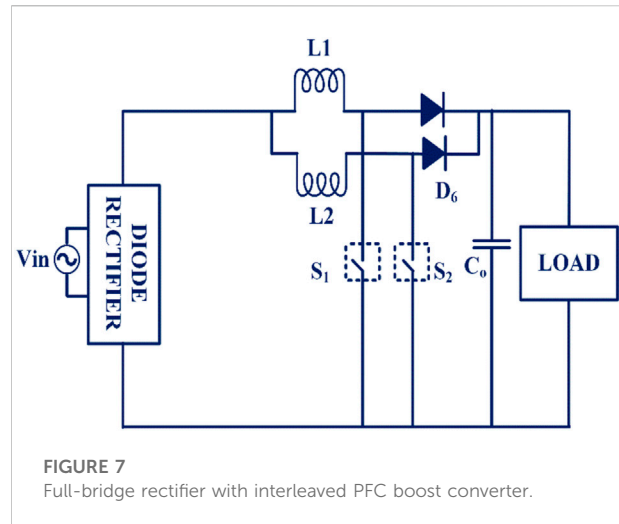

FIGURE 7
Full-bridge rectifier with interleaved PFC boost converter.

suppress the second harmonic effects. It leads to complex controller design and higher-order systems in controller design. The uncontrolled rectifier causes the accountable conduction loss as challenges of single-stage charger and output power, charging mode, and harmonic distortion which are shown in Table 2. The power ratings of single-stage unidirectional chargers are needed to improve for heavy vehicle charging in either one method that reduces the battery performance.

4.2 Two-stage unidirectional chargers

4.2.1 Power factor converter

The conventional EV charger consists of a diode bridge rectifier and has adverse power quality issues due to nonlinear input (Kushwaha and Singh, 2020). A two-stage AC–DC converter prefers better PQ in an EV charger since it has some limitations that the additional switching circuit and control circuitry (Kushwaha and Singh, 2019). A front stage is a rectifier circuit with a power factor correction (PFC) boost converter to attain a high-power factor and less harmonic distortion (Mc Donald and Lough, 2021). The rectifier level can be a half-bridge, full-bridge, or multilevel diode bridge. A half-bridge rectifier has a low cost since it has a smaller number of diodes/switches. The diode bridge rectifier is more complex and the components are subjected to lower stresses (Musavi et al., 2011a). The multilevel configuration gives a high-power rating to the AC–DC converter.

A bidirectional power flow can be obtained by replacing all the diodes with active switches. The interleaved topology is preferable in power factor converters. The interleaved boost converter is proposed (Hu et al., 2018) with a lower peak current and less ripple at the output voltage. As shown in Figure 7, an interleaved boost converter consists of two boost

FIGURE 8
Buck–boost PFC converter.

FIGURE 10
Totem-pole PFC.

FIGURE 9
Bridgeless PFC converter.
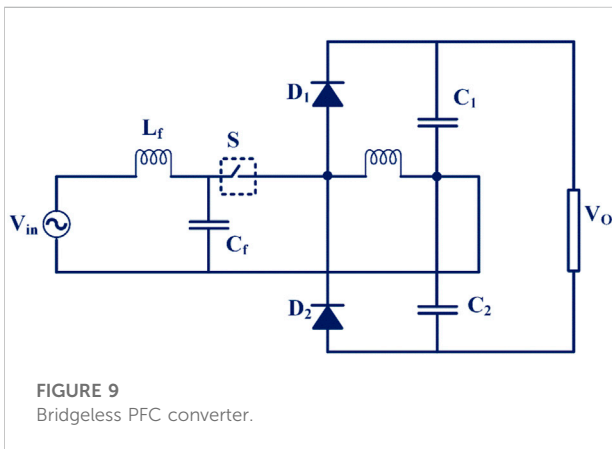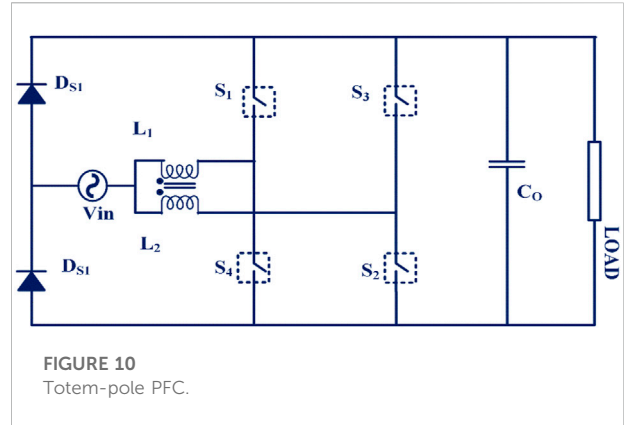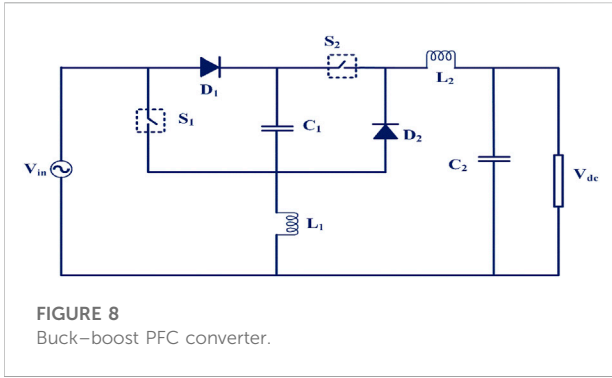
converters in parallel, operating 180° out of the phase (Lee et al., 2000). The interleaving method reduces the input current ripple and improves the output voltage, and also reduces the size of the EMI filter (Hu et al., 2017). The two-switch buck–boost cascaded PFC converters can give the output voltage less and above the given input voltage (Praneeth et al., 2019) and variable DC-link voltage provides the smooth transition between a buck to boost mode and vice versa Figure 8. This PFC converter with DC–DC converter gives a wide range of output voltage with a good power quality at the input.

The diode bridge and PFC boost converter are the lossy networks in conventional active front-end topology (AFE) as it uses diode bridge and AFE work in a CCM mode. This topology needs the PLL circuit to synchronize with the grid and control complexity with more devices (Musavi et al., 2011b). Unless a conventional bridge rectifier PFC converter is used, the single bridgeless buck–boost converter in Figure 9 connected with a voltage doubler circuit connects with a DC–DC converter that operates in DCM to attain PFC for wide input voltage variation (Dixit et al., 2020).

Despite more merits such as lower voltage stress, reduced number of sensors, soft turn-on of switches, and lower control complexity, it needs high-rated switching components. Since

the bridgeless totem-pole PFC in Figure 10, output is connected with input by a slow diode and half-line, and no CM interference occurs. It has the capacity of bidirectional conversion and also achieves ZCS throughout a wide range of loads with a low line input (Su and Lu, 2010). In Table.3, the PFC converter operates under the boost mode and suffers from high voltage stress with less efficiency, the interleave converter shares the stress but control complexity is more by adding the more networks.

4.2.2 DC-link capacitor

The input supply frequency ripple determines the DC-link capacitor size (Singh et al., 2017) that is needed for energy storage when the charger delivers direct power (Xue et al., 2013) and connects between the active front-end devices and DC–DC converter topology (Xue et al., 2015). Since the DC-link capacitor is an electrolytic capacitor and has a short lifespan, it is not preferable for on-board chargers. The DC-link capacitors size has been reduced by sinusoidal charging techniques for the battery so that it does not have a considerable impact on battery life degradation (Prasad et al., 2015). A thin-film capacitor is an alternative to electrolytic capacitors that is too expensive and bulky (Li et al., 2013b). The feed-forward controller and repetitive algorithm, as well as advanced control techniques, can remove distortion in output current such that the size of the DC-link capacitor can be low in size.

4.2.3 DC–DC converter topologies

Currently, high switching frequencies at the 10 kHz DC–DC converter are widely used (Shin and Lee, 2014). Despite many merits of high switching frequency such as less volume, it has many problems such as increasing EMI, switching loss, and less efficiency (Tao et al., 2019). To overcome these problems, soft-switching technologies are preferred which are ZVS, ZCS, and LLC (Chen, 2011; Hariya et al., 2016). The drawback of PSFFB is the loss of ZVS function at light load and the duty cycle problem (Wang et al., 2017).

TABLE 3 PFC converter summary.

| Input volt	Output power	p.f	Switch	Diode	Inductor	Capacitor	Efficiency	T.H.D	Switching frequency	Operation	Converter topology
110 V (Dixit et al., 2020)	1 kW	0.99	1	2	3	2	96%	3.1	50 kHz	DCM	Bridgeless boost converter
220 V (Xu et al., 2019)	3.3 kW	0.96	2	4	4	1	97.6%	—	80 kHz	DCM, BCM, CCM	Interleave boost converter
230 V (Singh and Kushwaha, 2019)	—	0.99	2	2	4	1	85%	3.9	20 kHz	DCM	Bridgeless CUK
220 V (Kushwaha and Singh, 2020)	850 W	1	2	2	2	3	—	1.8	20 kHz	DCM	Bridgeless LUO converter
230 V, 430 V (Zhao et al., 2020)	3 kW 10 kW	0.99	6	—	2	2	97%	1.99%	50 kHz	–	Universal converter
230 V (Itoh et al., 2020)	3 kW	0.99	—	2	—	1	95.4%	3.49%	50 kHz	DCM	Interleave Totem pole
230 V (Shipra et al., 2021)<	2.8 kW	0.99	2	2	1	2	95.7%	3.17	5 kHz	—	DBR boost converter
120 V (Dutta et al., 022)	1 kW	0.99	1	2	2	1	94%	3.49	50 kHz	DCM	Bridgeless-CUK converter
230 V (Praneeth and Williamson, 2022)	1 kW	0.99	2	1	2	2	97.4%	2.5	30 kHz	—	DBR boost converter
160–260 V (Kushwaha and Singh, 2022)	760 W	0.99	2	4	0	1	91.75%	3.6%	20 kHz	DCM	Isolated half-bridge converter
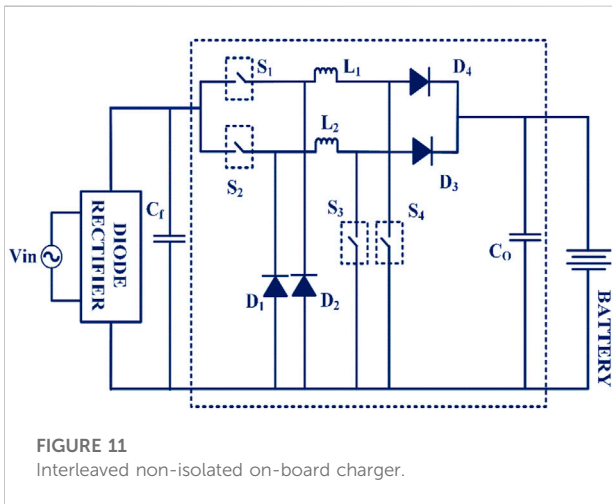
FIGURE 11
Interleaved non-isolated on-board charger.

4.2.3.1 Interleaved topologies

The interleave converter proposed with a synchronous PWM signal causes high inductor current on buck mode and hence conduction loss is more. In the study of Kim and Lee (2017), they proposed the converter Figure 11 which is a single-stage converter that improves system efficiency in the step-down by the asymmetric control algorithm. The asymmetric algorithm controls each switch asymmetrically using a phase-shift control. The inductor is designed based on the algorithm that reduces the size and inductance value and reduces the inductor ripple current. The proposed converter needs two clock counters to generate the PWM signal for buck switches. It made additional circuits to the converter than the conventional synchronous algorithm.

4.2.3.2 LLC resonant converter topologies

The LLC converter has the feature of soft switching under wide load variation. As a result, the rectifying diode experiences the low-voltage stress and there is no need for snubber circuits. However, it causes low efficiency at light load due to high-switching frequency. The charger has to charge the battery in a wide voltage range, a converter designed to meet high voltage gain. As a result, a large conduction current makes conduction loss. The LLC converter supports a wide output voltage with good efficiency. However, it suffers from the size of the resonant components. Hence two small transformers connected in parallel-series forms with a half-bridge LLC (Lin and Dong, 2011) improve the power density and fail to support high
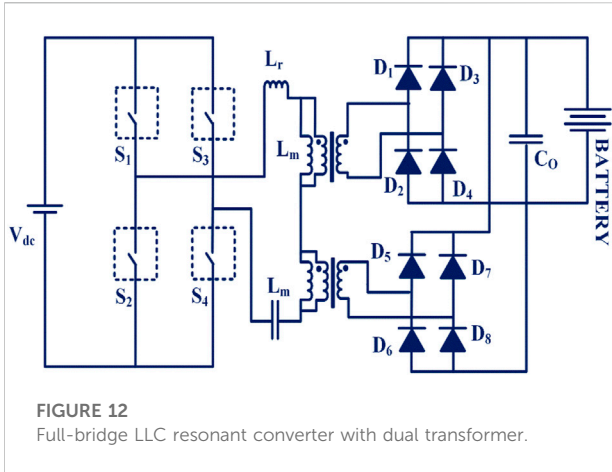
FIGURE 12
Full-bridge LLC resonant converter with dual transformer.

input voltage and high power. In the study of Shen et al. (2018), a full-bridge LLC Figure 12 with two same transformers is series-connected at the primary side to obtain the same primary side current and parallel-connected at the secondary side to get the same secondary voltage so that power is equal between these two transformers. The size of the transformer reduces as well as the cooling of the transformed is improved. But voltage stress on the diode is gradually reduced when the output voltage reaches maximum.

In the study of Ta et al. (2020), the dual LLC converter consists of the wide-bandgap device with two transformers connected in series and it is secondary connected with a voltage doubler rectifier circuit. To improve the light load efficiency when the output voltage is half of the rated input, one phase LLC only turns on while the other is off in a dual-phase structure converter. ZVS switching is realized in all three modes of operation so that the converter weight and size can be reduced. The leakage inductance is not equal in two transformers which causes an imbalance in transformer current during the converter operation and converter topologies, output power is depicted in Table 4 and the LLC converter frequency ranges are depicted in Table 5.

TABLE 4 Two-stage unidirectional converter summary.

Topology	Output power	Pf	Efficiency	Device	Switch	Diode	Isolation	L	C	No of transformer	Modulation technique
Interleaved (Kim and Lee, 2017)	3.7 kW	—	97.29%	Si	6	8	Non-isolated	2	2	—	PWM
Interleaved (Ahmed et al., 2022)	8.2 kW	—	98	Si	7	9	Non-isolated	5	2	—	PWM
LLC (Shen et al., 2018)	3.3 KW	0.98	96.31%	Si	4	8	Galvanic Isolation	2	2	2	PFM
LLC (Ta et al., 2020)	3.2 kW	—	98.5%	GaN	4	4	Galvanic Isolation	4	3	2	FBFM
LLC (Kim et al., 2019)	1 kW	—	96.4%	Si	4	4	Galvanic Isolation	1	2	1	PFM
LLC (Zhao et al., 2018)	2 kW	—	93.7%	Si	2	4	Galvanic Isolation	1	2	1	PFM
LLC (Nachankar et al., 2022)	1.25 kW	—	96.02	Si	4	4	Galvanic Isolation	1	5	1	Duplex control
LLC (Zhao et al., 2022)	3.7 kW	-	97.45	SiC	4	4	Galvanic Isolation	1	1	1	PWM
Hybrid (Kim and Lee, 2016)	6.6-kW	—	97.90%	Si	4	4	Galvanic Isolation	3	2	1	PWM
Hybrid (Lee, 2016)	3.3Kw	—	98.09%	Si	4	2	Galvanic Isolation	2	3	1	PWM
Hybrid (Choi et al., 2018)	6.6kw	0.99	97%	Si	4	6	Galvanic Isolation	1	1	1	PWM
PSFB (Tao et al., 2019)	600 W	—	95%	Si	6	2	Galvanic Isolation	2	1	1	PWM
PSFB (Kim et al., 2012)	3 kW	—	93.12	Si	4	2	Galvanic Isolation	2	1	1	PWM
PSFB (Hu et al., 2022)	3.3 kW	—	97.2	Si	9	4	Galvanic Isolation	4	2	1	ZVS PWM

TABLE 5 LLC converter frequency range summary.

| Switching frequency f_s	Resonant frequency fr (kHz)	Lm	Resonant inductor Lr	Resonant capacitor C_r
75–300 kHz (Shen et al., 2018)	220	120 µH	13.5 µH	81.6ηF
75–160 kHz (Ta et al., 2020)	110	73 µH	14.6 µH	120ηF
29.8 kHz (Kim et al., 2019)	28	500 µH	98 µH	0.33 µF
30–100 kHz (Zhao et al., 2018)	37	1.2 mH	0.18 mH	0.1 µF
150–500 kHz (Zhao et al., 2022)	350	62.8 µH	15.7 µH	13.15 ηF
104.119 kHz (Nachankar et al., 2022)	102.5	954 µH	51.29 µH	0.047 µF
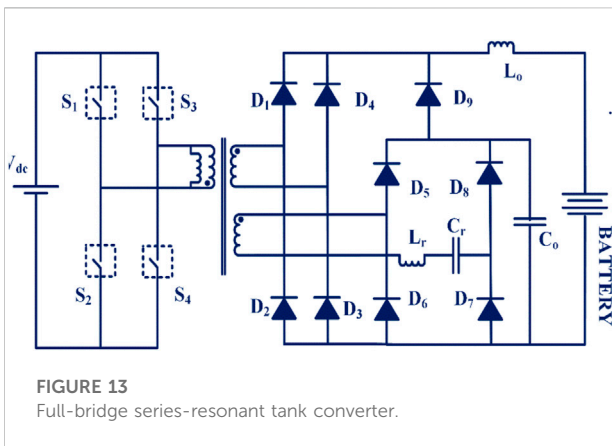
FIGURE 13
Full-bridge series-resonant tank converter.

The dual transformer improves voltage gain through control complexity but the cost is high.

4.2.3.3 Hybrid topologies

In the study of Kim and Lee (2016), a full-bridge converter and a resonant converter are coupled with a transformer to form the hybrid converter shown in Figure 13. Among the two-way power flow to the battery, one is from the full-bridge operation; another way is series resonance with the diode when full-bridge power becomes zero. So that it improves the converter gain, and reduces turn-off voltage spikes across the diode due to transformer leakage inductance and junction capacitance that improves the converter efficiency. Since the hybrid converter uses a low rating of rectifier diodes at the full-bridge side with fewer turns of the transformer, the snubber circuit can avoid. On the secondary side of the converter diode, components are high.

In the study of Lee (2016), PSFB combined with LLC converter is used for on-board charger reducing the circulating current with the fixed switching frequency. The energy recovery circuit overcomes the ZVS lagging leg problem and reduces the large circulation current by rectifying the diode. The size of the two transformers is less when compared with a single transformer because the utilization of two transformers is high compared with a single transformer with the same power capacity. Using the constant current and voltage algorithm methods, battery is charged and controlled by two PI controllers. In the study of Choi et al. (2018), a hybrid PWM DC/DC converter comprising a full-bridge converter with the resonant converter is proposed. Switching characteristics are similar to the PWM resonant converter. Transformer leakage inductance utilizes a resonant inductor that eliminates voltage spikes produced by the diode junction capacitance. The proposed charger does not need a dissipative snubber circuitry and output filter. The efficiency of the charger is slightly low when it reaches the rated load and the switching frequency is shown in Table 6.

4.2.3.4 Phase-shift full-bridge topologies

In the study of Tao et al. (2019), the proposed improved ZVS phase-shifted full-bridge DC/DC converter Figure 14 utilizes the clamping diodes in both the primary and secondary sides of the transformer to eliminate the voltage oscillation and improve the soft-switching range. Synchronous rectification in transformer secondary is to improve efficiency. Changing the switching frequency can increase the phase-shift angle under light load and decrease the phase-shift angle under heavy load to reduce circulating energy and keep ZVS on. To minimize the circulating current losses, the duty cycle method, fundamental component approximation, and optimal phase-shift ratio are used. On the other hand, the minimum amount of circulating current is used to achieve ZVS on.

The current doubler circuit is used at the output of the converter that minimizes the current ripple and current ratings (Kim et al., 2012). The current doubler circuit is minimizing the secondary current rating of the transformer, and the effective frequency of the output capacitor is twice the switching frequency. The magnetic loss of the transformer is increasing for a wide range of battery charging. Electrolytic capacitors present in two-stage chargers jeopardize system reliability because of the short life which is used for DC-link. The voltage doubler configuration has been proposed to reduce secondary component voltage stress by up to half of the output

TABLE 6 Hybrid converter frequency range summary.

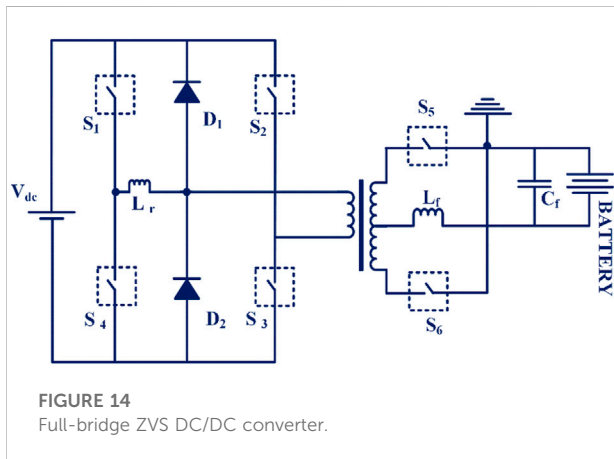| Switching frequency f_s	Resonant frequency f_r	Filter inductor L_o (µH)	Resonant inductor Lr	Filter capacitor C_o (µF)	Resonant capacitor C_r
50 kHz (Kim and Lee, 2016)	286 krad/s	130	15.3 µH	10	—
100 kHz (Lee, 2016)	100 kHz	250	17.75 µH	450	100 µF
50 kHz (Choi et al., 2018)	235 krad/s	65	—	200	500ηF

FIGURE 14
Full-bridge ZVS DC/DC converter.

voltage. Because this configuration increases the number of transformers, separating the battery stack into two modules is an alternative method.

5 Charging standards and safety standards

United States–based electric vehicle manufacturers are following the Society for Automobile Engineers (SAE) and IEEE standards while the European countries follow the International Electromechanical Commission (IEC). Japan has its EV charging standards named Japan Electric Vehicle Association (JEVS). The electric vehicle standards and safety standards dealing with both AC and DC charging with supporting equipment are depicted in Table 7.

Most EV firms are unwilling to release comprehensive topology details about their bidirectional OBCs due to privacy concerns shown in Table 8 and from the research article, various charger topology performances are shown in Table 9.

In Table 10, benefits of unidirectional chargers include a reduction in total PFC circuit components and reduced cost and enhanced functionality such as adjustable power factor

TABLE 7 Standards of electric vehicle charging and safety.

Organization	Standard	Detail
IEC (Das et al., 2020)	IEC 61851	EV conductive charging about on-board and off-board charging devices such as socket outlet of AC and DC charging
	IEC61980	Supply voltage level AC and DC
	IEC 62196	Standards for plugs, socket-outlets, vehicle connectors, and vehicle inlets that are used for conductive charging
SAE (Falvo et al., 2014)	SAE J2293	Standards for on and off-board charging equipment for conductive and inductive charging
	SAE J1772	Equipment current and voltage ratings for EV charging for AC and DC charging
	SAE J1773	Standards for minimum requirements about manually connected inductive charging
	SAE J2847 and SAE J2836	Communication requirements between an EV and the charging infrastructure
	SAE J2931	Requirements for digital communication between EVs, EVSE, utility, energy service interface, advanced metering infrastructure, and home area network
NFPA (A NFP, 2017)	NFPA 70	Instructions on electrical equipment wiring and safety on conductors and electric vehicle supply equipment installed for EV charging and grid integration
IEEE (Basso et al., 2015; Habib et al., 2018; Std, 2030)	IEEE P2690	Charging N/W management practice for EV charging systems
	IEEE 2030.1.1	DC fast charging in electric vehicles from grid
	IEEE 1547	Interconnection and interoperability between utility electric power systems (EPSs) and distributed energy resources (DERs)
JEVA (Habib et al., 2018)	JEVS C601	Plugs and sockets for EV charging
	JEVS D701	Testing procedure for battery
	JEVS G101-109	EV fast charging

TABLE 8 Commercial on-board charger summary.

Name	Output power	Efficiency (%)	Input voltage	Output voltage	Input current	Output current	Power factor	Weight (kg)
BRUSA (On-Board Charger NLG667, 2021)	22 kW	94	360–440	310–430 V	32 A	60 A	0.99	11
FICOSSA (On board charger-ficosa, 2017)	22 kW	96	—	—	—	—	0.99	5
VALEO (On Board Battery Charger for EVs, 2021)	3.3 kW	93	85–275	200–430 V	16 A	12 A	0.99	3.5
VISIC (VisIC's smallest, 2020)	6.7 kW	96	110–220 V	200–430 V	16–32 A	15 A	0.99	4.5
INNOLECTRIC (On-Board Charger, 2017)	22 kW	94	3 Phase AC	220–510 V	32 A	70 A	0.99	18
DELPHI (Delphi universal, 2021)	3.3 kW	94	85–265	170–440 V	16 A	12 A	0.99	5

control. To overcome the diode bridge rectifier causing considerable conduction loss, bridgeless PFC is proposed with optimization techniques. As the bidirectional chargers can support a lot of desirable features, they demand additional circuit components, which raises the burden on cost savings and dependability and may marginally degrade the OBC's power density and weight. No specific hardware is required except the outlet, and it also reduces the battery deformations that are mainly involved in bidirectional charging. To implement the unidirectional charging station, no additional cost is needed, whereas in implementing the bidirectional charging station, additional costs with efficient technological advancement are needed to supply reactive power to the grid for regulations.

6 Charging trends in future and challenges

6.1 Utilization of the motor drive system with the charger

The utilization of the existing inverter and motor winding for charging the battery gives a better solution for the on-board chargers that added weight to the vehicle due to passive devices (Rivera et al., 2015). It enables a higher charging level with a near to unity power factor in both unidirectional and bidirectional chargers (Habib et al., 2015), (Habib and Kamran, 2014). The integrated charger utilizes the winding of an induction motor (IM), permanent magnetic motor (PM), switched reluctance motor (SRM), and multiphase motor (He et al., 2021). The integrated charger needs the mechanical contact switch to access the motor winding on a charging (De Sousa et al., 2010). The main challenge of an integrated charger system is to ensure zero torque output during stationary operation (Subotic et al., 2016).

6.2 Wide-bandgap devices

Wide-bandgap (WBG) devices are used to improve the power density, and efficiency, and lower the size and cost than Silicon-based devices (Su and Tang, 2015). Si carbide has high thermal conductivity, higher junction temperature, and less co-efficient thermal expansion making the SiC devices more reliable over a wide range of temperatures (Hudgins et al., 2003). The SiC MOSFET is promising for EV chargers that require extremely high efficiency and high density (Li, 2018). An E-mode GaN HEMT on-board charger with maximum density is demonstrated (Lu et al., 2015). The development of wide-bandgap (WBG) devices is eliminating the need for a series low voltage MOSFET and parallel fast recovery diode (Liu et al., 2017).

6.3 Inductive charging

Recently, inductive charging is an alternative technology for on-board and off-board charging because it replaces the wired interface between the vehicle and power source (Mude, 2018). The vehicle is charging through the electromagnetic induction principle or it is said to wireless charging method. Inductive charging offers many benefits over conductive charging solutions for electric vehicles such as safety, no manual interaction, and the possibility of dynamic inductive charging (Ahmad et al., 2018; Patil et al., 2018). The increase in charging points leads to reduction in the size of the battery pack. This reduces the cost and weight of the vehicle. In conductive charging, cable insulation damage and worn conductor problem caused by contact friction in harsh environments such as underground and underwater are not in inductive charging that improves the safety and reliability (Kan et al., 2018). According to research studies optimizing the shape, arrangement, and number of turns in transmission and receiving coils can improve efficiency (Imura et al., 2009; Lee and Lorenz, 2011).

TABLE 9 Unidirectional charger comparison.

| Charger type	Topology	Merit	Demerit
Single-stage non-isolated (Praneeth and Williamson, 2019; Gupta et al., 2020; Mishra et al., 2020)	Buck–boost	1. Simple structure 2. High efficiency 3. High-power factor	1. Generally low power output 2. Harmonics distortion 3. Larger heat sink due to the high rating of the device
Single-stage isolated (Jeong et al., 2016)	Resonant	1. Moderate structure 2. High efficiency	1. Medium power 2. Less control complexity
Two-stage non-isolated (Kim and Lee, 2017; Ahmed et al., 2022)	Interleave	1. Low ripple current 2. Low stress on the output capacitor 3. Low size of the input inductor	1. Conduction loss due to DBR 2. Increasing component counts 3. High efficiency up to a few kW
Two-stage isolated (Shen et al., 2018; Zhao et al., 2018; Kim et al., 2019; Ta et al., 2020; Nachankar et al., 2022; Zhao et al., 2022)	LLC	1. Wide switching frequency 2. High switching frequency 3. Fewer losses 4. Low EMI emission	1. Resonant inductor value is high 2. More control circuits need to reduce the loss 3. Current ripple in the secondary side of the transformer is large
Two-stage isolated (Kim and Lee, 2016; Lee, 2016; Choi et al., 2018)	Hybrid	1. More befits due to hybrid 2. Loss minimized 3. Device stress is low due to voltage sharing of transformers	1. Narrow switching frequency 2. Large size 3. Control complexity 4. Power density is constrained due to the transformer
Two-stage isolated (Kim et al., 2012; Tao et al., 2019; Hu et al., 2022)	PSFB	1. High-power density 2. Symmetric structure	1. Poor efficiency and loss of ZVS under light load 2. Circulating current

TABLE 10 Unidirectional and bidirectional charger comparison.

Charger type	Merit	Demerit
Uni directional charger-[69,74,78-86,114-127]	1. Less circuit complexity 2. Compact size and less Volume 3. High reliability 4. Battery life is long	1. G2V function does not support the smart grid function 2. Conduction loss in the diode bridge rectifier in PFC converter
Bi directional charger-[40-42,160-162]	1. Low Harmonics in input supply 2. Enables G2V, V2G, V2L, and V2V	1. Negative impact on the charger power density 2. Battery life is low frequent charging and discharging cycles 3. Circuit complexity and reliability problem 4. Volume of the charger becomes larger

6.4 Vehicle-to-grid

To maintain the power system stability and reliability, vehicle-to-grid technology assists that battery power to the grid on demand (Hoang et al., 2017; Uddin et al., 2018). Vehicle-to-grid (V2G) technology significantly reduces the investment of money to install a new power generation infrastructure (Tan et al., 2016b). EVs also can function as an energy resource through vehicle-to-grid (V2G) operation by sending electricity back to the grid, thereby preventing or postponing load shedding (Daim et al., 2016). The subsection

of V2G is like vehicle-to-home (V2H) and vehicle-to-building (V2B), both of which draw power directly from the EV rather than through the power grid. EV is plugged into the power grid system under idle conditions and the batteries are served as the distributed storage system when there is unpredictability of renewable source energy in power gird (Goel et al., 2021). The distributed energy resource (DER) is on a larger scale and with greater significance (Buja et al., 2017). This market is just emerging, however, taking into account the number of electric vehicles and the energy stored in their batteries will have a significant impact on system services in the power grid.

FIGURE 15
Renewable energy with grid EV charging.
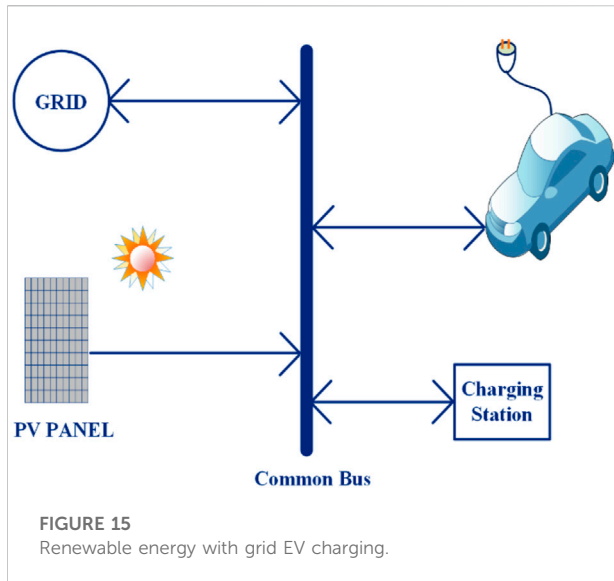
6.5 Renewable energy—based charging

The research has been carried out to integrate solar energy, electric vehicle, and grid with multifunctional operation on demand of power (Chandra Mouli et al., 2019). Solar PV panels are connected with the motor winding through the neutral point to charge the battery while the vehicle is under idle and driving conditions that are kept on the roof of the vehicle (Yu et al., 2022). The solar PV-mounted electric vehicle charging ensures driving range improvement as well as cost reduction on plug-in charging (Shrivastava et al., 2019). In the study of Divyapriya et al. (2021), they proposed the collective of unused battery power in street is connected to the grid to charge the electric vehicle depicted in Figure 15. By design, the recursive filter with the perturbing and observer algorithm-based solar PV with grid eliminates the fundamental frequency in the grid as well as the fast response for sudden changes in load current (Chauhan and Singh, 2019).

Various issues in integrating renewable energy systems with smart grids and control strategies have been discussed (Thirunavukkarasu and Sawle, 2021b). To reduce the reliance on fossil fuels, the authors designed a hybrid renewable-based energy system to satisfy the energy requirements of remote area households (Thirunavukkarasu and Sawle, 2020). The potential of available renewable energy resources for various locations in India has been investigated and a stand-alone renewable energy system has been developed to electrify remote areas (Thirunavukkarasu and Sawle, 2021a). Several optimization techniques have been discussed to optimize the system components, and by using the HOMER optimization technique, the optimal sizing of the components of a hybrid renewable energy system has been extracted (Sawle and Thirunavukkarasu, 2021). Due to the limited issues of

conventional fuel, the development of renewable energy-based electricity generation and hydrogen fuel to drive vehicles has attracted a great deal of attention. The authors focused on investigating the requirements of solar, wind, battery, and converter requirements to meet three different loads, such as electric, thermal, and hydrogen (Thirunavukkarasu and Sawle, 2022).

6.6 Challenges

Furthermore, the development of bidirectional OBC presents infrastructure issues in the related business. First and foremost, the bidirectional power flow must be compatible with modern smart grid functions. The converter efficiency and power density have relied on component count as well as saturation of the transformer inductance to limit the efficiency. A two-stage charger control design is fairly complicated because it necessitates two separate controllers for both converters. As the power density and efficiency of the charger depends on the size and reduction of the passive components such as transformer, capacitor, and inductor; effective optimal design and optimal circuit topology are needed (Merlin Mary and Sathyan, 2021). It is achieved by reducing device current stress and ripples allowing for the use of smaller devices, resulting in a smaller charger with a lower cost. It is necessary to forecast the availability of electric vehicles at a given time, as well as their energy requirements, strategies to improve voltage regulations, and the grid voltage profile. Due to the depletion of fossil fuels, it is necessary to integrate renewable energy sources and utilize their energy to charge electric vehicles. Finally, optimizations of various parameters of converter components are required to minimize in terms of sizing and cost requirements.

7 Conclusion

This review article provides an overview of the different types of on-board chargers in electric vehicles and their different levels of charging standards are discussed. Details of various charging methods and on-board charger topologies of single-stage, two-stage chargers of isolated and non-isolated topologies are studied. The single-stage charger reduces the volume of the charger and can support the higher rating, and research studies are in progress since the DC-link capacitor is not present. The usage of wide-bandgap devices in an on-board charger has a good impact on its size, weight, and volume and also improves the energy level that reduces the charging time. The off-board charger has the key benefit of quick charging of the battery but it needs good infrastructure. In inductive charging, the system

reduces the battery size and improves the efficiency of the vehicle. V2G and solar PV–enabled charging technology can be considered as the possible distributed energy source that can support the power system in the future storage requirements and costs. On-board chargers should be compatible with both single and three-phase voltage supplies. To accomplish good efficiency, advanced modulation techniques with machine learning are needed for the soft-switching of semiconductors.

Author contributions

SV: conceptualization, investigation, and writing–original draft. NS: validation and supervision.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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Glossary

AC alternating current

DC direct current

BEV battery electric vehicle

PHEV plug-in hybrid electric vehicle

FCEV fuel cell electric vehicle

OBC on-board charger

EV electric vehicle

G2V grid to vehicle

V2G vehicle-to-grid

EM electrical machine

CCM continuous conduction mode

DCM discontinuous conduction mode

BCM boundary conduction mode

PFM pulse frequency modulation

FBFM full-bridge converter with frequency modulation

ZVS zero voltage switching

ZCS zero current switching

IPT inductive power transfer

NLCC non-linear carrier control

AFE active front end

WBG wide-bandgap

IC internal combustion

PFC power factor correction

PWM pulse width modulation

THD total harmonic distortion

EMI electromagnetic interference

PLL phase locked loop

PQ power quality

PIC plug-in charging

RB regenerative braking

CC constant current

CV constant voltage

CP constant power