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TOPICAL REVIEW

Review of Electric Vehicle Charging Technologies, Standards, Architectures, and Converter Configurations

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ABSTRACT Electric Vehicles (EVs) are projected to be one of the major contributors to energy transition in global transportation due to their rapid expansion. High-level EVs integration into the electricity grid will introduce many challenges for the power grid planning, operation, stability, standards, and safety. Therefore, the wide-scale adoption of EVs imposes research and development of charging systems and EV supply equipment (EVSE) to achieve expected charging solutions for EV batteries as well as to improve ancillary services. Analysis of the status of EV charging technologies is important to accelerate EV adoption with advanced control strategies to discover a remedial solution for negative impacts and to enhance desired charging efficiency and grid support. This paper presents a comprehensive review of EV charging technologies, international standards, the architecture of EV charging stations, and the power converter configurations of EV charging systems. The charging systems require a dedicated converter topology, a control strategy, compatibility with standards, and grid codes for charging and discharging to ensure optimum operation and enhance grid support. An overview of different charging systems in terms of onboard and off-board chargers, AC-DC and DC-DC converter configuration, and AC and DC-based charging station architectures are evaluated. In addition, recent charging systems which are integrated with renewable energy sources are presented to identify the power train of modern charging stations. Finally, future trends and challenges in EV charging and grid integration issues are summarized as the future direction of the research.

INDEX TERMS Electric vehicle, charging configuration, grid integration, international standards, onboard and offboard charger, power converters.

I. INTRODUCTION

Electrification has become a major factor in social development, economic growth, and environmental contribution. Accordingly, electrification is projected to increase further into the transport sector focusing on the energy transition towards a zero-carbon emission economy. Electrified transportation is considered a desirable solution to reduce fossil fuel dependence and environmental impacts such as reducing greenhouse gas (GHG) emissions, climate change, and improving air quality. Electric vehicles (EVs) offer zero-emission, highly reliable, efficient, and low-maintenance vehicles compared to conventional internal combustion engine (ICE) vehicles [1]. Moreover, EVs will open the possibility of using alternative energy systems such as renewable energy sources (RESs) and energy storage systems (ESSs) to

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secure mobility and make road transport more independent from fossil fuels. The deployment of EVs will depend on a driving range, model, performance, costs of batteries, the convenience of re-charging, safety perception, and possible implied driving habits [2]. The charging time needs to be matched to the time required to refuel conventional ICE vehicles, and EV supply equipment (EVSE) needs to extend with higher power levels for ultra-fast charging. Smart charging coordinated control techniques, and high-power converters can be used to reduce the charging time. Therefore, many research studies have established advanced control strategies, architectures, and converter topologies for EV charging systems.

EV charging technologies can be evaluated based on the charging method of battery, power flow direction, onboard or offboard chargers, or power supply technique depending on requirement and location. The basic units of EV charging system are EV supply equipment (EVSE) which accesses power between EV and local electricity supply. Onboard or offboard chargers are used for grid integration of EVs via AC or DC power. Furthermore, EV charging systems have designed unidirectional or bidirectional power flow. Most commercial onboard chargers are equipped with unidirectional power flow, which is grid-to-vehicle (G2V) capabilities due to simplicity, reliability, low cost, and simple control strategy. In contrast, bidirectional chargers can inject power into the utility grid through vehicle-to-grid (V2G) mode. Hence, bidirectional chargers are considered active distributed resources with specific control modes to support load leveling, RES integration, and reduce power losses in the utility grid. Therefore, academics are becoming more interested in bidirectional chargers as a potential option for EVs in the future.

Modern EV chargers are integrated with smart charging algorithms to enable optimum charging/discharging and dynamic power sharing by communicating with EVs and the utility grid to improve the energy efficiency of chargers and decrease pressure on the local power grid. EV charging systems have been designed according to specific international standards to be compatible on both sides of the EV and the utility grid. Recently, many international standards and codes regarding EV charging and utility interface have been introduced to achieve widespread EV acceptance and reliable grid operation. International organizations have established various standards and codes, universal structures, associated peripheral devices, and user-friendly software for EV charging systems. Charging systems can be categorized into four groups based on the power level and four modes based on the application. Moreover, electrical, and physical parameters and communication protocol standards are defined by IEC and SAE organizations [3]. Fast-charging standards for AC and DC charging have recently been improved significantly by IEEE, IEC, and SAE organizations [4]. Generally preferred standards in the field of EV charging are described in the technical report in [5]. Moreover, government policies and standards for EVs have been introduced internationally to ensure reliable grid operation and mitigate negative impacts on the distribution grid [6].

The architecture of charging stations rapidly improves as the range of BEVs increases. Charging methods can be classified as conductive, inductive, or wireless and battery swapping. Onboard and offboard chargers have developed with conductive charging either using AC or DC power. Charging of EV battery packs depends on the rate of transfer power from the charging station. Therefore, fast and ultra-fast charging stations gain attention as they can charge the battery in less time at high power levels [7]. EV charging units are connected to the AC bus through separate rectifiers in common AC bus-based architecture. In contrast, common DC bus-based charging systems are flexible structures and comprise a single rectifier with high power levels on the grid side. Moreover, hybrid AC/DC and micro-grid charging architectures with RES have been designed to maximize RES energy use and improve micro-grid performance other than EV applications. Consequently, researchers have focused on improving charging stations with advanced converters and smart control techniques to manage public charging constraints.

The EV charging systems are comprised of several AC/DC power converters and control strategies to safely charge the battery with high efficiency. The AC-DC and DC-DC converters are employed to deliver power either unidirectional or bidirectional in the charging systems. The cost, size, performance, and efficiency of the charging system depend on the corresponding converter topology. High-power converters can be used to reduce the charging time which enhances ancillary services to the power grid. However, the increasing fleet of EVs and renewable energy sources (RES) in the distribution grid inject harmonics and deteriorates power quality and may cause an impact on grid operation, safety, and reliability. Therefore, different power converters, charging strategies, and grid integration techniques are being developed to strengthen the advantages of EVs. Integrated challenges of plug-in hybrid electric vehicles (PHEV) and EV charging infrastructures are assessed through the various optimization techniques in [8]. Various optimization techniques have been evaluated in [9] for charging infrastructures with the aim of power loss, peak load and cost of electricity minimization. Authors in [10] discussed the performances of various bio-inspired computational intelligence techniques for EV charging optimization.

Therefore, a comprehensive review of EV charging technologies, standards, architectures, and converter configurations is important to identify prevailing challenges and propose remedial solutions. Most EV charging stations are AC power-based configurations as they have mature technology and direct usage of local loads when compared to the DC power-based fast charging stations. On the other hand, DC power-based architectures are becoming popular in recent years due to their high efficiency, low cost, and flexibility to integrate RESs and ESS in the distribution grid. However, complexity is increased with additional energy sources in DC power-based charging stations. Hence, EV charging technologies, configurations, and architectures need to be analyzed comprehensively to identify the current state of EV charging systems, technical development, and challenges to identify a remedial solution. The following contributions are made in this paper.

- The Overview of the current state of EV charging technologies and requirements including different types of EVs, charging levels, modes, and connectors.
- Standards of EV charging, grid integration codes and safety standards.
- Architectures of EV charging stations based on AC and DC power-driven, and RES-based systems.
- Configurations of converter topology including onboard and offboard, AC-DC converters and DC-DC converters are reviewed comprehensively with the associated powertrain.

The rest of the paper is organized as follows. The overview of EV charging technologies is presented in section II including the status of charging technologies and requirements such as different types of EVs, charging levels, modes, connectors, and types of EV batteries. The international standards of EV charging and grid integration are reviewed in section III. In section IV, different architectures of EV charging stations are elaborated with conventional, and RES-based charging stations. EV charging topologies are reviewed in section V including G2V and V2G operation and onboard and offboard chargers. Power converter configurations of EV chargers are presented in section VI based on the AC-DC and DC-DC converters and isolated and non-isolated converters. Finally, future trends and challenges of EV are discussed in section VI, and the conclusion is drawn in section VII.

II. ELECTRIC VEHICLE CHARGING TECHNOLOGIES

Electrified transportation is achieving momentum in the current industry due to several factors, including clean environmental concepts, fossil fuel depletion, government subsidies, increasing charging infrastructures, and smart control propulsion strategies. Moreover, the widespread availability of fast charging stations will start a movement where EV charging will become as common as refueling ICE vehicles at existing service stations. This section explains an overview of EV charging technologies including the current state of EV charging technologies, different types of EVs, charging levels, modes, and different connector types and types of EV batteries.

A. CURRENT STATE OF EV CHARGING TECHNOLOGY

In 2021, global EV sales doubled from the previous year to a record of 6.6 million. The global electric car sales were 2 million in the first quarter of 2022, up 75% from the same duration in 2021 [12]. The projections indicate that the global EV fleet will reach 230 million vehicles in 2030 and 58% of vehicles are expected to be EVs in 2040 [13]. The global

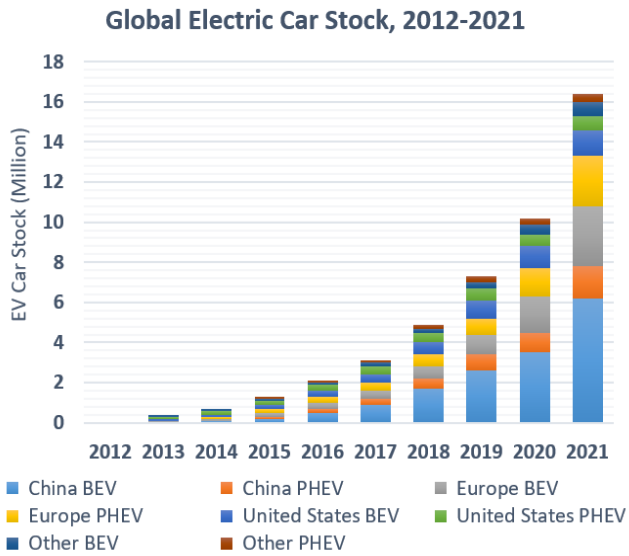


FIGURE 1. Electric passenger car stock, 2012-2021 [11].

EV stock is significantly increased in 2021 when compared to previous years and the total number of battery electric cars on road to over 16.5 million. As shown in Fig. 1, the largest EV market belongs to China where cumulative EV sales reached 9.4 million in 2021, which represented 50% of global EV stock [14]. The second largest EV market belongs to Europe with 2.3 million annual sales of light duty EVs and the United States has the third largest EV market [12], [15]. Currently, electrified transportation has attracted much attention from governments and private stakeholders to move towards carbon neutrality in 2040 through consistent policy support, incentives, and subsidies from the governments.

Several major automobile manufacturers are preparing for a shift to EVs and some jurisdictions and countries, including Europe and China, are planning to restrict fossil fuel-powered vehicle sales in the future [16]. The exponential growth of EV sales will be expected along with the facilitation of increasing high-charging equipment accessibility, public fast charging stations, and the development of RES-based EV charging. Most of the projects and developments are focused on the RES power changing infrastructures to make further advantages from EVs while supporting grid operations [17]. As a result, the carbon footprint declines, and additional grid support is provided by EVs through charging systems. The adoption of EVs is the consequence of much regulatory assistance in the present day, such as purchase incentives, subsidies for home charging insulation, benefits for drivers and parking, orchestration of international standards, and expanded access to public charging infrastructure [18].

Battery technology has a significant impact on the growth of EVs because the price, weight, volume, charging time, driving range and lifetime depend on the EV battery pack [19]. Extensive studies and funding have been dedicated to developing superior battery technologies that are appropriate for EVs at present. The cost of EV batteries has decreased significantly from over \$1000/kWh in 2010 to about \$132/kWh in 2021 [20]. Most analysts predict that the cost of battery packs will keep declining, reaching \$100/kWh between 2023 and 2025 and \$61–72/kWh by 2030 [21]. The average capacity of a lithium-ion EV battery is around 40kWh, and several models have 100kWh capacity. The investments in EVs have drastically increased to explore electrification strategies and battery life-cycle management to increase driving range, efficiency, and reliable charging and discharging capabilities for an affordable price.

Technological innovations in EVs have provided new concepts for EV grid integration, offering attractive and competitive regulated charging/discharging techniques [22]. The vehicle-to-grid (V2G) application is an emerging research area, EV batteries can be used to store surplus energy and supply energy to the utility grid using coordinated control strategies [23]. The EVs will play a new role in the emerging concept of smart charging technologies by exchanging energy with microgrids and the power grid via a bidirectional power flow with ancillary support [24]. The smart EV fleets program encourages the integration of EVs into their transportation system via RESs [25]. However, the rapid growth in EVs is expected to have further negative impacts on the distribution grid including power quality impacts, increasing peak demand, voltage instability, harmonic distortion, and overloading distribution grid [26]. The increased EV charging station may change the distribution network's load patterns, characteristics, and safety requirements. Therefore, extensive research studies have been progressing to identify the power network and environmental and economic impacts of EVs [27].

B. TYPES OF ELECTRIC VEHICLES

The EV comprises one or more electric motors and a high-voltage battery pack with a charging system. The electric motor either assists completely via electric power or ICE depending on the EV type. Additionally, the electric motor functions as a generator and provides power to charge the battery using a bidirectional DC-AC converter during the braking and deceleration of the vehicle. Conversely, the converter enables power to flow from the battery to the motor during driving mode [17]. The battery pack is recharged from electric energy through a charging system. Based on the current phase of development, EVs are categorized into two types: hybrid vehicles and all-electric vehicles (AEVs) by considering the degree of use of electricity as shown in Fig. 2.

The hybrid vehicle has a conventional ICE vehicle design and a battery to power the vehicle using fuel and electric energy. The capacity of the battery defines the driving range of the vehicle in electric mode. Hybrid EVs (HEVs) and plug-in hybrid EVs (PHEVs) are two types of hybrid vehicles in the market. The hybrid vehicle comprises ICE, an oversized electric motor, and a battery to reduce fossil fuel consumption. The HEVs have similar drive features to normal ICE vehicles and can make the vehicle move using stored battery power for short distances. The battery pack automatically chargers through regenerative braking by turning kinetic energy into electric energy when ICE is at a light load in HEVs [28], [29]. The propulsion mechanism of the PHEV is like the HEV, and it differs from the HEV by having a large battery pack being able to charge from the regenerative braking and plugs into the power grid. The PHEV has a more powerful electric motor than HEV, which is enabled to be operated in entirely electric mode by turning off the ICE [30], [31]. The all-electric driving range is about 25 km to 80+ km in PHEV depending on the model.

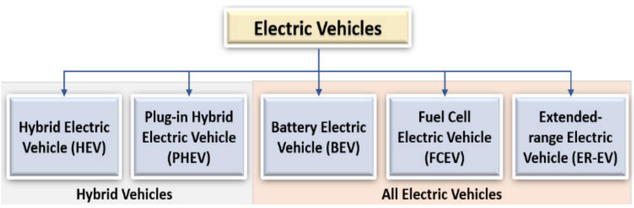


FIGURE 2. Types of electric vehicles.

AEV uses electric power as fuel to recharge the battery pack and consists of electric motors for propulsion. AEVs produce zero pipeline emissions as they are driven via electric power without any fuel combustion. There are three types of AEVs including battery EV (BEV), fuel cell EV (FCEV) and extended-range EV (E-REV). The AEVs use a large onboard battery pack to provide acceptable propulsion to the vehicle. BEVs are frequently called EVs which are driven by electric motors powered via a battery pack. The BEV is exclusively powered by electricity and thus tends to have a large battery capacity (kWh) when compared to hybrid vehicles as they rely only on electric power. The battery pack chargers by plugging the vehicle into the power grid or electric source and regenerative braking. The main challenges of BEV are shorter driving range per charge, limitation of public charging stations, and long charging period [32], [33]. Moreover, the deployment of BEVs can support the power grid via smart charging technologies and V2G functionality to increase variable renewable energy and interplay with communication technologies to minimize operational costs and maximize the technical features of power systems.

The FCEVs are powered by hydrogen gas and the propulsion system is the same as EVs. The FCEV uses hydrogen gas to power an electric motor entirely by electric power. The FCEV is refueled with hydrogen gas and the fuel cell is used to transform the chemical power into electric energy which drives the electric motor. The FCEV has a short refueling time and the driving range is comparable to ICE vehicles. Moreover, they are noise-free, very energy efficient, and have zero tailpipe emission vehicles which produced pure water as a waste [20]. The E-REVs comprise an electric motor and small ICE to produce additional power which is used to keep the battery charging for long distances. E-REVs are categorized as AEVs with many of the benefits of purely electric models. An E-REV comprises with electrical drivetrain (one or more electric motors and battery pack) and ICE to charge the battery pack. Therefore, E-REV needs to be both recharged from the power grid and refueled at a petrol station. The E-REV helps combat range anxiety, lower fuel costs, and are highly efficient and maximize the use of their vehicles by operating their engine constantly [34].

The specifications of distinct types of popular EVs are presented in Table 1 in terms of the type of vehicle, battery capacity, driving range and connector type. The driving range of an EV depends on the battery capacity, measured in kWh. Hence, modern BEVs have higher battery capacity and a driving range from 200 to 490 km on a single charge [35]. Fast and extremely fast charging stations are growing to meet high power requirements with EVSE. On average, a usual BEV takes about 8 hours to charge a 60kWh battery pack from empty to full, which can cover up to 320 km of distance [36]. BEVs have comparatively less driving range than FCEVs and E-REVs. The overall energy efficiency of EVs has been continuously improved by manufacturers, resulting in lower energy consumption per kilometer and longer range on a single charge.

C. CHARGING LEVELS AND MODES

EVs are designed with various charging technologies, capacities, and charging and discharging strategies to fulfil their unique requirements. Therefore, standardized charging levels and models are established to drive EV adoption forward in the industry. The electric powertrain of modern plug-in EV is similar and is designed with a high-power battery pack (to maintain voltage and current), a battery management system, various converters to supply appropriate voltage levels, controllers and drive inverters [42], [43]. EV chargers can be classified as onboard and offboard chargers as well as unidirectional and bidirectional chargers. Charging methods can be classified as conductive charging, battery swapping, wireless charging or inductive charging as shown in Fig. 3. The majority of commercial EVs use a conductive charging technique where the battery is connected to the power grid via a cable. Conductive chargers can be categorized into three charging levels as Level 1-3 according to SAE J1772 and four modes as Mode 1-4 according to the IEC 61851-1 standards [44], [45]. Time-varying magnetic fields are used in wireless charging methods to transmit power from the grid to EV battery. Wireless charging can be divided into three types such as capacitive, inductive and resonant inductive [46]. Three types of charging levels, four charging modes and different connectors and ports will be described in the following subsections.

1) CHARGING LEVELS

Conductive charging involves an electric connection between the charging inlet and the vehicle which follows three charging levels such as Level 1, Level 2, and Level 3 depending on the power level as shown in Table 2. Level 1 and Level 2 charging are used in onboard chargers with AC power and follow the same set of standards. The Level 1 charger uses a 120 V single-phase AC power supply and has the slowest charging speed which is generally used in domestic with low power levels (up to 1.92 kW) without any additional infrastructure [47], [48]. Therefore, Level 1 charging is appropriate

TABLE 1. Specifications of commercial electric vehicles [37], [38], [39], [40], [41].

Vehicle Model	Type	Battery Capacity (kWh)	Driving Range (km)	Connector Type
Chevrolet Volt	PHEV	18.4	85-Battery	Type 1 J1772
Mitsubishi Outlander	PHEV	20	84-Battery	CCS, Type 2
Volvo XC40	PHEV	10.7	43-Battery	CCS, Type 2
Toyota Prius Prime	PHEV	8.8	40-Battery	SAE J1772
Nissan Leaf Plus	BEV	64	480	CHAdeMO, Type 2
Tesla Model S	BEV	100	620	Supercharger
Tesla Model X	BEV	100	500	Supercharger
Tesla Model 3	BEV	82	580	Supercharger
Kia Niro- SUV	BEV	64	460	CCS, Type 2
Lexus UX 300e	BEV	54.3	320	CHAdeMO, Type 2
Ford Mustang	BEV	70	400	CCS, Type 2
Jaguar ev400	BEV	90	450	CCS, Type 2
Renault Zoe	BEV	52	390	CCS, Type 2
BMW i3	BEV	37.9	310	CCS, Type 2
Chevrolet Bolt	BEV	65	402	CCS, Type 2
Honda e	BEV	28.5	220	CCS, Type 2
Porsche Taycan	BEV	93	410	CCS, Type 2
Volkswagen e-Golf	BEV	35.8	230	CCS, Type 2
Mercedes-EQA	BEV	66.5	420	CCS, Type 2
Audi e-tron	BEV	95	400	CCS, Type 2
BMW iX3	BEV	80	460	CCS, Type 2
Toyota Mirai	FCEV	1.6	647	-
Hyundai Nexo	FCEV	40	570	-
Honda Clarity	FCEV	25.5	550	-
BYD Atto 3	E-REV	60.4	420-Battery	CCS, Type 2
Hyundai Kona	E-REV	64	577-Battery	CCS, Type 2

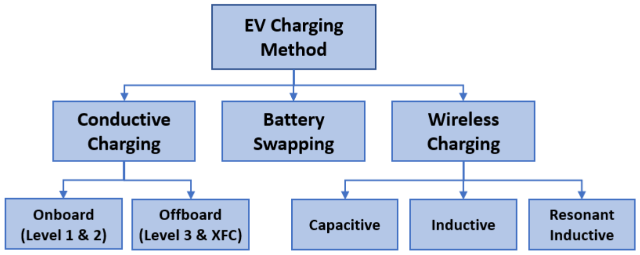


FIGURE 3. Electric vehicle charging methods.

TABLE 2. Comparison of different electric vehicle charging levels [47], [49].

Specification	Level 1	Level 2	Level 3	Extreme Fast Charging (XFC)
Charging Power	1.44 kW - 1.9 kW	3.1 kW – 19.2 kW	20 kW – 350 kW	>350 kW
Charger Type	Onboard - Slow charging	Onboard - Semi-fast charging	Offboard - Fast charging	Offboard – Ultra-fast charging
Charge Location	Residential	Private and commercial	Commercial	Commercial
Charging time	200 km: +/- 20 hours	200 km: +/- 5 hours	80% of 200 km: +/- 30 min	Approximately 5 min with high energy density
Power Supply	120/230 Vac, 12 A – 16 A, Single phase	208/240 Vac, 12A - 80A, Single phase/Split phase	208/240 Vac & 300-800Vdc, 250-500A Three phase	1000Vdc and above, 400A and higher Polyphase
Supply Interface and Protection Type	Convenience outlet (Breaker in cable)	Dedicated EV supply equipment (Breaker in the cable and pilot function)	Dedicated EV supply equipment (communication & event monitoring between EV and charging station)	Dedicated EV supply equipment (communication & event monitoring between EV and charging station)
Standards	SAE J1772, IEC 62196-2, IEC 61851-22/23, GB/T 20234-2		IEC 61851-23/24 IEC 62196-3	IEC 62196 SAE J2836/2 & J2847/2

for long-time or overnight charging. Level 1 chargers generally require about 11-36 hours for 1.9 kW charging power for a 16-50 kWh EV battery [49]. The primary charging method for private and public facilities is Level 2 charger, as they have comparatively fast charging abilities. The charging time of Level 2 is 3 to 5 times faster than Level 1 chargers due to high power usage [50]. Level 2 charging can provide power up to 19.2 kW for both single-phase and split-phase with 208 Vac or 240 Vac voltage. Dedicated components and installations are required in Level 2 chargers for high power transfer through the onboard charger. The charging time range is 2 - 3 hours for 19.2 kW with an EV battery capacity of 30 -50 kWh [3]. Level 1 and 2 charging connectors follow the IEC62196-2 standard in Europe, SAEJ1772 and Tesla superchargers in the USA [44], [51].

The DC fast charging or Level 3 charging uses AC and DC power to deliver high voltage DC power to the EV battery. The Level 2 chargers can manage a high-power range between 20 kW to 350 kW to supply DC voltage of around 300 Vdc to 800 Vdc in offboard chargers. DC fast chargers are directly connected to the vehicle via off-board chargers to the three-phase power grid. Charging time of 90 kW or larger Level 3 charger is range 0.2 - 0.5 hours which is faster than Level 1 and 2 [49]. CHAdeMO, Tesla superchargers and CCS combo 1, 3 connectors are considered for level 3 fast charging. However, low-power chargers including Level 1 and Level 2 have the lowest negative impact on the power network during peak time. The local distribution grid may become overloaded by the level 3 chargers due to high power usage during peak times [52].

Extrema fast charging (XFC) systems can deliver a refueling experience like ICE vehicles. The XFC systems can manage more than 350 kW power with 800 Vdc internal DC bus voltage and battery recharging time is approximately 5 min. The XFC stations are designed with power electronic components focusing on solid-state transformers (SST), isolated DC-DC converters, and front-end AC-DC converter stages and controllers. The installation cost of the XFC is very high and requires dedicated EVSE to deliver high power. The XFC station can be designed by combining several XFC systems to provide a chance to lower operational and capital investment to make it economically feasible. Additionally, SST provides advantages over conventional line-frequency transformers for converting medium voltage levels into low voltage levels and providing galvanic isolation in XFC stations [53].

2) CHARGING MODES

The International Electrotechnical Commission (IEC) defines 4 charging modes (IEC-62196 and 61851) for AC and DC charging systems and provides the general attributes of the safe charging process and energy supply requirements [54]. A comparison of charging modes is presented in Table 3 with specifications and charging configurations. The slow charging applications follow mode 1 which comprises with earthing system and circuit breaker for protection against leakage and overloading conditions. The current limit of mode 1 varies from 8 A to 16 A depending on the country. The EV is directly connected to the AC grid either 480 V in three-phase or 240 V in single-phase via a regular socket in mode 1. The charging cable is integrated with a specific EV protection device (In-cable control and protection device (IC-CPD) in mode 2 to enable control and protection. Mode 2 charger offers a moderate safety level and utilizes minimum standards. This mode delivers slow charging from a regular power socket which is ideally suited for home installation [55]. Single-phase or three-phase AC power can be used in this mode with a maximum power of 15.3 kW and 32 A current flow [5]. The mode 2 cable provides over-current, overheat protection, and protective earth detection. Therefore, mode 2 charging cables are more expensive than mode 1 due to high current flow and provide moderate safety for modern EVs [56].

Mode 3 is used for slow or semi-fast charging via a specific outlet with the controller. The dedicated circuit is permanently installed (on the wall) for protection, communication, and control in this mode. Public charging stations are commonly built with mode 2 and are able to facilitate integration with smart grids. Mode 3 allows a higher power level with a maximum current of 250 A which is used by fixed EVSE for single-phase or three-phase grid integration. The connection cable includes an earth and control pilot to enable proper communication between the EV and the utility grid. Fast charging station uses mode 4 via fixed EVSE to deliver DC to the vehicle which is utilized in public charging stations. The installation includes control, communication and protection features [57]. Mode 4 chargers are more expensive than mode 3 and the connection includes earth and a control pilot to control a maximum of 400 A current. Off-board chargers follow mode 4 specifications with a wide range of charging capabilities over 150 kW power [5].

D. ELECTRIC VEHICLE CHARGING CONNECTORS

EV charger components (including power outlets, connectors, cords, and attached plugs) are the main components of EVSE which provide reliable charging, discharging and protection for the charging system. The configuration of the peripheral devices, power ratings, and standards of EV chargers are various in different authorities. However, governing bodies and manufacturers are attempting to ensure compatibility by developing international standards, protocols, and couplers for slow and fast charging systems to avoid conflicts and difficulties [59]. Commercially available different AC and DC connectors are shown in Tables 4 and 5 respectively by following their specifications and standards. AC chargers are slow chargers which take 6 - 8 hours to fully charge EV. DC chargers are used for fast charging with a higher power range of up to 400 kW. The various connectors can be categorized into three groups according to the IEC 62196 - 2 standards.

Type 1 connectors are widely used in Japan and USA for AC single-phase charging and follow SAE J1772 standards. They have low power charging capability (maximum capacity of 19.2 kW) with a voltage of 120 V or 240 V with a maximum current of 80 A [60]. The charging cable of Type 1 connector is permanently installed to the station. Type 2 connectors are considered as standard type in all countries which support single-phase and three-phase charging by following IEC 61851-1 standards [61]. Type 2 - Mennekes connectors are utilized in Europe and Type 2 - GB/T are used in China. This connector supports mode 2 and 3 charging with higher power (22 kW) than Type 1. The detachable charging cable of the Type 2 station allows to charger of Type 1 vehicles with the correct cable [56], [62]. Type 3 connectors are used in France and Italy that includes Type 3A and 3C depending on the physical formats. Type 3 connectors or SCAME plugs allow both single-phase and three-phase charging with shutters to prevent and follow IEC 62196-2 standards.

The DC chargers or superchargers deliver the fastest charging rate which follows the combined current system (CCS) and IEC 62196 standards. The IEC 62196-3 standard specifies four types of coupler configurations for DC fast chargers. They are configuration AA (CHAdeMO), configuration BB (GB/T), configuration EE (CCS-Combo 1), and configuration FF (CCS-Combo 2) [63]. The Combo 1 and Combo 2 connectors are extended versions of Type 1 and 2 connectors with two added DC contacts to allow high-power charging. The CCS - Combo 1 connector is based on Type 1 chargers and is used in the USA. Europe preferred CCS - Combo 2 connectors which have a Type 1 coupler configuration. CCS connectors can withstand a high-power range of up to 350 kW. The GB/T fast charging DC connectors used in China follow GB/T 20234-3 standards. It is capable of operating higher power ratings up to 237 kW with a maximum voltage of 1000 V and 400 A current. CHAdeMO fast charging systems developed in Japan, and it competes with the supercharger network, CCS and GB/T standards. CHAdeMO connectors have ultra-fast charging and V2G integration ability for 400 kW with 1000 V maximum voltage and 400 A current [67]. Tesla offers a connector for both AC and DC charging for all the charging levels. Tesla superchargers offer excellent fast charging speeds via their own designed charging stations and connectors can supply 72 kW, 150 kW, or 250 kW electric power [68]. Type 2 connector required for AC charging with Tesla station which allowed power up to 11.5 kW and an AC voltage of 250 V single phase. Tesla superchargers are built for Tesla cars and version 3 models have a maximin power of 250 kW. The Australian standard for EV charging plugs and connectors (IEC 62196) encourages the adoption of both United State and Europe connector standards rather than imposing a single standard for EV charging systems [69].

E. ELECTRIC VEHICLE BATTERY TECHNOLOGY

The EVs represent the largest share of the global battery market which is expected to the continuous growth of energy density, fast charging capabilities with long cycle life, and compliance with safety and environmental standards [70], [71]. The battery is a key component of an EV that is capable to handle high energy capacity (kWh), and high power (kW) within limited weight, and space at an affordable price [72]. EV battery is connected to the DC-link via a DC-DC converter and the state of charge (SoC) demonstrates the control mechanisms of the battery. EV battery is capable of storing electrical energy in the form of chemical energy when

TABLE 3. Comparison of different charging modes [5], [58].

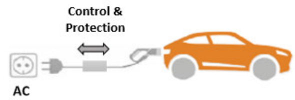
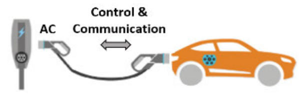
Charge Mode	Phase	Current	Voltage	Power (Max)	Specific Connector	Charging Configuration
Mode 1	AC - 1Φ AC - 3Φ	16A	230-250V 480V	3.8 kW 7.6 kW	No	
Mode 2	AC - 1Φ AC -3 Φ	32A	230-250V 480V	7.6 kW 15.3 kW	No	
Mode 3	AC - 1 Φ AC - 3 Φ	32-250A	230-250V 480V	60 kW 120 kW	Yes	
Mode 4	DC	250-400A	600-1000V	>150kW	Yes	

TABLE 4. Specifications of different AC charging connectors [61], [64], [65], [66].

Specifications	**Japan**	**USA**	**Europe**		**China**		**ALL Markets**	
Charger type								
	Type 1 (SAE J1772)		Type 2 (Mennekes)		Type 2 (GB/T)		Tesla	
	Level 1	Level 2	Mode 1	Mode 2-3	Mode 2	Mode 3	Mobile connection	Wall connection
Maximum Capacity	1.9 kW	19.2 kW	4 kW	22 kW	7 kW	27.7 kW	7.7 kW	11.5 kW
Input voltage	120 V Single phase	240 V Split phase	250 V Single phase	480 V Three phase	250 V Single phase	400 V Three phase	120/240 V Single phase	208/250V single phase
Current rating	16 A	80 A	16 A	32 A	16 A	32 A	16/32 A	48 A
Standards	SAE J1772-2017 IEC 62196-2, IEC 61851-22/23		IEC 62196-2 IEC 61851-22/23		GB/T 20234-2 IEC 62196-2		IEC 62196-2	

charging (G2V) and regenerative braking and feeding back to the power grid when discharging (V2G). Moreover, EV batteries can deliver power for long and sustainable periods of 10-15 years. The cost and driving range of the vehicle is determined by the energy density of the EV battery pack. Significant research studies and funding have been dedicated to developing advanced battery technologies that are appropriate for EVs. Various types of EV batteries are available in the market and the main types are lead acid, nickel-based, and lithium-ion batteries as shown in Fig. 4 [73]. Characteristics and specifications of commonly used EV battery types are presented in Table 6.

Lead-acid batteries are inexpensive (cell cost is 50-600 $/kWh), reliable, efficient, safe, and employed for high-power applications [77], However, they have low specific energy density (30 - 40 Wh/kg), a short lifetime (<1000 cycles), and weak performance in cold temperatures [78]. Nickel-based batteries have been widely used in EV batteries such as nickel metal hydride (NiMH), nickel-cadmium (NiCd) and nickel Zinc (NiZn), nickel ion (NiFe). NiMH battery is commonly employed in HEV and EV due to their longer life cycle (2000 cycles) than lead acid batteries, abuse tolerant and safe [79]. The maximum energy density of the NiMH battery is 120 Wh/kg, the power density

TABLE 5. Specifications of different DC charging connectors.

Specifications	Japan	USA	Europe	China	ALL Markets	
Charger type						
	CHAdeMO	CCS - Combo 1	CCS - Combo 2	GB/T	Tesla Supercharger	CHAdeMO
Capacity	50 - 400 kW	150 - 350 kW	350 kW	60 - 237 kW	250 - 350 kW	50 - 400 kW
Input voltage	50 - 1000 V	200 - 1000 V	200 - 1000 V	250 – 950 V	300 - 480 V	50 - 1000 V
Maximum Current	400 A	500 A	500 A	250 – 400 A	800 A	400 A
Standards	IEC 61851-23/4 IEC 62196-3 JEVS G105	SAE J1772 IEC 61851-23/24 IEC 62196-3	IEC 61851-23/24 IEC 62196-3 DIN EN 62196-3	GB/T 20234-3 IEC 62196-3	IEC 62196-3	IEC 61851-23/4 IEC 62196-3 JEVS G105

TABLE 6. Electric vehicle batteries with specifications [74], [75], [76].

Battery Type	Vehicle Model	Specific energy (Wh/kg)	Energy density (Wh/L)	Cycle life	Safety	Specifications
Lithium Nickel Cobalt Aluminum Oxide (NCA)	Tesla X, S, 3, Y	200-260	600	500	Good	• Provide good energy yield and is inexpensive • Extensively used in both portable electronics and EVs
Lithium Nickel Manganese Cobalt Oxide (NMC)	Nissan Leaf, Kia e-Soul, Volkswagen e-Golf, BMW i3, I3s Peugeot e-208	150-220	580	1000-2000	Good	• Stable chemistry, and low-cost materials • Provide a high energy density and can charge rapidly compared to other batteries
Lithium Manganese Oxide (LMO)	Chevy-Volt, Escape PHEV	100-150	420	300-700	Good	• Good energy performance and low cost of materials • Short life cycle
Lithium Iron Phosphate (LFP)	EVs, especially in e-bikes, e-rikshaw,	90-120	330	1000-2000	Excellent	• Stable, long lifecycle, and significant safety • High energy density and low rate of self-discharge make it ideal for larger EVs such as vans, buses, or trucks
Lithium Titanate (LTO)	Mitsubishi, Honda	50-80	130	3000-7000	Excellent	• Long life, fast charge using advanced Nanotechnology • very high rate of charging and discharging possible without compromising on safety

(1000 W/kg) and highest charge/discharge efficiency is 92% [80]. The main challenges in Ni-based batteries are high self-discharging, cost, heat generation at high temperatures, and required additional control systems to control losses.

Lithium-ion (Li-ion) batteries are the dominant power storage in EVs due to their improved performances, high energy efficiency, energy storage, low self-discharge rate, and superior performance in high temperatures. Commonly used Li-ion batteries are Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), Lithium Iron Phosphate (LFP), Lithium Manganese Oxide (LMO) and Lithium Titanate (LTO). The Li-ion battery is

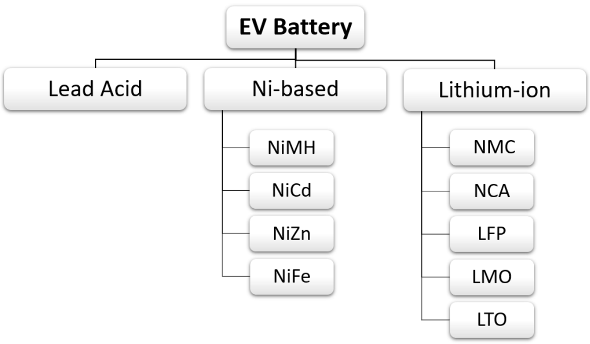


FIGURE 4. Types of electric vehicle batteries.

TABLE 7. Major standards of EV charging systems.

Standard	Description
SAE J1772	Conductive charger coupling of AEVs and HEV
SAE J2344	Guidelines for EV safety
SAE J2894/2	Power quality requirements
SAE J2953	Standards for interoperability of EV and charger
SAE J2847/1	Communication between EV and the grid
SAE J3068	EV power transfer system using a three-phase AC capable coupling
SAE J2931/7	Security for PEV communication
IEC 60038	Standards for the voltage for charging applications
IEC 62196	Standards for EV conductive charging components (outlets, plugs, connectors, and inlets)
IEC 60664-1	Installation coordination for charging equipment in low-voltage supply
IEC 62752	Standards for cable control and protection devices
IEC 61851	Covering safety-related specifications on the charging station
ISO 15118	Standards for V2G communication protocols and interfaces
ISO 17409	Specifications for the connection of EV with an external energy source

very efficient (90%) and can charge regularly at any SoC. The rapid charging capability, high specific energy (180 Wh/kg), power density (5000 W/kg), longer lifespans are recent achievements of Li-ion batteries. EV manufacturers use LMO batteries due to their high specific power and energy. Tesla cars have high power density NCA battery capacity (Tesla Model 3 has 80.5 kWh). A total capacity of 62 kWh NCM is used in Nissan Leaf and the new generation Chevrolet Bolt EV (2020) consists of a 68 kWh total battery capacity [81]. In [82], an extensive study of various control schemes for battery performance is evaluated under different conditions including stability, multi-power resources, distributed network, and the different size of ESS in EVs.

The battery management system (BMS) is responsible for the energy management of the battery to ensure reliable, efficient and safety performance of the vehicle. The BMS includes sensors, a power delivery unit, and communication protocols to reduce the stress of the battery charging and discharging and prevent sudden abruption current to avoid high discharging rates. Moreover, cell balancing, calculating the state of charge (SoC), computing the driving range, and other auxiliary are powered via the BMS. The energy management system (EMS) is critical to address the driving range, battery life, efficiency, and reliable operation the EVs [83]. The SoC and state of health (SoH) reflect battery performance and deliver essential data for energy management and optimal control design for the vehicle [84], [85]. The accurate estimation of battery states is complex due to its non-linear and high time-varying behaviors. SoC estimation is a key method used to maintain battery status, which displays the remaining capacity of the battery via advanced algorithms with measurements [86]. The SoC is the proportion of the remaining capacity of the battery to its rated capacity under a specific discharge rate.

The primary function of the SoC is to communicate between the vehicle and the instinctive battery state to avoid overcharging and discharging the battery [87], [88]. Furthermore, it provides critical information on available power, and battery usage until the next recharge, and executes a control system to improve the performance and life of the battery [89]. Numerous techniques have been proposed for real-time SoC estimation which can be categorized into five groups model-based estimation, lookup table-based, coulomb counting, data-driven estimation method, and hybrid method [88]. Model-based SoC estimate techniques such as equivalent circuit models, electrochemical models, and electrochemical impedance models are frequently used in EV charging [90]. The model based SoC estimation techniques is accurate and powerful due to the reliance on the deep analysis of electrical, chemical, and combination of both characteristics. The comprehensive review of SoC estimation methods is presented in [91] by highlighting algorithm/control design, advantages, disadvantages, and challenges to selecting appropriate SoC methods for EVs. The comparison of existing SoC estimation methods and robust SoC estimation techniques are proposed in [92] based on the non-linear model and experimentally. In [93], a novel adaptive Kalman filter algorithm is designed for the SoC estimation of Li-ion batteries used in EVs. The improved deep neural network approach has been used in [94] to implement a new SoC estimation method for Li-ion batteries in EV applications.

III. STANDARDS OF ELECTRIC VEHICLE CHARGING AND GRID INTEGRATION

Standards play a key role in the deployment and development of EV technology in society which serve as a crucial foundation for broad market penetration and customer satisfaction. The high level of EV charging integration has created new challenges and requirements in the automotive industry and electric networks. Standards and grid codes are designed to ensure reliable and safe EV integration with the power grid and other energy resources. Charging standards are applied to EVs to provide accurate functionality, protection, interoperability, and integration with various parameters and conditions [95], [96]. EV charging standards are employed around the world to interact with charging infrastructure. The Society of Automotive Engineers (SAE) and the Institute of Electrical and Electronics Engineers (IEEE) are two main contributors to charging and grid integration standardizations. The SAE and International Electrotechnical Commission (IEC) standards are widely used for EV conductive charging systems. Table 7 lists the preferred international standards for EV charging systems including conductive charging, safety, and grid integration regulations.

Charging standards and regulations can be categorized as charging components, grid integration, and safety [97]. The specifications of EV conductive charging components including connectors, plugs, outlet-socket, and inlets are provided by SAE J1772 and IEC 62196 standards. series of standards in IEC 62196 and IEC 61851 provided the specification for EV connectors in AC and DC charging systems. Inductive charging standards are SAE J1772, and IEC 61980, and battery swapping charging systems used IEC 62840 standards [98]. AC charging systems comprises SAE J1772 standards with 100V domestic power in US and Japan and 220V power in Europe. GB/T 20234 standards are employed in AC charging systems in China. Connectors and ports in DC charging systems are designed by using a set of IEC 61851 standards, CHAdeMO which is described in GB/T 20234, and CCS Combo standards [99], [100].

Internationally established standards, which supervise distinct characteristics of EVs are presented in Table 8. Charging and discharging of EVs through the grid is controlled by grid integration standards and codes. The EV is considered a distributed energy resource in V2G operation mode which is applied power grid integration EV standards. Grid integration standards include power regulations, safety, and power quality requirements, and important grid codes to ensure reliable integration of EVs. Grid interconnection standards and regulations are established by the Institute of Electrical and Electronics Engineers (IEEE), and Underwriters' Laboratories (UL) organizations. Standards for the interconnection of distributed resource in the power grid is included in IEEE 1547 which explains the performance, maintenance, testing, and safety requirements of all DER on distribution systems [102]. Power converters, controllers, and safety specifications of DERs are presented in UL 1741 standards [103]. Communication standards in IEEE 2030.5 and ISO 15118 provide interoperable control for EVs via information exchange, test procedures, response specification, and security requirements [104].

The EVSEs are used to communicate with the EV to ensure a safe and appropriate power supply other than delivering energy between the EV battery and energy source. Therefore, some of the standards are developed for signaling and communication with multiple devices. The primary objective of communication standards is to regulate the amount of current provided and manage the current flow of different devices. Moreover, the SoC of the battery also monitors and allows the use of EVSEs. Communication specifications of the DC off-board fast charger are designed with SAE J2847/2 standards [98] and PLC communication requirements can be observed in SAE J2931/4. International Organization for Standardization (ISO) is also developed many safety-related standards and technical regulations for lithium-ion battery packs (ISO 64691-3) and EVs in high voltage systems (ISO/DIS 21498) [105].

IV. ARCHITECTURES OF ELECTRIC VEHICLE CHARGING STATION

The primary purpose of the EV charging infrastructure is to offer convenient, efficient, and reliable charging and discharging of the EV battery. Charging station architecture relies on the power source such as grid, RES or ESS, and AC and DC bus configurations. The fast-charging stations are connected to the medium voltage network to supply high power from the grid. Therefore, they required high capital investments to design additional control techniques to maintain power requirements and standards on both sides of the fast-charging station. RES and ESS are widely preferred in the present EV charging station architecture to minimize impacts on the grid while providing additional network services. Moreover, charging stations with V2G capabilities are currently being extensively researched to enhance grid support. The architecture of EV charging stations can be classified as AC bus, DC bus, and a combination of AC and DC bus structures.

A. CONVENTIONAL CHARGING STATIONS

The three-phase AC bus operated between the 250V- 480V line-to-line voltage in the common AC bus-connected charging stations [47]. The EV side of this architecture consists of a DC-DC converter and AC-DC rectifier in each EV charging point as shown in Fig. 5(a). Therefore, the AC bus system causes an increase in cost, complexity, power conversion stages, and reduced efficiency of the charging system. The grid side comprises a step-down transformer that serves to supply appropriate voltage to the common AC bus. In contrast, the grid side of the common DC bus connected system has a single AC-DC converter to provide DC power to the common bus as shown in Fig. 5(b). Each EV load is employed with an independent DC-DC converter. Hence, common DC bus architectures are more efficient, cost-effective, small, and more flexible structures with greater dynamic performance when compared to the AC bus-based architecture. The DC bus system also offers a more adaptable structure with the possibility to connect ESS and RES. However, low operating PF of common DC bus charging stations can generate undesirable harmonic impacts on the utility grid.

AC charging stations are preferred as public charging stations due to their low manufacturing cost and they

TABLE 8. International EV charging standards and grid codes.

Organization	Standards	Description
The Institute of Electrical and Electronics Engineers (IEEE) [17]	IEEE 519-1992	Harmonic control in electrical power system
	IEEE 1159-1995	Monitoring electric power quality
	IEEE 1100-1999	Powering and grounding sensitive electronic equipment
	IEEE 1366-2012	Electric power distribution reliability indices
	IEEE1547	Standards for interconnecting distributed resources with electric power systems (10MVA or less PCC)
	P1547, P2100.1	Standards of various aspects of grid connection of DERs, charging system standardization
Society of Automotive Engineers (SAE, United States)	SAEJ2293	- Standards for on-board and off-board charging equipment (Conductive AC and DC, inductive charging) - Power requirement, system architecture for conductive AC, DC, and inductive charging - Communication and network requirements of EV charging [67]
	SAEJ1772	Ratings for all the equipment for EV charging- (voltage and current ratings of circuit breakers and AC and DC charging levels 1 & 2)
	SAEJ1773	Standards for inductively coupled charging systems
	SAEJ2847	Communication requirements between EV charging system interfaces
International Electro-technical Commission (IEC, Britain) [21]	IEC61851	- Standards for EV conductive charging system operation-Cable, plug setups - Onboard and offboard EMC requirements for conductive charging. - Onboard and offboard charging equipment for EVs /PHEVs with 1000V AC and 1500V DC supply voltage [104] - Digital communication of DC charging control between EV charging controller and supply equipment - DC fast charging requirements
	IEC61980	Standards for wireless power transfer for 1000V AC and 1500V DC supply voltage
	IEC62196	Standards for connectors, plugs, and socket outlets used for conductive charging
	IEC61000-2, 3, 4	Compatibility levels of low-frequency conductance, harmonic emission, EMC, flicker limits of voltage
National Electric Code (NEC) [19]	NEC625, NEC 626	Safety measures in the off-board EV charging system (conductors, connecting plugs, inductive charging devices)
Underwriters' Laboratories (UL) [24]	UL2231, UL2251, UL2202	Requirements for protection devices for EV charging circuits and charging system equipment
	UL2594, UL1741	Requirements for EV supply equipment (inverter, converter, charge controller, and output controllers used in power system)

consist of matured AC technology and standard charging components in the market. The slow charging application in AC bus-connected systems has a maximum of 19.2 kW power [106]. The AC bus connected to fast, and ultra-fast charging stations is necessary to be equipped with advanced components and controllers to maintain grid codes and EV charging standers. Therefore, common DC bus architecture is commonly preferred for fast and ultra-fast EV charging stations as they have a low impact on the utility grid, a simple control strategy, and high efficiency. The DC and fast charging (22 kW - 200 kW) and ultra-fast EV charging (>300 kW) capabilities are commonly designed in off-board chargers with high power flow and galvanic isolation is mandated between the EV battery and the grid according to the IEC standards [107]. The advantages and disadvantages of AC and DC bus-based charging systems are summarized in Table 9. The comparative analysis of AC and DC bus architectures is presented in [108] for grid-connected fact EV charging systems. The power quality of both AC and DC charging systems is evaluated under dynamic and steady-state conditions and different transformer configurations and concluded that common DC bus architecture has better performance than common AC bus architecture.

B. AC AND DC BUS-BASED CHARGING STATIONS

The AC and DC bus-based architectures are considered as a DC grid and AC microgrid which are particularly employed with DC power sources. This hybrid architecture of EV charging stations includes a power grid and different energy sources which are connected to the AC and DC buses via sep-

TABLE 9. Comparison of AC and DC bus-based charging stations architectures.

Architecture	Advantages	Disadvantages
AC bus-based EV charging systems	• Highly available and mature technology with standards. • The complexity of the protection devices is low. • Able to direct usage for local loads • Stability and scalability are high • Reliable switching and control techniques • Ability to control active and reactive power	• A large number of converters reduce rated power and efficiency. • High cost due to multiple converters. • Additional conversion stages are required for fast chargers to avoid harmonics. • Difficult to achieve high power quality and stability • Complex to integrate RESs and required additional DC/DC stage.
DC bus-based EV charging systems	• Provide high efficiency and power density due to low components. • The control strategy is simple • Low cost and flexible configuration which can integrate ESS and RES easily. • Helps to reduce the impacts of high penetration of EV loads on the power grid • Reduction in frequency fluctuation	• Complexity may increase with the additional energy sources. • Required protection devices to withstand sudden changes • The central converter needs server conditions due to an increase in nominal power.

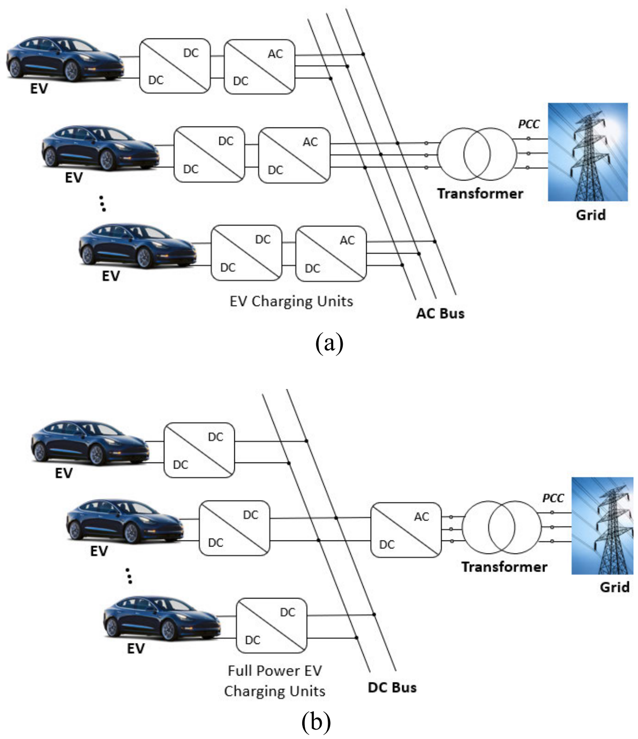


FIGURE 5. Architecture of conventional EV charging station: (a) Common AC bus-based system, and (b) Common DC bus-based system.

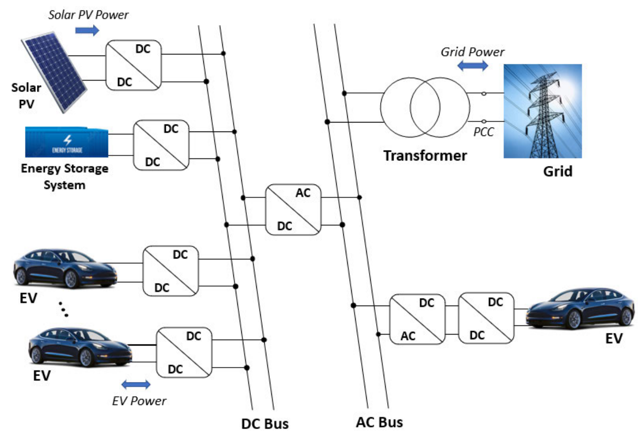


FIGURE 6. Architecture of AC and DC bus-based EV charging stations.

arate converters as shown in Fig. 6. This configuration provides simultaneous operation of both AC and DC charging by preventing additional power conversion states [109]. A single bidirectional converter is employed to connect AC and DC buses in the system which is called an interlinked power converter and the corresponding buses can be used to connect AC and DC loads. The interlink converter can maintain an energy balance between both sides and operate according to the load requirements. This architecture is very reliable, flexible, and more efficient than AC and DC bus configurations. The bidirectional DC-DC converter is connected between the EV and the DC bus to achieve fast DC charging and discharging via V2G operation. The AC and DC bus-based structure is used to investigate microgrids and ESS [110]. The stand-alone V2G control technique is proposed in [111] to examine charging and discharging performance and RES power characteristics in hybrid AC-DC charging architecture.

C. RENEWABLE ENERGY INTEGRATED CHARGING STATION

The RES-integrated EV charging systems have gained interest in the industry as a cost-effective, clean, and sustainable technique to charge EV batteries. RESs are capable of providing services to the power grid by reducing peak demand, energy efficiency, and reliability. EV charging systems have been introduced with solar PV, wind power, energy storage systems (ESSs), supercapacitors, and fuel cells in recent days. RES integrated architectures enable low emission, highly flexible, and economic EV charging as well as provide ancillary grid services [112], [113], [114]. Among different RESs, solar PV-powered EV charging stations are widely established due to their technological advancement. The ESSs are becoming an integral part of EV charging systems along with the RESs in microgrid and smart grid frameworks. The authors in [113] proposed a hybrid optimization algorithm for ESS and solar PV integrated EV charging stations to reduce the EV charging cost. In [115], a grid-based EV charging system is designed with multiple sources including solar PV, ESS, and diesel generators to provide constant charging in grid-connected and islanded modes. The decentralized EV charging optimization technique for building integrated wind energy is presented in [116] with real-time coordination. Smart coordination with maximum RES of charging systems can reduce the power load on the grid and ensure cleaner energy [117].

The EV charging station may be supported by the power grid, standalone RESs, or combined grid-connected RESs depending on the power grid's availability to prevent local power network overload and ensure a higher proportion of clean energy usage in RES-integrated architectures. Most researchers attempt to enable high renewable energy-based power generation on EV charging stations to decrease the power demand during the charging period by managing their charging patterns. The architecture of RES-connected common AC bus-connected EV charging station is shown in Fig. 7 (a) and DC bus-based architecture is shown in Fig 7(b) respectively. RES integrated architectures include a power grid, solar PV, wind power, ESS and bidirectional EV loads with relevant converters and control units. The AC bus architecture can be changed by using a common DC bus with reduced converter stages.

RES-based charging systems is increasingly developed due to several factors. The implementation of RESs and EVs deliver an exceptional opportunity for sustainable charging of EVs which can be directly utilized to charge EVs during peak time [118]. Solar PV-integrated EV charging systems can be employed to reduce peak demand by decreasing EV reliance on grid power. Solar PV panels have been installed rapidly, are more affordable at low cost, and EV batteries can be used to store energy for solar PV as they can consume a large amount of Solar PV energy [119], [120]. Many researchers have discovered that coordinate operation of PVs and EVs can decrease impacts encountered by individual PV and EV integration on the power grid [121]. However, the integration of EVs and RESs into the grid is a challenge due to the additional planning stages, converters, and control strategies needed to be considered in this type of charging station. The uncontrolled or uncoordinated effect on system consistency can be compromised and introduced many negative impacts on the distribution grid [122], [123]. The RESs connected to common DC bus-based EV charging architecture are extensively researched over other structures due to efficiency and flexibility to integrate different energy resources, and smart control capabilities [109].

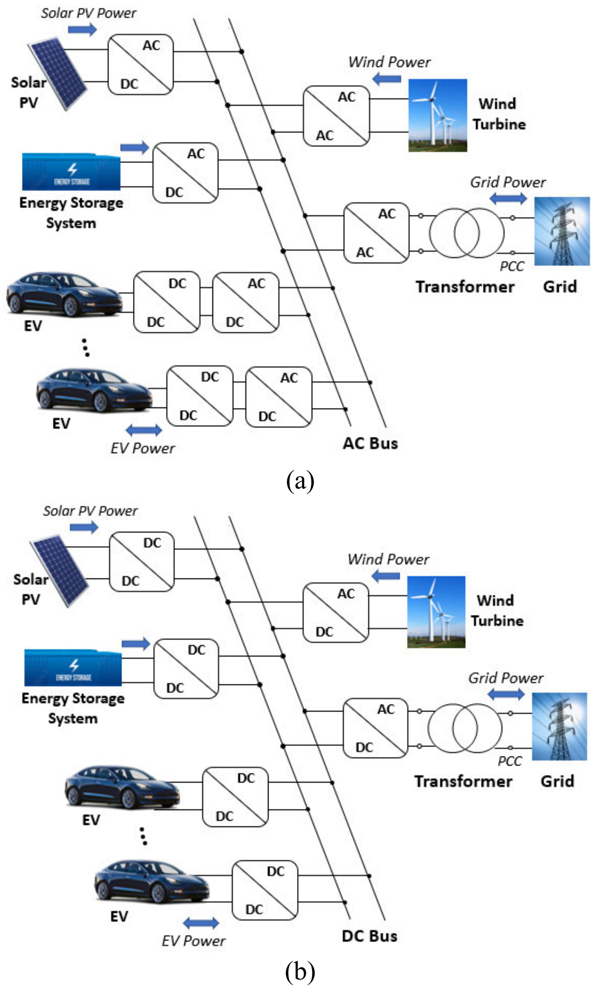


FIGURE 7. Architecture of renewable energy sources and energy storage systems connected (a) Common AC bus based, and (b) Common DC bus-based EV charging stations.

V. ELECTRIC VEHICLE CHARGING TOPOLOGIES

The expanding popularity of EVs results in various types of charging topologies, control strategies, converters, power requirements, and charging stations to maximize energy efficiency while satisfying the constraint of both EVs and the utility grid. Several articles have summarized EV structure and charging configuration [102], [124], [125]. Modern PEVs share a similar powertrain, which is comprised of a high-voltage battery pack to sustain moderate currents, an onboard charger, battery management system, drive inverters, DC-DC converters, and high voltage loads such as cooling system, and heaters [13]. EVs are highly dependent on energy storage techniques including high-voltage battery packs, supercapacitors, and fuel cells. Therefore, charging technology provides an essential link between the EV and energy supply resources. BEVs can be charged from AC and DC power via EVSE by communicating with the EV

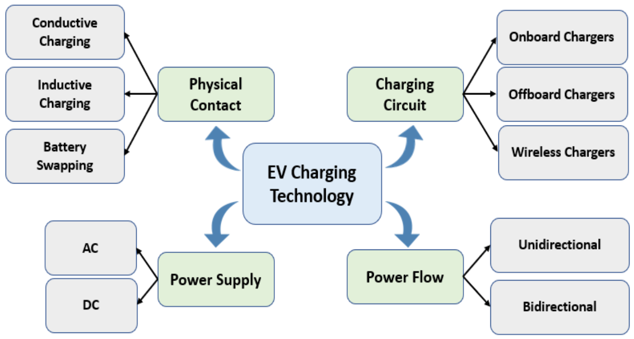


FIGURE 8. Classification of charging technologies used in electric vehicles.

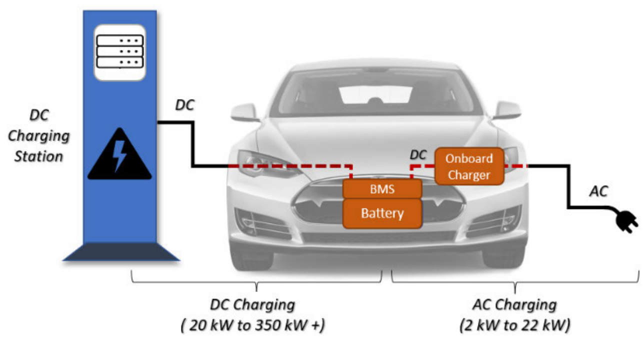


FIGURE 9. Onboard and offboard charging systems of electric vehicle.

and the charger to ensure an efficient and safe energy supply [98]. For EV charging systems, three charging methods are employed including conductive, inductive charging, and battery swapping as shown in Fig. 8 [126]. Both conductive and inductive or wireless charging have advantages over each other in terms of convenience, reliability, and efficiency, thus it is anticipated that both types of chargers will exist at the same time in the future EV market [127], [128].

A comprehensive review of conductive charging technology is presented in this paper. Many automakers equip their vehicles with both AC and DC chargers, giving customers great flexibility in charging their vehicles at home or in public charging stations [129]. Level 1 or level 2 chargers are designed used for charging EVs at home, whereas level 2 and level 3 or DC fast chargers are found at public charging stations [130]. Most EV chargers are compatible with a wide range of EV models [98]. EV manufacturers include both AC and DC chargers in the same vehicle to enable either onboard or offboard charging capabilities as shown in Fig. 9. Furthermore, EV battery chargers have various AC and DC power converters to provide high efficiency, reliability, and power density and either through coordinated or uncoordinated control [131]. EV chargers use either AC or DC power supplies to recharge the battery pack with specific power ratings, standards, and components. AC charging is the common method used in EVs which is converted AC-DC inside the EV in the onboard charger and then charge the battery [132]. The charging speeds depend on the converter capability and output power level of the charging point. Conventional AC chargers have limited power, less than 22kW, and require longer charging time. The DC charging used in fast chargers uses an off-board circuit to generate a high voltage (300 - 1000 V) [133].

The DC chargers convert power before entering the EV in the dedicated offboard charger and then directly charge the battery from DC power bypassing the in-built converter inside the vehicle. DC charging requires high power (20 kW - 350 kW), specific components, safety protocols, and large power control circuits to control high power levels. EV charging control systems can be classified as uncoordinated and coordinated or smart chargers. The battery starts to recharge instantly when plugged in or after a user-fixed delay in uncoordinated charging systems [134]. Therefore, uncoordinated chargers can cause a significant impact on the power grid when unpredictable EV charging loads arrive and lead to high peak demand loading, and power quality impacts [135]. Hence, well-synchronized charging coordination between EVs and grid operators is essential to maximize the load factor and minimize the power losses while enabling grid support [136].

A. GRID-TO-VEHICLE AND VEHICLE-TO-GRID MODE

The power flow direction of an EV can be either unidirectional or bidirectional according to the charging configuration built into the EV. The unidirectional charging system uses an AC-DC rectifier on the grid side and a unidirectional DC-DC converter in the onboard charger with a less complex control system. In contrast, bidirectional EV chargers can transfer power to the utility grid (discharging) as well as EV battery (charging) through off-board chargers using a bidirectional AC-DC converter and bidirectional DC-DC converter [137]. Most of the charger fleet operates in G2V mode which uses limited hardware and a simple control system to charge the battery from grid-supplied or locally generated electricity. A unidirectional charging system has simple structure which simplifies interconnection problems and tends to minimize battery degradation [3]. Unidirectional converters are executed in a single stage to reduce weight, volume, cost, and losses [138]. Moreover, active front-end unidirectional converters can offer reactive power support by controlling the phase angle of the current without discharging a battery. High penetration of unidirectional chargers can achieve power grid requirements while avoiding the cost, safety, and performance issues associated with bidirectional chargers. The comparison of unidirectional and bidirectional chargers of EV is presented in Table 10.

V2G mode has bidirectional energy transfer capability between EV and the electrical grid through a communication strategy in charging infrastructure [139]. The bidirectional mode of EV acts as distributed generation, storage, and load for the power grid. Many researchers have recently indicated that the application of V2G in the ancillary market is more essential to voltage controlling and spinning reserve other than reducing peak load. The spinning reserve refers to the excess generation that could provide immediate backup power to the power grid. Many studies have explored EV deployment in ancillary services providing many cost-effective services and generating revenue for utilities via V2G operation. The main duties of V2G include:

- Regulate battery charging operation to enhance battery life and reduce overcharging circumstances
- Track the SoC of the battery to ensure proper charging and discharging operations and provide appropriate values of SoC and depth of discharge (DOD) to the user
- Control the EV battery SoC.

The V2G can provide ancillary services including voltage and frequency regulations, improved system stability, load following, peak load shaving, energy supply, reactive power support, and RES integration. Technology improvements in EVs have introduced new energy transmission modes, vehicle-to-house/building (V2H, V2B), vehicle-to-load (V2L), and vehicle-to-vehicle (V2V). therefore, bi-directional energy transfer from EVs can be categorized as below [142].

- V2G – Power flows from EV to the distribution grid
- V2H/V2B – Power flows from an EV to a home or building
- V2L - Power flows from an EV to load
- V2V– Power flows from one EV to another EV.

The majority of current V2G analyses are focused on the simpler "Smart charging" control systems that extend standard demand response applications to PEVs [141]. The recommended test programs for V2G operation cover three broad areas of investigation: battery impact, network operation, and system response. For V2G applications, BEVs have a high battery capacity, which results in a longer range and support for electric grid integration. For future V2G scenarios, the major areas of attention in EV development are the energy storage system, powertrain, and charging infrastructure [143].

B. ONBOARD CHARGERS

The onboard chargers have either unidirectional or bidirectional power transfer capabilities which are compatible with Level 1 and 2 chargers due to limited size, weight, volume, and power. Most of the onboard chargers use two-stage converter topologies an AC-DC stage in the front end and a DC-DC stage in the back end [144]. A grid-connected front-end passive rectifier feeds a boost converter that operated as a PFC in onboard chargers. Then supplies appropriate power to the onboard DC-DC converter via a DC link to charge the battery [145]. The front-end rectifier stage can be achieved by a half-bridge, full-bridge, or multilevel converters. Onboard charging offers lower power transfer and therefore requires more charging time compared to offboard chargers. The configuration of the onboard charger is shown in Fig. 10. Onboard charges can deliver 1.9 kW (level 1) and 19.2 kW

TABLE 10. Characteristics of unidirectional and bidirectional power flow of electric vehicles.

Features	Unidirectional Charging (G2V)	Bidirectional Charging (both G2V and V2G)
Power flow	The charging rate of EV control with a unidirectional power flow which is based on energy scheduling of G2V	G2V and V2G modes enable bidirectional power flow to achieve a range of grid support and services
Type of Switches	Unidirectional power converters and diode bridge	Low and medium-power transistors and high-power gate thyristors
Control System	A simple and easy control system, active control of charging current, and energy-pricing techniques used to manage basic control	Complex control system with additional drive circuit. Required extensive measures and an accurate communication system
Services	Ancillary services, load leveling, load profile management, and frequency regulation [144]	Voltage and frequency regulation, backup power support during peak time, active and reactive power support, PFC and helps to integrate RESs to the gird
Safety	Isolated or non-isolated	Isolated or non-isolated, include high safety measures and anti-islanding protection [145]
Advantages	-Simple power control strategy -Minimized operational cost, power losses, emission, overloading, and interconnection issues. -Supply voltage and frequency regulations -Provide reactive power support by controlling the phase angle of the current.	-Improve voltage profile, power quality, active and reactive power support, load leveling, -Volage and frequency regulation and peak load shaving. -Grid power losses and emission minimization -Load factor improvement and increased profit -Enable RES integration with grid
Limitations	-Limited services required a power connection. -No extra degradation in battery	-Required 2-way power flow converters and communication. -High complexity, capital cost, energy losses, and stress on the devices. -Need for smart sensors and meters -Fast battery degradation

(level 2) AC power levels. AC power is directly fed to the AC-DC rectifier in the onboard charger from the AC charging station. Then DC-DC converter regulated appropriate power levels and feeds power to the battery pack through a protection circuit by communicating with BMS and the power control unit [146].

Onboard chargers with advanced control techniques have been proposed in many research studies to improve the controllability, efficiency, and grid support of the charging. In [147], a single-phase compact onboard charger with the current ripple compensator technique is proposed. The

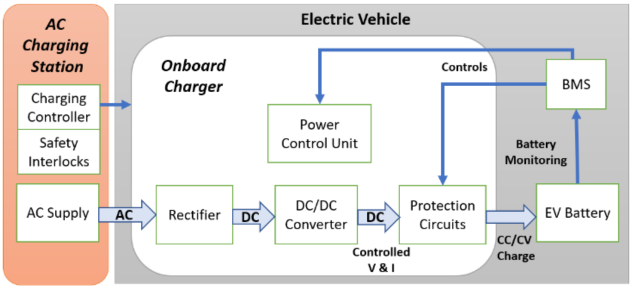


FIGURE 10. Configuration of conventional onboard EV.

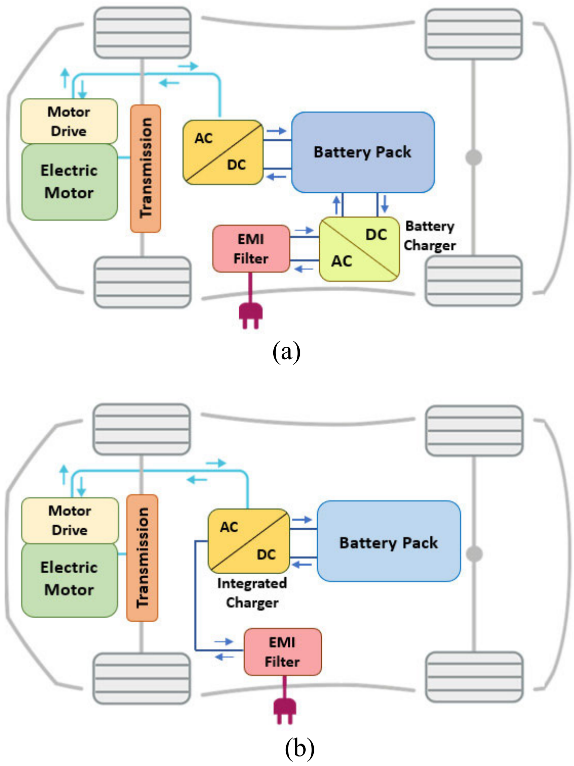


FIGURE 11. Configuration of onboard power electronic interface: (a) Dedicated onboard charger (b) Integrated onboard chargers.

compensator consists of a zeta and boost converter which is connected in series with the EV battery in a non-isolated charging system without using bulky inductors or capacitors. A comprehensive study of wide-bandgap devices is presented in [148] for onboard chargers and demonstrated a possible approach in the onboard application via 400V/80 A test bench with Si MOSFET components. The multifunctional onboard battery charger presented in [149] can operate as AC-DC converting with PFC as well as V2G operation through sharing inductors and switches in one system. A three-phase onboard charger is integrated with the EV propulsion system [150] by connecting the three-phase interface to the propulsion system. The system is implemented with a 3.3 kW three-phase integrated charger and unity power factor, 92.6% efficiency, and reduced harmonic restoration of 4.77%. Research in [151] proposed an active power decoupling function for low-power charging onboard in PEVs. The proposed onboard charger can operate in G2V, and V2G, and the EV battery can be charged from the high voltage ESS by sharing capacitors, switches, and transformers in the same system.

Onboard EV charges are broadly categorized into unidirectional or bidirectional and single-phase or three-phase chargers. Various types of onboard chargers have been introduced recently as an optimum solution to the high penetration of EVs. The conventional method of EV battery charging is achieved through a dedicated onboard charger. Conventional or dedicated onboard chargers comprise two converters used for battery charging and motor controlling as shown in Fig. 11(a). Dedicated onboard chargers have limited power transfer capabilities due to several constraints including volume, cost, and weight of the vehicle [152]. Integrated onboard chargers have been designed to overcome the above limitations which are tightly integrated with an electric motor using a single AC-DC converter as shown in Fig. 11(b). Integrated chargers can operate the existing propulsion system for battery charging by avoiding bulky components and dedicated configurations [153]. A review of dedicated and integrated onboard charging systems is presented in the next section.

1) DEDICATED CHARGERS

The conventional or dedicated charger is an independent device with the single purpose of charging an EV battery by providing conditional output power. Dedicated is small, lightweight and is operated with single-phase or three-phase AC power depending on the charging system by following Level 1 and 2 charging standards. The power level has been trending upward from 3.6 kW single-phase chargers to 22 kW three-phase chargers. A dedicated charger directly connects to the AC wall socket (Mode 1 or 2) and relevant conversions such as AC-DC and DC-DC power conversions are conducted inside the onboard charger. Modern onboard chargers are following IEC 61000 standards to reduce power quality impacts on the grid. Commercial EVs have limited AC charging power levels up to 22 kW (32A and 400V three phase) due to space and weight limitations of the vehicle. The main challenges of onboard chargers are dependence on the charging outlet, voltage limitations of battery, DC controlled with the AC voltage controller, and incompatibility of ground referenced. Moreover, extensive safety requirements need to be addressed at high power levels and the size and weight of the vehicle may increase as adding components. Dedicated DC chargers (22 kW) are installed in houses, workplaces, apartments, and shopping centers.

Most of the commercially available onboard chargers have two-stage power converter topologies. The usual onboard charging configuration includes an electromagnetic interference filter, AC-DC converter, and isolated DC-DC converter. Grid-side AC-DC converters are comprised of a PFC circuit to limit harmonics and supply power to the DC link as a first stage and then the DC-DC converter is connected to the battery interface which is comprised of two inductors and a capacitor (LLC) with two or four switches to supply

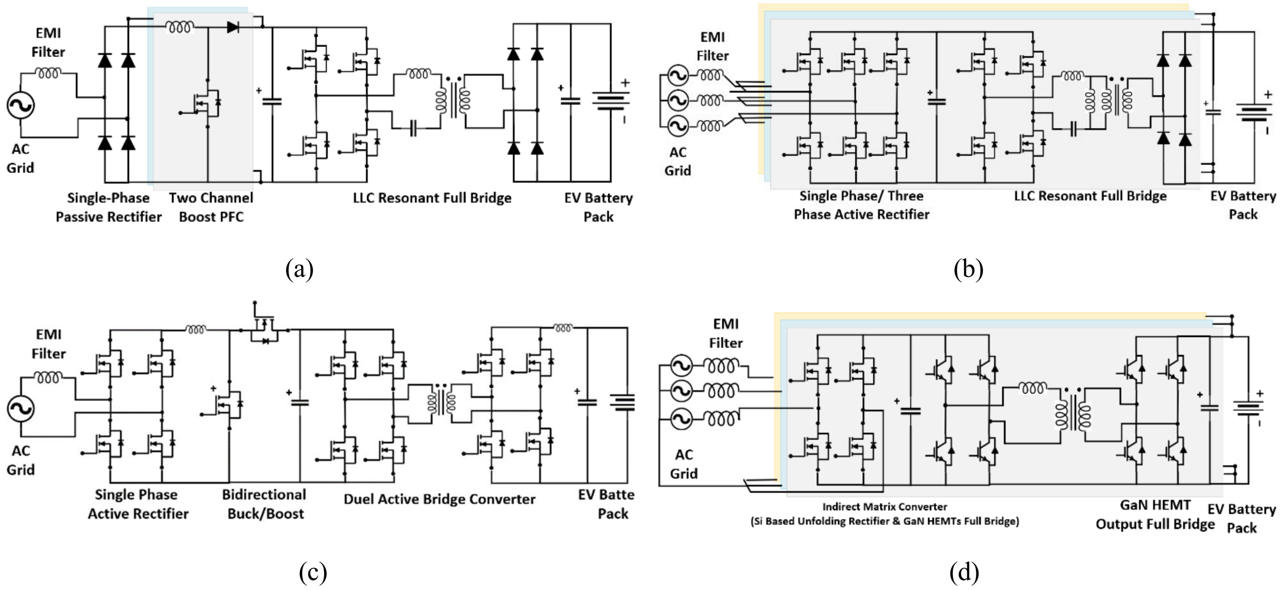


FIGURE 12. **Configurations of dedicated onboard charger (a) Second-generation volt, (b) Tesla Model 3/Y, (c) Hyundai vehicle-to-device, (d) Hella electronics/GaN systems.**

highly efficient power transfer. A large capacitor is required in between two converters to filter grid frequency. Various onboard charger topologies and control systems have been reviewed in [145], [154], and [155]. The onboard converter topology of the 2016 Volt is shown in [156]. Most conventional configurations of onboard chargers are interleaved PFC boost converters and diode bridge converters. According to General Motors' evaluations, interleaved topologies are widely used in front-end conversion stages for modern onboard chargers [157]. The second-generation Volt onboard charger is shown in Fig. 12(a) which comprises four diode bridges and two parallel interleaved boost converters on the grid side to enable approximately 400 V of intermediate DC link voltage. Resonant LLC full bridge converter is used for the DC-DC conversion stage to acquire output voltage for the battery.

The new version of the Tesla onboard charger adopted a similar trend in the DC-DC conversion stage and three parallel channels are integrated into the front end as shown in Fig. 12(b). The maximum charging capability of Tesla onboard chargers is 11.5 kW and 240kW V3 superchargers are used for EV battery charging in Tesla [158], [159]. Fig. 12(c) shows the topology of Hyundai onboard chargers which can support vehicle-to-device applications via bidirectional power flow. The onboard charger is comprised of a front-end single-phase active rectifier, and a bidirectional buck-boost converter followed by a ducal active bridge to facilitate bidirectional power flow as well as adjust the appropriate voltage for different configurations [160]. Bridgeless boost-type PFC topologies are also used in dedicated onboard chargers by replacing passive diode rectifiers to reduce conversion stages and power losses [161]. Matrix-type converters have been introduced by Hella electronics by further reducing the conversion stages. The matrix converter turns the input grid frequency into the intermediate frequency and a larger DC filter connects to the battery side in the Hella electronics onboard charger shown in Fig. 12(d). The maximum efficiency can be achieved up to 98% for a 7.2 kW single-phase operation in this converter [162].

2) INTEGRATED CHARGERS

Integrated chargers have been designed to overcome the limitations of conventional onboard chargers while preserving their advantages including fast charging capability, reduced components, cost, and volume of the charger [163]. Integrated onboard chargers utilize a propulsion system, electric motor, and inverter for battery charging by avoiding separate convention stages with bulky add-on capacitors and inductors. Therefore, they can offer bidirectional high-power levels (Levels 1 and 3) and more space for the battery [164]. The propulsion inverter operates as a bidirectional AC-DC converter and motor winding provide galvanic isolation and filter conductance [165], [166]. Split-winding AC motors are used in non-isolated integrated chargers. However, single-stage integrated chargers may have current ripples at the DC side and need additional components to reduce voltage ripples. The traction controllers may limit the charging power and the electric motor may be operate in charging mode in integrated chargers and technical requirements such as motor winding limitations, and zero average torque may exist [167]. Renault pioneered integrated charging design and Ford Motor Company currently uses an integrated onboard charger that combined battery charging and motor drive based on an induction motor. Renault pioneered integrated chargers [150], [168].

TABLE 11. Specifications of commercially available onboard chargers.

Model and Manufacturer	Battery Capacity (kWh)	Charging Power (kW)	Battery Voltage (V)	Charging Time (Minutes)	Drive Range (km)
Model S, long range - Tesla - 2022	100	200	400	24	624
Model 3 Performance - Tesla - 2021	79.5	120	360	33	567
Bolt EUV - Chevrolet - 2022	65	50	350	66	402
Leaf SL - Nissan - 2019	62	100	360	35	346
Leaf S - Nissan - 2019	40	50	350	36	378
Ioniq 5 Long Range - Hyundai - 2022	72.6	160	800	18	412
e-208 GT - Peugeot - 2019	50	100	400	30	450
Taycan 4S - Porsche - 2022	79.2	225	800	21	407
MX-30 - Mazda - 2021	35.5	50	355	34	265
e-tron 55 Quattro - Audi - 2022	95	150	396	26	441
Q4 Sportback 55 - Audi – 2022	82	110	400	38	460
i4 M50 - BMW – 2022	83.9	210	398.5	31	510
iX xDrive50 - BMW -2022	111.5	195	330	35	630
EQS 350 - Mercedes Benz - 2022	90.56	170	500	30	626
I-Pace S AWD - Jaguar - 2020	90	100	388	43	470

Most integrated chargers inversely use the electric drive inverter as a boost stage with more than 50 kW power, and it can utilize the propulsive components in the charging period. Different types of integrated charging topologies have been proposed in recent years using general DC-DC converters, switched reluctance motors, or alternating motors [127]. In [3], integrated converters are comprehensive analyses based on the motor type either isolated or non-isolated cases. The topology of the Renault Chameleon integrated charger is shown in Fig. 13(a) which employs a reverse-blocking IGBT rectifier with filtering components at the AC side for single and three-phase AC grids [169]. As the first commercially used first integrated charger, Chameleon chargers are currently used in Renault ZOE which is not required additional components between operating modes as torque is not generated in the motor [170]. The motor winding is function as a DC link and the traction inverter is connected between the motor and the battery to supply the required current for the battery pack [171], [172]. The Chameleon charger is designed to use the neutral point of the motor to turn the motor inverter into three separate boost-type converters [145]. Configuration of motor winding or additional grid to motor interface helps to enable high power charging without producing torque in the electric motor [145].

Valeo integrated charger is developed using a triple H-bridge inverter which is connected to s winding in the synchronous motor as shown in Fig. 13(b). The inverter can provide high voltage at an intermediate DC-link and a matching DC-DC converter is implemented between the battery and inverters to adjust the battery voltage. Passive rectifier and filter components are additionally used in Continental high-power onboard chargers as shown in Fig. 13(c). A high power charging rate is possible with a three-phase current (400 V) and galvanic isolation provides additional protection in Continental onboard chargers [173]. The multiphase integrated onboard charger presented [145] has decoupled inductors in the motor and a multiphase AC-DC converter that is directly connected to the battery. overview of multiphase integrated onboards chargers can be found in [165] and [169]. Another type of integrated charger is an isolated onboard charger which is equipped with multiterminal motors to execute traction mode as well as galvanic isolation during battery charging. Isolated integrated charger topology is shown in Fig. 13(d) which included two sets of three-phase motor winding. Stator windings are normally connected in series to form a three-phase set depending on the charging configuration. These dedicated chargers can be used for single-phase systems as well as operates as a high power isolated bidirectional fast charge is unity power factor [174]. Commercially available onboard chargers are presented in Table 11 with specifications including battery voltage, capacity, charging power, charging time, and driving range. Most modern electric cars utilized high voltage batteries (up to 800V) and hence isolated high-voltage transmission system is added for safety.

C. OFFBOARD CHARGERS

Offboard chargers are integrated with DC fast charging or ultra-fast charging systems for high power flow (>20 kW) between the utility grid and battery based on level 3 or

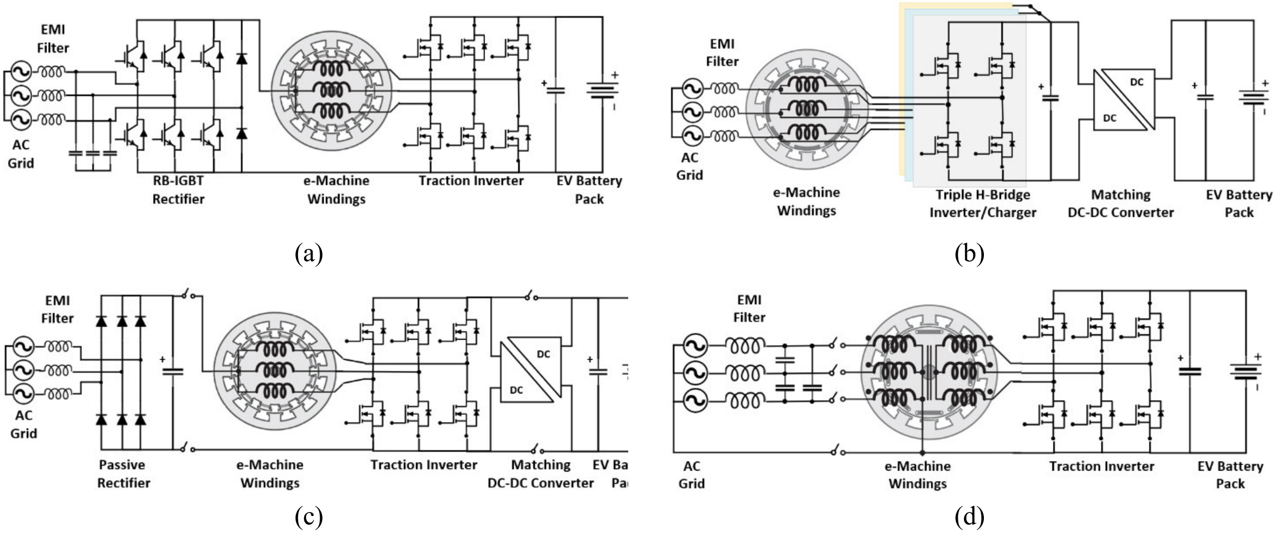


FIGURE 13. Configurations of integrated onboard charger (a) Renault chameleon, (b) Valeo dual-inverter charger, (c) Continental all charge system, (d) Galvanically isolated traction integrated charger.

extreme fast charging standards. The power conversion stage of the offboard charger is located outside of the EV and therefore the volume, weight, size, and cost of the charger are significantly reduced when compared to the onboard charger [7]. As a conductive charging process, EV offboard chargers are incorporated with either AC bus or DC bus configuration [47]. Most fast and ultrafast charging systems prefer AC bus-connected fast charging stations due to well-equipped configurations and matured power converters on the AC power grid. Offboard charges consist of two converter stages AC-DC and DC-DC conversion to adjust the DC current before reaching the EV as shown in Fig. 14. Central AC-DC converter is connected to the low-frequency transformer on the grid side in the DC bus connected to offboard charging systems. The DC-DC converter is connected to the DC link to provide DC power to the battery. DC bus-connected systems are more efficient and flexible than AC bus-based fast chargers and RESs can be connected via DC link and grid-side impacts are simply avoided [47]. Moreover, AC and DC bus-based configurations are also available for offboard chargers. However, fast charging stations have some drawbacks including high infrastructure costs, safety requirements, complex control strategies, and communication protocols that need to be used according to the standards [175]. A review of offboard charger topologies and control techniques have been presented in [3], [109], [141], and [176].

Integrated EV chargers can be classified as converter-integrated and machine-integrated which are comprehensively reviewed in [177]. The power grid is connected to the inverter through machine winding in single-stage integrated chargers that behave as an input filter. In two-stage chargers, the battery powers the traction machine through an inverter and a PFC circuit and AC-DC converter are implemented between the motor and the electricity grid. A comparison of different winding configurations in EVs is presented in [178]

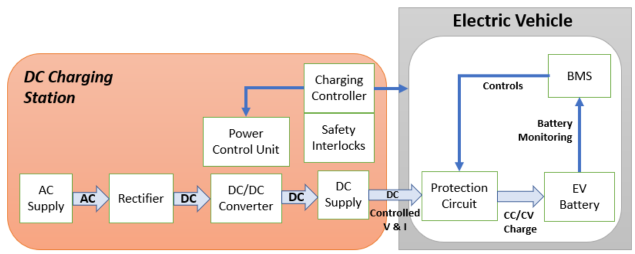


FIGURE 14. Configuration of conventional offboard charger.

and hairpin winding for electric motors are evaluated in [179]. The fast three-phase charging has been proposed in [180] which AC three-phase mains are linked to the middle point of each motor winding through an EMI filter and protection component.

Modern offboard chargers can provide more than 350 kW power to the EV battery for ultrafast charging and are compatible with 800 V EVs in the near future. Most of the offboard charging topologies are employed with galvanic isolation in the DC-DC converter stage using a high-frequency transformer (50 kHz – 300 kHz) instead of a line-frequency transformer to provide safety for the components, better control of voltage adjustments, and compactness [3]. Most EV manufacturers tend to design chargers by modularizing them to achieve compatibility, high efficiency, and economic benefits from their chargers. Specifications of currently available ultra-fast and fast charging systems are presented in Table 12. Terra 53/54 series fast charger is designed based on a power electronic building block (PEBB) by ABB as a benchmark for offboard chargers as shown in Fig. 15(a). The PEBB is a widely accepted concept which incorporates several topologies to reduce cost, size, losses, and components of the applications [181]. The number of active power stages varies

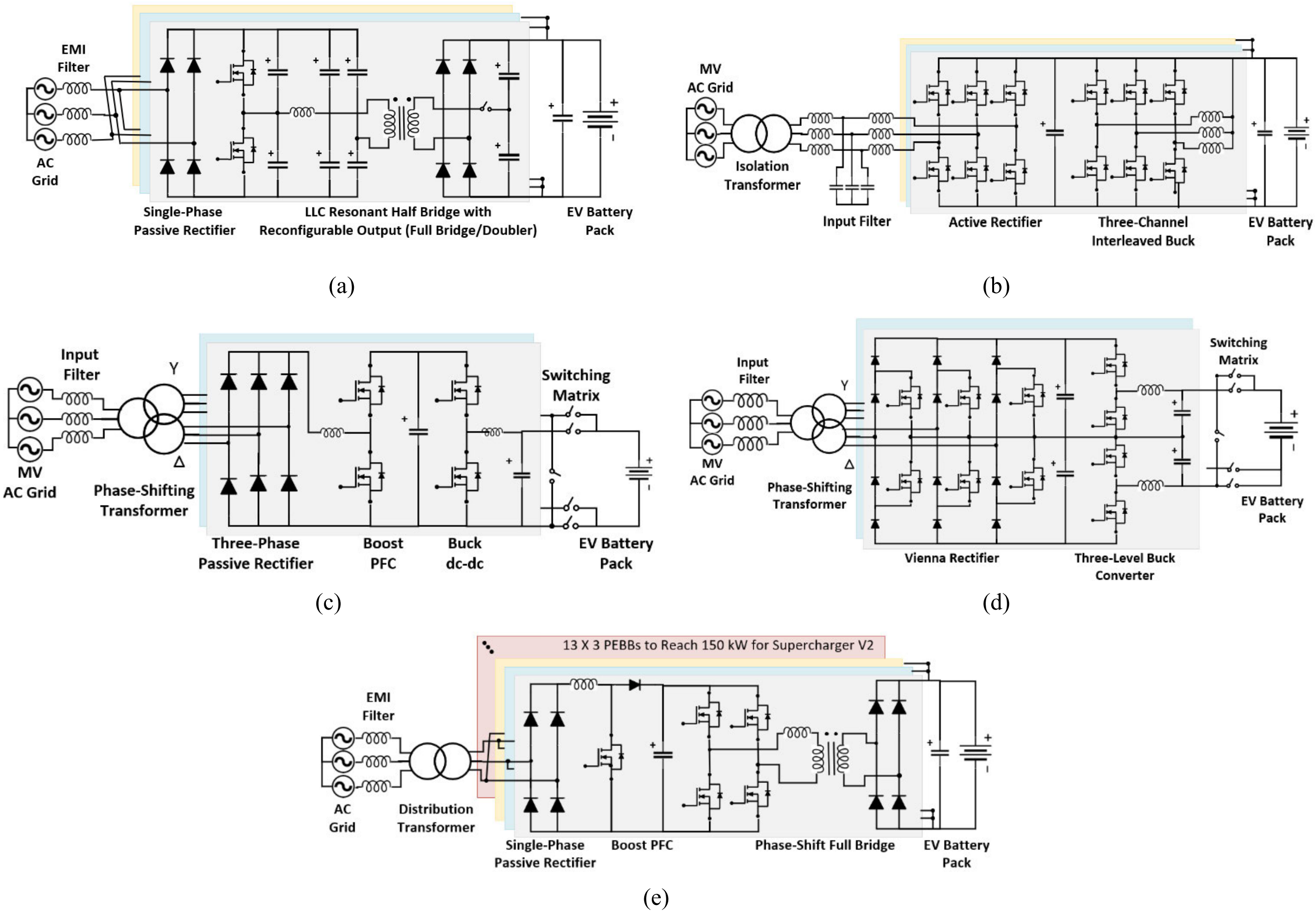


FIGURE 15. **Configurations of offboard chargers (a) ABB Terra 53/54 50-kW fast charger, (b) ABB Terra HP 150-kW high-power charger, (c) Porsche modular fast charger Park A, (d) Porsche modular fast charging Park B, and (e) Tesla V2 Supercharger.**

with output requirements and an isolated DC-DC converter is used to meet high power level and isolation requirements. The modular system of ABB Terra 53/54 fast charger is designed by replicating the same type of PEBB (5×3 PEBBs to Reach 50 kW) and efficiency is 94% [182], [183]. ABB Terra high power charger series is shown in Fig. 15(b) which is also configured with the modular system (three PEBB to reach 150 kW high power). An isolation transformer and LCL filter are used to reduce grid side harmonics and an active rectifier and interleaved buck converter are used in the modular configuration in high-power ABB Terra offboard charger.

Porsche fast charger can manage 800V with modular fast charging topology. Porsche Modular Park A and park B fast charging configurations are shown in Fig. 15(c) and (d) respectively. A phase-shifting transformer is used after the input filter to provide galvanic isolation and improve the power quality of the AC grid side in both configurations. Three-phase passive rectifier and boost PFC converter used after phase shift transformer and DC-DC buck converter utilized to lower current ripple and step-down voltage as required for EV battery in Porsche Modular Park A fast charger [184]. A combination of the Vienna converter and three-level interleaved buck converter enables modifications in the battery charging converter to provide PFC, reduce current ripples, and be compatible with other configurations in Park B fast charger [185], [186]. DC fast chargers are still in the developing phase and therefore standards and protection requirements are not well established due to specifications in high power, complex grounding topologies, and fault types [187]. Moreover, protection and metering requirements are critical for bidirectional fast chargers as they are very sensitive to grid disturbances and a review of coordination techniques is presented [188]. Tesla superchargers have a combination of PEBBs (13×3 PEBBs) to provide 150 kW power with 92% efficiency as shown in Fig. 15(e). The simplified one-line diagram of the Tesla supercharging station is presented in [182].

VI. CONVERTER CONFIGURATIONS OF EV CHARGING SYSTEMS

The power electronic converters are an integral part of electrification to achieve efficient, and reliable operation of EV charging systems. As advances in power electronic techniques have made conversions possible to achieve cost-effective and maximum power conversion. The power con-

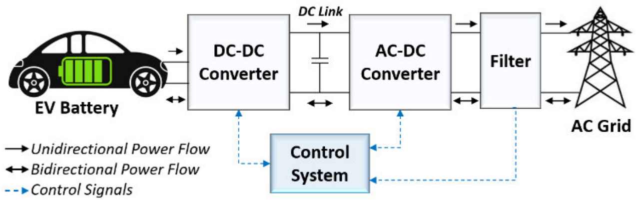


FIGURE 16. Block diagram of conventional EV charging system.

verter topologies are interfacing between the EV battery system and power network which is responsible for improving charging performances and controllability of the charging system [189]. Moreover, advanced power converters and controllers are continuously developing with the increasing integration of EV charging systems into the RESs in recent years. The AC-DC converters and DC-DC converters are equipped with EV charging systems to supply power to the vehicle components and deliver power from a power grid to an onboard high-voltage battery pack. The AC-DC converters are used for rectification and power factor correction (PFC) of the EV charging system and are further able to control charging cost and complexity and improve power quality. The front end of the charger consists of the AC-DC converter to convert single/three-phase power to DC power and supply the required DC link power and function as a power factor corrector topology. The DC-DC converters are primarily employed in an EV charging station, classified as unidirectional or directional converters and isolated or non-isolated power converters [155].

The significant advantages of EVs over other conventional clean energy applications are due to improvements in converter topologies. The improved power converters in EV charging systems can operate bidirectionally concerning the power demand of the grid, improve power quality and provide ancillary services. The simplified diagram of a conventional EV system is shown in Fig. 16 which comprises a DC-DC converter, AC-DC converter, and filter in between the EV battery and grid. The AC-DC converter rectifies AC voltage to regulated intermediate DC link voltage and the DC-DC converter controls the DC input voltage for the EV battery. The control system is maintained the transient and steady-state performance of the system by providing relevant control signals for converters. Moreover, PFC techniques are implemented parallelly with the AC-DC converter to achieve a unity power factor and overcome current harmonic impacts [200]. The PFC circuit is sensing input voltage and current and then controls the input currents close to sinusoidal and in phase with relevant voltages by controlling the converter switches. The desired DC link voltage is regulated via a DC-DC converter to charge the EV battery.

A. AC-DC CONVERTERS

The AC-DC converter provides the interface between the DC link and the power grid by providing high power quality on the DC and AC sides of the charging system. They are generally designed as single-phase H-bridge inverters or three-phase three-leg inverters either controlled or uncontrolled rectifiers [134]. The AC-DC conversion is the first stage of the EV charging system, and it controls reactive power consumption and grid-side current harmonics [201]. The PFC technique is implemented in the AC-DC converter to supply efficient and safe power output to protect the connected devices, users, and the grid. The AC-DC converters can be classified as unidirectional and bidirectional as well as single-stage and multistage AC-DC power converters. The unidirectional chargers deliver G2V operation (charging) with a low-cost and simple charging structure and supply moderate grid support with minimum power infrastructure modernization [202]. Conversely, bidirectional converters can offer G2V and V2G (charging and discharging) operation with advanced and coordinated control between EV, charging station, and grid with a high level of ancillary services.

The single-stage AC-DC converter is combined with a DC-DC converter which reduced expensive components including DC link capacitors and inductors in the system. However, a single-stage converter has less output voltage range and non-isolated converters have a limited conversion ratio [154]. The single-stage modular three-phase AC-DC converter is introduced in [203] to voltage regulation and PFC and single phase isolated AC-DC converter is proposed in [204] from a differential boost converter by using the AC decoupling waveform technique to address reliability issues. In contrast, multistage converter topologies are designed with two or more converter levels and high-power levels of the converter are provided efficient and reliable control for the charging system. The two-level and three-level voltage source converters are widely used for charging applications including buck/boost converters and multilevel converters. Moreover, the filter is connected between the AC-DC converter and the power grid to reduce harmonics, and di/dt on semiconductors, and isolate the converter from the power grid [205]. The commonly used filters are LC and LCL filters for AC-DC converters and more advanced filters are used for fast and ultra-fast charging stations.

1) BUCK-TYPE RECTIFIER

The buck type of converter is used to regulate the output voltage which is lower than the input voltage with unidirectional power flow. The three-phase buck converter has a wide range of features in the AC-DC power stage when compared to the three-phase boost-type converters. They have a wider voltage control range, inherent inrush-free direct startup, allow dynamic current limitation at the output, provide overcurrent protection during short circuits, and can maintain PFC capability at the input side [206], [207]. The buck converter-based PFC topologies can be classified as bridgeless, interleaved, and bridgeless interleaved buck converters [208]. The conventional six-switch three-phase buck converter shown in Fig. 17 (a) includes three legs that are connected to the three phases and one freewheeling diode to lower the conduction

TABLE 12. Specifications of currently available ultra-fast and fast chargers.

Model	Input Voltage (Vac)	Output voltage (Vdc)	Output current (A)	Power (kW)	Supported Protocols
ABB Terra 54 [196]	400 Vac +/- 10 %	150-500	125	50	CHAdeMO, CCS
ABB Terra High Power GEN III [197]	400 Vac +/- 10 %	150-920	500	350	CHAdeMO, CCS1, CSS2
Tesla Supercharger V3 [198]	380 - 480 Vac	880-970	640	250	Superchargers
Signet FC100K-CC [199]	480 Vac	150-500	200	100	CHAdeMO, SAE Combo
Tritium PK350 [200]	480 Vac	200-920	200-500	350	CHAdeMO, CSS2
Blink 60kW DCFC [201]	480 Vac	150-500	140	60	CCS1
Blink 180kW High Power DCFC [202]	480 Vac	150-1000	240	180	CCS1
EVBox Troniq 100 [203]	400 Vac	50-500	200	100	CHAdeMO, CCS2
Siemens VersiCharge Ultra 175 [204]	480 Vac +/- 10 %	200-920	200-350	178	CHAdeMO, CCS
Ingeteam - INGEREV RAOID ST400 [205]	380-440 Vac	50-920	500	360	CHAdeMO, CCS

losses during the freewheeling condition. The freewheeling diode is divided into a series connected by two diodes and the common node is connected to the input neutral point in the study [209] to reduce voltage stress on the converter switchers. Conventional buck converters are employed for low-power charging systems (<300 W) due to their capability to provide improved power quality and efficiency at different line voltages [208]. The input filter is critical for the buck converter as shown in Fig.13 (a) to reduce the inherent input current disturbances (high ripple) from the charging system [210].

The bidirectional five-level buck converter has been proposed in [211] which is employed two voltage sensors with a complex control strategy to balance voltages across the two capacitors and high voltage side power switches ratings are equal to twice the DC voltage output. The distributed parasitic capacitance of the high-density three-phase buck converters is a major challenge in high-frequency operation which leads to input current distortion and an increase in THD under light load condition. The modified three-phase buck converter has been presented in [212] to reduce the impact of distributed parasitic capacitance between the DC link output and the system ground. Moreover, high step-down voltage gain may appear when the multiple EVs are charging due to variations in the range of the EV battery. Furthermore, power quality impacts and losses increase when the voltage output is less than three quarters of input voltage due to decreasing modulation index of less than 0.5 of the standard buck converters. The matrix-based three-phase buck converter has been implemented in [213] and [214] to regulate the modulation index and improve grid support.

2) BOOST-TYPE RECTIFIER

DC voltage output, low current stress and THD, bidirectional power flow, and high efficiency with a simplified control scheme. The boost converters are integrated with PFC configuration for EV charging systems which are operating in continuous conduction mode which is selected for medium and high-power applications. The boost converter exhibits lower conducted electromagnetic interference (EMI) than other buck and buck-boost converters because of continuous current flow capability [215]. The main limitation of this converter is high conduction losses due to the current flowing via semiconductor components and the diode recovery losses are imposed by the high-frequency operation of the converter [7]. The three-phase six-switch boost converter shown in Fig. 17(b) consists of six switches in the three-legs and an LC filter to reduce input current harmonics and boost the voltage. The switchers upper and lower are executed in complementary and inductors are employed to boost the voltage and reduce input current harmonics. The three-phase three-level boost converters can balance the input AC system during unbalanced input voltage and reduce harmonics at the DC link voltage by employing a bulky capacitor or developing an active control method [216]. The power losses increased in conventional boost converter topology at a high-power rate due to the high ripple occurring at the output capacitor.

The EV charging systems incorporate a variety of boost converter topologies, including bridgeless, interleaved, and bridgeless interleaved boost topologies. In addition, asymmetrical, and symmetrical bridgeless boost rectifiers have enhanced efficiency when compared to the regular boost converter due to the fewer operating electronic devices. The

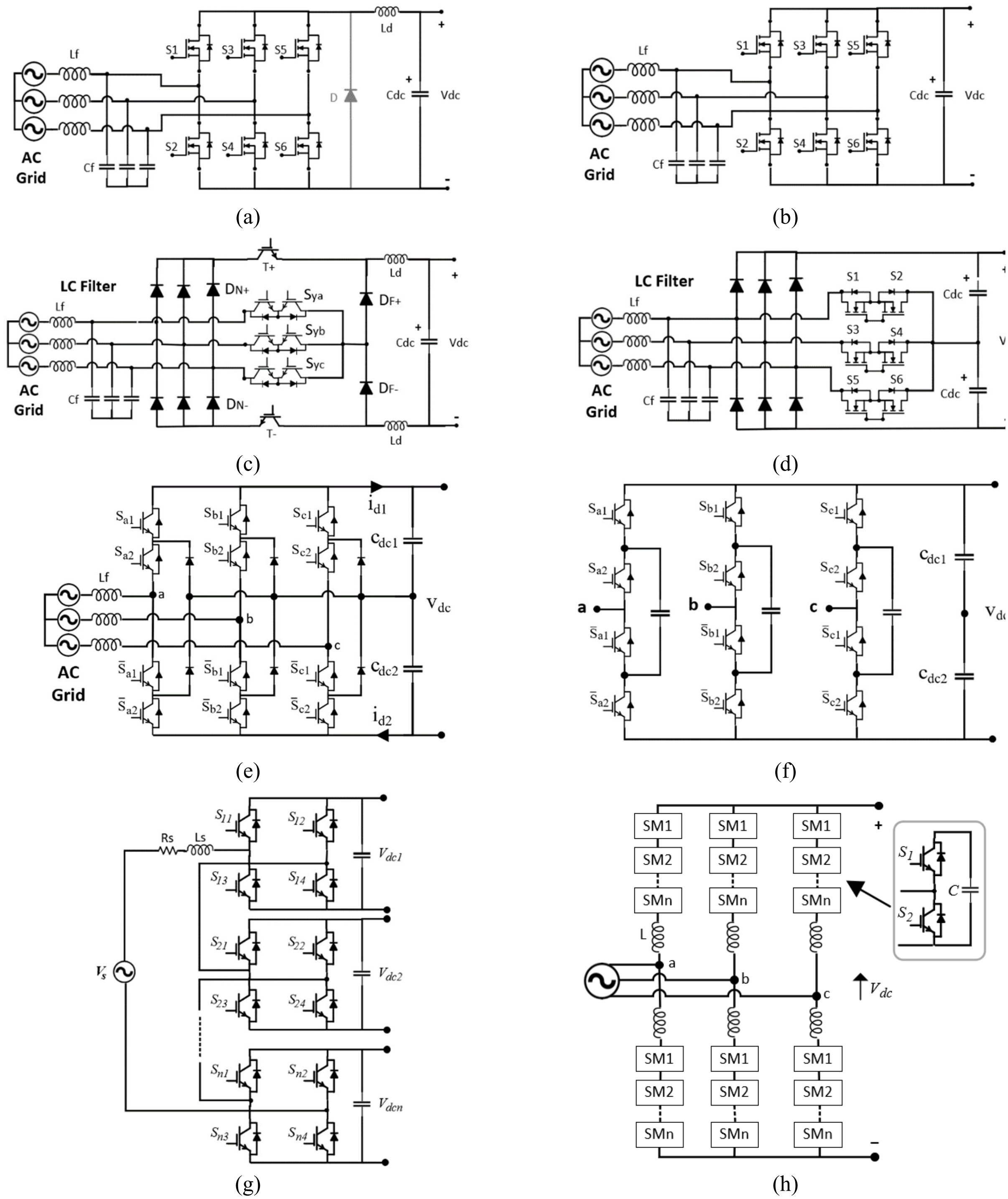


FIGURE 17. AC-DC converter configurations (a) Three-phase six-switch buck-type converter, (b) Three-phase six-switch boost converter, (c) Three-phase Swiss converter, (d) Vienna converter (e) Three-level neutral point clamped (NPC) converter, (f) Three-phase three-level flying capacitor inverter, (g) Cascaded H-Bridge (CHB) multilevel active rectifier, and (h) Modular multilevel inverter.

semi-bridgeless boost rectifier is presented in [217] for font-end AC-DC converter of PHEV charger to minimize the charger size, cost, and EMI and increase efficiency at light load. The isolation approaches such as power supplier separation or transformers are used in high-power applications to avoid current circulating which may increase the volume, passive components, and cost of the system. The parallel three-phase boost converter circuit has presented in [218] with the potential of zero-sequence current circulating capability, modular design, and high efficiency. The harmonics of the unbalanced ac input voltage can be mitigated by adding a bulky capacitor and improving active control techniques to reduce harmonics in the DC-link voltage [216]. The magnetic circuit effects and size of the converter can be reduced by an interleaving of boost-type two converters which doubles the switching frequency and improved energy efficiency [138].

3) SWISS RECTIFIER

The Swiss converter is a buck-type PFC converter topology suitable for EV charging systems with 250 - 450V DC bus voltage and 380 V three-phase AC voltage [219]. The Swiss converter has low common mode noise, switching losses lower complex power circuits, control strategy, and inherent free inrush limitation [220], [221]. The Swiss converter is implemented with three phase unfolder circuit and two DC-DC buck converters. The Swiss converter's three-phase unfolder electric circuit uses two full bridge circuits to transform the AC voltage into time-varying two positive voltages. As a result, fewer high-frequency transistors are required than in single-stage isolated converters. The schematic of eight switches Swiss converter is shown in Fig. 17(c) comprises an uncontrolled three-phase converter bridge and three sets of low-frequency bidirectional switchers Sya, Syb, and Syc which can be defined as six voltage segments concerning the frequency of the phase voltage. The two active switches T+ and T− operate corresponding to the two-phase voltage which is involved in generating output voltage [47].

The single-stage full-bridge Swiss converter is presented in [219] and the midpoint clamper is used to integrate the PFC method of the converter. The system achieved 95.4% efficiency under half-rated power in a 10kW system and showed 5% input current THD under-rated power. The higher switching frequency or increased AC input filter is used to decrease voltage and current ripples at the input. But those options may increase the volume, cost, and losses of the system. The interleaving of Swiss rectifiers can be used to overcome the above drawbacks and offer high reliability, power, and bandwidth, low current and voltage ripple at the input and output as well as lowering filter requirement. The three-phase Swiss converter with interleaved DC-DC output has been presented in [222] and the efficiency of the system is 99.3% in the 8 kW rated power. The multilevel Swiss rectifiers are also used for high-power applications but the control scheme becomes complex [223]. Moreover, bidirectional Swiss converters can be incorporated with the smart coordinate controller to operate V2G in EV charging systems [224].

4) VIENNA RECTIFIER

The Vienna converter is used to supply controlled DC bus voltage in high-power applications and performs as a three-phase boost-type PFC rectifier. Vienna converter provides many advantages when compared to the other three-level converters such as high-power density, efficiency, stable voltage output, reduced number of switches, low voltage stress of the semiconductor, lower THD, unity PF, and neutral connection-free structure [225], [226]. Conventional control methods of the Vienna converter are sliding mode variable strategy, hysteresis current control, and double closes-loop control techniques which can be used to regulate the voltage of the DC-link and unity PF. Moreover, the dead zone is not required to drive switches and voltage stress on the switches appears on half of the two-level converter at the same DC link voltage [227]. The schematic diagram of three phase Vienna converter is shown in Fig. 17(d). The converter is consisting of three inductors for the boost state at the input side, three power bridges for three phases, and two series output split capacitors on the DC link. The power flow of this converter is unidirectional, and each power bridge comprises two fast rectifier diodes and two reverse series connected switchers.

The Vienna converter is designed to enhance the large-scale integration of EVs on the grid [228] using a virtual synchronous machine control strategy. The sliding mode control loop method is utilized in a three-phase AC-DC Vienna rectifier in [229], which consists of loss-free resistor behavior in each phase for PFC. The three-phase interleaved Vienna rectifier is implemented in [230] by focusing on switching frequency circulating current generation with interleaving control. The efficiency of the converter is 99.98% in a 3kW prototype at normal load conditions. Furthermore, a comparison of power losses of different Vienna converter-based configurations is analyzed in [230] and it was found that the lowest power loss belongs to three phase Vienna converter. In [47] bidirectional Vienna converter is implemented for V2G operation by replacing six fast rectifier diodes of Fig. 17 (d) with switchers to modify it as a T-type PFC configuration. The bidirectional T-type PFC Vienna converter has higher efficiency, and lower conduction losses and it is suitable for V2G operation and storage applications. Additionally, the Vienna converter works with bipolar DC-bus structures, which improve power flow capabilities while lowering DC-DC power stage step-down ratio [231].

5) MULTILEVEL AC-DC CONVERTER

Multilevel converters are widely accepted for AC-DC conversion in fast and ultra-fast charging applications over other converters due to several reasons. The multilevel converter concept is developed for high voltage and power applications with the ability to unidirectional and bidirectional power flow, transformer-less operation, and high-quality outputs [138], [232]. The level 3 EV charging systems comprise multilevel converters as they provide high efficiency and power density as well as supply alternating voltages from various lower dc voltages [233]. The functionality of the multilevel inverter is depending on either an isolated DC source or a series of connected split capacitors which are connected to the single DC source to provide sub-level voltage outputs [234]. The multilevel converter topologies can be categorized as cascaded converters, neutral point clamped (NPC), and flying capacitors as shown in Fig. 18. The cascaded multilevel

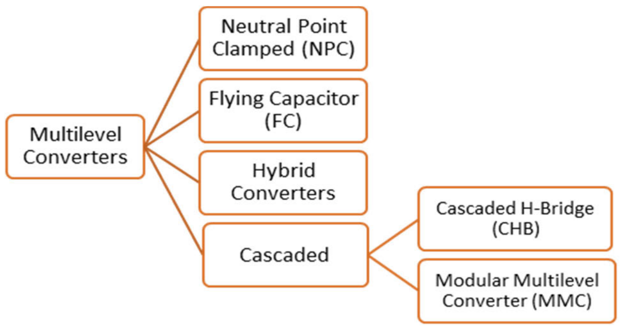


FIGURE 18. Classification of multilevel converters.

converters can be divided into cascaded H-bridge (CHB) and modular multilevel converter (MMC). The hybrid multilevel converters are designed by using two or more of the mentioned converter topologies [235].

The neutral point clamped converter is used in low and medium voltage operation applications which can reduce harmonics, and dv/dt stress across converter switches, enhance the power capability of the EV charging stations and reduce step-down effort by DC-DC charger [236]. The three-phase 3-level NPC multilevel AC-DC converters are shown in Fig. 17(e) and the switching loss can be reduced by blocking all switches to half of the DC-link voltage. The NPC with a central AC-DC converter is designed for the EV charging system in [237] via a medium voltage grid and bipolar DC bus. However, uncertainties of random EV connections and unbalanced problems in bipolar DC buses are unable to control with the NPC modulation stage. Therefore, an additional circuit was added to the NPC converters for voltage balancing with the three legs [238]. The next multilevel type is a flying capacity multilevel converter which required lower component volume, used low voltage switches, and has fewer losses than other converters [239]. The schematic of three phases three-level flying capacitor multilevel converter is shown in Fig. 17(f). The flying capacitor with closed-loop control techniques is presented in [240] and six levels interleaved flying capacitor converter is proposed in [241] to achieve high power density and efficiency.

The cascaded H-bridge multilevel converter is comprised of a series of connected H-bridge (full bridge) cells that are coupled in cascade on the AC voltage side [242]. The output waveform of the synthesized multilevel converter includes more steps as the level count increases, which generates a staircase wave with the intended waveform [243]. The modular structure of the multilevel converters or modular multilevel converters (MMC) is the most attractive AC-DC converter used in EV and RES applications. The cascaded H-bridge multilevel and modular multilevel converters are shown in Fig. 17(g) and (h) respectively. The MMC is playing a major role in the industry due to its advantages over other converters [244]. The MMC is frequently used in RES and EV charging systems to mitigate large-scale grid integration and improved power quality. The large EV or HEV drives and EV charging stations are utilized with modular multilevel AC-DC converters [233]. A novel MMC topology was proposed in [245] which compensates for voltage imbalances.

B. DC-DC CONVERTERS

The DC-DC converter is directly connected to the EV battery and requires specific features to integrate with the high-voltage DC link of the charging systems. It converts intermediate DC voltage into a desired regulated DC voltage level to charge the EV battery pack. The DC-DC converters can be divided into unidirectional and bidirectional or isolated and non-isolated according to the requirement. They are light-weighted, highly efficient converters and have high voltage gain, a wide range of power delivering voltage, and less passive components [246], [247]. The isolation is essential for high-power fast charging stations which are granted in between the EV battery and the grid such as a line-frequency transformer connected in front of the AC-DC converter, or a high-frequency transformer connected to the DC-DC converter. However, high-voltage DC-DC converters have some disadvantages such as low efficiency due to hard switching, difficulty in designing high bandwidth control loops, inability to achieve high power density, and providing flat voltage with moderate switching gate signals [246], [248], [249].

The DC-DC conversion is the second stage of EV charging systems which involved additional requirements on the battery side such as charging speed, power controlling, isolation, or non-isolation. Moreover, the converter is performing as a PFC circuit to minimize THD, and current harmonics and maintain unity PF. The common non-isolated DC-DC converter topologies include conventional, interleaved, and multilevel converters, and isolated DC-DC converters comprised of half-bridge, full-bridge, Z-source, forward, flyback, and multiport converters [250], [251]. The current and voltage-fed full-bridge converters are the extensively used configuration for EV charging systems. The ZVS (Zero voltage switching) circuit is gained on the side of the voltage-fed converter and ZCS (Zero current switching) circuit is acquired on the side of voltage-fed converters. In addition, the dual active full bridge with voltage-fed converters is widely used for the primary and secondary sides of the converter [47].

1) ISOLATED DC-DC CONVERTERS

The dual active bridge (DAB) converter is commonly used for EV charging systems due to its high efficiency, reliability, bidirectional power flow, buck and boost capability, low stress on components, and small filter requirements [252], [253]. The DAB converters are preferred for many applications as they have improved power density and converter efficiency based on the new SiC and GaN-based semiconductor devices [254]. The converter has a fixed switching frequency and small passive components, as well as primary and secondary bridges of the converter, which is controlled by ZVS operating due to simplicity. The schematic diagram of the DAB DC-DC converter is shown in Fig. 19(a). The

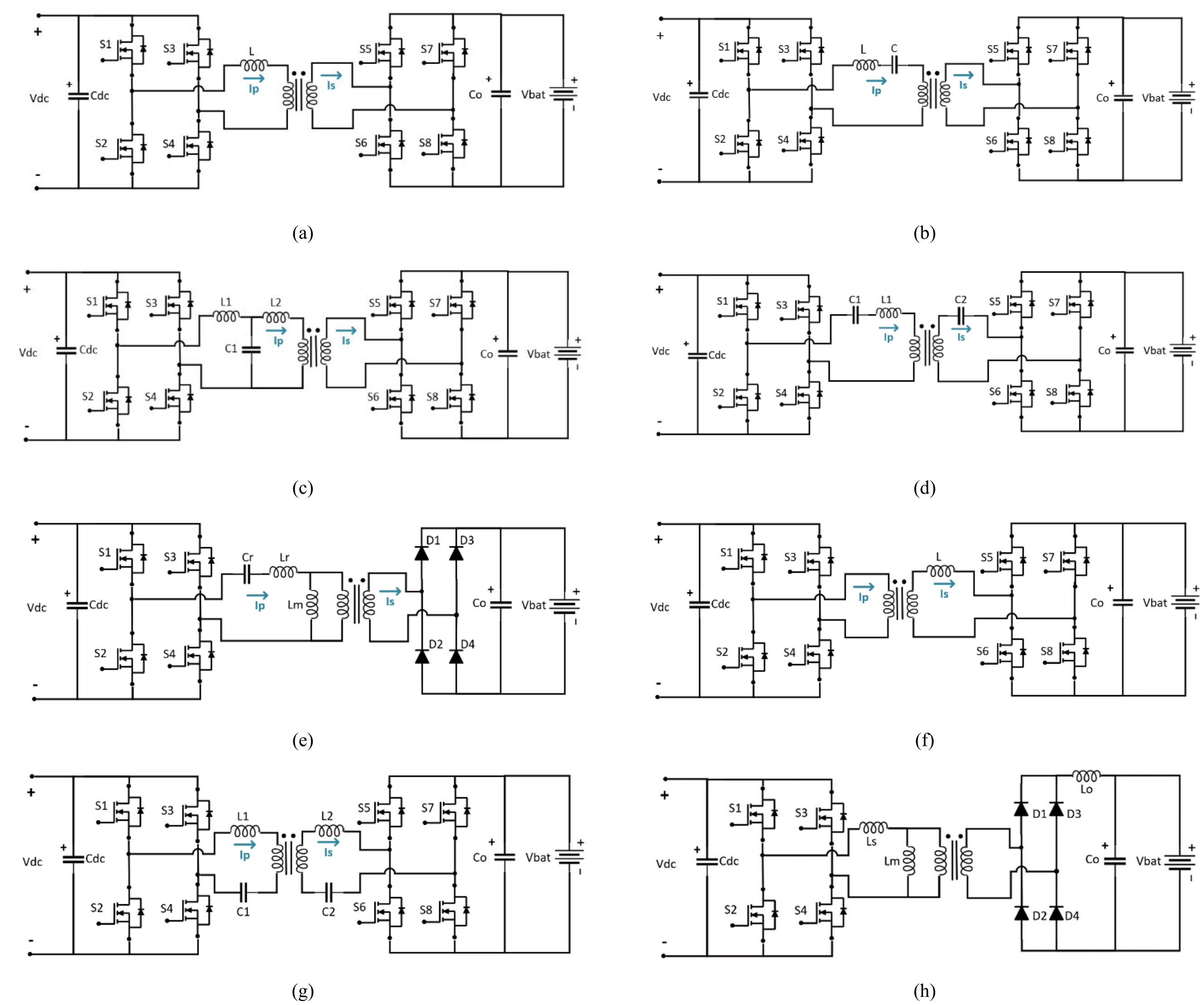


FIGURE 19. Isolated DC-DC converter configurations (a) Dual active bridge converter, (b) DAB series resonant converter (LC), (c) LCL resonant tank, (d) CLC resonant tank, (e) LLC resonant converter, (f) LLL resonant converter, (g) CLLC resonant tank, and (h) Phase-shifted full-bridge converter.

DAB DC-DC stage is utilized to achieve sinusoidal waveform by adjusting the phase shift between primary and secondary voltage. The bidirectional power flow can be simply achieved from DAB converters when compared to the other resonant converters. The power flows from left to right when the positive phase shift angle is measured in between the input and output bridge voltage and enables the reverse power flow by changing the phase shift angle polarity [255].

The resonant tank can be integrated between the primary and secondary bridges of the DAB converter with an improved modulation technique to extend the range of the ZVS of EV battery charging [256]. The research works have used various types of resonant tanks for DAB converters such as LC, LCL, CLC, LLL, and CLLC [257], [258], [259]. The series LC resonant tank with DAB is shown in Fig. 19(b). The LC resonant frequency is set less than the switching frequency of the converter and therefore it works in continuous current mode and may suffer from hard switching with a variation of battery voltages. The controlled switch inductor network is added in the DAB LC type converter to reduce the hard switching effects range and improve the operating battery voltage range [260]. The LCL and CLC type DAB resonant converters are shown in Fig. 19(c) and (d) respectively [261], [262]. The reactive power is reduced as the bridge currents are in phase and sinusoidal and therefore the efficiency of these converters is extremely high. Moreover, conduction losses are very low compared to the DAB converter as they have a soft-switching range over all diodes and switchers. However, the use of a single central resonant tank may increase electric stress on the passive components and lead to an increase in current and voltage range [263], [264].

The LLC-type DC-DC converter is widely used for EV charging systems due to its wide range of voltage output, ability to control voltage output at light load states, high

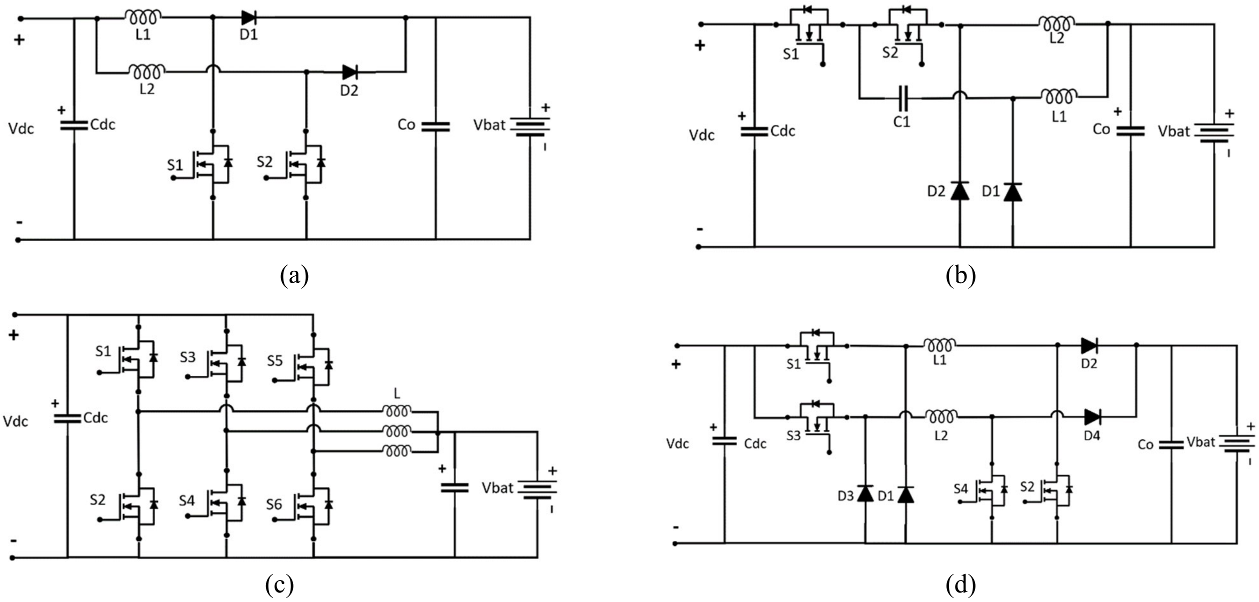


FIGURE 20. **Non-isolated DC-DC converter configurations (a) Interleaved boost converter, (b) Interleaved two-phase buck converter, (c) Interleaved three-phase buck converter, and (e) Interleaved two-phase cascaded buck-boost converter.**

efficiency, power density, and soft switching control capabilities [261]. The schematic diagram of DAB with LLC resonant tank is shown in Fig. 19(e) which is included a full-bridge converter, resonant tank, and filter capacitor. In [265], the two-stage onboard charger is designed with interleaved boost converter with a full bridge multi-resonant LLC converter. The efficiency of the proposed chargers is 95.4% and THD is less than 4% with an extendable voltage range. The current flow in the additional auxiliary inductor helps to achieve ZVS in LLL type DAB converter and the energy of the auxiliary inductor helps to charge and discharge the switching capacitance. The schematic diagram of the LLL tank-based DAB converter is shown in Fig. 19(f). The analysis of triple phase shift LLL tank-based DAB is presented in [256] which is a modified resonant tank with the controller to ensure efficient operation in various load conditions and voltage gains. Fig. 19(g) shows the schematic diagram of the DAB bidirectional CLLC resonant converter. The CLLC resonant converter has a wide range of output voltage, great soft switching, and symmetrical bidirectional power flow capabilities. However, the converter has low efficiency and voltage regulation challenges under light load conditions. The extended phase shift control scheme is introduced in [266] for CLLC-type converter to improve efficiency in light load conditions.

The phase-shifted full bridge (PSFB) converters are commonly used for onboard chargers due to many advantages such as low EMI, current stress on the components, soft switching capability, simple PWM control, and high-power density [267]. In the schematic diagram of the PSFB converter shown in Fig. 19(h) the secondary side active switches are replaced with the diodes for unidirectional power flow. However, the PSFB converters have conduction loss due to current circulation during the freewheeling gap, voltage overshoots across the secondary side, limited ZVS range, and duty cycle loss [268]. In [269], LLC resonant-based PSFB converter is presented to overcome the above challenges by using a hybrid modulation technique for LLC resonant converter. The PSFB converter with ZVS is presented in [270] to overcome conduction losses and the high circulating energy of the converter. The primary side of the converter is built with the passive auxiliary circuit in [267] to ensure ZVS is activated for total battery range and secondary side voltage overshoots are decreased. Furthermore, a hybrid converter [271] and center tap clamp circuit [272] are integrated into the LLC-type PDFB converter for the EV battery charging system to improve efficiency and power density.

2) NON-ISOLATED DC-DC CONVERTER

The non-isolated DC-DC converters are widely used in EV charging systems as they are simple, magnetic isolation free, low cost, lightweight, high energy, and power density converters compared to the isolated DC-DC converters. They are compatible with line frequency transformer-based EV charging systems [273], [274]. The load and input of the non-isolated DC-DC converters share a common ground and in contrast, isolated converters have electrically isolated between the input and load [249]. The fundamental unidirectional non-isolated DC-DC converters are a buck, boost, buck-boost, SEPIC/Zeta, and Cuk and improved converter topologies are cascaded, interleaved, multilevel, bridge less, and modified bridge converters which are designed using basic converters. The boost converter is commonly used for the EV battery interface as the output voltage of the AC-DC converter is higher than the EV battery voltage. The interleaved boost converter is shown in Fig. 20 (a). The interleaved boost converters can provide better performances by reducing input/output ripples, conduction losses, high power, reduced size, and EMI in EV energy storage systems [275]. In [276], the boost PFC converter is presented with soft switching techniques to minimize the heating problem in the diode bridge and losses in boost diodes.

The single-phase buck converters can be employed for fast charging systems because the voltage of the EV battery is less than the input voltage of the DC-DC converter. The power rating is limited as one switch is preserving the total current and the inductor size is selected to be sufficiently large to reduce charging/discharging losses caused by current ripples in the buck converter [277]. Therefore, interleaved buck converters with multiple inductors are used for EV charging systems to reduce inductor volume, current ripples, and heating impacts and increase power rating and efficiency [278]. A non-isolated interleaved two-phase and three-phase buck converters are shown in Fig. 20(b) and (c) respectively. The EV is designed with different battery voltage levels and therefore buck-boost converters are appropriate topologies to offer variable input/output voltages and bidirectional power flow in EV charging applications. The buck-boost converters can form single or two-stage power converters for charging applications with a wide range of output voltage operation, high efficiency, high PFC performance, and voltage matching capabilities. The non-isolated onboard charger with the interleaved two-phase cascaded buck-boost converter is implemented in [279]. The proposed converter is shown in Fig. 20 (d) which can be achieved high power density, and efficiency with 97.6% and 0.99 PF in 3.7 kW of hardware implementation.

VII. FUTURE TRENDS AND CHALLENGES

The exponential growth of EVs over the past decade has created an advanced electrified transportation system as well as new challenges on the distribution grid. Manufacturers are attempting to overcome driving range limitations, higher upfront costs, longer recharge time, EV battery-related constraints, and limited charging facilities [280]. Therefore, Evaluation of the emerging technologies, control strategies, and future trends in EV charging systems is important for exploring the value of finding novel solutions and improvements. EVs will reach a power density of 33 kW/L, 480 000 km/ 15-year lifetime, and 100 kW electric drive capacity in 2025 according to the Department of Energy roadmap [281]. Automated EVs are one of the trending topics in the BEV industry due to design freedom in the same structure. Therefore, predictions indicate that performance and customer satisfaction will further increase while reducing the operational and charging costs of EVs. Ultra-fast charging technologies are also increasingly developing to make sure the same experience as ICE vehicles at gas stations.

Wireless charging will acquire market acceptance due to many advantages including extremely fast charging capabilities, low maintenance, reduced components (ports, connectors, and cables), and automated charging capabilities. Wireless charging systems are considered safe, cost-effective, flexible, and reliable charging methods. The resonant wireless power transfer technique is most preferred and future challenges and opportunities of wireless charging systems are reviewed in [46]. V2G and V2X (V2H, V2B) technologies are developed to enable feeding EV battery energy back according to the user requirements [282]. V2G operation has smart charging control which can balance variations in energy consumption and production. V2G solutions are ready to reach the market and enhance grid support. The intelligent algorithm designed is another accepted revolution of future EV technology to further improve electrical infrastructure. Intelligent methods are commonly employed in BMS to address dynamic, complex, and non-linear attributes of EV batteries [283], [284]. Moreover, they can predict future states based on previous information and improve the performance of the charging system.

The Internet of Vehicles (IoV) is one of the most promising applications for developing intelligent transportation systems in smart cities. The network of the EV is equipped with communications technology to improve transportation infrastructure by providing parking assistance, efficient vehicle maintenance, energy saving, and reducing traffic congestion [285], [286]. Cost and size are key challenges to achieving high power density in EV charging systems. The cost and size of the EV depend on the energy storage system. The improvements in battery charging density, charging, and discharging methods, materials, durability, and SoC estimation method are critical factors of energy storage systems as they determine the cost and performance of the EV. Automakers are attempting to develop long-rage high power density EVs with limited space. Replacing silicon switches with wide bandgap power electronic devices is considered to reduce the size of the power modules, and the high temperature and frequency impacts of the charging system [281].

Lack of EV charging stations potentially limits EV growth due to rising range anxiety. Range anxiety can be defined as a psychological experience of EV drivers regarding the fear of running out of battery power before reaching the destination or charging station. The recharging time of the EV is higher than the refueling time of an ICE vehicle. The price of EV and charging expenses may increase because of the innovative designs and large batteries. The research suggests that range anxiety problems may not have their ideal remedies in the near future due to the economic and technical challenges. The maximum charging rate of the EV and charging point, battery size, and SoC estimation method are the main factors associated with battery charging time. Local regulatory issues and electric grid upgrades also play an important role in growing charging stations [287]. Adaptive charging strategies can be used in public parking lots to limit simultaneous power in charging points. Moreover, the integration of intelligent load balancing systems may help to manage efficient charging systems, and grid performances and satisfy the charging demands. The high level of EV integration into the distribution network has introduced many technical challenges for power grid operations, safety, and network planning due to increased load demand, voltage and current fluctuations, power quality impacts, and power losses [288]. Modern EV charging systems tend to use other energy sources link solar PV, wind power, and energy storage systems. Therefore, the intermittency nature and grid integration of RESs also need to be controlled to minimize grid impacts [289]. Various control strategies have been employed to improve charging and discharging capabilities and mitigate impacts on the distribution grid [77], [290].

VIII. CONCLUSION

The large-scale adoption of EVs necessitates investigation and development of charging technologies and power converters to achieve highly efficient, low-cost, and reliable charging solutions for an EV. Standardization of charging requirements, infrastructure designs, smart control strategies and enhanced battery technologies are essential to successful EV adoption. The performance of the battery not only depends on design and type but also on characteristics of the charger, charging and discharging infrastructure, and the SoC estimation method. This paper has reviewed EV charging technologies, standards, architectures of charging stations and power converter configurations. The status of charging technologies and requirements are evaluated by considering different types of EVs, charging levels, modes, connectors, and EV batteries. Comparative analysis has been conducted for the charging station architecture in terms of AC/DC power flow, control strategy, advantages, and disadvantages. Most multiport EV charging stations are integrated with solar PV and energy storage to reduce stress on the utility grid while providing ancillary services.

Conductive charging topologies can be divided into onboard and offboard chargers, unidirectional and bidirectional as well as AC and DC chargers according to the emerging technology. Onboard and offboard charging are discussed comprehensively with examples to understand the powertrain of different chargers. Integrated chargers are gaining more attention due to their advantages over dedicated onboard chargers. Integrated solutions can overcome the cost, weight, volume, and power limitations of conventional onboard chargers and can control charging voltage via drive inverter and motor inductance without employing separate stages. The modularity concept plays the main success of ultra-fast and fast charging and enables versatility in different power electronic solutions. Power converter configurations of EV charging systems are presented based on AC-DC and DC-DC converters with circuit topologies and explained. Finally, future trends and challenges of EV charging systems are evaluated in terms of the technical limitations, charging/discharging capabilities, smart charging, battery performance, and grid integration. EV charging technologies, standards and grid codes, the architecture of EV charging systems and power converter configurations are comprehensively evaluated by highlighting the advancements to motivate the development of novel designs.

REFERENCES

[1] L. Lachvajderova and J. Kadarova, "Analysis of internal combustion engine vehicle, battery electric vehicle and emissions from transport," *Transp. Logistics*, vol. 21, pp. 21–33, Dec. 2021.

[2] A. Perujo, C. Thiel, and F. Nemry, "Electric vehicles in an urban context: Environmental benefits and techno-economic barriers," in *Electric Vehicles—The Benefits and Barriers*. London, U.K.: IntechOpen, Sep. 2010, pp. 1–19.

[3] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2151–2169, May 2013.

[4] L. Wang, Z. Qin, T. Slangen, P. Bauer, and T. van Wijk, "Grid impact of electric vehicle fast charging stations: Trends, standards, issues and mitigation measures—An overview," *IEEE Open J. Power Electron.*, vol. 2, pp. 56–74, 2021, doi: 10.1109/OJPEL.2021.3054601.

[5] A. Bahrami, "EV charging definitions, modes, levels, communication protocols and applied standards," *Changes*, vol. 1, pp. 1–10, Jan. 2020, doi: 10.13140/RG.2.2.15844.53123/11.

[6] L. I. Dulau and D. Bica, "Effects of electric vehicles on power networks," *Proc. Manuf.*, vol. 46, pp. 370–377, Dec. 2020, doi: 10.1016/j.promfg.2020.03.054.

[7] M. R. Khalid, I. A. Khan, S. Hameed, M. S. J. Asghar, and J.-S. Ro, "A comprehensive review on structural topologies, power levels, energy storage systems, and standards for electric vehicle charging stations and their impacts on grid," *IEEE Access*, vol. 9, pp. 128069–128094, 2021, doi: 10.1109/ACCESS.2021.3112189.

[8] I. Rahman, P. M. Vasant, M. Singh, M. Abdullah-Al-Wadud, and N. Adnan, "Review of recent trends in optimization techniques for plug-in hybrid, and electric vehicle charging infrastructures," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 1039–1047, May 2016, doi: 10.1016/j.rser.2015.12.353.

[9] M. K. Das and S. K. Jain, "Review on optimization techniques used for scheduling of electric vehicle charging," in *Proc. Int. Conf. Control, Autom., Power Signal Process. (CAPS)*, Dec. 2021, pp. 1–6, doi: 10.1109/CAPS52117.2021.9730621.

[10] I. Rahman and J. Mohamad-Saleh, "Plug-in electric vehicle charging optimization using bio-inspired computational intelligence methods," in *Sustainable Interdependent Networks*. Cham, Switzerland: Springer, Feb. 2018, pp. 135–147, doi: 10.1007/978-3-319-74412-4.

[11] International Energy Agency. (2022). *Global EV Outlook 2022*. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2022

[12] International Energy Agency. (2022). *Global EV Outlook 2022—Securing Supplies for an Electric Future*. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2022/trends-in-electric-light-duty-vehicles

[13] S. Rivera, S. Kouro, S. Vazquez, S. M. Goetz, R. Lizana, and E. Romero-Cadaval, "Electric vehicle charging infrastructure: From grid to battery," *IEEE Ind. Electron. Mag.*, vol. 15, no. 2, pp. 37–51, Jun. 2021, doi: 10.1109/MIE.2020.3039039.

[14] H. Cui and D. Hall, "Annual update on the global transition to electric vehicles: 2021," in *Proc. Int. Council Clean Transp.*, May 2022, pp. 1–11. [Online]. Available: https://theicct.org/wp-content/uploads/2022/06/global-ev-update-2021-jun22.pdf

[15] C. McKerracher, N. Soulopoulos, A. Grant, and S. Mi. (2022). *Electric Vehicle Outlook 2022*. [Online]. Available: https://about.bnef.com/electric-vehicle-outlook/

[16] S. Habib, M. M. Khan, F. Abbas, L. Sang, M. U. Shahid, and H. Tang, "A comprehensive study of implemented international standards, technical challenges, impacts and prospects for electric vehicles," *IEEE Access*, vol. 6, pp. 13866–13890, 2018, doi: 10.1109/ACCESS.2018.2812303.

[17] J. A. Sanguesa, V. Torres-Sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-Barja, "A review on electric vehicles: Technologies and challenges," *Smart Cities*, vol. 4, no. 1, pp. 372–404, Mar. 2021, doi: 10.3390/smartcities4010022.

[18] IRENA. (2017). *Electric Vehicles: Technology Brief, International Renewable Energy Agency*. [Online]. Available: https://www.irena.org/publications/2017/Feb/Electric-vehicles-Technology-brief

[19] Washington State University Energy Program. (2021). *EV Batteries: Getting Better All the Time*. [Online]. Available: https://www.energy.wsu.edu/documents/EV-Batteries-GettingBetterAllTheTime-6-28-21.pdf
[20] M. Houache, C.-H. Yim, Z. Karkar, and Y. Abu-Lebdeh, "On the current and future outlook of battery chemistries for electric vehicles—Mini review," *Batteries*, vol. 8, no. 7, p. 70, Jul. 2022, doi: 10.3390/batteries8070070.
[21] R. MacIntosh, S. Tolomiczenko, and G. V. Horn. (2022). *Electric Vehicle Market update—Version Six*. Environmental Defense Fund. [Online]. Available: https://blogs.edf.org/climate411/files/2022/04/electric_vehicle_market_report_v6_april2022.pdf
[22] M. A. Hannan, M. M. Hoque, A. Mohamed, and A. Ayob, "Review of energy storage systems for electric vehicle applications: Issues and challenges," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 771–789, Mar. 2017, doi: 10.1016/j.rser.2016.11.171.
[23] Electric Vehicle Council. (2020). *State of Electric Vehicles*. Accessed: Jun. 13, 2022. [Online]. Available: https://electricvehiclecouncil.com.au/wp-content/uploads/2020/08/EVC-State-of-EVs-2020-report.pdf
[24] A. Ahmad, Z. A. Khan, M. S. Alam, and S. Khateeb, "A review of the electric vehicle charging techniques, standards, progression and evolution of EV technologies in Germany," *Smart Sci.*, vol. 6, no. 1, pp. 36–53, Jan. 2018, doi: 10.1080/23080477.2017.1420132.
[25] K. M. Tan, K. V. Ramachandaramurthy, and J. Y. Yong, "Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 720–732, Jan. 2016, doi: 10.1016/j.rser.2015.09.012.
[26] R. Rawdah, S. S. Ali, and K. N. Hasan, "Operational challenges and enabling technologies for grid integration of electric vehicles," in *Proc. 31st Australas. Universities Power Eng. Conf. (AUPEC)*, Sep. 2021, pp. 1–6, doi: 10.1109/AUPEC52110.2021.9597832.
[27] N. Shaukat, "A survey on electric vehicle transportation within smart grid system," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 1329–1349, Jan. 2018, doi: 10.1016/j.rser.2017.05.092.
[28] NRMA. (2022). *What Are the Different Types of Electric Vehicles?* [Online]. Available: https://www.mynrma.com.au/cars-and-driving/electric-vehicles/buying/types-of-evs
[29] S. F. Tie and C. W. Tan, "A review of energy sources and energy management system in electric vehicles," *Renew. Sustain. Energy Rev.*, vol. 20, pp. 82–102, Apr. 2013, doi: 10.1016/j.rser.2012.11.077.
[30] F. Un-Noor, S. Padmanaban, L. Mihet-Popa, M. Mollah, and E. Hossain, "A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development," *Energies*, vol. 10, no. 8, p. 1217, Aug. 2017, doi: 10.3390/en10081217.
[31] D. Knutsen and O. Willën. (2013). *A Study of Electric Vehicle Charging Patterns and Range Anxiety*. [Online]. Available: http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-201099
[32] Council Cities. (2021). *Electric Vehicle Basics*. [Online]. Available: https://afdc.energy.gov/files/u/publication/electri_vehicles.pdf
[33] A. Purwadi, J. Dozeno, and N. Heryana, "Simulation and testing of a typical on-board charger for ITB electric vehicle prototype application," *Proc. Technol.*, vol. 11, pp. 974–979, Dec. 2013, doi: 10.1016/j.protcy.2013.12.283.
[34] R. M. Dell, P. T. Moseley, and D. A. J. Rand, "Chapter 5—Progressive electrification of road vehicles," in *Towards Sustainable Road Transport*, R. M. Dell, P. T. Moseley, and D. A. J. Rand, Eds. Boston, MA, USA: Academic, 2014, pp. 157–192.
[35] T. W. Team. (2023). *How do EVs Compare to Gas Cars?* [Online]. Available: https://blog.wallbox.com/en-au/how-do-evs-compare-to-gas-cars/
[36] A. Faraz, A. Ambikapathy, T. Saravanan, and G. Prasad. (2021). *Battery Electric Vehicles (BEVs)*. [Online]. Available: https://www.evgo.com/ev-drivers/types-of-evs/
[37] T. Pomroy. (2021). *Nissan Leaf E+ Review*. [Online]. Available: https://www.mynrma.com.au/cars-and-driving/buying-a-car/reviews/nissan/2021-nissan-leaf-ev
[38] (2022). *E-Tron. Audi E-Tron|E-Tron Sportback Australian Specifications*. [Online]. Available: https://www.audi.com.au/au/web/en.html
[39] BWM. (2022). *BMW iX: Models & Technical Data*. [Online]. Available: https://www.bmw.com/en-au/models/i-series/ix/showroom/bmw-ix-technical-data.bmw-ix-xdrive50.html
[40] L. McDonald, "GM's 10(+) future EV models: Our estimated specs & sales volume," CleanTechnica, ED., 2020. Accessed: Jul. 13, 2022. [Online]. Available: https://cleantechnica.com/2020/03/09/gms-10-future-ev-models-our-estimated-specs-sales-volume/
[41] Elecric Vehicles Council. (2022). *State of Electric Vehicles*. [Online]. Available: https://electricvehiclecouncil.com.au/wp-content/uploads/2022/03/EVC-State-of-EVs-2022.pdf
[42] W. Zhang, K. Spence, R. Shao, and L. Chang, "Grid power-smoothing performance improvement for PV and electric vehicle (EV) systems," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2018, pp. 1051–1057, doi: 10.1109/ECCE.2018.8557954.
[43] A. M. Andwari, A. Pesiridis, S. Rajoo, R. Martinez-Botas, and V. Esfahanian, "A review of battery electric vehicle technology and readiness levels," *Renew. Sustain. Energy Rev.*, vol. 78, pp. 414–430, Oct. 2017, doi: 10.1016/j.rser.2017.03.138.
[44] *SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler*, Standard J1772, SAE, 2017.
[45] *International Electrotech Commission, Electric Vehicle Conductive Charging System—Part 1*, IEC, General Requirements, Geneva, Switzerland, 2017.
[46] A. Mahesh, B. Chokkalingam, and L. Mihet-Popa, "Inductive wireless power transfer charging for electric vehicles—A review," *IEEE Access*, vol. 9, pp. 137667–137713, 2021, doi: 10.1109/ACCESS.2021.3116678.
[47] M. Safayatullah, M. T. Elrais, S. Ghosh, R. Rezaii, and I. Batarseh, "A comprehensive review of power converter topologies and control methods for electric vehicle fast charging applications," *IEEE Access*, vol. 10, pp. 40753–40793, 2022, doi: 10.1109/ACCESS.2022.3166935.
[48] *Electric Vehicle Inductive Coupling Recommended Practice*, Standard SAE 5-1773, Feb. 1995.
[49] M. Shahjalal, T. Shams, M. N. Tasnim, M. R. Ahmed, M. Ahsan, and J. Haider, "A critical review on charging technologies of electric vehicles," *Energies*, vol. 15, no. 21, p. 8239, Nov. 2022, doi: 10.3390/en15218239.
[50] PNW. (2020). *Charging Your Electric Vehicle*. [Online]. Available: https://www.pnm.com/ev-charging
[51] IEC. (2021). *Plugs, Socket-Outlets, Vehicle Connectors and Vehicle Inlets—Conductive Charging of Electric Vehicles*. [Online]. Available: https://webstore.iec.ch/publication/6582
[52] S. Bae and A. Kwasinski, "Spatial and temporal model of electric vehicle charging demand," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 394–403, Mar. 2012.
[53] H. Tu, H. Feng, S. Srdic, and S. Lukic, "Extreme fast charging of electric vehicles: A technology overview," *IEEE Trans. Transport. Electrific.*, vol. 5, no. 4, pp. 861–878, Dec. 2019.
[54] *IEEE Guide—Adoption of IEC/TR 61000-3-7:2008, Electromagnetic Compatibility (EMC)—Limits—Assessment of Emission Limits for the Connection of Fluctuating Installations to MV, HV and EHV Power Systems*, Standard 1453.1-2012, 2012, doi: 10.1109/IEEESTD.2012.6232421.
[55] PLC. (2022). *Electric Vehicle Charging—Domestic Electric Vehicle Charging Solution*. [Online]. Available: https://www.farnell.com/datasheets/2813749.pdf
[56] T. Brünl. (2020). *EV Charging Standards*. The University of Western Australia. [Online]. Available: http://www.therevproject.com/doc/2012-EVcharging-s.pdf
[57] A. Kersten, A. Rodionov, M. Kuder, T. Hammarström, A. Lesnicar, and T. Thiringer, "Review of technical design and safety requirements for vehicle chargers and their infrastructure according to national Swedish and harmonized European standards," *Energies*, vol. 14, no. 11, p. 3301, Jun. 2021, doi: 10.3390/en14113301.
[58] D. Chargers. (2022). *Charging Modes*. [Online]. Available: https://deltrixchargers.com/about-emobility/charging-modes/
[59] (2020). *EV Charging Standards in China and Japan*. [Online]. Available: https://ihsmarkit.com/research-analysis/ev-charging-standards-in-china-and-japan.html
[60] D. K. Ronanki and A. Williamson, "Extreme fast charging technology-prospects to enhance sustainable electric transportation," *Energies*, vol. 12, no. 9, p. 3721, Dec. 2019.
[61] Wikipedia. (2022). *IEC 61851*. [Online]. Available: https://en.wikipedia.org/wiki/IEC_61851
[62] *IEC 62196 Electric Vehicle Charge Connector Assembly (Type 2 for Mode 2 and 3)*, Standard IEC 62196, 2016. [Online]. Available: https://www.dalroad.com/wp-content/uploads/2016/08/Type-II-connector-product-spec.pdf

[63] (2015). *Plugs, Socket-Outlets and Couplers for Industrial and Similar Applications, and for Electric Vehicles*. [Online]. Available: https://www.iec.ch/ords/f?p=103:38:516082676922542::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1426,20,22301

[64] H. S. Das, M. M. Rahman, S. Li, and C. W. Tan, "Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review," *Renew. Sustain. Energy Rev.*, vol. 120, Mar. 2020, Art. no. 109618, doi: 10.1016/j.rser.2019.109618.

[65] Wikipedia. (2022). *IEC 62196*. [Online]. Available: https://en.wikipedia.org/wiki/IEC_62196

[66] Cannon. (2021). *CCS 1 and CCS 2 DC Fast Charging Connectors*. [Online]. Available: https://www.mouser.com/pdfDocs/ITT-Cannon-CCS-1-and-CCS-2-Fast-Charging-Brochure.pdf

[67] CHAdeMO. (2022). *What is CHAdeMO?* [Online]. Available: https://www.chademo.com/about-us/what-is-chademo

[68] K. Field. (2022). *CARS*. [Online]. Available: https://cleantechnica.com/2019/07/01/teslas-nanochargers-deliver-250-kw-charging-1722-km-hr-today/

[69] E. D. Queensland. (2018). *Electric Vehicle (EV) Charging Infrastructure*. [Online]. Available: https://www.statedevelopment.qld.gov.au/_data/assets/pdf_file/0016/18142/practice-note-electric-vehicle-charging.pdf

[70] A. A. Tidblad, K. Edström, G. Hernández, I. de Meatza, I. Landa-Medrano, J. J. Biendicho, L. Trilla, M. Buysse, M. Ierides, B. P. Horno, Y. Kotak, H.-G. Schweiger, D. Koch, and B. S. Kotak, "Future material developments for electric vehicle battery cells answering growing demands from an end-user perspective," *Energies*, vol. 14, no. 14, p. 4223, Jul. 2021.

[71] I. T. Tsiropoulos and D. Lebedeva, "Li-ion batteries for mobility and stationary storage applications," Publications Office Eur. Union, Luxembourg, U.K., Tech. Rep., 2018. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/e65c072a-f389-11e8-9982-01aa75ed71a1/language-en

[72] K. Young, C. Wang, L. Wang, and K. Strunz, "Electric vehicle battery technologies," in *Electric Vehicle Integration into Modern Power Networks*. Boston, MA, USA: Springer, 2013, pp. 15–56, doi: 10.1007/978-1-4614-0134-6_2.

[73] C. H. T. Lee, W. Hua, T. Long, C. Jiang, and L. V. Iyer, "A critical review of emerging technologies for electric and hybrid vehicles," *IEEE Open J. Veh. Technol.*, vol. 2, pp. 471–485, 2021, doi: 10.1109/OJVT.2021.3138894.

[74] M. Danylenko. *What Materials Are Behind the EV Battery Revolution?* [Online]. Available: https://matmatch.com/resources/blog/what-materials-are-behind-the-ev-battery-revolution/

[75] S. Bhowmick. *A Detailed Comparison of Popular Li-Ion Battery Chemistries Used in Electric Vehicles*. Accessed: Jan. 14, 2023. [Online]. Available: https://circuitdigest.com/article/a-detailed-comparision-of-popular-li-ion-battery-chemistries-used-in-evs

[76] S. Fletcher. *GM's New Battery Chemistry? It's Already In the Chevy Volt*. Accessed: Jan. 11, 2023. [Online]. Available: https://www.popsci.com/cars/article/2011-01/gms-new-battery-chemistry-its-already-chevy-volt/

[77] M. Stecca, L. R. Elizondo, T. B. Soeiro, P. Bauer and P. Palensky, "A comprehensive review of the integration of battery energy storage systems into distribution networks," *IEEE Open J. Ind. Electron. Soc.*, vol. 1, pp. 46–65, 2020. Accessed: Feb. 14, 2023, doi: 10.1109/OJIES.2020.2981832.

[78] E. L. Cready, P. John, W. Josh, and S. Irwin, "Technical and economic feasibility of applying used EV batteries in stationary applications," U.S. Dept. Energy-Energy Efficiency Renew. Energy Alternative Fuels Data Center, Washington, DC, USA, Tech. Rep., 2003.

[79] United States Department of Energy. *Batteries for Electric Vehicles*. Accessed: Jan. 29, 2023. [Online]. Available: https://afdc.energy.gov/vehicles/electric_batteries.html

[80] A. Townsend and R. Gouws, "A comparative review of lead-acid, lithium-ion and ultra-capacitor technologies and their degradation mechanisms," *Energies*, vol. 15, no. 13, p. 4930, Jul. 2022. Accessed: Dec. 11, 2022, doi: 10.3390/en15134930.

[81] P. Lima. *Comparison of Different EV Batteries in 2020*. [Online]. Available: https://pushevs.com/2020/04/04/comparison-of-different-ev-batteries-in-2020/

[82] H. Shareef, M. M. Islam, and A. Mohamed, "A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles," *Renew. Sustain. Energy Rev.*, vol. 64, pp. 403–420, Oct. 2016. Accessed: Aug. 15, 2022, doi: 10.1016/j.rser.2016.06.033.

[83] B. Sakhdari and N. L. Azad, "An optimal energy management system for battery electric vehicles," *IFAC-PapersOnLine*, vol. 48, no. 15, pp. 86–92, Dec. 2015, doi: 10.1016/j.ifacol.2015.10.013.

[84] M. Danko, J. Adamec, M. Taraba, and P. Drgona, "Overview of batteries state of charge estimation methods," *Transp. Res. Proc.*, vol. 40, pp. 186–192, Jan. 2019, doi: 10.1016/j.trpro.2019.07.029.

[85] Z. He, Z. Yang, X. Cui, and E. Li, "A method of state-of-charge estimation for EV power lithium-ion battery using a novel adaptive extended Kalman filter," *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 14618–14630, Dec. 2020, doi: 10.1109/TVT.2020.3032201.

[86] R. Aalund, W. Diao, L. Kong, and M. Pecht, "Understanding the non-collision related battery safety risks in electric vehicles a case study in electric vehicle recalls and the LG chem battery," *IEEE Access*, vol. 9, pp. 89527–89532, 2021, doi: 10.1109/ACCESS.2021.3090304.

[87] H. Chaoui, N. Golbon, I. Hmouz, R. Souissi, and S. Tahar, "Lyapunov-based adaptive state of charge and state of health estimation for lithium-ion batteries," *IEEE Trans. Ind. Electron.*, vol. 62, no. 3, pp. 1610–1618, Mar. 2015, doi: 10.1109/TIE.2014.2341576.

[88] M. Zhang and X. Fan, "Review on the state of charge estimation methods for electric vehicle battery," *World Electr. Vehicle J.*, vol. 11, no. 1, p. 23, Mar. 2020, doi: 10.3390/wevj11010023.

[89] MathWorks. (2021). *Battery State of Charge-Estimate Battery State of Charge With Simulink*. Power Electronics Control Design with Simulink. [Online]. Available: https://au.mathworks.com/solutions/power-electronics-control/battery-state-of-charge.html

[90] D. N. How, M. A. Hannan, M. H. Lipu, and P. J. Ker, "State of charge estimation for lithium-ion batteries using model-based and data-driven methods: A review," *IEEE Access*, vol. 7, pp. 136116–136136, 2019, doi: 10.1109/ACCESS.2019.2942213.

[91] R. Xiong, J. Cao, Q. Yu, H. He, and F. Sun, "Critical review on the battery state of charge estimation methods for electric vehicles," *IEEE Access*, vol. 6, pp. 1832–1843, 2017, doi: 10.1109/ACCESS.2017.2780258.

[92] W. Kim, P.-Y. Lee, J. Kim, and K.-S. Kim, "A robust state of charge estimation approach based on nonlinear battery cell model for lithium-ion batteries in electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 70, no. 6, pp. 5638–5647, Jun. 2021, doi: 10.1109/TVT.2021.3079934.

[93] H. He, R. Xiong, X. Zhang, F. Sun, and J. Fan, "State-of-charge estimation of the lithium-ion battery using an adaptive extended Kalman filter based on an improved Thevenin model," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1461–1469, May 2011, doi: 10.1109/TVT.2011.2132812.

[94] D. N. How, M. A. Hannan, M. S. H. Lipu, K. S. Sahari, P. J. Ker, and K. M. Muttaqi, "State-of-charge estimation of Li-ion battery in electric vehicles: A deep neural network approach," *IEEE Trans. Ind. Appl.*, vol. 56, no. 5, pp. 5565–5574, Sep./Oct. 2020, doi: 10.1109/TIA.2020.3004294.

[95] H. Hirsch, S. Jeschke, L. Wei, M. Trautmann, J. Barenfanger, M. Maarleveld, J. Heyen, and A. Darrat, "Latest development of the national and international EMC-standards for electric vehicles and their charging infrastructure," in *Proc. IEEE Int. Symp. Electromagn. Compat. (EMC)*, Aug. 2015, pp. 708–713, doi: 10.1109/ISEMC.2015.7256250.

[96] G. Rajendran, C. A. Vaithilingam, N. Misron, K. Naidu, and M. R. Ahmed, "A comprehensive review on system architecture and international standards for electric vehicle charging stations," *J. Energy Storage*, vol. 42, Oct. 2021, Art. no. 103099, doi: 10.1016/j.est.2021.103099.

[97] IRENA. (2019). *A New World—The Geopolitics of the Energy Transformation*. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/Global_commission_geopolitics_new_world_2019.pdf

[98] D. Kettles and R. Raustad. (2017). *Electric Vehicle Charging Technologies Analysis and Standards: Final Research Project Report*. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/32266

[99] J. Francfort. (2010). *Electric Vehicle Charging Levels and Requirements Overview*. Idaho National Laboratory. [Online]. Available: https://avt.inl.gov/sites/default/files/pdf/presentations/CleanCitiesWedinarCharging12-15-10.pdf

[100] M. Gjelaj, C. Traholt, S. Hashemi, and P. B. Andersen, "Cost-benefit analysis of a novel DC fast-charging station with a local battery storage for EVs," in *Proc. 52nd Int. Universities Power Eng. Conf. (UPEC)*, Aug. 2017, pp. 1–6, doi: 10.1109/UPEC.2017.8231973.

[101] K. Kusakana, J. L. Munda, and A. A. Jimoh, "Feasibility study of a hybrid PV-micro hydro system for rural electrification," in *Proc. AFRICON*, Sep. 2009, pp. 1–5, doi: 10.1109/AFRCON.2009.5308185.

[102] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces*, IEEE Standard 1547-2018, 2018, doi: 10.1109/IEEESTD.2018.8332112.

[103] *Distributed Energy Integration Program—Electric Vehicles Grid Integration*, AEMO, Melbourne, VIC, Australia, 2021.

[104] R. Frost. *Power of ISO Standards for Electric Vehicles*. [Online]. Available: https://www.iso.org/news/2013/03/Ref1715.html

[105] *Regulations and Standards for Clean Trucks and Buses: On the Right Track?* OECD Publishing, Paris, France, 2020. Accessed: Jun. 11, 2022. [Online]. Available: https://www.itf-oecd.org/sites/default/files/docs/regulations-standards-clean-trucks-buses_0.pdf

[106] Y. Wu, Z. Wang, Y. Huangfu, A. Ravey, D. Chrenko, and F. Gao, "Hierarchical operation of electric vehicle charging station in smart grid integration applications—An overview," *Int. J. Electr. Power Energy Syst.*, vol. 139, Jul. 2022, Art. no. 108005, doi: 10.1016/j.ijepes.2022.108005.

[107] M. A. H. Rafi and J. Bauman, "A comprehensive review of DC fast-charging stations with energy storage: Architectures, power converters, and analysis," *IEEE Trans. Transport. Electrific.*, vol. 7, no. 2, pp. 345–368, Jun. 2021, doi: 10.1109/TTE.2020.3015743.

[108] G. Sharma, V. K. Sood, M. S. Alam, and S. M. Shariff, "Comparison of common DC and AC bus architectures for EV fast charging stations and impact on power quality," *eTransportation*, vol. 5, Aug. 2020, Art. no. 100066, doi: 10.1016/j.etran.2020.100066.

[109] G. Rituraj, G. R. C. Mouli, and P. Bauer, "A comprehensive review on off-grid and hybrid charging systems for electric vehicles," *IEEE Open J. Ind. Electron. Soc.*, vol. 3, pp. 203–222, 2022, doi: 10.1109/OJIES.2022.3167948.

[110] S. Amirkhan, M. Radmehr, M. Rezanejad, and S. Khormali, "A robust control technique for stable operation of a DC/AC hybrid microgrid under parameters and loads variations," *Int. J. Electr. Power Energy Syst.*, vol. 117, May 2020, Art. no. 105659, doi: 10.1016/j.ijepes.2019.105659.

[111] B. Aluisio, A. Conserva, M. Dicorato, G. Forte, and M. Trovato, "Optimal operation planning of V2G-equipped microgrid in the presence of EV aggregator," *Electr. Power Syst. Res.*, vol. 152, pp. 295–305, Nov. 2017, doi: 10.1016/j.epsr.2017.07.015.

[112] S. M. Shariff, M. S. Alam, F. Ahmad, Y. Rafat, M. S. J. Asghar, and S. Khan, "System design and realization of a solar-powered electric vehicle charging station," *IEEE Syst. J.*, vol. 14, no. 2, pp. 2748–2758, Jun. 2019, doi: 10.1109/JSYST.2019.2931880.

[113] K. Chaudhari, A. Ukil, K. N. Kumar, U. Manandhar, and S. K. Kollimalla, "Hybrid optimization for economic deployment of ESS in PV-integrated EV charging stations," *IEEE Trans. Ind. Informat.*, vol. 14, no. 1, pp. 106–116, Jan. 2018, doi: 10.1109/TII.2017.2713481.

[114] S. S. G. Acharige, M. E. Haque, M. T. Arif, N. Hosseinzadeh, and S. Saha, "A solar PV based smart EV charging system with V2G operation for grid support," in *Proc. 31st Australas. Universities Power Eng. Conf. (AUPEC)*, Sep. 2021, pp. 1–6, doi: 10.1109/AUPEC52110.2021.9597741.

[115] A. Verma and B. Singh, "Multimode operation of solar PV array, grid, battery and diesel generator set based EV charging station," *IEEE Trans. Ind. Appl.*, vol. 56, no. 5, pp. 5330–5339, Sep. 2020, doi: 10.1109/TIA.2020.3001268.

[116] Y. Yang, Q.-S. Jia, X. Guan, X. Zhang, Z. Qiu, and G. Deconinck, "Decentralized EV-based charging optimization with building integrated wind energy," *IEEE Trans. Autom. Sci. Eng.*, vol. 16, no. 3, pp. 1002–1017, Jul. 2019, doi: 10.1109/TASE.2018.2856908.

[117] A. Tavakoli, S. Saha, M. T. Arif, M. E. Haque, N. Mendis, and A. M. T. Oo, "Impacts of grid integration of solar PV and electric vehicle on grid stability, power quality and energy economics: A review," *IET Energy Syst. Integr.*, vol. 2, no. 3, pp. 243–260, Sep. 2020, doi: 10.1049/iet-esi.2019.0047.

[118] G. R. C. Mouli, "Economic and CO_2 emission benefits of a solar powered electric vehicle charging station for workplaces in The Netherlands," in *Proc. IEEE Transp. Electrific. Conf. Expo (ITEC)*, Jun. 2016, pp. 1–7.

[119] G. R. C. Mouli, J. Schijffelen, M. van den Heuvel, M. Kardolus, and P. Bauer, "A 10 kW solar-powered bidirectional EV charger compatible with Chademo and COMBO," *IEEE Trans. Power Electron.*, vol. 34, no. 2, pp. 1082–1098, Feb. 2019, doi: 10.1109/TPEL.2018.2829211.

[120] C. M. G. Ram, "Charging electric vehicles from solar energy: Power converter, charging algorithm and system design," M.S. thesis, Delft Univ. Technol., Delft, The Netherlands, 2018.

[121] D. Mishra, B. Singh, and B. K. Panigrahi, "Sigma-modified power control and parametric adaptation in a grid-integrated PV for EV charging architecture," *IEEE Trans. Energy Convers.*, vol. 37, no. 3, pp. 1965–1976, 2022, doi: 10.1109/TEC.2022.3145884.

[122] M. Abdelhamid, K. Rhodes, E. Christen, and D. Kok, "Solar panels on electrified vehicles: Applications and off-cycle CO_2 credit," *SAE Int. J. Alternative Powertrains*, vol. 7, no. 3, pp. 311–322, Apr. 2018. [Online]. Available: https://www-jstor-org.ezproxy-f.deakin.edu.au/stable/26789709

[123] B. Singh, A. Verma, A. Chandra, and K. Al-Haddad, "Implementation of solar PV-battery and diesel generator based electric vehicle charging station," *IEEE Trans. Ind. Appl.*, vol. 56, no. 4, pp. 4007–4016, Apr. 2020, doi: 10.1109/TIA.2020.2989680.

[124] S. George. (2020). Modeling and configurations of an electric vehicle. [Online]. Available: http://iaeme.com/Home/issue/IJARET?Volume=11&Issue=12

[125] S. Haghbin, S. Lundmark, M. Alakula, and O. Carlson, "Grid-connected integrated battery chargers in vehicle applications: Review and new solution," *IEEE Trans. Ind. Electron.*, vol. 60, no. 2, pp. 459–473, Feb. 2013.

[126] V.-B. Vu, J. M. Gonzalez-Gonzalez, V. Pickert, M. Dahidah, and A. Trivino, "A hybrid charger of conductive and inductive modes for electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 68, no. 12, pp. 12021–12033, Dec. 2021, doi: 10.1109/TIE.2020.3042162.

[127] T. Na, X. Yuan, J. Tang, and Q. Z. Hang, "A review of on-board integrated electric vehicles charger and a new single-phase integrated charger," *CPSS Trans. Power Electron. Appl.*, vol. 4, no. 4, pp. 288–298, Dec. 2019, doi: 10.24295/CPSSTPEA.2019.00027.

[128] D. K. K. Morrow and J. Francfort, "Plug-in hybrid electric vehicle charging infrastructure review," U.S. Department of Energy National Laboratory Operated by Battelle Energy Alliance, Washington, DC, USA, Tech. Rep., 2008.

[129] Orion Market Research Private Limited. *Global Electric Vehicle on Board Charger Market 2019–2025*. Accessed: Jun. 23, 2022. [Online]. Available: https://www.researchandmarkets.com/reports/4841464/global-on-board-chargermarket-2019-2025

[130] S. LaMonaca and L. Ryan, "The state of play in electric vehicle charging services—A review of infrastructure provision, players, and policies," *Renew. Sustain. Energy Rev.*, vol. 154, Feb. 2022, Art. no. 111733, doi: 10.1016/j.rser.2021.111733.

[131] United States Department of Energy. (2021). *Workplace Charging for Plug-in Electric Vehicles*. Alternative Fuels Data Centre. [Online]. Available: https://afdc.energy.gov/fuels/electricity_charging_workplace.html

[132] A. N. Y. Cao, O. Kaiwartya, G. Puturs, and M. Khalid, "Intelligent transportation systems enabled ICT framework for electric vehicle charging in smart city," in *Handbook of Smart Cities*, M. Maheswaran and E. Badidi, Eds. Cham, Switzerland: Springer, 2018, doi: 10.1007/978-3-319-97271-8_12.

[133] S. Arar. *The Challenges of AC and DC Charging May be Slowing EV Adoption*. [Online]. Available: https://www.allaboutcircuits.com/news/challenges-ac-dc-charging-slowing-electric-vehicle-adoption/

[134] V. T. Tran, D. Sutanto, and K. Muttaqi, "The state of the art of battery charging infrastructure for electrical vehicles: Topologies, power control strategies, and future trend," in *Proc. Australas. Universities Power Eng. Conf.*, Nov. 2017, pp. 1–6. Accessed: Jan. 5, 2022.

[135] M. Usman, W. U. K. Tareen, A. Amin, H. Ali, I. Bari, M. Sajid, M. Seyedmahmoudian, A. Stojcevski, A. Mahmood, and S. Mekhilef, "A coordinated charging scheduling of electric vehicles considering optimal charging time for network power loss minimization," *Energies*, vol. 14, no. 17, p. 5336, Aug. 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/17/5336

[136] M. S. H. Nizami, M. J. Hossain, and K. Mahmud, "A coordinated electric vehicle management system for grid-support services in residential networks," *IEEE Syst. J.*, vol. 15, no. 2, pp. 2066–2077, Jun. 2021, doi: 10.1109/JSYST.2020.3006848.

[137] M. C. Kisacikoglu, M. Kesler, and L. M. Tolbert, "Single-phase on-board bidirectional PEV charger for V2G reactive power operation," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 767–775, Mar. 2015, doi: 10.1109/TSG.2014.2360685.

[138] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, "A review of three-phase improved power quality AC–DC converters," *IEEE Trans. Ind. Electron.*, vol. 51, no. 3, pp. 641–660, Jun. 2004.

[139] A. Mohammad, R. Zamora, and T. T. Lie, "Integration of electric vehicles in the distribution network: A review of PV based electric vehicle modelling," *Energies*, vol. 13, no. 17, p. 4541, Sep. 2020, doi: 10.3390/en13174541.

[140] C. Guille and G. Gross, "A conceptual framework for the vehicle-to-grid (V2G) implementation," *Energy Policy*, vol. 37, no. 11, pp. 4379–4390, 2009, doi: 10.1016/j.enpol.2009.05.053.

[141] S. Habib, M. M. Khan, F. Abbas, and H. Tang, "Assessment of electric vehicles concerning impacts, charging infrastructure with unidirectional and bidirectional chargers, and power flow comparisons," *Int. J. Energy Res.*, vol. 42, no. 11, pp. 3416–3441, Sep. 2018, doi: 10.1002/er.4033.

[142] G. A. Putrus, P. Suwanapingkarl, D. Johnston, E. C. Bentley, and M. Narayana, "Impact of electric vehicles on power distribution networks," in *Proc. IEEE Vehicle Power Propuls. Conf.*, Sep. 2009, pp. 827–831.

[143] M. Sepahi, A. Mirzaei, and E. Saadati, "Impacts of electric vehicles on power distribution system," Tech. Rep., 2016.

[144] M. Brenna, F. Foiadelli, C. Leone, and M. Longo, "Electric vehicles charging technology review and optimal size estimation," *J. Electr. Eng. Technol.*, vol. 15, no. 6, pp. 2539–2552, Nov. 2020, doi: 10.1007/s42835-020-00547-x.

[145] A. Khaligh and M. D'Antonio, "Global trends in high-power on-board chargers for electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 68, no. 4, pp. 3306–3324, Apr. 2019, doi: 10.1109/TVT.2019.2897050.

[146] R. K. Lenka, A. K. Panda, A. R. Dash, N. N. Venkataramana, and N. Tiwary, "Reactive power compensation using vehicle-to-grid enabled bidirectional off-board EV battery charger," in *Proc. 1st Int. Conf. Power Electron. Energy (ICPEE)*, Jan. 2021, pp. 1–6, doi: 10.1109/ICPEE50452.2021.9358582.

[147] D. Patil and V. Agarwal, "Compact onboard single-phase EV battery charger with novel low-frequency ripple compensator and optimum filter design," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 1948–1956, Apr. 2016, doi: 10.1109/TVT.2015.2424927.

[148] L. Zhu, H. Bai, A. Brown, and M. McAmmond, "Transient analysis when applying GaN+Si hybrid switching modules to a zero-voltage-switching EV onboard charger," *IEEE Trans. Transport. Electrific.*, vol. 6, no. 1, pp. 146–157, Mar. 2020, doi: 10.1109/TTE.2020.2966915.

[149] S. Kim and F. S. Kang, "Multifunctional onboard battery charger for plug-in electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 62, no. 6, pp. 3460–3472, Jun. 2015, doi: 10.1109/TIE.2014.2376878.

[150] C. Shi, Y. Tang, and A. Khaligh, "A three-phase integrated onboard charger for plug-in electric vehicles," *IEEE Trans. Power Electron.*, vol. 33, no. 6, pp. 4716–4725, Jun. 2018, doi: 10.1109/TPEL.2017.2727398.

[151] H. V. Nguyen, D.-D. To, and D.-C. Lee, "Onboard battery chargers for plug-in electric vehicles with dual functional circuit for low-voltage battery charging and active power decoupling," *IEEE Access*, vol. 6, pp. 70212–70222, 2018, doi: 10.1109/ACCESS.2018.2876645.

[152] J. Gao, D. Jiang, W. Sun, and Y. Zhang, "Zero torque three phase integrated on-board charger by multi-elements motor torque cancellation," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2019, pp. 563–568, doi: 10.1109/ECCE.2019.8913159.

[153] L. Pan and C. Zhang, "A high power density integrated charger for electric vehicles with active ripple compensation," *Math. Problems Eng.*, vol. 2015, pp. 1–18, Nov. 2015, doi: 10.1155/2015/918296.

[154] K. Fahem, D. E. Chariag, and L. Sbita, "On-board bidirectional battery chargers topologies for plug-in hybrid electric vehicles," in *Proc. Int. Conf. Green Energy Convers. Syst. (GECS)*, Mar. 2017, pp. 23–27.

[155] H. Karneddi, D. Ronanki, and R. L. Fuentes, "Technological overview of onboard chargers for electrified automotive transportation," in *Proc. 47th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2021, pp. 1–6, doi: 10.1109/IECON48115.2021.9589679.

[156] D. Cesiel and C. Zhu, "A closer look at the on-board charger: The development of the second-generation module for the Chevrolet volt," *IEEE Electrific. Mag.*, vol. 5, no. 1, pp. 36–42, Mar. 2017, doi: 10.1109/MELE.2016.2644265.

[157] G. Motors. (2022). *Our Path to an All—Electric Future Zero Crashes, Zero Emissions, Zero Congestion*. [Online]. Available: https://www.gm.com/electric-vehicles#product

[158] Tesla. (2022). *Onboard Charger*. [Online]. Available: https://www.tesla.com/support/home-charging-installation/onboard-charger

[159] Tesla. (2013). *Introducing V3 Supercharging*. [Online]. Available: https://www.tesla.com/blog/introducing-v3-supercharging

[160] J. Lee. (2018). *Bidirectional Powering on-Board Charger, Vehicle Power Supply System Including the Same, and Control Method Thereof*. [Online]. Available: https://patentimages.storage.googleapis.com/6a/9e/56/4a20a2df3d5fb0/US10046656.pdf

[161] R. Pandey and B. Singh, "A power factor corrected resonant EV charger using reduced sensor based bridgeless boost PFC converter," *IEEE Trans. Ind. Appl.*, vol. 57, no. 6, pp. 6465–6474, Nov. 2021, doi: 10.1109/TIA.2021.3106616.

[162] H. Bai, M. McAmmond, J. Lu, Q. Tian, H. Teng, and A. Brown, "Design and optimization of a 98%-efficiency on-board level-2 battery charger using E-mode GaN HEMTs for electric vehicles," *SAE Int. J. Alternative Powertrains*, vol. 5, no. 1, pp. 205–213, Apr. 2016, doi: 10.4271/2016-01-1219.

[163] X. Lu, K. L. V. Iyer, K. Mukherjee, and N. C. Kar, "Investigation of integrated charging and discharging incorporating interior permanent magnet machine with damper bars for electric vehicles," *IEEE Trans. Energy Convers.*, vol. 31, no. 1, pp. 260–269, Mar. 2016, doi: 10.1109/TEC.2015.2467970.

[164] K. T. Chau, C. C. Chan, and C. Liu, "Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2246–2257, Jun. 2008.

[165] M. Y. Metwly, M. S. Abdel-Majeed, A. S. Abdel-Khalik, R. A. Hamdy, M. S. Hamad, and S. Ahmed, "A review of integrated on-board EV battery chargers: Advanced topologies, recent developments and optimal selection of FSCW slot/pole combination," *IEEE Access*, vol. 8, pp. 85216–85242, 2020, doi: 10.1109/ACCESS.2020.2992741.

[166] A. K. Singh and M. K. Pathak, "A comprehensive review of integrated charger for on-board battery charging applications of electric vehicles," in *Proc. IEEE 8th Power India Int. Conf. (PIICON)*, Dec. 2018, pp. 1–6, doi: 10.1109/POWERI.2018.8704399.

[167] A. Clark, "Charging the future: Challenges and opportunities for electric vehicle adoption," Harvard Kennedy School, Cambridge, MA, USA, HKS Work. Rep. RWP18-026, 2018.

[168] J. Lu, "A modular-designed three-phase high-efficiency high-power-density EV battery charger using dual/triple-phase-shift control," *IEEE Trans. Power Electron.*, vol. 33, no. 9, pp. 8091–8100, Sep. 2018, doi: 10.1109/TPEL.2017.2769661.

[169] I. Subotic, N. Bodo, E. Levi, B. Dumnic, D. Milicevic, and V. Katic, "Overview of fast on-board integrated battery chargers for electric vehicles based on multiphase machines and power electronics," *IET Electr. Power Appl.*, vol. 10, no. 3, pp. 217–229, 2016, doi: 10.1049/iet-epa.2015.0292.

[170] R. P. Kit. *Renault ZOE: The Electric Supermini for Everyday Use*. Accessed: Feb. 2013. [Online]. Available: https://www.press.renault.co.uk/en-gb/releases/502

[171] Renault Group. (2021). *The Electric Car: Connector Types and Charging Modes*. [Online]. Available: https://www.renaultgroup.com/en/news-on-air/news/the-electric-car-connector-types-and-charging-modes/

[172] Electric Vehicle. (2010). *Rapid Reversible Charging Device for an Electric Vehicle*. [Online]. Available: https://patents.google.com/patent/WO2010146092A1/en

[173] Continental. (2017). *Mobility Fair EVS30: Continental Presents Innovative Charging Technologies for All Applications*. [Online]. Available: https://www.continental.com/en/press/press-releases/2017-10-09-charging-solutions/

[174] S. Haghbin, S. Lundmark, M. Alakula, and O. Carlson, "An isolated high-power integrated charger in electrified-vehicle applications," *IEEE Trans. Veh. Technol.*, vol. 60, no. 9, pp. 4115–4126, Nov. 2011, doi: 10.1109/TVT.2011.2162258.

[175] P. Van den Bossche, "Chapter twenty—Electric vehicle charging infrastructure," in *Electric Hybrid Vehicles*, G. Pistoia, Ed. Amsterdam, The Netherlands: Elsevier, 2010, pp. 517–543.

[176] F. M. Shahir, M. Gheisarnejad, M. S. Sadabadi, and M.-H. Khooban, "A new off-board electrical vehicle battery charger: Topology, analysis and design," *Designs*, vol. 5, no. 3, p. 51, Aug. 2021, doi: 10.3390/designs5030051.

[177] U. Mustafa, R. Ahmed, A. Watson, P. Wheeler, N. Ahmed, and P. Dahele, "A comprehensive review of machine-integrated electric vehicle chargers," *Energies*, vol. 16, no. 1, p. 129, Dec. 2022, doi: 10.3390/en16010129.

[178] S. Wang, Z. Zhu, A. Pride, J. Shi, R. Deodhar, and C. Umemura, "Comparison of different winding configurations for dual three-phase interior PM machines in electric vehicles," *World Electr. Vehicle J.*, vol. 13, no. 3, p. 51, Mar. 2022, doi: 10.3390/wevj13030051.

[179] P. Shams Ghahfarokhi, A. Podgornovs, A. J. M. Cardoso, A. Kallaste, A. Belahcen, and T. Vaimann, "Hairpin windings for electric vehicle motors: Modeling and investigation of AC loss-mitigating approaches," *Machines*, vol. 10, no. 11, p. 1029, Nov. 2022, doi: 10.3390/machines10111029.

[180] L. De Sousa, B. Silvestre, and B. Bouchez, "A combined multiphase electric drive and fast battery charger for electric vehicles," in *Proc. IEEE Vehicle Power Propuls. Conf.*, Sep. 2010, pp. 1–6.

[181] T. Ericsen, Y. Khersonsky, and P. K. Steimer, "PEBB concept applications in high power electronics converters," in *Proc. IEEE 36th Conf. Power Electron. Spec.*, Jun. 2005, pp. 2284–2289, doi: 10.1109/PESC.2005.1581950.

[182] S. Srdic and S. Lukic, "Toward extreme fast charging: Challenges and opportunities in directly connecting to medium-voltage line," *IEEE Electrific. Mag.*, vol. 7, no. 1, pp. 22–31, Mar. 2019, doi: 10.1109/MELE.2018.2889547.

[183] Casteren. (2022). *Battery Charger for Electric Vehicles*. [Online]. Available: https://patentimages.storage.googleapis.com/3f/b8/5c/98f0a475ef6d58/US10166873.pdf

[184] Porsche. (2021). *First Porsche Fast Charging Park Featuring 800-Volt Technology*. [Online]. Available: https://newsroom.porsche.com/en/company/porsche-fast-charging-park-berlin-adlershof-electric-cars-electro-mobility-plug-in-technology-turbo-infrastructure-15814.html

[185] A. Danese, B. N. Torsëter, A. Sumper, and M. Garau, "Planning of high-power charging stations for electric vehicles: A review," *Appl. Sci.*, vol. 12, no. 7, p. 3214, Mar. 2022, doi: 10.3390/app12073214.

[186] G. Reber. (2021). *Modular Power Electronics System for Charging An Electrically Operated Vehicle* https://patentimages.storage.googleapis.com/13/fc/f9/2d715fbcf15910/US20180162229A1.pdf

[187] D. Salomonsson, L. Söder, and A. Sannino, "Protection of low-voltage DC microgrids," *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 1045–1053, Jul. 2009, doi: 10.1109/TPWRD.2009.2016622.

[188] D. M. Bui, S.-L. Chen, C.-H. Wu, K.-Y. Lien, C.-H. Huang, and K.-K. Jen, "Review on protection coordination strategies and development of an effective protection coordination system for DC microgrid," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Dec. 2014, pp. 1–10, doi: 10.1109/APPEEC.2014.7066159.

[189] M. Ehsani, K. V. Singh, H. O. Bansal, and R. T. Mehrjardi, "State of the art and trends in electric and hybrid electric vehicles," *Proc. IEEE*, vol. 109, no. 6, pp. 967–984, Jun. 2021, doi: 10.1109/JPROC.2021.3072788.

[190] ABB. (2013). *Smarter Mobility—Terra 54 Multi-Standard DC Charging Station*. [Online]. Available: https://library.e.abb.com/public/9f72c044f8ab4ff29c5ae0eb915c0843/4EVC901707-LFEN_Terra%2054_11_19.pdf

[191] ABB. (2021). *Electric Vehicle Infrastructure Terra High Power—GEN III*. [Online]. Available: https://search.abb.com/library/Download.aspx?DocumentID=9AKK107991A9632&LanguageCode=en&DocumentPartId=&Action=Launch

[192] Tesla. (2015). *Tesla Charging Station*. [Online]. Available: https://crw.codb.us/etrakit3/viewAttachment.aspx?Group=PERMIT&ActivityNo=C2006-161&key=RLR%3A2006290945020551

[193] SIGNET. (2013). *Electric Vehicle Charging Infrastructure Solutions DC Fast Chargers*. [Online]. Available: https://www.novacharge.net/wp-content/uploads/2015/11/Signet-_-GPT-market-material-100-Kw-Chad.pdf

[194] Tritium. (2020). *PK350/350kW—Specifications*. [Online]. Available: https://tritiumcharging.com/wp-content/uploads/2020/11/TRI105.DTA_.002_Veefil-PK350-Specifications.pdf

[195] Blink. (2022). *60 kW Standard Power DCFC*. [Online]. Available: https://blinkcharging.com/wp-content/uploads/2022/07/UL_DCFAST_60kW_SpecSheet_March_2022.pdf

[196] Blink. (2022). *180 kW High Power DCFC*. [Online]. Available: https://blinkcharging.com/wp-content/uploads/2022/07/UL_DCFAST_180kW_SpecSheet_March_2022.pdf

[197] EVBox. (2022). *EVBox Troniq 100—Fast Charging Solution*. [Online]. Available: http://evchargesolutions.com/v/downloads/evbox-troniq-spec-sheet.pdf

[198] SIEMENS. (2022). *VERSICHARGE—Ultra 175 DC Charger*. [Online]. Available: https://assets.new.siemens.com/siemens/assets/api/uuid:1777fe11-fa33-45f6-a339-bd522d5f6059/sidst40085004auslores.pdf

[199] Ingeteam. (2022). *Ingerev Rapid ST—200—400—Installation and Operation Manual*. [Online]. Available: https://www.ingerevtraining.com/wp-content/uploads/2021/07/ABX2011IQM01_EN.pdf

[200] S. Habib, "Contemporary trends in power electronics converters for charging solutions of electric vehicles," *CSEE J. Power Energy Syst.*, vol. 6, no. 4, pp. 911–929, Dec. 2020, doi: 10.17775/CSEEJPES.2019.02700.

[201] S. Piasecki, J. Zaleski, M. Jasinski, S. Bachman, and M. Turzyåski, "Analysis of AC/DC/DC converter modules for direct current fast-charging applications," *Energies*, vol. 14, no. 19, p. 6369, Oct. 2021, doi: 10.3390/en14196369.

[202] S. A. Q. Mohammed and J.-W. Jung, "A comprehensive state-of-the-art review of wired/wireless charging technologies for battery electric vehicles: Classification/common topologies/future research issues," *IEEE Access*, vol. 9, pp. 19572–19585, 2021, doi: 10.1109/ACCESS.2021.3055027.

[203] N. Rathore, S. Gangavarapu, A. K. Rathore, and D. Fulwani, "Emulation of loss free resistor for single-stage three-phase PFC converter in electric vehicle charging application," *IEEE Trans. Transport. Electrific.*, vol. 6, no. 1, pp. 334–345, Mar. 2020, doi: 10.1109/TTE.2020.2976878.

[204] A. Tausif, H. Jung, and S. Choi, "Single-stage isolated electrolytic capacitor-less EV onboard charger with power decoupling," *CPSS Trans. Power Electron. Appl.*, vol. 4, no. 1, pp. 30–39, Mar. 2019, doi: 10.24295/CPSSTPEA.2019.00004.

[205] D. Aggeler, F. Canales, H. Zelaya-De La Parra, A. Coccia, N. Butcher, and O. Apeldoorn, "Ultra-fast DC-charge infrastructures for EV-mobility and future smart grids," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur.*, Oct. 2010, pp. 1–8.

[206] L. Huber, M. Kumar, and M. M. Jovanovic, "Analysis, design, and evaluation of three-phase three-wire isolated AC–DC converter implemented with three single-phase converter modules," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2016, pp. 38–45.

[207] M.-C. Ancuti, C. Sorandaru, S. Musuroi, and V.-N. Olarescu, "High efficiency three-phase interleaved buck-type PFC rectifier concepts," in *Proc. 41st Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2015, pp. 7763–7768.

[208] S. S. Sayed and A. M. Massoud, "Review on state-of-the-art unidirectional non-isolated power factor correction converters for short-/long-distance electric vehicles," *IEEE Access*, vol. 10, pp. 11308–11340, 2022, doi: 10.1109/ACCESS.2022.3146410.

[209] J. Lei, S. Feng, J. Zhao, W. Chen, P. Wheeler, and M. Shi, "An improved three-phase buck rectifier topology with reduced voltage stress on transistors," *IEEE Trans. Power Electron.*, vol. 35, no. 3, pp. 2458–2466, Mar. 2020.

[210] L. Huber, L. Gang, and M. M. Jovanovic, "Design-oriented analysis and performance evaluation of buck PFC front end," *IEEE Trans. Power Electron.*, vol. 25, no. 1, pp. 85–94, Jan. 2010, doi: 10.1109/TPEL.2009.2024667.

[211] H. Vahedi and K. Al-Haddad, "A novel multilevel multioutput bidirectional active buck PFC rectifier," *IEEE Trans. Ind. Electron.*, vol. 63, no. 9, pp. 5442–5450, Sep. 2016.

[212] Q. Chen, J. Xu, L. Wang, R. Huang, and H. Ma, "Analysis and improvement of the effect of distributed parasitic capacitance on high-frequency high-density three-phase buck rectifier," *IEEE Trans. Power Electron.*, vol. 36, no. 6, pp. 6415–6428, Jun. 2021.

[213] Q. Chen, J. Xu, R. Huang, W. Wang, and L. Wang, "A digital control strategy with simple transfer matrix for three-phase buck rectifier under unbalanced AC input conditions," *IEEE Trans. Power Electron.*, vol. 36, no. 4, pp. 3661–3666, Apr. 2021.

[214] J. Afsharian, D. Xu, B. Wu, B. Gong, and Z. Yang, "A new PWM and commutation scheme for one phase loss operation of three-phase isolated buck matrix-type rectifier," *IEEE Trans. Power Electron.*, vol. 33, no. 11, pp. 9854–9865, Nov. 2018.

[215] J. P. R. Balestero, F. L. Tofoli, R. C. Fernandes, G. V. Torrico-Bascope, and F. J. M. D. Seixas, "Power factor correction boost converter based on the three-state switching cell," *IEEE Trans. Ind. Electron.*, vol. 59, no. 3, pp. 1565–1577, Mar. 2012, doi: 10.1109/TIE.2011.2160136.

[216] X. H. Wu, S. K. Panda, and J. X. Xu, "Analysis of the instantaneous power flow for three-phase PWM boost rectifier under unbalanced supply voltage conditions," *IEEE Trans. Power Electron.*, vol. 23, no. 4, pp. 1679–1691, Jul. 2008, doi: 10.1109/TPEL.2008.925158.

[217] F. Musavi, W. Eberle, and W. G. Dunford, "A phase shifted semi-bridgeless boost power factor corrected converter for plug in hybrid electric vehicle battery chargers," in *Proc. 26th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2011, pp. 821–828, doi: 10.1109/APEC.2011.5744690.

[218] Z. Ye, D. Boroyevich, J.-Y. Choi, and F. C. Lee, "Control of circulating current in two parallel three-phase boost rectifiers," *IEEE Trans. Power Electron.*, vol. 17, no. 5, pp. 609–615, Sep. 2002, doi: 10.1109/TPEL.2002.802170.

[219] B. Zhang, S. Xie, Z. Li, P. Zhao, and J. Xu, "An optimized single-stage isolated Swiss-type AC/DC converter based on single full-bridge with midpoint-clamper," *IEEE Trans. Power Electron.*, vol. 36, no. 10, pp. 11288–11297, Oct. 2021, doi: 10.1109/TPEL.2021.3073742.

[220] A. K. Singh, E. Jeyasankar, P. Das, and S. K. Panda, "A matrix-based nonisolated three-phase AC–DC rectifier with large step-down voltage gain," *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4796–4811, Jun. 2017.

[221] M. A. Ahmed, J. D. Dasika, M. Saeedifard, and O. Wasynczuk, "Interleaved Swiss rectiers for fast EV/PHEV battery chargers," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Apr. 2014, pp. 3260–3265.

[222] L. Schrittwieser, M. Leibl, M. Haider, F. Thony, J. W. Kolar, and T. B. Soeiro, "99.3% efficient three-phase buck-type all-SiC Swiss rectifier for DC distribution systems," *IEEE Trans. Power Electron.*, vol. 34, no. 1, pp. 126–140, Jan. 2019.

[223] T. B. Soeiro, M. L. Heldwein, and J. W. Kolar, "Three-phase modular multilevel current source rectifiers for electric vehicle battery charging systems," in *Proc. Brazilian Power Electron. Conf.*, Oct. 2013, pp. 623–629.

[224] L. Schrittwieser, J. W. Kolar, and T. B. Soeiro, "Novel SWISS rectifier modulation scheme preventing input current distortions at sector boundaries," *IEEE Trans. Power Electron.*, vol. 32, no. 7, pp. 5771–5785, Jul. 2017, doi: 10.1109/TPEL.2016.2609935.

[225] R. Gowthamraj, C. V. Aravind, and O. K. S. Prakash, "Modeling of Vienna rectifier with PFC controller for electric vehicle charging stations," in *Proc. 12TH EURECA Int. Eng. Res. Conf.*, Dec. 2019, pp. 2137–2138.

[226] L. Zhang, "A modified DPWM with neutral point voltage balance capability for three-phase Vienna rectifiers," *IEEE Trans. Power Electron.*, vol. 36, no. 1, pp. 263–273, Jan. 2021.

[227] S. Liu, J. Jiang, and G. Cheng, "Research on vector control strategy of three phase Vienna rectifier employed in EV charger," in *Proc. Chin. Control Decis. Conf. (CCDC)*, Jun. 2019, pp. 4914–4917, doi: 10.1109/CCDC.2019.8832878.

[228] X. Yan, F. Qin, J. Jia, Z. Zhang, X. Li, and Y. Sun, "Virtual synchronous motor based-control of Vienna rectifier," *Energy Rep.*, vol. 6, pp. 953–963, Dec. 2020, doi: 10.1016/j.egyr.2020.11.098.

[229] F. Flores-Bahamonde, H. Valderrama-Blavi, L. Martínezâ-Salamero, J. Maixé-Altés, and G. García, "Control of a three-phase AC/DC Vienna converter based on the sliding mode loss-free resistor approach," *IET Power Electron.*, vol. 7, no. 5, pp. 1073–1082, May 2014, doi: 10.1049/iet-pel.2013.0405.

[230] Q. Wang, X. Zhang, R. Burgos, D. Boroyevich, A. M. White, and M. Kheraluwala, "Design and implementation of a two-channel interleaved Vienna-type rectifier with >99% efficiency," *IEEE Trans. Power Electron.*, vol. 33, no. 1, pp. 226–239, Jan. 2018, doi: 10.1109/TPEL.2017.2671844.

[231] T. Friedli, "The essence of three-phase PFC rectifier systems—Part I," *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 176–198, May 2013.

[232] K. Gnanasambandam, A. K. Rathore, A. Edpuganti, D. Srinivasan, and J. Rodriguez, "Current-fed multilevel converters: An overview of circuit topologies, modulation techniques, and applications," *IEEE Trans. Power Electron.*, vol. 32, no. 5, pp. 3382–3401, May 2017, doi: 10.1109/TPEL.2016.2585576.

[233] R. Hariri and H. Y. Kanaan, "A review on modular multilevel converters in electric vehicles," in *Proc. 46th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Apr. 2020, pp. 1993–4987.

[234] A. Sheir, M. Z. Youssef, and M. Orabi, "A novel bidirectional *T*-type multilevel inverter for electric vehicle applications," *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6648–6658, Jul. 2019, doi: 10.1109/TPEL.2018.2871624.

[235] P. Qashqai, A. Sheikholeslami, H. Vahedi, and K. Al-Haddad, "A review on multilevel converter topologies for electric transportation applications," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Oct. 2015, pp. 1–6.

[236] B. W. S. Rivera, S. Kouro, V. Yaramasu, and J. Wang, "Electric vehicle charging station using a neutral point clamped converter with bipolar," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 1999–2009, Nov. 2015.

[237] L. Tan, B. Wu, and S. Rivera, "A bipolar-DC-bus EV fast charging station with intrinsic DC-bus voltages equalization and minimized voltage ripples," in *Proc. 41st Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2015, pp. 2190–2195, doi: 10.1109/IECON.2015.7392426.

[238] S. Rivera, B. Wu, J. Wang, H. Athab, and S. Kouro, "Electric vehicle charging station using a neutral point clamped converter with bipolar DC bus and voltage balancing circuit," in *Proc. 39th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2013, pp. 6219–6226, doi: 10.1109/IECON.2013.6700158.

[239] K. Kesarwani and J. T. Stauth, "Resonant and multi-mode operation of flying capacitor multi-level DC–DC converters," in *Proc. IEEE 16th Workshop Control Modeling Power Electron. (COMPEL)*, Jul. 2015, pp. 1–8, doi: 10.1109/COMPEL.2015.7236511.

[240] J. Huang and K. A. Corzine, "Extended operation of flying capacitor multilevel inverters," *IEEE Trans. Power Electron.*, vol. 21, no. 1, pp. 140–147, Jan. 2006, doi: 10.1109/TPEL.2005.861108.

[241] Z. Liao, D. Chou, K. Fernandez, Y.-L. Syu, and R. C. N. Pilawa-Podgurski, "Architecture and control of an interleaved 6-level bidirectional converter with an active energy buffer for level-II electric vehicle charging," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2020, pp. 4137–4142, doi: 10.1109/ECCE44975.2020.9236108.

[242] S. Kouro, "Recent advances and industrial applications of multilevel converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2553–2580, Aug. 2010, doi: 10.1109/TIE.2010.2049719.

[243] F. Ciccarelli, A. Del Pizzo, and D. Iannuzzi, "An ultra-fast charging architecture based on modular multilevel converters integrated with energy storage buffers," in *Proc. 8th Int. Conf. Exhib. Ecol. Vehicles Renew. Energies (EVER)*, Mar. 2013, pp. 1–6.

[244] I. Marzo, A. Sanchez-Ruiz, J. A. Barrena, G. Abad, and I. Muguruza, "Power balancing in cascaded H-bridge and modular multilevel converters under unbalanced operation: A review," *IEEE Access*, vol. 9, pp. 110525–110543, 2021, doi: 10.1109/ACCESS.2021.3103337.

[245] S. Rivera, S. Kouro, A. Lier, and C. Reusser, "Four-level double star multilevel converter for grid-connected photovoltaic systems," in *Proc. 19th Eur. Conf. Power Electron. Appl.*, Sep. 2017, pp. 1–10.

[246] A. Kolli, A. Gaillard, A. De Bernardinis, O. Bethoux, D. Hissel, and Z. Khatir, "A review on DC/DC converter architectures for power fuel cell applications," *Energy Convers. Manag.*, vol. 105, pp. 716–730, Nov. 2015, doi: 10.1016/j.enconman.2015.07.060.

[247] S. Chakraborty, M. M. Hasan, and M. A. Razzak, "Transformer-less single-phase grid-tie photovoltaic inverter topologies for residential application with various filter circuits," *Renew. Sustain. Energy Rev.*, vol. 72, pp. 1152–1166, May 2017, doi: 10.1016/j.rser.2016.10.032.

[248] A. Emadi, L. J. Young, and K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2237–2245, Jun. 2008, doi: 10.1109/TIE.2008.922768.

[249] M. Forouzesh, P. Y. Siwakoti, A. S. Gorji, F. Blaabjerg, and B. Lehman, "Step-up DC–DC converters: A comprehensive review of voltage-boosting techniques, topologies, and applications," *IEEE Trans. Power Electron.*, vol. 32, no. 12, pp. 9143–9178, Dec. 2017, doi: 10.1109/TPEL.2017.2652318.

[250] D. C. Erb, O. C. Onar, and A. Khaligh, "Bi-directional charging topologies for plug-in hybrid electric vehicles," in *Proc. 25th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Feb. 2010, pp. 2066–2072.

[251] S. L. Y. Du, B. Jacobson, and A. Huang, "Review of high power isolated bi-directional DC–DC converters for PHEV/EV DC charging infrastructure," in *Proc. IEEE Energy Convers. Congr. Expo.*, Phoenix, AZ, USA, Dec. 2021, pp. 553–560.

[252] L. M. M. R. J. Ferreira, R. E. Arëjo, and J. P. Lopes, "A new bi-directional charger for vehicle-to-grid integration," in *Proc. 2nd IEEE PES Int. Conf. Exhib. Innov. Smart Grid Technol.*, Nov. 2011, pp. 1–5.

[253] H. van Hoek, M. Neubert, and R. W. De Doncker, "Enhanced modulation strategy for a three-phase dual active bridge-boosting efficiency of an electric vehicle converter," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5499–5507, Dec. 2013.

[254] T. Y. H. Akagi, N. M. L. Tan, S. Kinouchi, Y. Miyazaki, and A. M. Koyama, "Power-loss breakdown of a 750-V 100-kW 20-kHz bidirectional isolated DC–DC converter using SiC-OSFET/SBD dual modules," *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 420–428, Dec. 2015.
[255] X. Li and A. K. S. Bhat, "Analysis and design of high-frequency isolated dual-bridge series resonant DC/DC converter," *IEEE Trans. Power Electron.*, vol. 25, no. 4, pp. 850–862, Apr. 2010.
[256] S. S. Muthuraj, V. K. Kanakesh, P. Das, and S. K. Panda, "Triple phase shift control of an LLL tank based bidirectional dual active bridge converter," *IEEE Trans. Power Electron.*, vol. 32, no. 10, pp. 8035–8053, Oct. 2017.
[257] P. He and A. Khaligh, "Comprehensive analyses and comparison of 1 kW isolated DC–DC converters for bidirectional EV charging systems," *IEEE Trans. Transport. Electrific.*, vol. 3, no. 1, pp. 147–156, Mar. 2017.
[258] Y. Xuan, X. Yang, W. Chen, T. Liu, and X. Hao, "A novel three-level CLLC resonant DC–DC converter for bidirectional EV charger in DC microgrids," *IEEE Trans. Ind. Electron.*, vol. 68, no. 3, pp. 2334–2344, Mar. 2021.
[259] M. Yaqoob, K. H. Loo, and Y. M. Lai, "A four-degrees-of-freedom modulation strategy for dual-active-bridge series-resonant converter designed for total loss minimization," *IEEE Trans. Power Electron.*, vol. 34, no. 2, pp. 1065–1081, Feb. 2019.
[260] M. Yaqoob, K. H. Loo, and Y. M. Lai, "Extension of soft-switching region of dual-active-bridge converter by a tunable resonant tank," *IEEE Trans. Power Electron.*, vol. 32, no. 12, pp. 9093–9104, Dec. 2017, doi: 10.1109/TPEL.2017.2654505.
[261] H. Haga and F. Kurokawa, "Modulation method of a full-bridge three-level LLC resonant converter for battery charger of electrical vehicles," *IEEE Trans. Power Electron.*, vol. 32, no. 4, pp. 2498–2507, Apr. 2017.
[262] M. I. Shahzad, S. Iqbal, and S. Taib, "Interleaved LLC converter with cascaded voltage-doubler rectifiers for deeply depleted PEV battery charging," *IEEE Trans. Transport. Electrific.*, vol. 4, no. 1, pp. 89–98, Mar. 2018.
[263] I. Alhurayyis, A. Elkhateb, and J. Morrow, "Isolated and nonisolated DC-to-DC converters for medium-voltage DC networks: A review," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 9, no. 6, pp. 7486–7500, Dec. 2021, doi: 10.1109/JESTPE.2020.3028057.
[264] L. A. D. Ta, N. D. Dao, and D.-C. Lee, "High-efficiency hybrid LLC resonant converter for on-board chargers of plug-in electric vehicles," *IEEE Trans. Power Electron.*, vol. 35, no. 8, pp. 8324–8334, Aug. 2020.
[265] H. Wang, S. Dusmez, and A. Khaligh, "Design and analysis of a full-bridge LLC-based PEV charger optimized for wide battery voltage range," *IEEE Trans. Veh. Technol.*, vol. 63, no. 4, pp. 1603–1613, Apr. 2014, doi: 10.1109/TVT.2013.2288772.
[266] T. Zhu, F. Zhuo, F. Zhao, F. Wang, H. Yi, and T. Zhao, "Optimization of extended phase-shift control for full-bridge CLLC resonant converter with improved light-load efficiency," *IEEE Trans. Power Electron.*, vol. 35, no. 10, pp. 11129–11142, Oct. 2020, doi: 10.1109/TPEL.2020.2978419.
[267] V. R. K. Kanamarlapudi, B. Wang, N. K. Kandasamy, and P. L. So, "A new ZVS full-bridge DC–DC converter for battery charging with reduced losses over full-load range," *IEEE Trans. Ind. Appl.*, vol. 54, no. 1, pp. 571–576, Dec. 2018.
[268] J. Dudrik, M. Bodor, and M. Pastor, "Soft-switching full-bridge PWM DC–DC converter with controlled output rectifier and secondary energy recovery turn-off snubber," *IEEE Trans. Power Electron.*, vol. 29, no. 8, pp. 4116–4125, Aug. 2014.
[269] G. Li, J. Xia, K. Wang, Y. Deng, X. He, and Y. Wang, "Hybrid modulation of parallel-series *LLC* resonant converter and phase shift full-bridge converter for a dual-output DC–DC converter," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 7, no. 2, pp. 833–842, Dec. 2019, doi: 10.1109/JESTPE.2019.2900700.
[270] G.-B. Koo, G.-W. Moon, and M.-J. Youn, "New zero-voltage-switching phase-shift full-bridge converter with low conduction losses," *IEEE Trans. Ind. Electron.*, vol. 52, no. 1, pp. 228–235, Feb. 2005, doi: 10.1109/TIE.2004.841063.
[271] J.-H. Kim, I.-O. Lee, and G.-W. Moon, "Analysis and design of a hybrid-type converter for optimal conversion efficiency in electric vehicle chargers," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 2789–2800, Apr. 2017, doi: 10.1109/TIE.2016.2623261.
[272] C.-Y. Lim, Y. Jeong, M.-S. Lee, K.-H. Yi, and G.-W. Moon, "Half-bridge integrated phase-shifted full-bridge converter with high efficiency using center-tapped clamp circuit for battery charging systems in electric vehicles," *IEEE Trans. Power Electron.*, vol. 35, no. 5, pp. 4934–4945, May 2020, doi: 10.1109/TPEL.2019.2931763.
[273] S. A. Gorji, H. G. Sahebi, M. Ektesabi, and A. B. Rad, "Topologies and control schemes of bidirectional DC–DC power converters: An overview," *IEEE Access*, vol. 7, pp. 117997–118019, 2019, doi: 10.1109/ACCESS.2019.2937239.
[274] L. Schmitz, D. C. Martins, and R. F. Coelho, "Comprehensive conception of high step-up DC–DC converters with coupled inductor and voltage multipliers techniques," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 67, no. 6, pp. 2140–2151, Jun. 2020, doi: 10.1109/TCSI.2020.2973154.
[275] A. Gupta, R. Ayyanar, and S. Chakraborty, "Novel electric vehicle traction architecture with 48 V battery and multi-input, high conversion ratio converter for high and variable DC-link voltage," *IEEE Open J. Veh. Technol.*, vol. 2, pp. 448–470, 2021, doi: 10.1109/OJVT.2021.3132281.
[276] F. Musavi, W. Eberle, and W. G. Dunford, "A phase-shifted gating technique with simplified current sensing for the semi-bridgeless AC–DC converter," *IEEE Trans. Veh. Technol.*, vol. 62, no. 4, pp. 1568–1576, May 2013, doi: 10.1109/TVT.2012.2231709.
[277] M. J. Brand, M. H. Hofmann, S. F. Schuster, P. Keil, and A. Jossen, "The influence of current ripples on the lifetime of lithium-ion batteries," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 10438–10445, Nov. 2018.
[278] O. Garcia, P. Zumel, A. de Castro, and J. A. Cobos, "Automotive DC–DC bidirectional converter made with many interleaved buck stages," *IEEE Trans. Power Electron.*, vol. 21, no. 3, pp. 578–586, May 2006.
[279] C.-Y. Oh, D.-H. Kim, D.-G. Woo, W.-Y. Sung, Y.-S. Kim, and B.-K. Lee, "A high-efficient nonisolated single-stage on-board battery charger for electric vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5746–5757, Dec. 2013, doi: 10.1109/TPEL.2013.2252200.
[280] R. Collin, Y. Miao, A. Yokochi, P. Enjeti, and A. von Jouanne, "Advanced electric vehicle fast-charging technologies," *Energies*, vol. 12, no. 10, p. 1839, May 2019.
[281] USDRIVE. (2017). *Electrical and Electronics Technical Team Roadmap*. U.S. Department of Energy. [Online]. Available: https://pdf4pro.com/amp/view/electrical-and-electronics-technical-team-roadmap-5f392a.html
[282] Virta. (2021). *Vehicle-to-Grid (V2G): Everything You Need to Know*. [Online]. Available: https://www.virta.global/vehicle-to-grid-v2g
[283] M. S. H. Lipu, M. A. Hannan, T. F. Karim, A. Hussain, M. H. M. Saad, A. Ayob, M. S. Miah, and T. M. I. Mahlia, "Intelligent algorithms and control strategies for battery management system in electric vehicles: Progress, challenges and future outlook," *J. Cleaner Prod.*, vol. 292, Apr. 2021, Art. no. 126044, doi: 10.1016/j.jclepro.2021.126044.
[284] R. Bass, R. Harley, F. Lambert, V. Rajasekaran, and J. Pierce, "Residential harmonic loads and EV charging," in *Proc. IEEE Power Eng. Soc. Winter Meeting. Conf.*, vol. 2, Aug. 2010, pp. 803–808, doi: 10.1109/PESW.2001.916965.
[285] (2022). *Internet of Vehicles (IoV): Revolutionizing Transportation of Tomorrow Riding on 5G and Edge AI*. [Online]. Available: https://www.wipro.com/infrastructure/
[286] J. Wang, K. Zhu, and E. Hossain, "Green Internet of Vehicles (IoV) in the 6G era: Toward sustainable vehicular communications and networking," *IEEE Trans. Green Commun. Netw.*, vol. 6, no. 1, pp. 391–423, Mar. 2022, doi: 10.1109/TGCN.2021.3127923.
[287] S. Pareek, A. Sujil, S. Ratra, and R. Kumar, "Electric vehicle charging station challenges and opportunities: A future perspective," in *Proc. Int. Conf. Emerg. Trends Commun., Control Comput.*, Feb. 2020, pp. 1–6, doi: 10.1109/ICONC345789.2020.9117473.
[288] I. Aretxabaleta, I. M. De Alegria, J. Andreu, I. Kortabarria, and E. Robles, "High-voltage stations for electric vehicle fast-charging: Trends, standards, charging modes and comparison of unity power-factor rectifiers," *IEEE Access*, vol. 9, pp. 102177–102194, 2021, doi: 10.1109/ACCESS.2021.3093696.
[289] F. Manríquez, E. Sauma, J. Aguado, S. de la Torre, and J. Contreras, "The impact of electric vehicle charging schemes in power system expansion planning," *Appl. Energy*, vol. 262, Mar. 2020, Art. no. 114527, doi: 10.1016/j.apenergy.2020.114527.
[290] A. S. Al-Ogaili, "Review on scheduling, clustering, and forecasting strategies for controlling electric vehicle charging: Challenges and recommendations," *IEEE Access*, vol. 7, pp. 128353–128371, 2019, doi: 10.1109/ACCESS.2019.2939595.

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