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Review Article

Battery charging technologies and standards for electric vehicles: A state-of-the-art review, challenges, and future research prospects

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ABSTRACT

Countries worldwide are rapidly transitioning to clean energy sources to achieve the UN's (United Nations) Sustainable Development Goals (SDGs), particularly SDG 7 on affordable and clean energy. Electric vehicles (EVs) play a crucial role in this shift, offering an eco-friendly transportation option. Recognizing their importance, this paper delves into recent advancements in EV charging. It examines rapidly evolving charging technologies and protocols, focusing on front-end and back-end power converters as crucial components in EV battery charging. Through a quantitative analysis of current EV-specific topologies, it compares their strengths and weaknesses to guide future research and development. Additionally, it summarizes recent optimization techniques in EV charging solutions. Moving on, the paper examines advancements and challenges in vehicle-to-grid (V2G) technology, a key smart charging solution for future smart grids. It explores its potential to enhance grid reliability and integrate renewable energy sources, while acknowledging challenges beyond feeding energy back to the grid, such as bi-directional power flow management and infrastructure development. Finally, the paper concludes by dedicating a section to future research opportunities in EV charging, highlighting areas like wireless charging, grid integration, and battery life optimization. This in-depth exploration aims to be a valuable resource for researchers and stakeholders, guiding them in identifying promising future directions for this critical technology.

1. Introduction

Electric vehicles (EVs), an eco-friendly automotive alternative, are growing quickly in popularity worldwide. Governments are actively promoting this shift through various incentives, including tax incentives, VAT (Value-Added Tax) exemption, decreased license tax, purchase aids, toll exemption, free public parking, etc. The adoption of EVs over conventional internal combustion engine (ICE) vehicles has been accelerated by several compelling factors. These are:

- Fossil Fuel Depletion: Fossil fuel reserves are running out globally. As a result, there is a shortage of fossil fuels. The cost of fossil fuels is also significantly rising.
- Zero Emission: Unlike conventional ICE vehicles, EVs do not produce any air pollutants like carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), or particulate matter (PM), etc.
- Advances in Supporting Technology: Advancements in grid infrastructure like G2V (Grid to Vehicle) and V2G (Vehicle to Grid) systems enable smarter energy management and grid stability, while the development of renewable energy sources like solar and wind power provides a clean and sustainable charging solution for EVs. Additionally, rapid improvements in EV charging technologies and electronic control systems have made them more convenient and efficient, further boosting their appeal.

These combined factors have led to a significant boom in global EV sales, especially in the past two years, as evidenced by Figs. 1 and 2.

The rapid growth of EVs as eco-friendly alternatives has driven researchers worldwide to focus on optimizing EV battery charging technologies. This surge in interest is reflected in the increasing number of EV-related research papers published by reputable scientific publishers. For example, in 2022 alone, IEEE Xplore published 11,281 EV-related papers, including 3263 journal articles, while Elsevier's ScienceDirect boasted 20,943 publications, with 20,341 journal articles. Springer Link also saw a significant contribution, publishing 17,543 EV-related papers in 2022. Fig. 3 illustrates the impressive growth in research paper publications by these three major publishers over the past decade. Notably, they have witnessed a roughly 300% increase in EV-related publications over the past ten years.

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List of Abbreviations

AC	Alternating Current
BCS	Battery Charging Station
BDC	Bidirectional DC-DC converter
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BMS	Battery Management System
CM	Common-Mode
CP	Charging Post
CPM	Charging Post Manager
CPT	Capacitive Power Transfer
DAB	Dual Active Bridge
DB	Depleted Battery
DC	Direct Current
DSO	Distribution System Operator
DVR	Double Voltage Rectification
EMF	Electromagnetic Field
EMI	Electromagnetic Interference
ER-EV	Extended-Range Electric Vehicle
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FB	Fully Charged Battery
FCEV	Fuel Cell Electric Vehicle
G2V	Grid to Vehicle
GA	Genetic Algorithm
GaN	Gallium Nitride
HEV	Hybrid Electric Vehicle
HF	High Frequency
ICE	Internal Combustion Engine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPT	Inductive Power Transfer
IPTS	Inductive Power Transfer System
IRENA	International Renewable Energy Agency
NACS	North American Charging Standard
PFC	Power Factor Correction
PHEV	Plug-In Hybrid Electric Vehicle
PSO	Particle Swarm Optimization
RCD	Residual Current Device
RES	Renewable Energy Sources
RUL	Remaining Useful Life
SAC	Standards Administration of China
SAE	Society of Automotive Engineers
Si	Silicon
SiC	Silicon Carbide
SOC	State of Charge
SOH	State of Health
SUV	Sports Utility Vehicle
TSO	Transmission System Operator
UPS	Uninterruptible Power Supplies
V2G	Vehicle to Grid
VAT	Value-Added tax
WBG	Wide Bandgap
WPT	Wireless Power Transfer
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

Recent review articles delve deep into specific research areas of EV battery charging technologies and standards, but a holistic understanding of the entire field remains largely missing. This gap is further emphasized by the lack of a review paper offering a comprehensive comparison of all current EV power electronic converter options, including their topologies, performance, and efficiency. For instance, while İnci et al. (2021) provide a thorough review of fuel cell electric vehicles (FCEVs) under various headings, their scope is limited to FCEVs and excludes other EV types. Similarly, Mohamed et al. (2020) offer a comprehensive review of inductive charging technologies but neglect other charging techniques. Similarly, Habib et al. (2020) focus solely on power electronics converters for EV charging, yet lack a comparative analysis of these converters. Skouras et al. (2019) review EVs in general but fail to address the specific topic of power electronics converter topologies suitable for EVs. This highlights the need for a comprehensive review that encompasses the entire spectrum of EV battery charging technologies, including a detailed analysis of all current EV power electronic converters. Such a review would provide a valuable resource for researchers and engineers working in this rapidly evolving field.

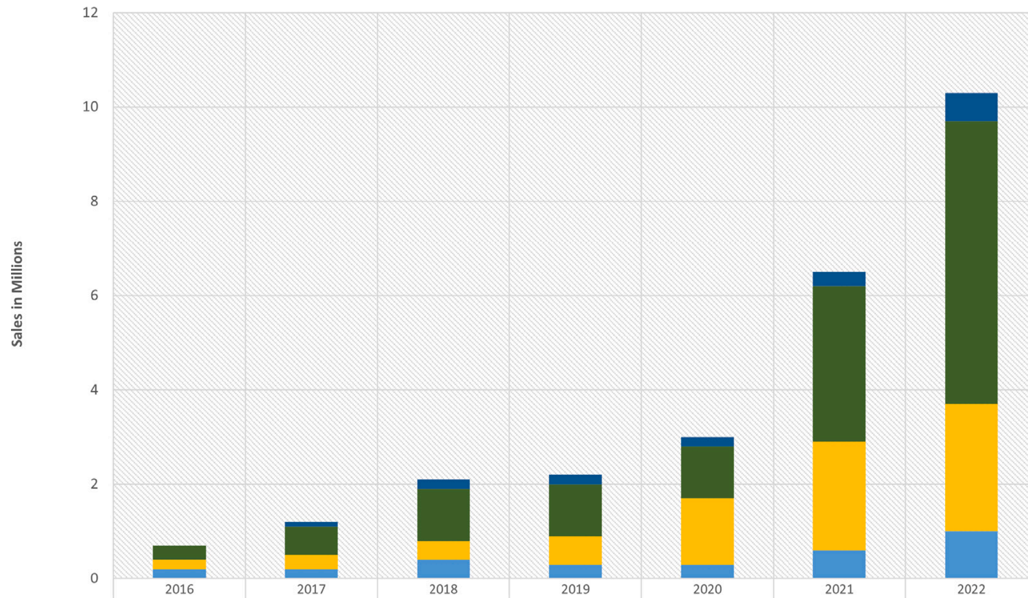
In this context, this review paper addresses a research gap in previous studies by providing an extensive comparative analysis of all current power electronic converters related to EV battery charging based on their performance, efficiency, and other relevant criteria. The strengths and weaknesses of these converters are compared in a clear and concise tabular format. Additionally, a comprehensive review of current charging standards and methods, including conductive charging, wireless charging, and battery swap stations (BSS), is presented. Recent EV charging station types, such as AC and DC stations, and their structures are covered in detail. Furthermore, the paper reviews recent EV optimization techniques, including various artificial intelligence (AI) and machine learning (ML)-based approaches. The following section delves into current V2G technology, exploring its control techniques, benefits, and present challenges. Finally, the paper discusses potential research opportunities regarding EV charging technologies. As a whole, this paper can assist EV research enthusiasts and policymakers in quickly reviewing and understanding the latest advancements in EV battery charging. The rest of the paper is organized into the following eight sections:

- Section 2 explores EV types, charger ratings, and their pros and cons.
- Section 3 delves into EV battery charging methods, different types of charging stations, and charging standards.
- Section 4 examines the advantages, drawbacks, and future research potential of AC–DC and DC–DC power conversion strategies for EV battery charging.
- Section 5 highlights recent EV optimization techniques, including machine learning algorithms and demand response strategies, and their benefits.
- Section 6 describes in detail the methods, benefits, challenges, and prospects of G2V and V2G technologies, including bi-directional charging and smart grid integration.
- Section 7 identifies promising areas for further investigation in the field of EV research, such as advanced battery materials and wireless charging technologies.
- Finally, Section 8 concludes by summarizing the key findings and emphasizing the significance of this research.

2. Electric vehicles types

We can categorize EVs into five different types based on their engine technology. Following is a brief overview of these types:

- Battery Electric Vehicles (BEVs): This is a fully electric vehicle that is powered entirely by electricity. It can move without using any ICE or liquid fuel. BEVs are consequently better for reducing global warming and climate change. Large battery packs are used to power the vehicle. Regenerative braking is a feature of BEVs



	2016	2017	2018	2019	2020	2021	2022
Others	0	0.1	0.2	0.2	0.2	0.3	0.6
China	0.3	0.6	1.1	1.1	1.1	3.3	6
Europe	0.2	0.3	0.4	0.6	1.4	2.3	2.7
United States	0.2	0.2	0.4	0.3	0.3	0.6	1

Fig. 1. Changes in the global sales of electric cars (Institute of Transport Economics, Norwegian Centre for Transport Research, 2022; Wikipedia, 2022a; European Commission, 2022; Irle, 2022).

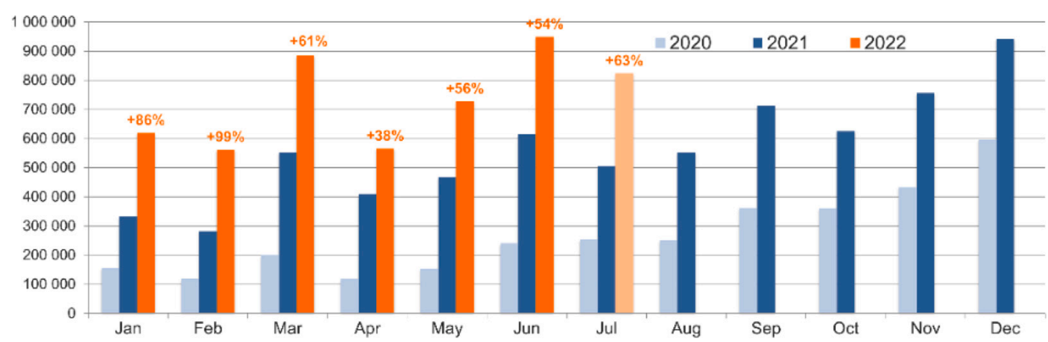


Fig. 2. Global monthly plug-in EV sales and year-to-year growth (Irle, 2022).

that converts kinetic energy back into electrical energy that can be retained by the battery. As a result, EVs are preferred for city driving since city driving regularly requires starting and stopping, which enables the vehicle to recover some of the kinetic energies into the batteries. Fig. 4 depicts the structure and essential elements of a BEV. A typical BEV can go 95 to 695 km on a single charge (Electric Vehicle Database, 2022). The Ford Mustang Mach-E, a BEV compact crossover Sports Utility Vehicle (SUV) manufactured by Ford in December 2020, is an instance of this kind of vehicle. It presently offers a 68–88 kWh battery that allows consumers to have an autonomy of 370–483 km. The vehicle was named the 2021 North American SUV of the Year (Wikipedia, 2022b).

- Plug-In Hybrid Electric Vehicles (PHEVs): A traditional internal combustion engine and an electric motor, powered by an external electric source that can be plugged in, work together to drive plug-in hybrid automobiles. PHEVs have the capacity to store enough grid power to dramatically lower their fuel use under normal driving circumstances. They have regenerative braking, just like BEVs. The structure and key components of a PHEV are shown in Fig. 5. The 8.8 kWh battery in the Toyota Prius PHEV (Wikipedia, 2022c) enables it to go around 40 km on its electric powertrain alone. It has an average driving range of 1030 km. It is also important to note that PHEVs use more gasoline than car manufacturers claim (Plötz et al., 2020).
- Hybrid Electric Vehicles (HEVs): HEVs use both an electric motor and a gas engine to propel the vehicle. Regenerative braking, which recovers energy normally lost during braking to support the gasoline engine during acceleration, provides all of the energy for the batteries. This braking energy often escapes from a standard ICE car as heat in the brake pads and rotors. Regular hybrids cannot use the grid to recharge, in contrast to PHEVs. Fig. 6 illustrates an HEV's structure and key components. If one can afford the higher price tag, HEVs are a no-brainer because we do not have to worry about finding charging stations or spending extra time powering up. They are often more expensive than gas-powered automobiles by a few thousand dollars, but less expensive than PHEVs. For instance, the base price of a gas-powered Toyota Rav 4 in 2022 is $26,975 (Toyota, 2022b). The cost of the same car HEV model is $29,575 while the PHEV model is $40,300 (Toyota, 2022b). However, it is simple to see how the expense eventually balances out whenever gas prices increase.

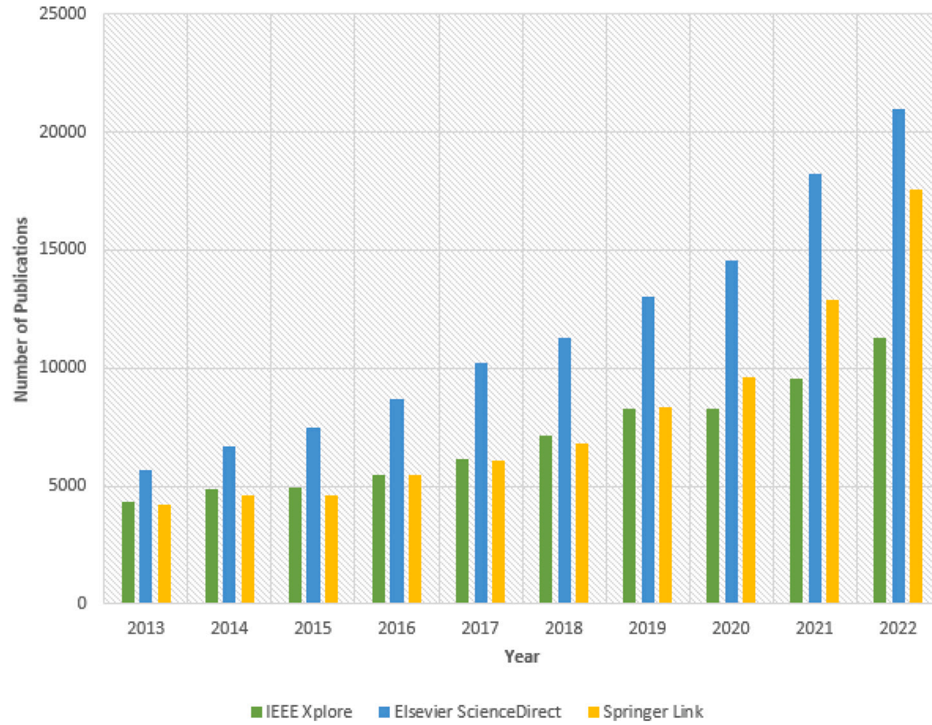


Fig. 3. Number of research paper publications in IEEE Xplore, Elsevier ScienceDirect, and Springer Link website in the last ten years.

- Fuel Cell Electric Vehicles (FCEVs): These cars are equipped with an electric motor that burns a combination of compressed hydrogen (H_2) and oxygen (O_2) that is taken from the air, with water being the sole waste product. Despite the fact that these vehicles are regarded as having zero emissions, it is important to note that while there is green hydrogen, the majority of the hydrogen consumed is produced from natural gas. Fig. 7 shows an FCEV's basic components and structural layout. An example of one of these cars is the Toyota Mirai (Toyota, 2022a), whose most recent model was introduced in 2021 and has a range of 650 km without refueling and produces only clean water as emissions.
- Extended-Range EVs (ER-EVs): A range extender is an additional power source that extends the driving range of an extended-range electric vehicle (ER-EV). The majority of range extenders use tiny internal combustion engines to power an electric generator, which supplies power to the motor and electric batteries. When an ER-EV's tiny range-extender motor is running, CO_2 is produced, but not when the ER-EV is using electric power. An ER-EV will emit much less CO_2 than an ICE vehicle over the course of its lifespan. Fig. 8 illustrates an ER-EV's structure and key components. The BMW i3 (BMW, 2022) is an instance of an ER-EV. It has a lithium-ion battery pack and an optional range-extending gasoline engine.

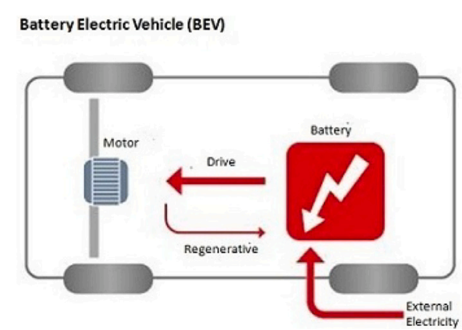


Fig. 4. The structure and key elements of a BEV (Omazaki Group, 2022).

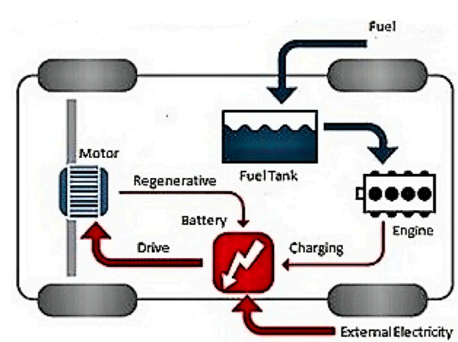


Fig. 5. The structure and key components of a PHEV (Omazaki Group, 2022).

3. EV battery charging methods and standards

This section provides a brief explanation of the various EV charging configurations, including on-board and off-board, charging stations, charging standards like IEC (International Electrotechnical Commission) and SAE (Society of Automotive Engineers), and country-specific EV charging stations and connectors.

3.1. EV charging standards

To handle EV charging infrastructure, various governing bodies have created uniform charging standards. Different countries use different charging standards. For instance, Japan and Europe utilize CHAdeMO (CHAdeMO, 2022) as their charging standard, while the United States prefers the Institute of Electrical and Electronics Engineers (IEEE) and SAE standards. The Standardization Administration of the People's Republic of China (SAC) employs IEC-compliant GB/T standards (China National Standards, 2023; Standardization Administration of the People's Republic of China , SAC). The term "Level" is used to describe the power rating in SAE standards, whereas "Mode"

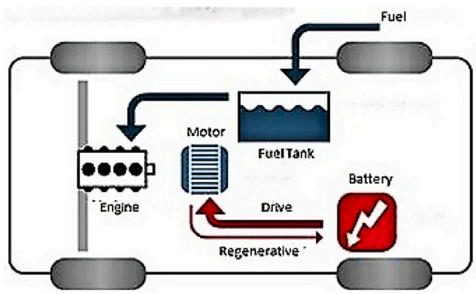


Fig. 6. The structure and essential elements of a HEV (Omazaki Group, 2022).

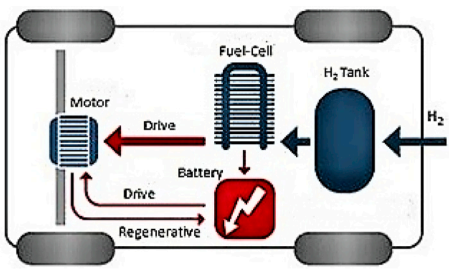


Fig. 7. The structural layout and basic elements of an FCEV (Omazaki Group, 2022).

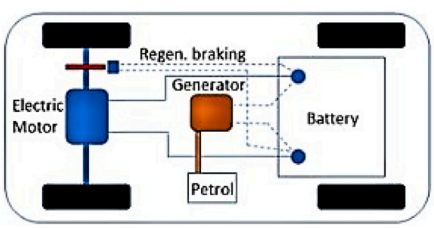


Fig. 8. The structure and essential elements of an ER-EV (Sustainability-in-practice, 2022).

is used in IEC standards. Table 1 provides a summary of the IEC and SAE charging standards. According to the SAE-J1772 Standard, SAE International (2017), AC level 1 and level 2 onboard chargers have been created for power supplies of 120 V and 240 V AC, and are able to produce 1.9 kW and 19.2 kW, respectively. Due to their low power consumption, these onboard chargers are perfect for charging throughout the day. Offboard chargers with a power supply between 200 and 450 V are designed to use a DC fast charger with an optimal capacity of 50 kW and, most recently, up to 350 kW. The IEC-62196 Standard (IEC, 2022) contains three AC levels and one DC level. It lists four distinct couplers for dc fast charger systems, including Configuration AA (CHAdeMO Association), Configuration BB (also called GB/T and applicable in China), Configuration CC (Type 1 combined charging system, accepted in North America), and Configuration FF (Type 2, integrated charging system, adopted in Europe and Australia) (IEC, 2022). The IEC-61851 Standard (IEC, 2017) uses two AC levels with voltage levels of 120 V and 240 V and one DC level ranging from 200 to 450. The North American Charging Standard (NACS), which is based on the Tesla supercharger, was just released by Tesla Inc. In a small package, it can provide up to 1 MW of DC charging as well as AC charging. This standard is available in 500-V and 1000-V variations (Tesla, 2022).

Different EV charging modes serve various purposes and provide various charging facilities. Following is a brief description of the charging modes:

- Mode 1 (Slow Charging): Fig. 9 illustrates how an electric vehicle is charged in Mode 1. The term "Mode 1 Charging Technology" implies charging in homes or workplaces using a straightforward extension wire with no safety. An EV is charged using this method by being plugged into a regular home outlet. It offers a single-phase or three-phase power socket facility with neutral and earth wires, and a maximum current intensity of 16 A. Users are not protected from DC-current shock by this charging technique. There is no communication with or control over the vehicle. As a result, it provides the car owner with minimal protection. Because of this, several nations forbid using this mode of charging.
- Mode 2 (Semi-fast Charging): In contrast to Mode 1 charging, Mode 2 charging cables can offer an in-cable RCD (residual-current device), over temperature and over current protection, and protective earth detection. A domestic and industrial cable with built-in shock protection against AC and DC currents is used for charging in mode 2. Fig. 10 depicts the charging process for an electric vehicle in Mode 2. This mode is typically placed on portable chargers for EVs. The pricey nature of this charging option is a result of the strict cable requirements. One-phase or three-phase lines with earthing implemented can be used for charging. In single-phase AC applications, the maximum current and voltage ratings are 32 A and 250 V, respectively, and 32 A and 480 V in three-phase AC applications. The EV supply equipment (EVSE) must meet the following criteria before electricity will be sent to the EVs.
  - Adequate earthing protection
  - No fault conditions, such as an over-current or an overheat, etc.
  - EV has been linked and has requested electricity, which can be seen on the pilot data line

  This method is subject to different restrictions in the United States, Canada, Switzerland, Denmark, France, Norway, and Italy.
- Mode 3 (Fast Charging): Use of a dedicated charging point or a wall-mounted wall box at home is required for mode 3 charging. Both offer AC or DC current shock prevention. In Mode 3, the EV does not require a specific cable for charging because the connecting cable is included with the wall box or charging station. This mode also allows communication between the vehicle and the EVSE device. It controls how much energy is used, keeps track of the charging process, and has an integrated safety system. Fig. 11 shows how an electric vehicle in Mode 3 is charged. Currently, Mode 3 charging is the favored method for EV charging. It is the only method permitted in Italy for AC automobile charging in public areas. Even if there are no restrictions imposed by law, charging points functioning in mode 3 typically permit charging up to 32 A and 250 V in single-phase AC and up to 32 A and 480 V in three-phase AC.
- Mode 4 (Ultra-fast Charging): The DC charging feature is only available in this charging mode. This charging option needs a current converter that is external to the car where the charging cable is attached. Due to the converter, which converts AC electricity into DC before flowing through the charging cable and toward the electric car, the charging station is often significantly larger than a basic one. With the EVSE, protection, and control features are also available in this mode. Fig. 12 portrays how to charge an electric vehicle in Mode 4. This mode offers a maximum charging power rating of up to 400 kW with a maximum voltage rating of 1000 V and a current rating of up to 400 A, in accordance with the most recent IEC-62196-3 standard (IEC, 2022).

3.2. EV charging methods

There are three major charging methods for EV charging. They are conductive charging, inductive charging, and battery swap station (BSS). Compared to inductive charging technology solutions, which

Table 1
Summary of EV charging standards.

Standards	Source	Phase	Level/Mode	Voltage (V)	Current (A)
SAE-J1772	AC	Single	Level 1	120	16
		Single	Level 2	240	32-80
	DC	DC	Level 1	200–450	80
		DC	Level 2	200–450	200
IEC-62196	AC	Single	Mode 1	120	16
		Single	Mode 2	240	32
		Single	Mode 3	250	32-250
	DC	DC	Mode 4	600	400
IEC-61851-1	AC, non-dedicated	Single	Mode 1	250	16
		Three		480	16
	AC, non-dedicated	Single	Mode 2	250	32
		Three		480	32
	AC, dedicated	Single	Mode 3	250	32
		Three		480	32
	DC, dedicated	DC	Mode 4	400	200
Tesla-NACS	AC/DC	Single, Three & DC	Compatible to IEC-62196 & IEC-61851–1	500/1000	Up to the manufacturer

Fig. 9. Mode 1 EV charging technology (Deltrix Chargers, 2022).

Fig. 10. Mode 2 EV charging process (Deltrix Chargers, 2022).

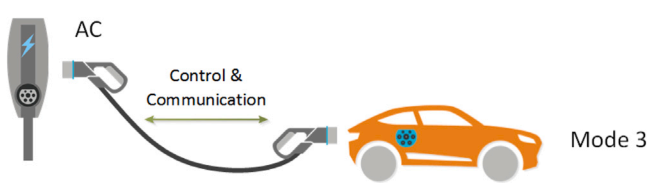


Fig. 11. EV charging technique for Mode 3 (Deltrix Chargers, 2022).

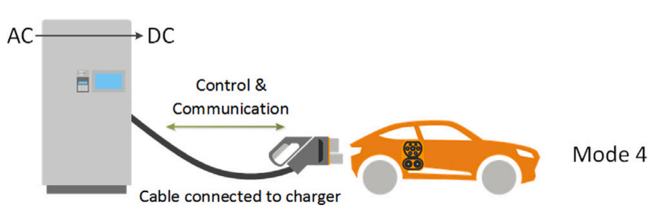


Fig. 12. EV charging technology for Mode 4 (Deltrix Chargers, 2022).

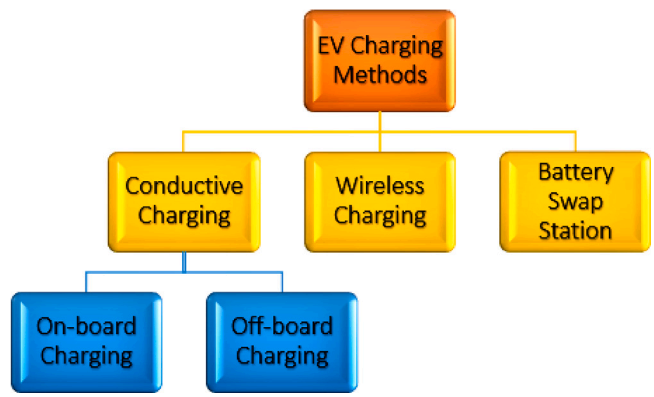


Fig. 13. A schematic layout of EV charging methods.

are still being researched and are not yet widely used in the field of electric transportation, conductive charging techniques are more well-established and prevalent. Compared to the other two charging techniques, BSS is less commonly used. Current EV charging methods are depicted in Fig. 13.

3.2.1. Conductive charging

A direct contact between the car and the charging inlet is necessary to transfer power for conductive charging. Because of the direct connection, this charging technique is quite effective. It offers a variety of charging options, including level 1, level 2, level 3 as well as level 4 charging. Conductive charging technology provides a V2G infrastructure, reduces grid losses, maintains system voltage, prevents grids overloading, provides active power, and can even make use of the vehicle's battery to make up for reactive power (Yoldaş et al., 2017). Onboard and off-board charging are the two main categories of conductive charging. Off-board charging refers to charging that takes place outside the vehicle, while onboard charging is primarily used for slow charging inside the vehicle. Off-board chargers are preferable because they provide fast charging capabilities, higher kW transfers, and lighter vehicle weights. The transfer of high power in onboard charging is constrained by weight, size, and cost factors. Because of this, it requires more time to charge than the off-board charging configuration. In contrast to off-board charging, which delivers DC power to the EV battery packs, onboard charging supplies AC power to the batteries. Fig. 14 depicts the onboard and off-board charging methods. The vehicle's internal battery pack is charged under the control of the battery management system (BMS). The majority of EV manufacturers currently use conductive charging.

3.2.2. Wireless charging

Wireless power transfer (WPT) has been in existence since the late 19th century. Hertz displayed the first demonstration of WPT. Using a spark gap, he demonstrated the propagation of electromagnetic waves in space. Ever since, numerous research teams from across the globe have been investigating the WPT system for use in a variety of applications, including EVs, consumer electronics, mobile phones, laptops, household appliances, medical equipment, and electric machinery A categorization chart for various WPT technologies is shown in Fig. 15. WPT technology, as can be seen, can be split into four

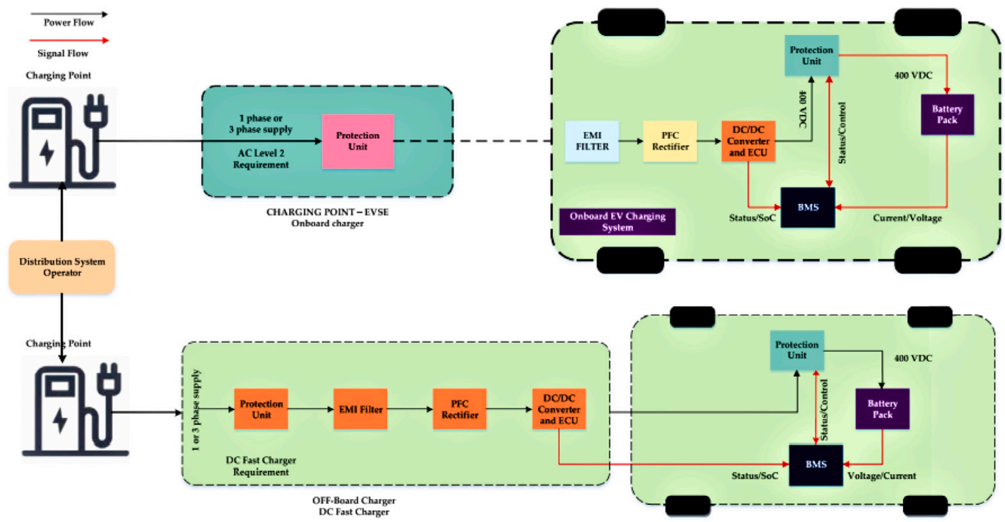


Fig. 14. A schematic layout of onboard and off-board EV charging systems (Rajendran et al., 2021a).

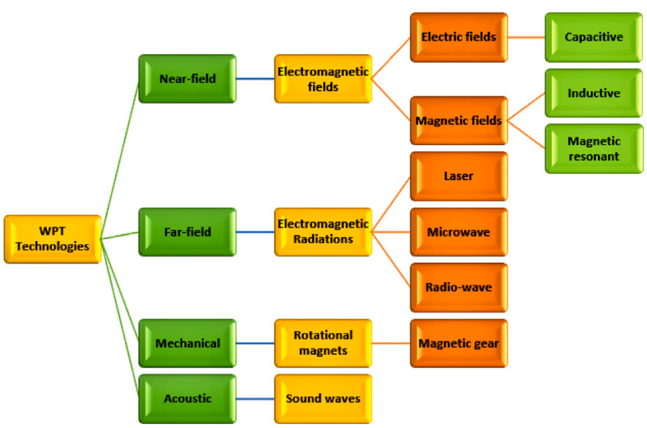


Fig. 15. A categorization chart for various WPT technologies.

primary categories: near-field transfers (Ahmad et al., 2017; Garnica et al., 2013), such as inductive, magnetic resonant, and capacitive; far-field transfers (Garnica et al., 2013), such as laser, microwave, and radio-wave; mechanical force, such as magnetic gear (Mohamed et al., 2022); and acoustic (Tseng et al., 2017; Roes et al., 2013).

Capacitive power transfer (CPT) and inductive power transfer (IPT) are the two available wireless charging methods for EVs at the moment. The most often used technique, however, is IPT because it can be employed with a variety of gap lengths as well as power ratings. Contrarily, CPT is only suitable for smaller gap power transfers, although exhibiting promising outcomes with large power levels in kilowatt-level applications. CPT is based on the idea of a capacitor, where a dielectric material-filled air gap is made between the conducting plates. Every half-cycle, an AC excitation reverses the electric field's direction, and the charging and discharging are repeated alternately. The advantages of CPT technology include power transfer over a metal barrier, little eddy current loss, and reduced EMI (Ahmad et al., 2017; Dai and Ludois, 2015).

IPT charging technique is the most appealing for EV charging applications because it can transmit high power across a reasonably broad air-gap $(10-40\text{ cm})$ (Mohamed and Mohammed, 2018), which satisfies the ground clearance for the most EVs; it is also quiet; has no moving parts, requires no maintenance; is unaffected by impurities; and has electrically isolated parts. Additionally, it can recharge even if the EV is moving and does not need a traditional connector (although requires a standardized coupling technology). Fig. 16 shows a diagram of the IPT system (IPTS) for EV charging applications. The system contains two electrically separated sides: transmitter and receiver. The grid-rectifier, HF inverter, compensation network, and transmitter coil are stationary components on the primary side that are wired to the power source (grid). The receiver coil, compensation network, and rectifier that are mounted within the car and connected to the battery system make up the secondary side. To receive low-frequency AC power from the grid, the transmitter side is buried in the road. A grid rectifier, a dc link, and an HF inverter are used to convert low-frequency (LF) AC power to high-frequency (HF) AC power. The transmitter coil then makes use of this converted HF AC to produce an alternating magnetic field. In order to induce HF AC voltages and currents in the secondary circuit, the EMFs produced by the transmitter coil are coupled with the receiver coil (in the vehicle). To charge the vehicle's battery packs, the HF secondary AC power is then rectified. Through a wireless communication link, the two sides (primary and secondary) remain in contact with one another. To minimize the size of the transmitter, receiver, and power converters, the IPT should be utilized at a high frequency (Mohamed et al., 2016). Resonance capacitors create a compensation network that is coupled to both the transmitter and receiver coils for high-efficiency operation. By providing the necessary reactive power for magnetizing this airgap, these capacitors assist in reducing the significant leakage inductances caused by the large airgap.

Three main forms of IPTS are available for EV charging: static, dynamic, and quasi-dynamic. Long-term parking places like parking lots, working places, public parking, and home garages are suitable sites to implement static charging. The dynamic charging technology can charge the car steadily as it is moving through specially designated charging lanes along the route, increasing the EV's driving range and minimizing the battery size. The transmitter coil in this situation might either be a long track or a series of linked pads. Due to the high energy requirements of the vehicle and the restricted availability of stops and parking, dynamic charging is the most practical method to support highway travel. Quasi-dynamic charging charges the car when it is briefly halted, as at a traffic signal or a bus stop, expanding the driving range and enabling EVs to store less energy.

The IPT, however, is often not strong. Furthermore, until the transmitter coil is switched off, eddy current loss is another problem with the IPT. Since a real-time connection between the transmitter and the EV is required for data transfer, communication latency is a possibility. Another issue is the cost of implementation. In comparison to charging by wire, the magnetic couplers and related power electronics will add to the cost. The IPT's electromagnetic field (EMF) can endanger

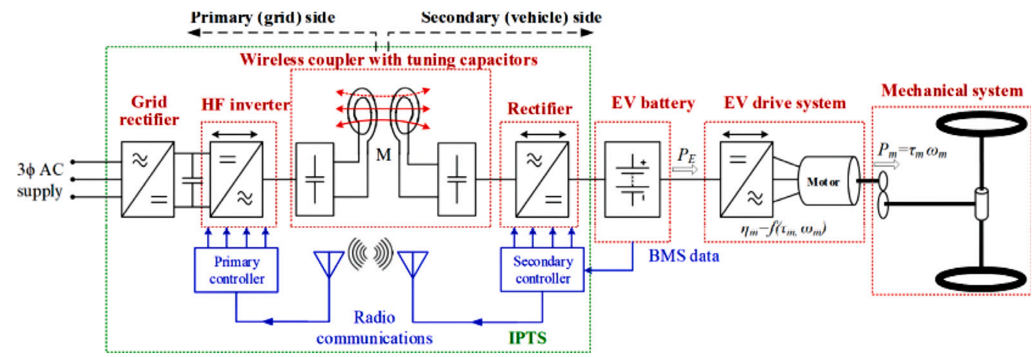


Fig. 16. A diagram of the IPT system for EV charging applications (Mohamed et al., 2020).

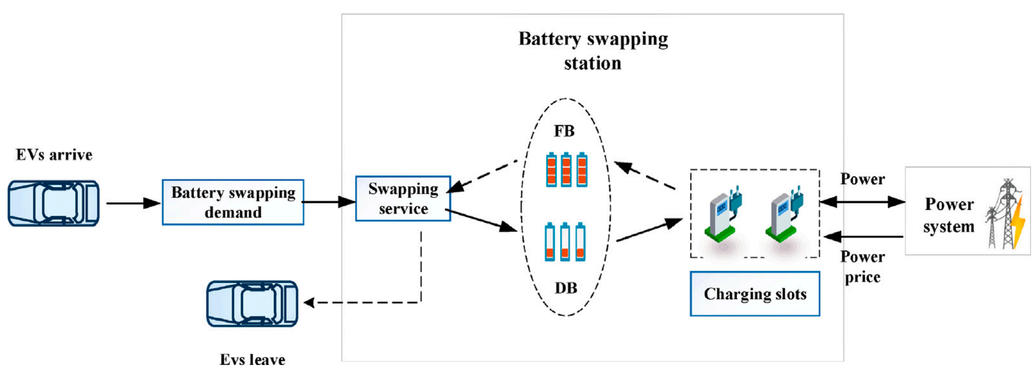


Fig. 17. An operational structure of a BSS (Feng and Lu, 2021).

human health and safety by heating human tissue, implanted medical equipment, and metals (Patil et al., 2017). Therefore, future research should focus on investigating novel shield designs for safety, lowering implementation costs, designing effective fast chargers, etc.

3.2.3. Battery Swap Stations (BSS)

One of the fastest and least complicated techniques of charging is the battery swapping or exchange method which is similar to the traditional gas stations. This approach relies on paying the BSS owner a monthly fee for the BMS-enabled battery, which significantly lowers the cost of purchasing electric cars and eliminates the issue of lengthy charging periods. EV owners can use this method to quickly recharge the battery without exiting the vehicle. Slow charging on the BSS adds to extended battery life. This BSS system is more readily linked with distributed RESs such as solar and wind.

Fig. 17 depicts a BSS's operational structure. EV owners, BSSs, and power grids all communicate with one another through this mechanism. When the EV battery exceeds the charging threshold, a BSS swaps out the depleted battery (DB) for a fully charged battery (FB) before placing the battery in the charging station (BCS). When the charging is finally completed, the BCS sends it back to the BSS for swap in EVs. If the BSS does not have any FB, EVs need to wait. One significant feature of BSSs is their ability to do large bidirectional power transfers with the grid. As a V2G system, the FBs can deliver power to the grid during periods of peak demand while charging takes place during off-peak times (Xian and Wang, 2016; Gschwendtner et al., 2021; Brenna et al., 2021).

However, it also has several drawbacks:

- High initial outlay: This method necessitates a sizable space to store the batteries, which might require pricey real estate in a busy neighborhood. Batteries are quite expensive; too many batteries raise expenses, while too few batteries cannot keep up with demand from customers.
- Hefty cost of EV charging: For EV owners, this method of EV charging might be more expensive than fueling the ICE engines because of the high monthly rental rates levied by the BSS owner.
- Lack of interoperability: The stations may use a specific battery model, while the EVs may use batteries that differ in standards (Erdinç et al., 2018; Li et al., 2018).

3.3. EV charging stations

The layout of a charging station with multiple charging nodes is of interest because EV chargers are intended to serve a function similar to that of a traditional fuel station. Keeping this in mind, EV charging stations can be broadly classified as AC or DC charging stations. Figs. 18 and 19 illustrate the two layouts for the EV charging station.

3.3.1. AC charging stations

In the AC charging station, shown in Fig. 18, a three-phase distribution step-down transformer transforms the medium voltage (MV) utility supply line into a low voltage (LV) utility supply line (up to 480 V line to line), which serves as a common AC bus for the onboard EV chargers. In contrast to DC fast-charging stations, which use common AC/DC converters attached to the MV-LV step-down transformer, AC charging stations use AC/DC converters that are an integral part of the onboard chargers (Ronanki et al., 2019; Srdic and Lukic, 2019; Bayram et al., 2013). These AC/DC converters could be bidirectional, able to feed power to the grid in response to DSO requests. Switchgear cabinets with breakers and disconnects are used to connect the MV-LV transformer to the AC charging station. This provides the station subsystem with the appropriate protection. The energy storage systems (ESS) and generation capabilities, such as photovoltaic (PV) systems and wind energy systems, can be included in the station system to reduce demand costs paid during peak power consumption at the station (Mehrjerdi and Hemmati, 2019). One benefit of an AC charging station is the availability and development of converter technology,

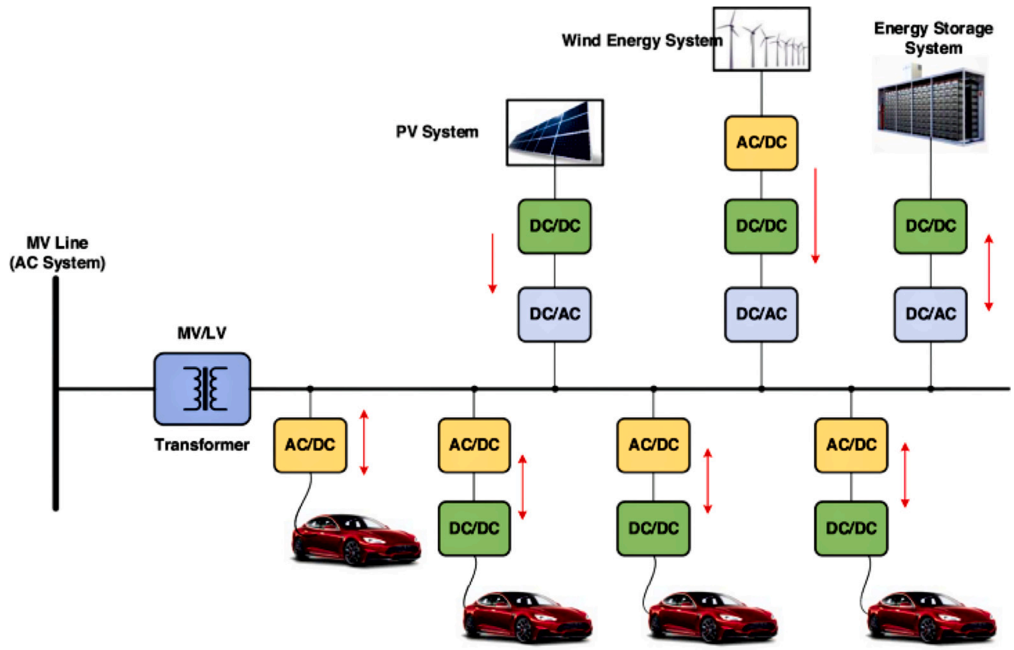


Fig. 18. A layout for the EV AC charging station (Rajendran et al., 2021a).

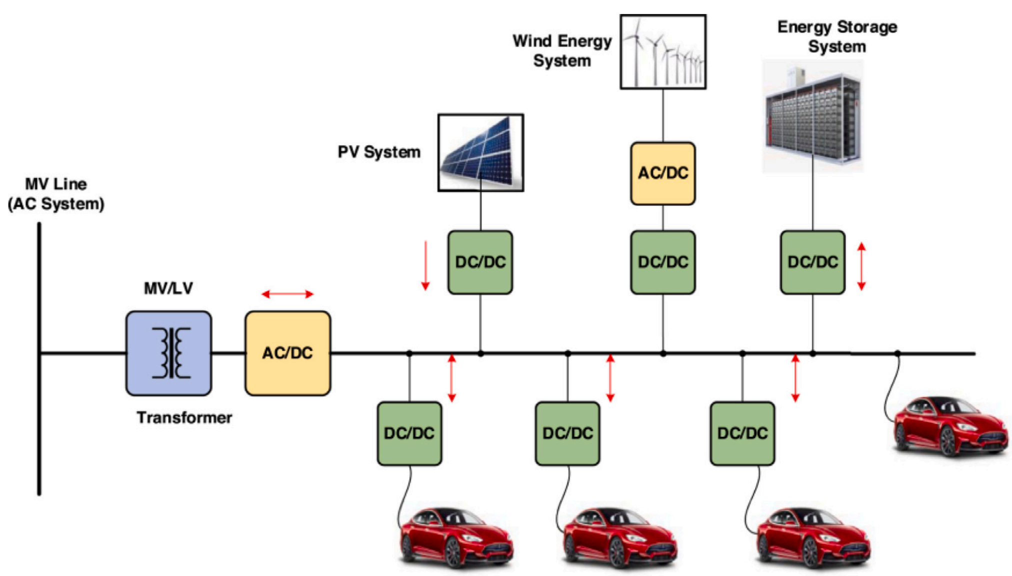


Fig. 19. An illustration of the EV DC charging station. Rajendran et al. (2021a).

switchgear, and protective devices. Another benefit is the existence of well-established standards and procedures for AC distribution systems. The primary drawback of the AC charging station is the need for extra conversion stages (to connect DC loads, DC generator, and ESS to the AC system). These conversion phases make the system more complicated and less efficient. Furthermore, since they must deal with power balance control, voltage control, and frequency control throughout the system's islanded operation, AC-linked systems are tougher to operate than DC-connected systems.

3.3.2. DC charging stations

The DC charging station in Fig. 19 links to the distribution system through a three-phase distribution transformer and an LV bidirectional rectifier stage. The single LV rectifier stage receives electricity from the three-phase distribution transformer at LV AC (up to 480 V line to line) and supplies the DC power to various station subsystems. The rectifier stage offers the DC charging station voltage control, isolation, and bidirectional capabilities (Saidi et al., 2015; Borkowski, 2017). After the rectifier stage, a common DC bus is formed that connects all of the EV chargers in the DC charging station through isolated bidirectional DC/DC converters, providing the necessary isolation and bidirectional facility between the DC bus and the EV ports. The key benefits of DC charging stations are as follows: they remove the need for AC/DC and DC/AC conversion stages, they reduce the number of conversion stages required when transferring power from an ESS to a charger, and they simplify the integration of RES such as PV and wind energy, as well as ESS that produces dc power. It is also often less expensive and smaller, with higher dynamic performance than AC charging stations (He et al., 2017). However, because DC voltage does not have natural zero-crossings, developing protective systems for DC fast-charging stations is difficult (Beheshtaein et al., 2019).

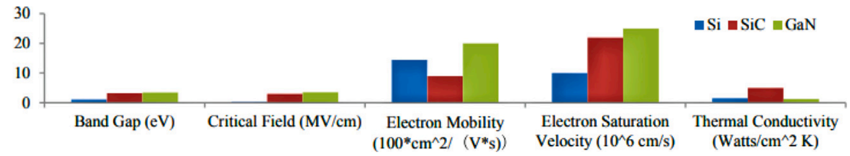


Fig. 20. The characteristics of power semiconductor devices made of Si, SiC, and GaN (Wang et al., 2019a).

Table 2
Comparison of isolation converters based on Si, SiC, and GaN (Su, 2018).

Specifications	Si isolation converter	SiC isolation converter	GaN isolation converter
Power (kW)	5.2	6.8	6.6
Volume (L)	1.34	1.02	0.63
Mass (kg)	3.27	2.35	0.69
Power density (kW/L)	3.9	6.7	10.5
Specific power (kW/kg)	1.6	2.9	9.6
Peak efficiency (%)	98.4 (40 kHz)	99.0 (100 KHz)	99.0 (100 kHz)

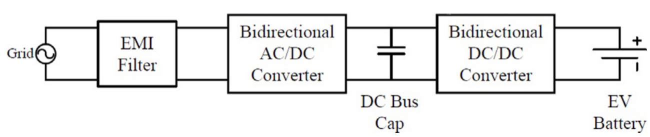


Fig. 21. Block schematic of a typical EV onboard charger (Shahed and Rashid, 2022).

4. Power conversion topologies for EV battery charging applications

Since converters are a key component of electric vehicles, it is necessary to develop efficient converter designs and to analyze various converter types. With continuous advancements in power electronics technology, particularly in the field of power conversion, the function of converters has enabled researchers to make major contributions to attaining maximum power conversion in EV applications. WBG semiconductors are increasingly used in this EV sector in the modern age. WBG power semiconductors such as SiC and GaN provide several benefits over conventional silicon (Si) devices, including high efficiency, high power density, and superior thermal performance. Fig. 20 depicts the characteristics of power semiconductor devices made of Si, SiC, and GaN. As a result, WBG semiconductors have recently been used in EV power converters (Wang et al., 2019a). For instance, as compared to an EV charger with a similar rating based on Si, a 15 kW EV charger based on SiC supplied 33% more power while taking up 25% less space (Wolfspeed, 2020). Compared to Si device-based isolated converters, it has been proven in Su (2018) that the GaN device-based isolated converter has a volume reduction of 53%, a weight reduction of 79%, an increase in power density of 170%, and an increase in specific power of 500%, as depicted in Table 2. As shown in Fig. 21, two different types of power electronics converters- AC–DC converters or rectifiers with PFC stage and DC–DC converters- are employed for charging EV batteries. To function in V2G mode, converters must be bidirectional. To accomplish unity PFC and AC-to-DC conversion, the AC–DC PFC stage is coupled to the AC grid and a DC link capacitor (Shahed and Rashid, 2022). To ensure current and voltage control as well as galvanic isolation, the bidirectional DC–DC converter links the DC link capacitor and an EV battery pack (Shahed and Rashid, 2022). These bidirectional DC–DC converters can provide power feedback to the electrical grid while also powering EV battery loads.

4.1. AC-DC converters for EV battery charging applications

Currently, several topologies are used for the front-end AC–DC power conversion of EV battery chargers. Fig. 22 depicts the most recent state-of-the-art AC–DC converters used in EVs. Fig. 23 displays

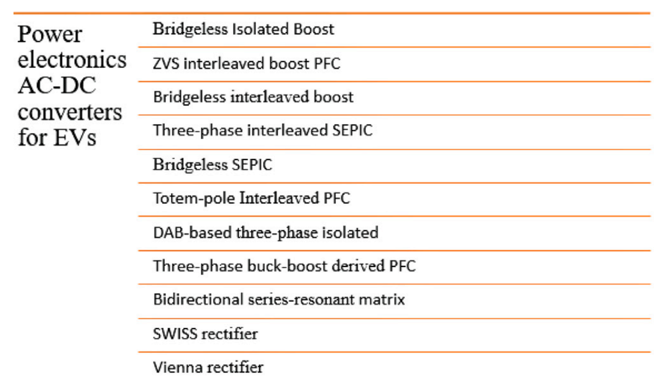
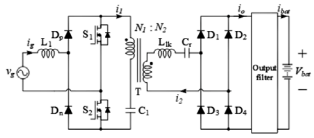


Fig. 22. AC–DC converters used in EVs.

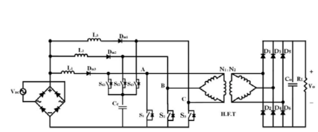
the circuit diagrams of these various EV-specific AC–DC converters. A comparison of these AC–DC converters is presented in the following Table 3. Among the various converters listed, the Vienna rectifier has lower THD and higher efficiency than the others, but it has some drawbacks such as no V2G capability and no galvanic isolation for vehicle safety. Other tabulated converters have some drawbacks that need to be addressed in future research. There is, therefore, plenty of room for future research in the area of AC–DC converters for EVs (see Fig. 23).

4.2. DC–DC converters for EV battery charging applications

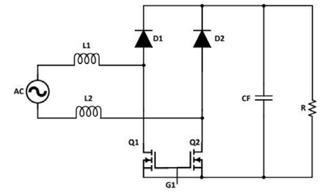
The DC–DC converters serve as battery chargers in the back end of EV charging systems. The front-end AC–DC topology accomplishes the rectification operation using PFC, while the back-end DC–DC converter adjusts the voltage level from the rectification operation to make it appropriate for EV battery charging. The design of an EV battery charger presents significant hurdles, including achieving more efficiency, cheaper cost, larger power density, isolation, and satisfying safety criteria. The increased switching frequency allows for a reduction in the cost of passive components. The rationale for limiting the switching frequency is due to high switching losses. As a result, resonant circuits and soft-switching technologies are extensively used to improve the switching frequency. The converter topology used must be capable of controlling the greater output current. Back-end DC–DC converter topologies are classified as isolated or non-isolated based on the presence of galvanic isolation between the input signal and the output circuit. An overview and comparison of the various DC–DC converter topologies used in EV battery charging are provided in this section. Fig. 24 illustrates the classification of DC–DC converters for EV applications.



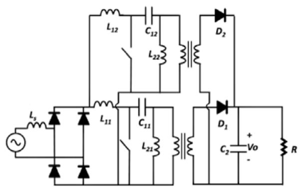
(a) Bridgeless Isolated Boost converter [Jeong et al. (2019)].



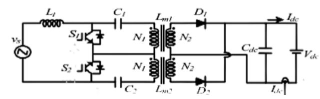
(b) ZVS interleaved boost PFC converter [Abosnina and Moschopoulos (2019)].



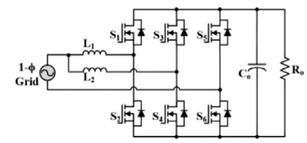
(c) Bridgeless interleaved boost converter [Praneeth and Williamson (2018)].



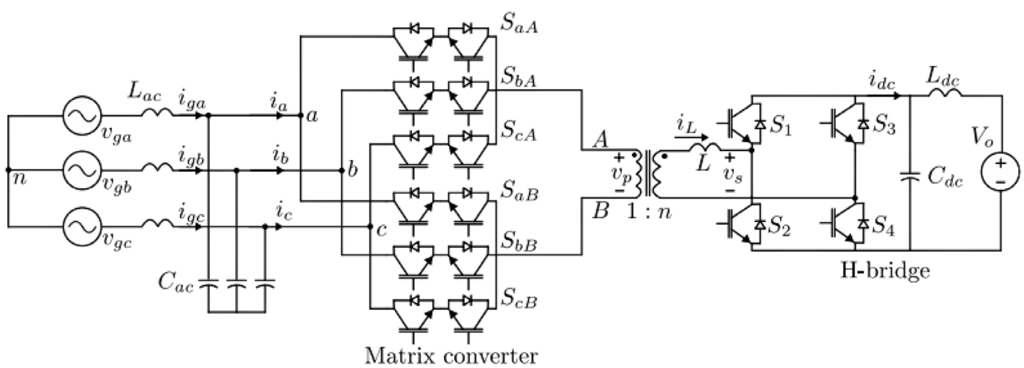
(d) Three-phase interleaved converter based on SEPIC [Hussein et al. (2021)].



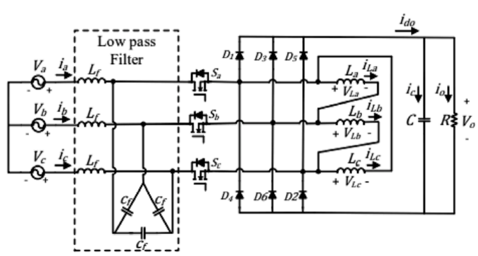
(e) Bridgeless SEPIC [Singh and Kushwaha (2020)].



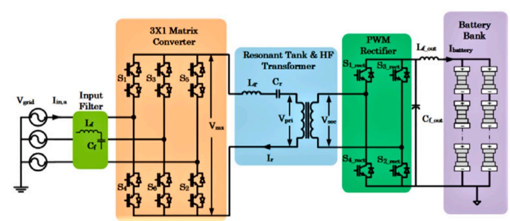
(f) Totem-pole Interleaved PFC converter [Tang et al. (2016)].



(g) DAB-based three-phase isolated converter [Das et al. (2019)].

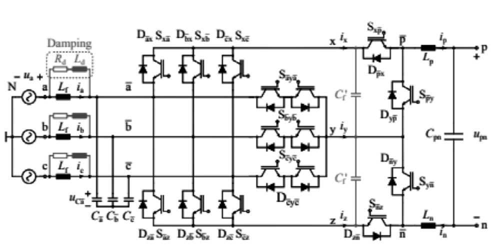


(h) Three-phase buck-boost derived PFC converter [Gangavarapu and Rathore (2019)].

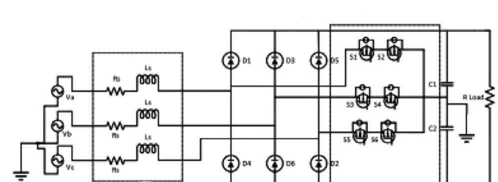


(i) Bidirectional series-resonant matrix converter [Sandoval et al. (2015)].

Fig. 23. Circuit diagrams of various EV-specific AC–DC converters.



(j) SWISS rectifier [Schrittwieser et al. (2017)].



(k) Vienna rectifier [Rajendran et al. (2021b)].

Fig. 23. (*continued*).

Table 3
Comparison of various AC–DC converters for EV applications.

Converter topologies	Rated power (kW)	Maximum efficiency (%)	Strength	Weakness	Refs.
Bridgeless Isolated Boost	1.7	96.2	• Lesser conduction loss • Higher power capability and high efficiency • Galvanic isolation	• High component count • High input and output ripple • Increased EMI • Unidirectional power flow	Jeong et al. (2019)
ZVS Interleaved Boost PFC	3	~98	• Can guarantee ZVS • Higher efficiency • Reduced EMI • Low input and output ripple	• Complex control circuitry • Heating issues for input diode bridge • No Galvanic isolation • Unidirectional power flow	Abosnina and Moschopoulos (2019)
Bridgeless Interleaved Boost	3.4	98.9	• High efficiency • Reduced output capacitor ripple current • Low power loss	• High component co-unt • High cost • Moderate EMI • No Galvanic isolation • Unidirectional power flow	Praneeth and Williamson (2018)
Three-phase interleaved SEPIC	4	92	• Modularity • Fault ride through capabilities • Low THD (4.22%) • Provides galvanic isolation • Reduced switching stress	• High conduction loss due to input diode bridge • Hard to keep synchronism between three single-phase units • Triplen harmonics due to parametric variation between the three units. • Unidirectional power flow	Hussein et al. (2021)
Bridgeless SEPIC	0.76	92.1	• Provides galvanic isolation • Low conduction losses • Reduced size and costs	• Unidirectional power flow • High current stress due to DCM mode.	Singh and Kushwaha (2020)
Totem-pole Interleaved PFC	3.3	98.8	• V2G power transfer facility • Smaller current ripple • Lower EMI • Lower conduction and switching losses	• High cost • No galvanic isolation	Tang et al. (2016)
DAB-Based Three-Phase Isolated Converter	1.38	82.1	• Bidirectional power flow • Soft switching of primary and secondary side power converters • Galvanic isolation	• Higher conduction losses • High component count	Das et al. (2019)
Three-Phase Buck-Boost Derived PFC	2	96	• Less control complexity • Less number of sensors • High power density	• High current and voltage stress • No galvanic isolation • Unidirectional power flow	Gangavarapu and Rathore (2019)
Bidirectional Series-Resonant Matrix Converter	30	Un-specified	• Bidirectional power flow capability • Galvanic isolation • High power density due to absence of electrolytic capacitors	• High number of switches • Less efficiency	Sandoval et al. (2015)
SWISS Rectifier	7.5	96.5	• Low rating devices • Low harmonics • Bidirectional power flow capability	• Number of switches • Less efficiency • Complex controller • No galvanic isolation	Schrittwieser et al. (2017)
Vienna Rectifier	1.865	99.84	• Low THD (3.25%) • Smaller filtering requirements	• Unidirectional power flow • No galvanic isolation • High output voltage	Rajendran et al. (2021b)

4.2.1. Non-isolated DC-DC converters for EV battery charging applications

A non-isolated DC–DC converter is one that does not have any electrical isolation between its input and output. These converters are beneficial when dielectric isolation is not a major consideration. These converters have a common ground between their input and output, allowing current to flow between them. Non-isolated converters are often used when the voltage has to be stepped up or down by a relatively modest ratio. These converters are better suited for use in mid- and high-range vehicles. Non-isolated converters have higher efficiency, lower cost, and less control complexity than isolated converters. They, too, have certain downsides. They cannot provide protection against high electrical voltages and produce greater noise. As a result, there are safety concerns with non-isolated converters. These converters can be characterized as unidirectional or bidirectional based on their capacity to reverse power flow. There are five basic types of non-isolated DC–DC converters that are frequently used: multi-device interleaved bidirectional, Cuk, SEPIC, switched capacitor interleaved bidirectional, coupled inductor interleaved bidirectional, and quasi Z-source bidirectional. The circuit schematics of these non-isolated converters are shown in Fig. 25. Table 4 contains a comprehensive analysis and comparison of these converters. As can be seen, each of the tabulated converters has its own set of strengths and drawbacks. One of these converters' common strengths is the ability to provide bidirectional power flow, which is critical for V2G applications. Table 4

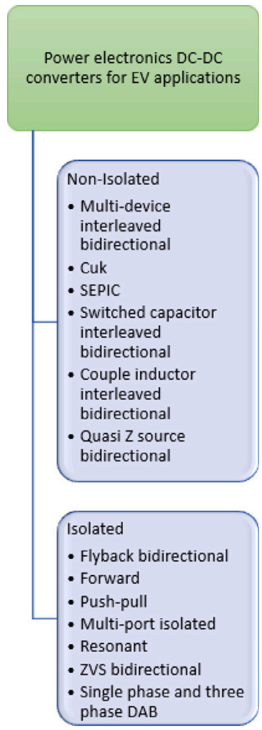


Fig. 24. DC–DC converters used in EVs.

summarizes the converters' other strengths and weaknesses. Hopefully, future research will focus on these shortcomings to enhance their performances.

4.2.2. Isolated DC-DC converters for EV battery charging applications

To electrically separate the input and output side voltages for safety or regulatory reasons, isolated DC–DC converters employ galvanic isolation. For instance, if the input side is linked to voltages that are high enough to put people in danger, safety regulations may mandate the use of an isolated DC–DC converter, which transfers voltage and current using a transformer (or, in some circumstances, coupled inductors) across the gap between the input and output terminal. Again, these isolated DC–DC converters are beneficial for removing ground loops, which will help to isolate noise-sensitive circuitry from the noise sources. Conversely, utilizing a transformer for isolation might result in design tradeoffs, most notably costs, size, performance instability, and assembly issues. Isolated DC–DC converters are widely used in low- and medium-power automotive applications. Flyback bidirectional, forward, push-pull, multiport isolated, resonant, ZVS bidirectional, single phase and three phase DAB are some of the key isolated DC–DC converters used in EV applications. Fig. 26 depicts the circuit diagrams for these isolated converters. Table 4 provides a comprehensive evaluation and comparison of these isolated converters. Except for the forward converter, all of these converters are capable of bidirectional power flow, which is required for V2G operation. Resonant and DAB converters are among the tabulated converters that are growing in popularity because of their high efficiency and ZVS operation. Each set of converters has its own set of strengths and weaknesses. Hopefully, future research will address these weaknesses to improve the converters' efficiency for EV battery charging applications.

5. EV optimization techniques

Researchers have proposed several optimization techniques to optimize the operation of EVs. Elkasrawy et al. (2023) proposed an artificial neural network (ANN) model to reduce queuing delay time by ranking the EVs arriving at the station at the same time. They discovered that this optimization technique reduces the average charging time, including the queuing delay (Elkasrawy et al., 2023). The ANN model takes three inputs: the distance between the EV and the station (d_n), the initial state of charge (SOC_i), and the charging capacity of the battery (CC) (Elkasrawy et al., 2023).

In Nageshrao et al. (2017), A nonlinear autoregressive network with exogenous inputs (NARX) NN model is presented for minimizing charging costs and forecasting daily energy demand. When compared to the non-optimal charging method, the developed strategy resulted in significant cost savings (Nageshrao et al., 2017). Furthermore, the battery's health was improved by SOC and temperature constraints (Nageshrao et al., 2017).

Li et al. (2020) proposed an optimal charging and discharging schedule using a safe deep reinforcement learning (SDRL) model based on the randomness of the EV's arrival time, departure time, remaining energy, and real-time electricity price. The proposed constrained charging/discharging scheduling strategy successfully reduced charging costs while also ensuring that the EV could be fully charged (Li et al., 2020).

Zeb et al. (2020) utilized the particle swarm optimization (PSO) algorithm to optimize the sizing and placement of various types of EV charging stations in the active distribution systems of commercial and residential buildings, including offices and homes. The technique presented ensured minimal transformer loading, resulting in fewer transformers (Zeb et al., 2020). It has also been discovered that integrating PV enhances the voltage profile and minimizes the adverse effects of EV load (Zeb et al., 2020).

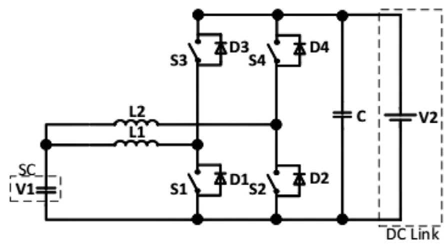
Zhang et al. (2022) proposed a back propagation neural network-based electric vehicle charging safety warning model optimized by an improved gray wolf optimization (IGWO) algorithm. It has been demonstrated that the proposed early warning model can reliably detect abnormal EV charging voltage states and issue timely warnings (Zhang et al., 2022).

6. G2V and V2G technology

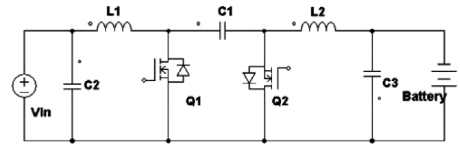
Grid-to-vehicle power or energy flows are referred to as "G2V" or "charging mode", while vehicle-to-power or energy flows are referred to as "V2G" or "discharging mode". Fig. 27 shows a V2G framework that has interactions among power system operators, consumers, and EV users. Here, these V2G systems can work in a G2V mode. Traditional generators, RESs, and transmission infrastructure are included in the power systems. Both customers (such as household, commercial, and industrial users) and V2G systems are supplied with energy by the power systems. The V2G networks are made up of EVs that are connected to the power grid through aggregators and public and private charging stations. A mediator who controls and optimizes energy flow between the power grid and V2G systems is known as an aggregator. It functions as energy storage in V2G mode and as a consumer in G2V mode. V2G communication, which consists of communications networks like wireless networks and processing capabilities like data centers and cloud computing, enables data and information interchange between power systems, electricity consumers, and V2G systems. The power system operators can efficiently optimize power generation and auxiliary services from EVs thanks to the V2G communications networks, which allow them to get the data they need from V2G systems and electricity users.

6.1. Smart G2V or V2G systems

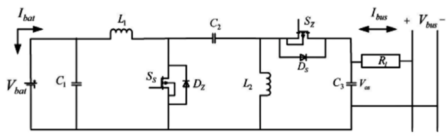
Fast charging or G2V infrastructure is expanding globally due to the rapid expansion of EVs. When an EV is attached to a charger, the EV battery will either begin charging instantly or after a wait. If most EVs charge at the same time, there will be a high demand for power and energy from the power grid, which will lead to an undesirable low voltage within the distribution network. The term "uncoordinated



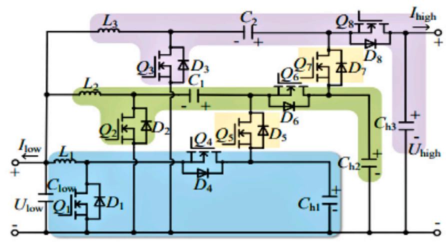
(a) Multidevice Interleaved Bidirectional Converter [Lai et al. (2015)].



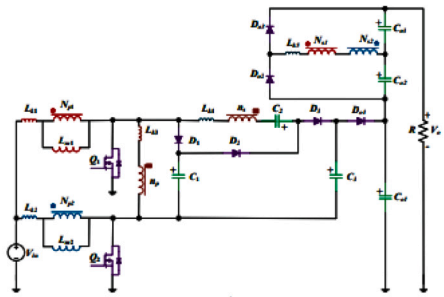
(b) Cuk Converter [Suryoatmojo et al. (2020)].



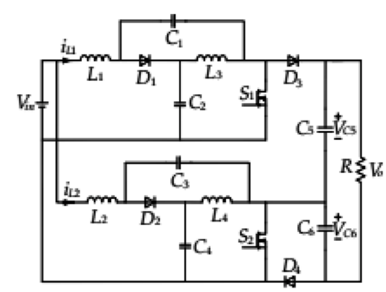
(c) SEPIC [Bairabathina and Balamurugan (2022)].



(d) Switched Capacitor Interleaved Bidirectional Converter [Zhang et al. (2020)].



(e) Coupled Inductor Interleaved Bidirectional Converter [Moradisizkoohi et al. (2020)].

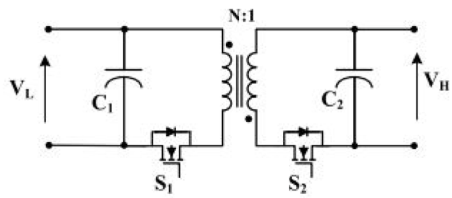


(f) Quasi Z-Source Bidirectional Converter [Huangfu et al. (2021)].

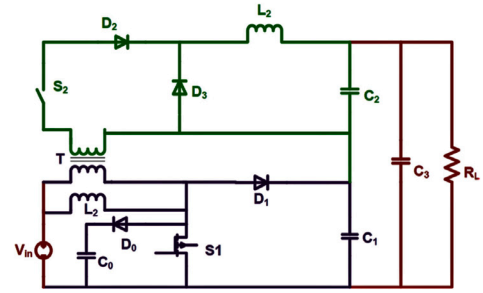
Fig. 25. Circuit schematics of various EV-specific Non-isolated DC–DC converters.

charging" or "uncontrolled charging" is frequently used to describe this circumstance. Such a condition could negatively impact the distribution grid by increasing actual power losses, violating voltage limitations, and overloading distribution network assets such as transformers and cables/lines (Houbbadi et al., 2019). The lifespan of distribution transformers will eventually be shortened. It will lead to network congestion and reliability issues for the transmission grid. And it will cause problems for the generation grid including an increase in unit pricing, capacity expansion, and higher use of generation assets (Houbbadi et al., 2019). Unmanaged vehicle-to-grid (V2G) networks might have similar effects. By managing the charging in a planned manner, smart charging can address these problems. By implementing dynamic pricing regulations, coordinated smart charging could save charging costs while enhancing the functioning of the power grid (Moghaddam et al., 2017). The advantages of smart charging may be passed on to individual consumers in two ways: directly by lowering their charging prices and indirectly by decreasing distribution grid losses, distribution network capital costs, transformer life loss, valley filling (timed mechanisms to drain electricity while grid demand is low), and peak shaving (lowering the grid's peak electricity demand) (Limmer, 2019). In order to successfully integrate EVs and renewable energy sources (RES) into the grids in the future, the International Renewable Energy Agency (IRENA) thinks that smart charging and consumer subsidies have become two crucial aspects (IRENA, 2019).

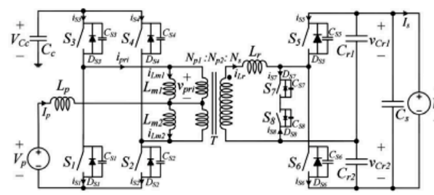
Smart charging and discharging control systems are divided into two categories: centralized and decentralized approaches. With centralized approaches, an authorized energy service provider known as an aggregator is in charge of all EV charging and discharging operations through CPs (Charging Post) or CPMs (Charging Post managers). If DSO (Distribution System Operator) requests a load reduction or increase, the aggregator will carry out the power purchase directly in the day-ahead electricity market after receiving TSO (Transmission System Operator) approval. If the TSO requests ancillary services like secondary and tertiary frequency regulation, the aggregator can also engage in the ancillary services market in addition to the day-ahead market. The centralized control framework for EVs is shown in Fig. 28. In contrast, choices regarding charging and discharging are made and carried out by EVs themselves in decentralized approaches. Fig. 29 demonstrates the decentralized control framework used by EVs. Even though the centralized strategy can achieve the best outcomes for both the provider and the EVs, it might not be feasible to execute since with this approach the EVs are unable to independently regulate their charging and discharging processes. Due to user acceptability and reduced communication, the decentralized method is therefore preferred in real systems.



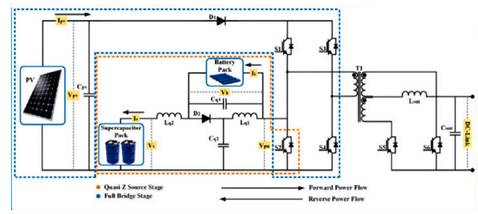
(a) Flyback Bidirectional Converter [Gorji et al. (2019)].



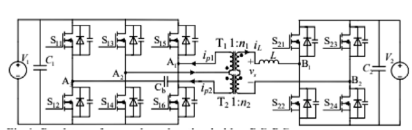
(b) Forward Converter [Joseph and Devaraj (2019)].



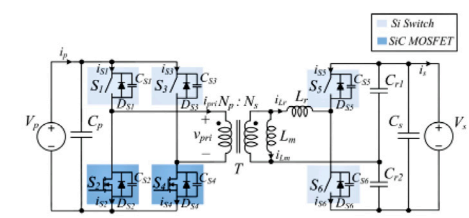
(c) Push Pull Converter [Lim et al. (2021)].



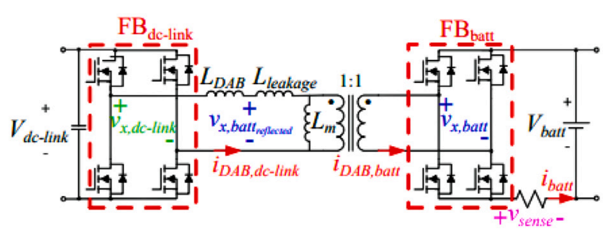
(d) Multiport Isolated Converter [Savrun and Atay (2020)].



(e) ZVS Bidirectional Converter [Liang et al. (2020)].



(f) Resonant Converter [Bai et al. (2020)].



(g) Single Phase and Three Phase DAB Converter [Assadi et al. (2020)].

Fig. 26. Circuit diagrams of various EV-specific Isolated DC–DC converters.

6.2. V2G systems benefits

Smart V2G of EVs can enhance the efficiency, reliability, and stability of the smart grids (SGs) (IRENA, 2019). Additionally, they benefit EV users economically. The following are some advantages of V2G technology:

- Ancillary Services: EVs are viewed as dynamic distributed energy sources in this V2G that assist the electrical grid (Noel et al., 2019a). This is conceivable since EVs are projected to be parked 96% of the time (Saldaña et al., 2022). They are able to offer ancillary services like spinning reserves, voltage regulation, and frequency regulation (Knezović et al., 2017). A smart V2G of EV can provide active power regulation, load balancing, harmonic filtering, inertia support, reactive power support, and the best possible use of variable RESs. As a result, system administrators would be able to manage the power system safely with lower synchronous generation.
- Improved Quality of Service: Modern battery technology allows smart V2G systems to instantly return energy to the grid. As a result of the V2G system's quick response, system operators can provide consumers with better power quality.
- Storage Solution for Renewable Energy Integration: By utilizing EVs as storage devices, the power quality from RESs like solar and wind energy can be significantly enhanced. The power grid can be made more reliable and stable by combining EVs and RESs.
- Increased Revenue for EV Users: In exchange for joining the V2G system, EV users can get payment from the V2G operators for the energy they discharge. Therefore, EV customers might balance their needs and charging/discharging operations by using intelligent energy management solutions, such as charging during off-peak hours and discharging throughout peak hours, to increase earnings.
- Reduced Environmental Pollution: EVs, as opposed to traditional vehicles that use fossil fuels, can dramatically reduce environmental pollution, even when power-generating emissions are taken

Table 4
Comparison of various DC–DC converters for EV applications.

Converter types	Converter topologies	Rated power (kW)	Maximum efficiency (%)	Strength	Weakness	Refs.
Non-isolated	Multidevice Interleaved Bidirectional	150	98	• High efficiency • Reduced component size • Lower current stress • Bidirectional power flow	• Complex analysis during transient and steady-state conditions • No galvanic isolation	Lai et al. (2015), Wen and Su (2016), de Melo et al. (2020), Wang et al. (2019b)
	Cuk	0.85	94	• Continuous and reduced ripple current at input and output • Improved PF • Bidirectional power flow possible with modified cuk	• Larger inductors subjected to higher electrical stress • High-voltage rating for the transfer capacitor • High number of passive components • No galvanic isolation	Suryoatmojo et al. (2020), Kushwaha and Singh (2019), Chinmaya and Singh (2018), Pires et al. (2019)
	SEPIC	1.5	98	• Gate drive circuitry is less complicated. • Less voltage stress than CUK • Non-pulsating input current • Bidirectional power flow possible with modified SEPIC	• No Galvanic isolation • High current stress in diode and switches	Bairabathina and Balamurugan (2022), Kavin and Subha Karuvelam (2021), Gayen et al. (2018)
	Switched Capacitor Interleaved Bidirectional	0.8	95.9	• Topology scalability • Wide voltage gain range • Low current ripple on the low voltage side • Low voltage stress across power switches • Common ground between input and output • Bidirectional power flow capability	• High current ripple • No galvanic isolation	Zhang et al. (2020, 2019a, 2018b)
	Coupled Inductor Interleaved Bidirectional	4.5	98.67	• Wide voltage conversion ratio • Reduced current and voltage ripple • Lower current rating of power components • lesser components • Increased efficiency • Bidirectional power flow capability	• Leakage inductance causing voltage and current spikes • No galvanic isolation between input and output	Moradisizkoohi et al. (2020), Mayer et al. (2021), Rahimi et al. (2021)
	Quasi Z-Source Bidirectional	0.4	96.44	• Bidirectional power operation • Reduced voltage stress • Wide voltage gain range • Common ground between input and output • Continuous input current	• No galvanic isolation • High cost due to higher number of components	Zhang et al. (2018c, 2019a, 2018a), Huangfu et al. (2021)
Isolated	Flyback Bidirectional	6	~96	• Bidirectional power flow • Suitable for high voltage step-up situations • Fewer number of components • Capable of working with multiple power sources • Topology scalability • Galvanic isolation	• High ripple current • High voltage stress due to leakage inductance • Unsatisfactory utilization of the transformer	Eskandarian et al. (2020), Gorji et al. (2019)
	Forward	5	95.4	• High efficiency • Fast balancing time • Easy to control • Less number of components and circuitry • Galvanic isolation	• Nonuniform secondary voltage • Limited maximum duty cycle during the transformer reset process due to peak flux reaching higher levels during startup and transient states • Unidirectional power flow	Jeong et al. (2020), Moghaddam and Van den Bossche (2019), Joseph and Devaraj (2019), Ibanez et al. (2015)

(*continued on next page*)

Table 4 (*continued*).

Converter types	Converter topologies	Rated power (kW)	Maximum efficiency (%)	Strength	Weakness	Refs.
	Push Pull	22	96.85	• Low conduction losses • Less filtering is required • Galvanic isolation • Bidirectional power flow capability	• Additional circuitry required for soft switching • Protection required during switching • Imbalance magnetic flux	Lim et al. (2021), Le et al. (2021)
	Multiport Isolated	9.6	96	• Bidirectional power flow capability • Galvanic isolation • Low output voltage ripple current • Wide voltage gain • Reduced number of circuit components	• High sensitivity in response to duty cycle under load changes • It is challenging to achieve accurate synchronization.	Savrun and Atay (2020), Itoh et al. (2015), Vahid and El-Refaie (2020)
	ZVS Bidirectional	3.5	96.8	• Achieves ZVS under all load conditions • Low EMI • High power density • Easy control • Galvanic isolation • Bidirectional power flow	• Inadequate fault tolerance	De Oliveira Filho et al. (2016), Liang et al. (2020)
	Resonant	3.5	97.8	• High efficiency • High conversion ratio • Bidirectional power flow • Galvanic isolation • ZVS	• Complex integrated transformer	Shahed and Rashid (2022, 2023), Xuan et al. (2021), Bai et al. (2020), Kim et al. (2019)
	Single Phase and Three Phase DAB	6.6	~99	• Bidirectional power flow • Galvanic isolation • High power density • ZVS • Low voltage and current stresses	• Circulating current in the high-frequency transformer and power switches • Higher pulsating current at the input side • Limited range of soft switching	Assadi et al. (2020), Jiang and Liu (2021), Sharifuddin et al. (2020)

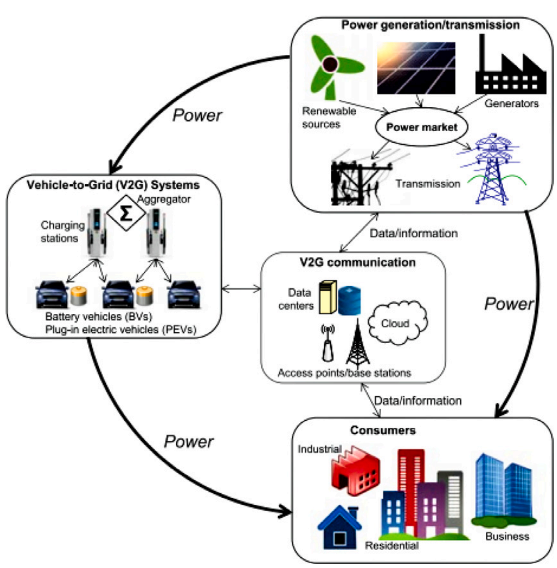


Fig. 27. A V2G framework (Hoang et al., 2017).

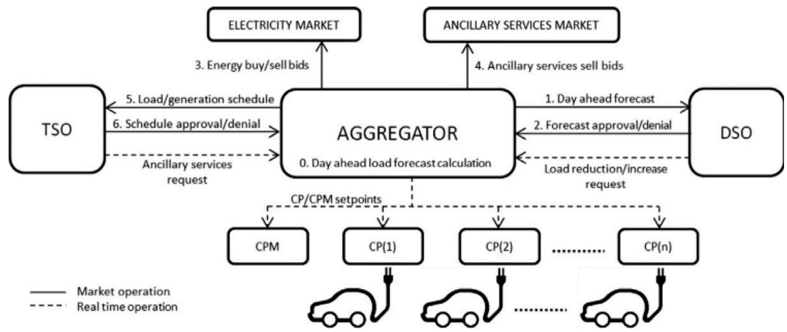


Fig. 28. A centralized control framework for EVs (Galus et al., 2013; García-Villalobos et al., 2014).

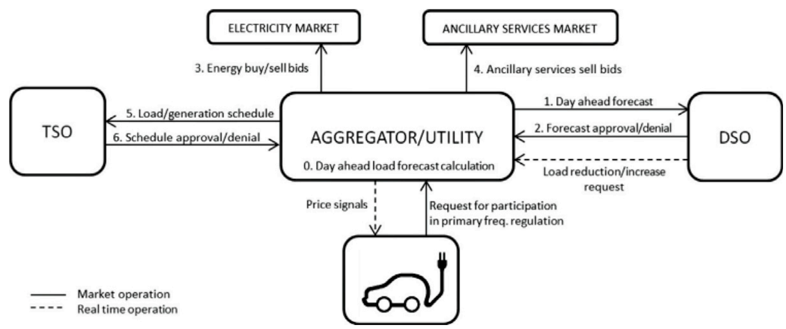


Fig. 29. A decentralized control framework for EVs (Galus et al., 2013; García-Villalobos et al., 2014).

into account. According to estimates, emissions of CO_2 can be reduced by 2.2 tons annually by switching from a traditional vehicle to an EV (Islam and Pota, 2014).

However, there are still a number of difficulties that V2G must overcome, including early battery deterioration, investments in communications networks to enable interactions between EVs and the grids, protection against cyber-attacks, impacts on grid equipment, additional infrastructure modifications, and social, cultural, political, and technological barriers (Noel et al., 2019b). Even though V2G operations can shorten the life of battery packs, it is anticipated to provide financial advantages for both EV owners and system operators (Noel et al., 2018).

7. Future research directions

Aside from existing research, more efforts are required to improve charging performance and develop sustainable solutions to the challenges that EV technology faces. Future research could focus on the following areas:

- To facilitate widespread EV adoption, research should prioritize the development of cost-effective and standardized wireless charging infrastructure. Additionally, optimizing battery technologies and charging protocols for faster and more efficient charging infrastructure is crucial. Strategic deployment of public rapid charging systems capable of charging up to 80% in under 15 min, alongside highways and in key locations, is essential. Furthermore, urgent action is needed to reduce charging system costs by utilizing more affordable materials and streamlining manufacturing and installation processes.
- As the deployment of grid-connected EV fast-charging stations increases, concerns about power quality emerge. Unplanned EV fleet additions, for instance, can lead to voltage fluctuations, power factor issues, and harmonic distortion, potentially jeopardizing grid stability. Research in this area should focus on developing smart charging algorithms, demand-response protocols, and integration of distributed energy resources to ensure grid stability and enable further EV penetration, ultimately preventing outages and optimizing grid operations.
- Seamless integration of EVs into the grid through V2G systems necessitates optimized load distribution and careful attention to system harmonics. Smart charging control, empowered by smart energy metering and real-time communication, holds the key to addressing these challenges. By actively mitigating harmonic distortion caused by power electronic converters, intelligently managing charging and discharging cycles to preserve battery health, and effectively scheduling EV fleets based on grid load demand, we can ensure a harmonious V2G ecosystem. Moreover, strategic EV load management during peak and off-peak periods can minimize the impact on power generation units. Research focusing on these areas will pave the way for widespread V2G implementation, fostering a more sustainable and resilient energy landscape.
- Current power electronic converters used in EVs face limitations in terms of power density, efficiency, and weight. To address these, researchers are focusing on developing innovative WBG-based converters that deliver longer range, faster charging, and reduced energy consumption. Additionally, lightweight converters with minimal electromagnetic interference (EMI) and ripples are crucial for optimal driving experience and regulatory compliance. Another critical challenge lies in efficient thermal management, as high operating temperatures can lead to malfunctions and failures. Extensive research is therefore needed to develop advanced cooling technologies and materials to ensure reliable and long-lasting power conversion in EVs.
- Artificial intelligence (AI) and machine learning (ML)-based intelligent control strategies can revolutionize EV operations by automating and optimizing various aspects. AI techniques can be applied to optimize both the battery management system (BMS) and controllers for EV powertrains, leading to enhanced efficiency, performance, and safety. Extensive research is needed to explore the full potential of AI in optimizing charging strategies, predicting battery health, and improving energy management,

ultimately paving the way for a more sustainable and efficient future of transportation.

- By storing and analyzing real-time data from various EV components (current, voltage, power, temperature, battery SOC, etc.) on a cloud platform using 'Internet of Things' (IoT) technology, the performance of EV operations can be comprehensively monitored and analyzed. This IoT-powered EV technology has the potential to enhance efficiency, accuracy, and robustness by optimizing charging strategies, predicting battery health, and enabling real-time data analysis for remote diagnostics. Therefore, further research is needed in areas like secure data communication, AI-driven predictive maintenance, and cost-effective IoT sensor integration to fully realize the potential of IoT for revolutionizing EV operations and maintenance.
- Battery health monitoring, estimation, and maintenance are crucial areas of research for EV operations. Accurately estimating key parameters like State of Charge (SOC), State of Health (SOH), and Remaining Useful Life (RUL) is critical for optimal battery protection and energy management. While various techniques, including model-based, data-driven, and hybrid approaches, have been employed, research continues to refine their accuracy and robustness. Precise parameter estimation enables efficient battery replacement, minimizes operational downtime, and enhances safety by preventing potential failures. Therefore, research efforts should focus on developing real-time estimation algorithms, improving accuracy under diverse operating conditions, and exploring innovative sensor-based and non-intrusive estimation methods to further optimize battery health management in EVs.

8. Conclusions

This paper comprehensively evaluates current advancements and challenges in EV technology to identify potential future directions in EV charging methods. It begins by examining the market's current electric vehicle landscape, highlighting the growing demand and diversifying types of EVs. Next, the paper focuses on charging advancements, including an overview of existing technologies and standards, a detailed comparison of front-end and back-end converter topologies, and analyses of recent optimization techniques for EV optimal operation. Building on this, it explores V2G technology and its prospects, discussing its potential impact on future smart grids and identifying remaining challenges in its implementation. Finally, the paper concludes by presenting potential future research directions in EV technology. In conclusion, constructive discussions, comparative assessments, concerns, and recommendations can offer academics and decision-makers valuable resources and insights for continued advancements in this crucial field.

CRediT authorship contribution statement

Md. Tanvir Shahed: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **A.B.M. Harun-ur Rashid:** Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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