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A PRECISE REVIEW ON EV BATTERY CHARGING TECHNOLOGY

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ABSTRACT:
The world is now focusing on renewable energy sources to achieve sustainable development in clean and green energy. Electric Vehicles (EV) are a crucial component in this context. EVs are an environmentally conscious mode of transportation. EV charging's latest developments are the focus of this paper. EV battery charging relies heavily on front-end and back- end power converters. Vehicle-to-grid (V2G) technology, a crucial smart charging solution for future smart grids is the subject of this paper. Toward the end, it concludes with an article on future research prospects in EV charging: Wireless chargebacks, grid integration and battery life improvement.

INTRODUCTION:

Electric vehicles (EVs) are growing quickly as an eco-friendly automotive alternative. Governments are also promoting EVs through various incentives like tax benefits, VAT (Value Added Tax) exemption, decrease 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 described below:

i. 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.
ii. 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.
iii. 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.

This review paper offering a comprehensive comparison of all current EV power electronic converter options, including their topologies, performance, and efficiency. Such a review would provide a valuable resource for researchers and engineers working in this rapidly evolving field.

This paper addresses comprehensive review of current charging standards and methods, including conductive, inductive and wireless charging. Recent EV charging station types, such as AC and DC stations, and their structures are covered in detail. The following section delves into current V2G technology, exploring its control techniques, benefits, and present challenges. As a whole, this paper can assist EV researchers in quickly reviewing and understanding the latest advancements in EV battery charging. The rest of the paper is organized into the following four sections:

Section II explores EV types, charger ratings, and their pros and cons.

Section III delves into EV battery charging methods, different types of charging stations, and charging standards.

Section IV examines the advantages, drawbacks, and future research potential of AC–DC and DC–DC power conversion strategies for EV battery charging.

Section V describes in detail the methods, benefits, challenges, and prospects of G2V and V2G technologies, including bi-directional charging and smart grid integration.

ELECTRIC VEHICLES TYPES

EVs are categorized into five different types based on their engine technology. A brief overview of these types is discussed below:

a) **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 that converts kinetic energy back into electrical energy that can be retained by the battery. Fig. 1 depicts the structure and essential elements of a BEV.

b) **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 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. 2.

c) **Hybrid Electric Vehicles (HEVs):** HEVs use both an electric motor and an oil 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. 3 illustrates an HEV's structure and key components.

d) **Fuel Cell Electric Vehicles (FCEVs):** These vehicles 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. 4 shows an FCEV's basic components and structural layout.

e) **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. 5 illustrates an ER-EV's structure and key components.

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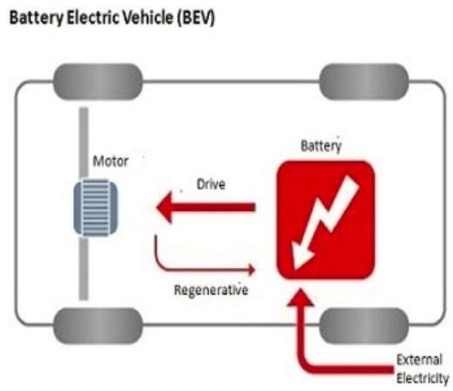

Fig.1. The structure and key elements of a BEV (Omazaki Group, 2022).

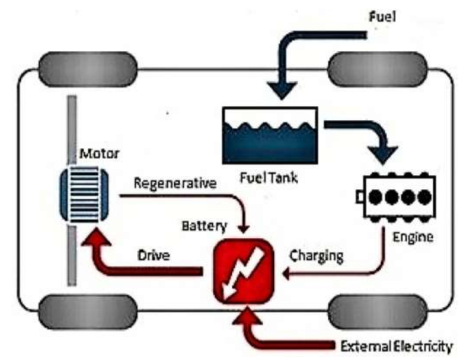

Fig. 2. The structure and key components of a PHEV (Omazaki Group, 2022).

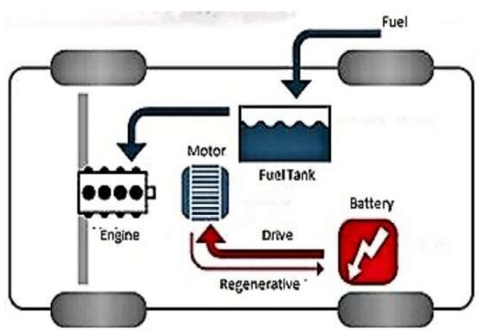

Fig. 3. The structure and essential elements of a HEV (Omazaki Group, 2022).

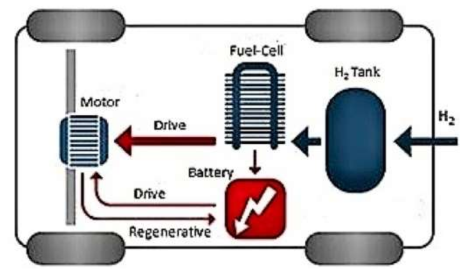

Fig. 4. The structural layout and basic elements of an FCEV (Omazaki Group, 2022).

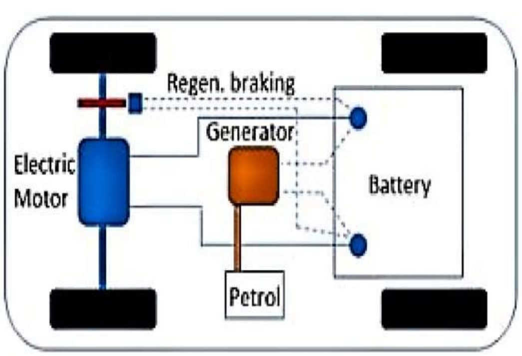

Fig. 5. The structure and essential of an ER-EV (Sustainability-in-practice, 2022).

III.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 Electro technical

Commission) and SAE (Society of Automotive Engineers), and country-specific EV charging stations and connectors.

EV 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 Adminis- tration of the People's Republic of China , SAC). The term ''Level'' is used to describe the power rating in SAE standards, whereas ''Mode'' is used in IEC standards. Table 1 provides a summary of the IEC and SAE charging standards.

Table 1
Summary of EV Charging Standards

Standards	Source	Phase	Level/Mode	Voltage(V)	Current(A)
SAE-J1772	AC AC	Single Single	Level-1 Level-2	120 240	16 32-80
	DC DC	DC DC	Level-1 Level-2	200-450 200-450	80 200
IEC-62196	AC	Single Single Single	Mode 1 Mode 2 Mode 3	120 240 250	16 32 32-250
	DC	DC	Mode 4	600	400
IEC-61851-1	AC, non-dedicated	Single Three	Mode 1	250 480	16 16
Standards	**Source**	**Phase**	**Level/Mode**	**Voltage(V)**	**Current(A)**
IEC-61851-1	AC, non-dedicated	Single Three	Mode 2	250 480	32 32
IEC-61851-1	AC, dedicated	Single Three	Mode 3	250 480	32 32
IEC-61851-1	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

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. Off-board chargers with a power

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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. 6 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.

Fig. 6. Mode 1 EV charging technology (Deltrix Chargers, 2022).

Mode 2 (Semi-fast 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. 7 depicts the charging process for an electric vehicle in Mode 2. This mode is typically placed on portable chargers for EVs. 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.

Fig. 7. Mode 2 EV charging process (Deltrix Chargers, 2022).

- **Mode 3 (Fast Charging):** Use of a dedicated charging point or a wall-mounted wall box at home is required for mode 3 charging. 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. 8 shows how an electric vehicle in Mode 3 is charged.

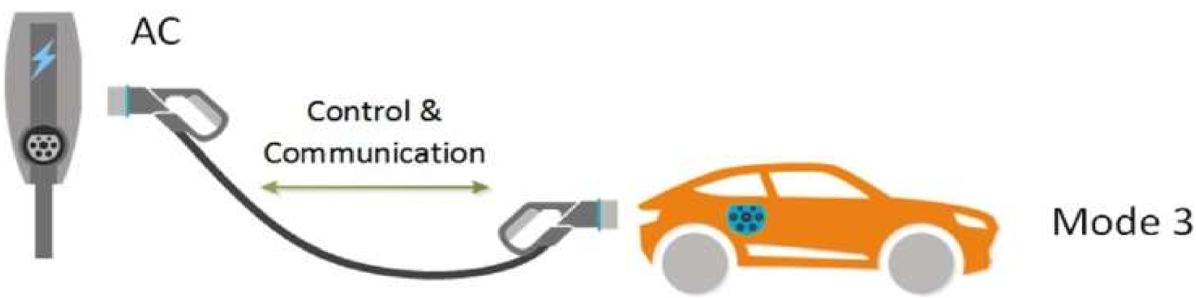

Fig. 8. EV charging technique for Mode 3 (Deltrix Chargers, 2022).

- **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 vehicle 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 vehicle, 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. 9 portrays how to charge an electric vehicle in Mode 4.

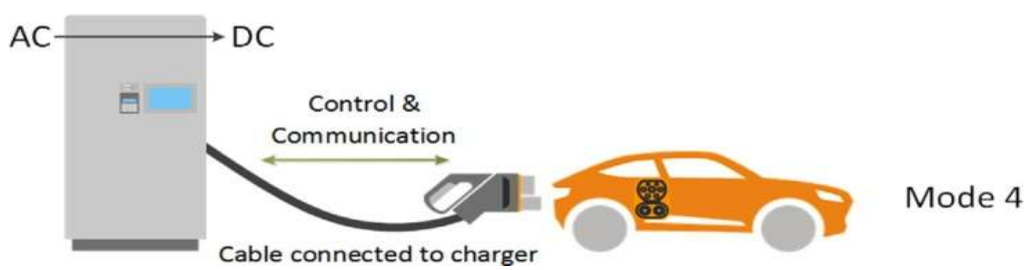

Fig. 9. EV charging technology for Mode 4 (Deltrix Chargers, 2022).

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, 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. 10.

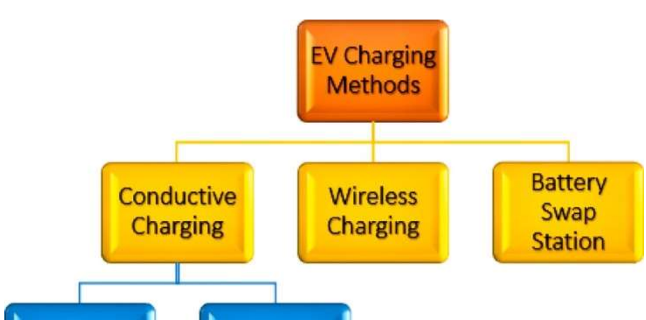

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Fig. 10. A schematic layout of EV charging methods.

Conductive charging

A direct contact between the vehicle 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. Fig. 11 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.

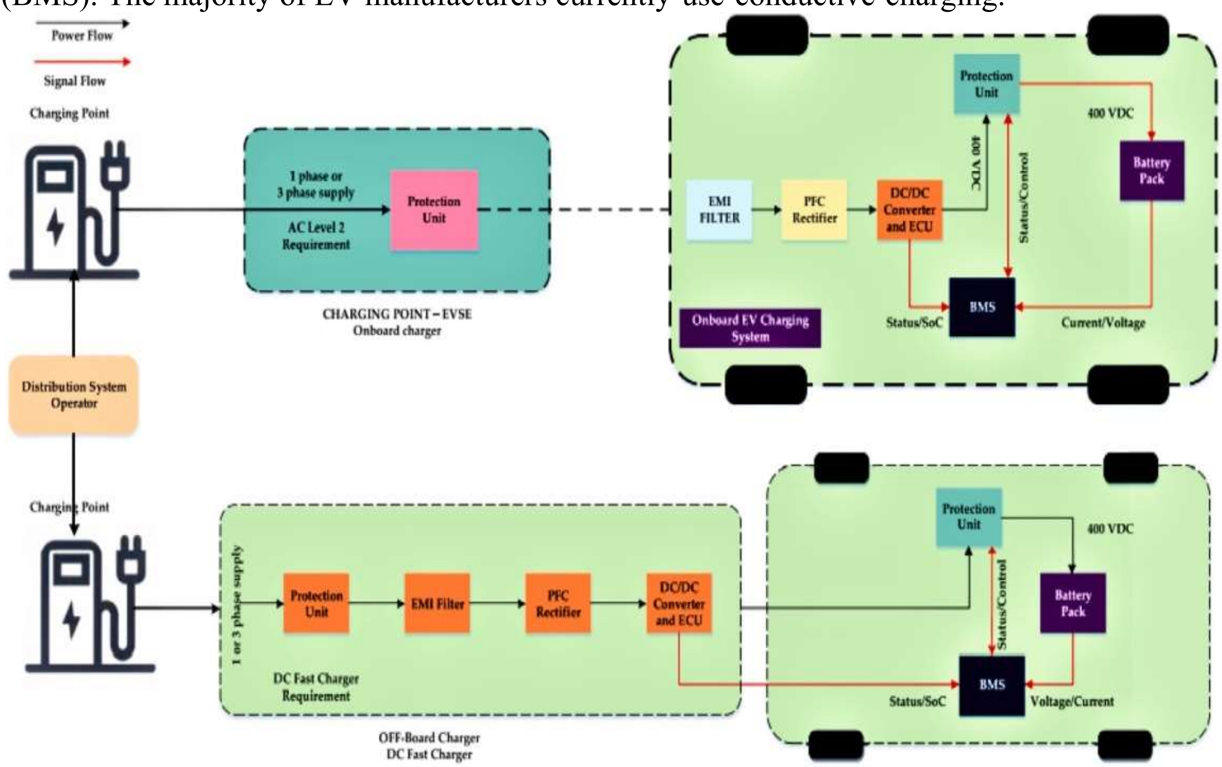

Fig. 11. A schematic layout of onboard and off-board EV charging systems (Rajendran et al., 2021a).

Wireless charging

Wireless power transfer (WPT) has been in existence since the late 19th century. Hertz displayed the first demonstration of WPT. A categorization chart for various WPT technologies is shown in

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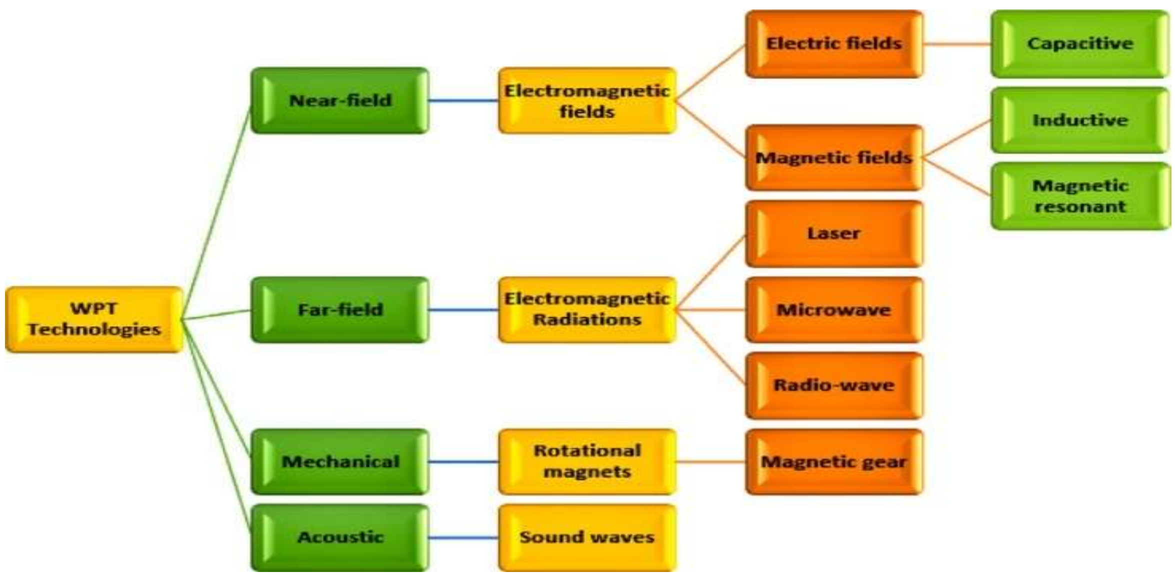
Fig. 12. WPT technology, as can be seen, can be split into four primary categories: **near-field transfers** (Ahmad et al., 2017; Garnica et al., 2013), such as inductive, magnetic resonant, and capacitive; **far- field transfers** (Garnica et al., 2013), such as laser, microwave, and radio-wave; **mechanical force**, such as magnetic gear (Mohamed et al., 2022); and **acoustic** (Tseng et al., 2017; Roes et al.).

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 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. 13 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 air gap, these capacitors assist in reducing the significant leakage inductances caused by the large air gap.

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 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.

EV charging stationsEV chargers are intended to serve a function similar to that of a traditional fuel station. EV charging stations can be broadly classified as AC or DC charging stations. Figs. 13 and 14 illustrate the two layouts for the EV charging station.

AC charging stationsIn the AC charging station, shown in Fig. 12, 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.

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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, switchgear, and protective devices.

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.

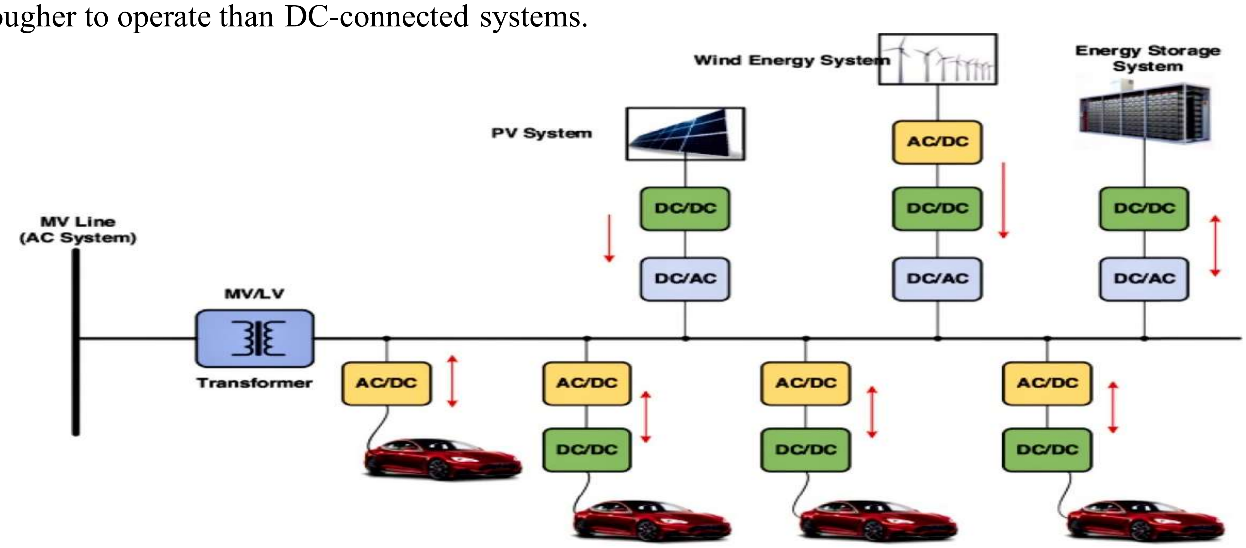

Fig. 12. A layout for the EV AC charging station (Rajendran et al.,2021a)

DC charging stations

The DC charging station in Fig. 13 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, 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).

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The drawback of this charging system is that DC voltage does not have natural zero-crossings, developing protective systems for DC fast-charging stations is difficult (Beheshtaein et al., 2019).

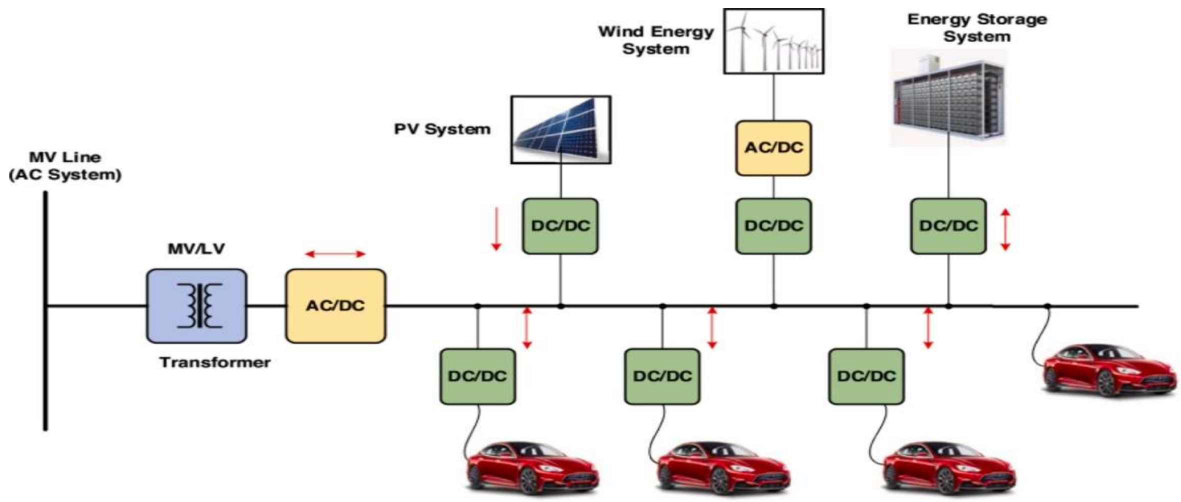

Fig. 13. An illustration of the EV DC charging station. Rajendran et al. (2021a).

IV.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. 14 shows a V2G framework that has interactions among power system operators, consumers, and EV users. Traditional generators, RESs, and transmission infrastructure are included in 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 .

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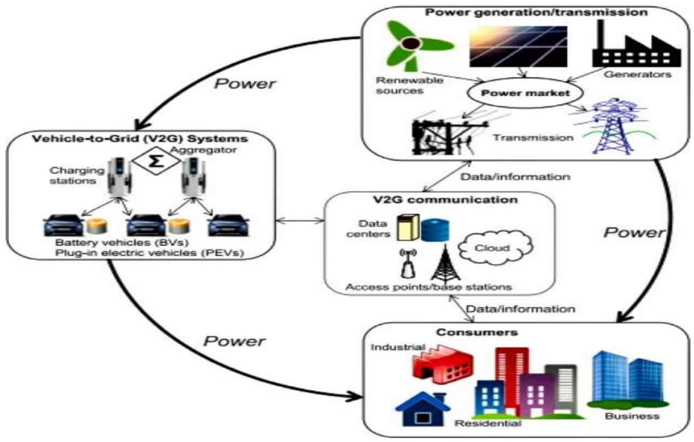

Fig. 14. A V2G framework (Hoang et al., 2017).

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 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).

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. 15. In contrast, choices regarding charging and discharging are made and carried out by EVs themselves in decentralized approaches. Fig.16

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demonstrates the decentralized control framework used by EVs.

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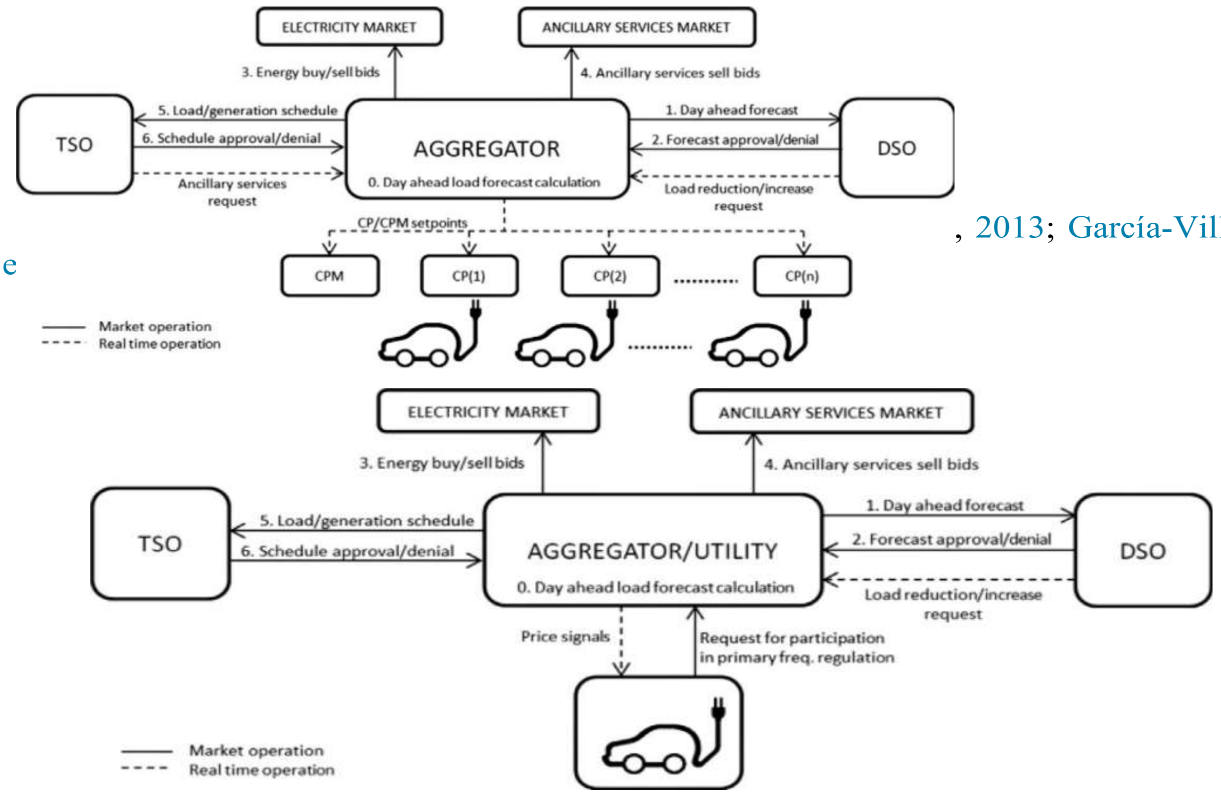

Fig. 16. A decentralized control framework for EVs (Galus et al., 2013; García-Villalobos et al., 2014).

V. 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:

1. 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.
2. 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 jeop- ardizing 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.
3. 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.
4. Artificial intelligence (AI) and machine learning (ML)-based intelligent control strategies

can revolutionize EV operations by automating and optimizing various aspects.

VI.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. 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.

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