

Review

Electric vehicle charging stations and the employed energy management schemes: a classification based comparative survey

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Abstract

Increased adoption of the electric vehicle (EV) needs the proper charging infrastructure integrated with suitable energy management schemes. However, the available literature on this topic lacks in providing a comparative survey on different aspects of this field to properly guide the people interested in this area. To mitigate this gap, this research survey is an effort to provide know-how about the important aspects of the overall EV charging setup with 239 relevant references. It reviews the achievements of energy management systems in terms of improving fuel consumption efficiency and reducing carbon dioxide emissions in EV charging systems. State-of-the-art and most up-to-date standards of EV technology and charging infrastructure are presented. EV charging schemes based on standard grid and renewable energy resources are introduced with a brief comparison of the standard grid and photovoltaic-grid charging systems. Moreover, this article describes centralized and decentralized control configurations of EV charging. A comparative survey of different energy management algorithms is presented while highlighting the benefits and drawbacks of each algorithm. The work presented in this review will help frame future research needs. It is anticipated that the material gathered in this article will become a valuable source of information for the researchers working on this area of study.

Keywords Charging infrastructure · Electric vehicle · Energy management · EV charging schemes · PV-grid charging · Standard grid charging

1 Introduction

Electric vehicle (EV) technology is gaining more attention due to its superior efficiency, lower maintenance, and eco-friendly nature [1]. More than 60% of the major global energy demand is accounted for by the transportation sector and electricity generation [2]. Environmental issues have grown as a result of growing air pollution and greenhouse gas (GHG) emissions. Organizations in the transportation sector are working to integrate EVs into modern power grids to maintain a clean energy perspective [3]. The development and use of EVs on a large scale can result in a major reduction in oil use, GHG emissions, and fossil fuel consumption [4, 5]. Despite these benefits, lack of charging infrastructure, long charging periods, mileage anxiety, existing battery technology, and behavior of internal combustion engine vehicle

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(ICEV) users may limit the applicability of EVs [6]. So, EV charging stations must have reliable, efficient, and cost-effective infrastructure to compete with the existing oil filling stations [7]. Currently, a driving range of more than 321 km has been achieved using advanced technology, and EV chargers with a power rating of more than 350 kW can recharge EVs in less than 10 min [8].

Compared with ICEVs, EVs have less impact on the environment and health because these do not directly release any pollutants or emissions [9]. The largest contributors to tail-pipe emissions are nitrogen oxides (NO_x) and particulate matter (PM) [10]. From the well-to-wheel perspective, the use of battery EVs (BEVs) reduces PM by four times and NO_x by twenty times [11]. As a result, EVs help protect public health and prevent climate change [12] and can play a significant role in the development of smart cities [13].

With the growing adoption of EVs, it is imperative to establish charging stations with smart energy management schemes (EMSs) to meet the EV user's requirements [14]. The main purpose of any scheme should be defining the power delivery sequences for each source of the system to achieve required EV charging objectives under the defined limitations [15].

Over the years, numerous schemes were proposed to control EV charging stations to achieve various objectives other than charging. In general, the main objectives considered in the existing scheme are: charging EVs with cheaper electricity prices, reducing grid burden during system operation, and earning maximum profit from charging stations. Based on different objectives, the charging scheme may be suitable for certain purposes but not for others. For instance, some of the schemes yield better performance in terms of reducing the grid burden but fail to resolve the need for interruption-less charging. The importance of energy storage facilities, which result from the broad use of electric vehicles, is becoming more significant. Nevertheless, the energy that is stored in electric vehicles is intrinsically distributed. Vehicle-to-everything (V2X) functionality enables to access this distributed energy storage, providing a range of utilities to the system [16]. Electrical connections and operational modes are both included in V2X technology, which is categorized as vehicle-to-grid (V2G), vehicle-to-vehicle (V2V), vehicle-to-home (V2H), vehicle-to-load (V2L), vehicle-to-building (V2B), and vehicle-to-grid (V4G) [17]. Similarly, some can provide cheaper charging but at the expense of EV participation in vehicle-to-grid (V2G) or vehicle-to-vehicle operations which causes fast degradation of batteries [18].

V2G is the utilization of energy and power derived from plug-in electric vehicles to offer services to organizations responsible for managing the electrical grid. These organizations include distribution utilities, electrical system operators, integrated load-serving entities, capacity planners, and other grid managers [19]. When comparing the V2B and V2H methods of operation, it is evident that V2G offers a more extensive range of services. The aggregator has an essential function in monitoring the load profile and maximizing the efficiency of charging and discharging of electric vehicles in V2G systems [20]. The aggregator performs two functions as an interface between the electric vehicles and electric grid. First and foremost, electric vehicle operators must establish a connection with the aggregator and furnish all the requisite data for each EV. The aggregator determines whether an electric vehicle should be completely charged prior to being unplugged by analysing this data [21]. During the second phase, the aggregator establishes a connection with the grid to identify the specific services offered by the EVs and the precise amount of power that has to be transmitted to or received from the grid [22]. Smart buildings have the ability to conserve energy and transfer it to nearby devices and low-voltage networks through the use of energy-efficient technologies [23]. The V2G mode of operation for EVs offers a range of services, such as providing backup power in case of failure of renewable energy sources, actively regulating power, reducing peak power demand, filling in low-demand periods, supporting reactive power, compensating for harmonics in grid current, and providing additional services such as frequency and voltage regulation [24].

Vehicle-to-Building (V2B) functions on a large-scale and has the capability to combine a whole fleet or utilize a small number of electric vehicles to enhance the energy efficiency of a building or site, such as a mini-grid. The benefits of V2B are particularly prominent as it focuses on industrial and commercial buildings, creating additional opportunities compared to V2H [25]. Industrial and Commercial consumers pay significantly higher capacity-charges, along with additional charges for line phase imbalances caused by inductive loads, which result in surge-power losses into line. V2B economics relies on the utilization of commercial as well as industrial rate tariffs, which encompass both the cost of overall energy consumption and the cost associated with the peak demand during the billing period [26]. The primary objective of V2B technology is to reduce peak load, thereby minimizing the substantial billing cost. The capacity costs, often referred to as demand charges, can account for over half of the monthly electricity bill for commercial or industrial buildings. These expenses are incurred due to occasional surges in the building's electrical load [27]. Hence, any V2B technology that has the potential to reduce those peaks by a marginal kW can result in substantial cost savings. Integration of V2B technology can provide supplementary benefits such as decreasing operating expenses, reducing carbon emissions and deferring development expenditures [17].

This paper presents a strategic review of EMSs for the standard grid and PV-grid EV charging systems. However, before presenting this review, the background of EVs and the approaches of their charging control are given. Followed by this, the comparison between the two above-mentioned charging systems is presented to select the suitable one for day-time charging in an office parking space. Considering the most favorable for the interests of EV users (office employees), the aggregator-based charging schemes are the focus of this research; especially employed in PV-grid systems. Moreover, the algorithms used for developing the schemes are explored and compared. Lastly, the various system sizing methods are reviewed. The sizing method is used to determine the least boundaries (that is minimum size) of the system at which it can be operated without facing economic losses while achieving certain objectives without failure.

Thus, this review would be useful for the reader who requires a comprehensive background of EMSs being used for EV charging, as well as to keep track of the latest development in this area. The ultimate and primary purpose of the literature review is to identify technical gaps in the existing EV charging schemes and to perform subsequent research so that this gap can be overhauled.

1.1 Background of electric vehicles

EVs can be defined as vehicles that get some or all of their propulsion energy from batteries [28]. A battery is combined with an ultracapacitor in the hybrid energy storage system (ESS) to increase the driving range of EVs [29]. EVs are growing in popularity as an alternative to conventional ICEVs [30, 31]. Naturally, this adoption is resulting in a huge reduction in the consumption of fossil fuels. Based on the share of propulsion energy drawn from the battery, EVs can be classified as (i) purely BEVs, (ii) hybrid EVs (HEVs), and (iii) plug-in hybrid EVs (PHEVs). Table 1 presents the characteristics of these EVs in brief [32].

BEVs are fully powered by a large onboard battery. The use of energy in this vehicle is much more efficient than ICEVs. The ICEVs typically have an efficiency of 15.0–18.0%, but the BEV can have a fuel efficiency of 60.0–70.0%. It has provision for the plug-in to the external socket. The HEV's powertrain is a combination of electric and gasoline fuel. It has a much smaller battery that provides energy to the engine, thus optimizing the operational efficiency and performance of the combustion engine. It has no electric socket outlet for charging, that is it cannot be charged through the external power source. Its battery is charged either by the engine or by kinetic braking energy captured (regenerative braking). PHEVs seem to be similar to HEVs in concept but with larger battery storage and provision of charging from the utility grid. This makes it feasible for the vehicle to go a considerable distance in all-electric mode and allows faster battery charging.

In this research, the scope is limited to BEVs and PHEVs, as both are capable of being charged from an external power source.

Table 1 Classifications of electric vehicles

EVs type	Characteristics/Overview	Famous manufacturers
Battery electric vehicles (BEVs)	Battery recharged by the plug-in Electric battery bank	Tesla Roadster Nissan Leaf
Hybrid electric vehicles (HEVs)	Smaller and compact electric battery arrangement (bank) Internal combustion engine Dual-fuel vehicle No plug-in provision Battery recharged either by the engine or regenerative braking	Toyota Prius Ford Fusion Hybrid Honda Civic Hybrid
Plug-in hybrid electric vehicles (PHEVs)	Electric battery bank Internal combustion engine Dual fuel vehicles Battery recharged by plug-in, ICE, and regenerative braking	Chevrolet Volt Toyota Prius

2 EV Battery and charging power levels

A battery can be classified either as primary (non-rechargeable) or secondary (rechargeable) [33]. The primary type is of no concern for EVs, whereas the evolution of secondary battery technology matters for EVs. It started with Lead Acid, then moves on to Nickel-based, and eventually to Lithium-based [34]. Lithium-ion batteries are used because of their high efficiency and power density, extended life, and environmental benefits [35, 36]. Driving range per charge is a crucial EV characteristic that is directly connected to the power density and weight ratio of the lithium-ion battery storage system to the entire vehicle. Many countries have set goals to design lithium-ion battery systems with high power density as energy density is most important factor for attaining a long driving range of EVs. For example, in China, the goal for energy density is 350.0 Wh/kg for cell and 250.0 Wh/kg for battery bank, while the mileage of EVs will be 400 km on a single charge [37]. Many efforts are going on to produce high-capacity anode and cathode materials for the lithium-ion battery system to meet the stated energy density requirements [38–41]. Digital twinning of battery systems is also foreseen by integrating communication and artificial intelligence (AI) techniques to enhance safety, working, and economy in transportation systems [42]. The characteristics of the widely used Lithium batteries for EVs are shown in Table 2 [32, 43]. The state of charge (SOC) for some models with level 3 DC fast charging (DCFC) is also given.

The vehicle charging can be carried out at the home garage on a standard household socket during the night-time using the standard grid connection [43]. For this purpose, level 1 charging is provided through a 120 Vac plug. Level 2 charging, which requires a 240 Vac plug, is commonly defined as the primary charging method for public and private facilities. For levels 1 and 2 charging, generally, single-phase solutions are utilized. The level 3 charging utilizes the three-phase or DC power supply for fast EV charging. The fast-charging platforms that work like filling stations are suitable for commercial and public applications. Table 3 summarizes these charging levels and charger types [43–45].

The electrical components utilized in three charging levels (1, 2, and 3) of EVs are shown in Fig. 1. All these charging levels take AC power from the utility power grid and convert it into the appropriate voltage levels required for the charging. In the application of EV charging, the level 1, and 2 charging systems are integrated within EVs. On the other hand, in the level 3 charging system, the charging operations are split between EV charging stations and on-board chargers for EVs. In these EVs, unidirectional and bidirectional isolated or non-isolated converter topologies are generally utilized. Level (1 and 2) charging systems are powered by a single or three-phase AC source, whereas level 3 charging systems are powered by a three-phase AC source, which has the same functions as level 1 and level 2 charging systems, but at a higher power level. The control algorithm that each of the three charging levels uses is represented by the power control unit. The power control unit includes PID controllers, PI controllers, fuzzy logic controllers, neural networks, and adaptive sliding mode controllers [43].

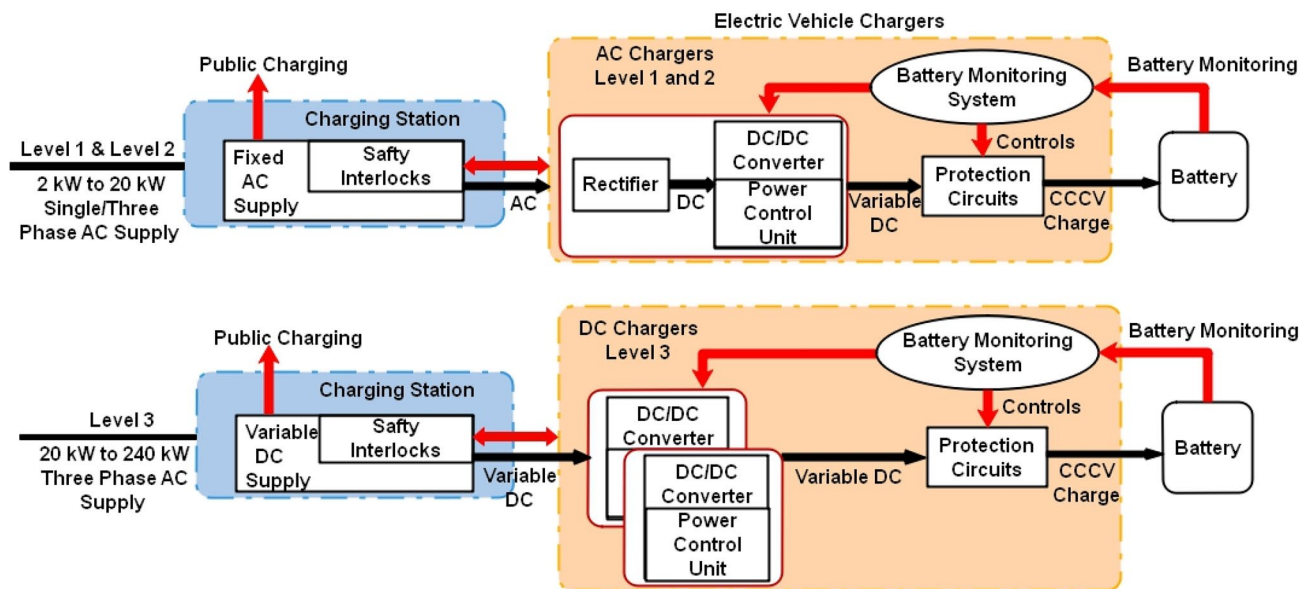
Table 2 The widely used Li-ion EV batteries and their charging characteristics [32, 43]

Model	Max. driving distance (km)	Li-ion battery rating (kWh)	Approximate charging duration for a full charge (Hours)		
			Level 1 (120 V _{ac})	Level 2 (240 V _{ac})	Level 3 (DCFC)
Chevrolet Volt PHEV	610.0	16.0	10–16	4–5	N/A
Tesla Model S BEV*	426.0	85.0	> 24	9–15	0.5 (80%SOC)
Ford Focus BEV	122.0	23.0	< 20	4–5	N/A
Chevy Volt PHEV	61.0	16	13	6.5	0.3 (80%SOC)
Nissan Leaf BEV	117.0	24	12–16	6–8	0.5 (80%SOC)
Mitsubishi i-MiEV BEV	100.0	16	22	7–8	0.5 (80%SOC)
Fisker Karma PHEV	370.0	20.1	< 15	4–5	N/A
BMW i3 BEV	160.0	22	7–10	3–5	0.5 (80%SOC)
Honda Fit BEV	132.0	20	< 15	4–5	N/A
Toyota Prius PHEV	870.0	4.4	3	1.5	N/A

*Available for quick swapping of battery

Table 3 Charging power levels

Charging levels and charger types	Expected power levels (kW)	Charging time (Hours)	Vehicle technology
Level 1 (Opportunity) On-board 1-phase 120 V _{ac} (US) 230 V _{ac} (EU)	1.4 (12A) 1.9 (20A)	4–11 11–36	PHEV (5–15kWh) BEV (16–50kWh)
Level 2 (Primary) On-board 1- or 3-phase 240 Vac (US) 400 Vac (EU)	4 (17A) 8 (32A) 19.2 (80A)	1–4 2–6 2–3	PHEV (5–15kWh) BEV (16–30kWh) BEV (3–50kWh)
Level 3 (Fast) Off-board 3-phase (280–600 Vac or Vdc)	50 100	0.4–1 0.2–0.5	BEV or PHEV (20–50kWh)

**Fig. 1** Electrical components utilized in three charging levels (1, 2, and 3) of electric vehicles

2.1 EV Battery chargers

EV chargers are divided into primarily two types: (i) on-board chargers, (ii) off-board chargers. Because of space, cost, and weight constraints, the rated power of traditional vehicle chargers is limited [46]. The two types of EV charging methods that have been studied so far are constant voltage (CV) and constant current (CC). The most optimal and best way for rapid EV charging is the combination of CC and CV modes that combine the favorable results of both methods. But, the anticipated rise in the number of EVs [8] may lead to a significant load increase on the national power grid, because of charging of EV batteries. On the other hand, during peak load demand, EVs with battery storage can also help the utility system by injecting energy in to the power grid while working in the V2G mode [47].

The conventional on-board charger limits the high power because of cost, size and weight constraints and it is typically employed for level 1 and level 2 charging. On the other hand, the latter is less constrained by weight and size, so it can easily be used for level 3 charging to increase the autonomy of charging [48]. Thus, the DC fast charger (level 3) is considered to be the most suitable charging platform; thus, many developed countries are in favor of using this charger [49]. In addition, a level 3 charger can be used for uni-directional power flow or bi-directional power flow. However, unidirectional charging is a logical and suitable first step that decreases battery degradation while limiting hardware needs and simplifying interconnection issues [43]. Bidirectional chargers support charging from the national utility grid and injecting battery storage energy back into grid which is a V2G arrangement [50].

The design of ad-hoc microgrids has been encouraged by the development of DC fast chargers for electric vehicle batteries (EVBs). In these microgrids, the electrical architecture of microgrid can be made lighter and more efficient by substituting a solid-state transformer (SST) for a low-frequency service transformer [51]. In the field of electric vehicle (EV) charging stations, advancements in power electronics technology are critical as they address important issues including environmental concerns, sustainability and charging efficiency. The importance of Solid State Transformer (SST) technology is emphasised in the research study [52]. SST considered the most advanced option for adjusting to changes in electrical network architectures because it incorporates advanced and sophisticated power electronics and allows two independent electrical grids to be connected through isolation. Its broad application in offshore wind farms, railways, data centres and smart grids demonstrates its bright future. In addition to providing V2G functionality, a solution based on SSTs could be designed to provide either unidirectional or bidirectional power flow, which better manages the active and reactive power. Furthermore, it has protection characteristics like fault current limiting and isolation in addition to performing power factor correction function. In order to ensure fewer conversion stages and higher efficiency, the EV charging station based on solid state transformer features a common DC bus to create an interface among renewable energy sources, battery energy storage systems, and EVs using DC/DC converters [53].

The most famous chargers used for DCFC are the Tesla-S supercharger, SAE J1772 Combo and IEC CHAdeMO [43, 54]. Tesla has a total of 1431 supercharging stations around the world, including 294 in the Asia–Pacific region, 442 in Europe and 694 in North America [55]. Canadian Automobile Association announced that 7906 charging stations had been developed/constructed in major Canadian cities with the help of another charging infrastructure provider, Charge Hub [56]. The Japanese protocol famous as CHAdeMO has gained international recognition. This DC fast charger is conductive and capable of charging up to 200.0 A at 50 kilowatt. The CHAdeMO connector is used by several currently available EVs that are capable of accepting DCFC, such as the Mitsubishi i-MiEV and Nissan Leaf. A controller area network protocol is used to establish secure communication between the charger control units and EV management system. Society of Automotive Engineers (SAE) has developed a “hybrid connector” that is standard for fast-charging which attaches DC power contact pins of high-voltage to J1772 connector, allowing the same receptacle to be used for all charging levels. Therefore, SAE J1772 Combo 1 and 2 defines the electrical, physical, and functional standards to supports AC levels (1, 2, and 3) and DCFC. Combo 1 (IEC Type 1) is widely used in United States, while Combo 2 (IEC Type 2) is more often used in the Europe. The Tesla supercharger (135 kilowatt) is a specialized DC fast charging station for the Tesla-S Series (Tesla-X vehicle and All Wheel Drive (AWD)). Tesla is the only organization that has installed it after standardization.

2.2 EV Charging and grid integration standards

The development of EVs has created new aspects for the transportation and power industries. All facets of this new technology need to be standardised in order to operate consistently on a global basis. Table 4 includes the global regulatory agencies and established standards that are responsible for overseeing various aspects of EVs. Electric vehicle charging standardization is divided into three categories: EV grid integration standards, EV safety standards as well as EV charging component standards. In the standardization organization for EV, International Organization for Standardization (ISO) is committed to the overall standardization of EVs, and other organizations are committed to component-level specifications.

Electric vehicle charging and discharging with the utility grid is covered under the grid integration standard. EVs operate like distributed energy resources (DERs) during charging and discharging from the utility grid. Therefore, the grid connection standard of DERs is also applicable to EV grid integration. Underwriters Laboratories and Institute of Electrical and Electronics Engineers (IEEE) are the two key stakeholders in grid interconnection standards. On the other hand, organizations like the National Electric Code and the National Fire Protection Association focus primarily on safety measures.

3 Electric vehicle charging infrastructure and control

3.1 Power infrastructure in EV charging station

Power infrastructure in the EV charging station is classified in accordance with type of power used, physical contacts, and the direction of power flow. The classification of Power infrastructure in the EV charging station is shown in Fig. 2.

Table 4 Regulatory organizations and standards related to electric vehicles

Serial No.	Organization name	Standards	Details
1	International Electrotechnical Commission (IEC Britain) [57]	IEC61850 IEC61851 IEC61980 IEC62196	Communication protocol for intelligent electronic equipment in an electric substation Standards associated with general charging requirements Wireless Power Transmission (WPT) standard for electric vehicles Standards for connectors, sockets, and plugs for the conductive-charging of EVs
2	Society of Automotive Engineers (SAE, United States) [58]	SAEJ2293 SAEJ2847 SAEJ2836 SAEJ2931 SAEJ2954	EVs and off-board EV power supply equipments requirement for charging from the grid Communication standards between utility grid, EV, and off-board DC charger Provide digital and analog communications between utility grid and EVs A standard for digital communications between the grid and EVs WPT for EVs
3	Institute of Electrical and Electronics Engineers (IEEE) [59]	SAEJ2894 P1547 P2100.1 P2030 P2030.1	EVs power quality specifications and testing protocols Standards for different features of DERs and grid connection Standardization of WPT and charging systems Standard for dealing with smart grid interoperability Electrified transportation infrastructure
4	Underwriters' Laboratories (UL) [60]	UL2231 UL2594	Requirement for protection device of the EV charging circuit Requirement for power supply equipment for EVs
5	Japan Electric Vehicle Association (JEVA, Japan) & CHADEMO Association [61]	D001-002 D701-709	Standardize the battery characteristics of EVs Battery test instructions
6	National Fire Protection Association NFPA [62]	70 70B	Grid-integration safety standards for DERs Contains the safety protocols for the maintenance of electrical equipment
7	National Electric Code (NEC) [61]	625 626	Standards for off-board charging systems like connecting plugs, conductors, and inductive charging equipment Requirement for the electric truck parking lots, such as those for conductors and other charging apparatus

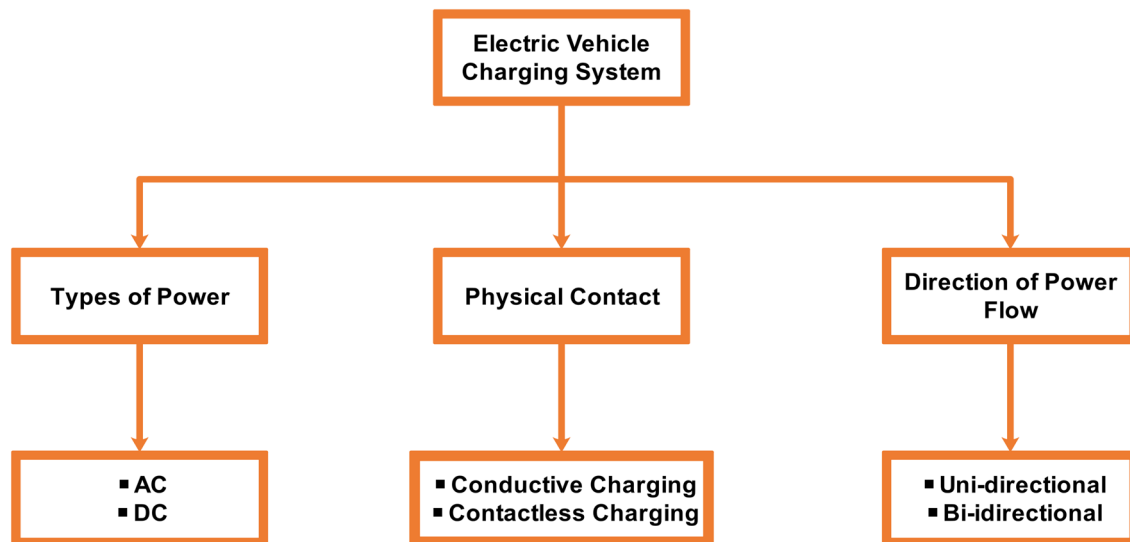


Fig. 2 Classification of power infrastructure in the electric vehicle charging station

3.1.1 Types of power used

EV charging can be done with either AC or DC power. According to the power system of the country, AC charging stations have different frequencies and voltage levels. According to the voltage level, AC charging stations are divided into three voltage levels (level 1, level 2 & level 3). In all three levels, level 3 has maximum charging voltage. Charging stations (level 1 and 2) may be installed on private places. However, the installation of charging stations (level 3) requires separate electrical transformers and wiring; and also require permission from national power supply companies. Level 3 stations are generally installed as public charging stations. At the same voltage level, the DC charging method has a higher charging power capacity and a faster charging speed [63]. EVs are fully charged in 20 min by using modern DCFC technology [55, 64].

3.1.2 Physical contact

The charging infrastructure is classified into two types based on physical contact: (i) conductive charging and (ii) contactless charging. Conductive charging systems keep physical contact between vehicle battery and source of power, while contactless charging systems transmit the power without requiring any physical contact [43]. Contactless charging systems usually use wireless power transfer (WPT) systems to charge EV batteries. WPT systems can operate on each voltage level (1, 2 & 3) with a rated power up to 20.0 kilowatt. Up to 90% efficiency has been achieved [65]. A detailed review of WPT is presented in [66].

3.1.3 Direction of power flow

The uni-directional charger is easy to control due to its low simplicity. When compared with the bidirectional charger, the unidirectional charger minimizes battery degradation and reduces interconnection problems [67]. The bidirectional EV charger has DC-DC converters and grid-connected AC-DC converters [68]. Figure 3 shows the concept of power flow for bi-directional and uni-directional EV charging schemes [61, 69, 70].

3.2 Centralized and decentralized EV charging control

Centralized control also called direct control relies on an aggregator (charging station owner) which is directly responsible for all EV charging within the assigned zone. The aggregator can also manage other units, like the charging post manager, which manages a group of EVs within a parking lot. Under this kind of control structure, the autonomy of EV users is sacrificed. The primary concept underlying centralised charging is the central processing and collection of data

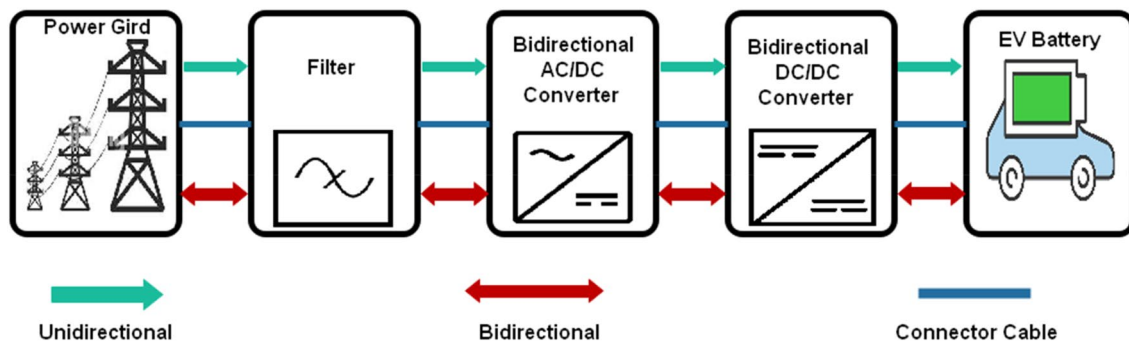


Fig. 3 Uni-directional and bi-directional EV charging schemes

from EVs through a centralised framework. Due to central data processing, centralized control provides the global optimum solution that accounts for all grid and user constraints [71–75]. Rates and scheduling of EV charging are decided by the main control engine. The limitation of centralized charging of EVs is that the scale of the optimization problem increases with number of the EVs in a specific area increases. This issue is resolved by developing a hierarchical based control architecture that divides EV loads into multiple groups based on their locations. The central controller mainly manages the load demands of each group, while each group manages power distribution to individual EVs using a local controller [76–82]. The centralized EV charging control is shown in Fig. 4.

On the other hand, in decentralized control (also called local or indirect control), the decision-making power is in each EV user rather than in external entities such as aggregators. In this approach, each user autonomously considers the desired charging preferences without providing any private or sensitive information to external entities. Therefore, EV charging can be realized by centralized or decentralized control [83, 84]. The key elements influencing the charge decision in this sort of control are the price of electricity and the convenience of the user [85]. Table 5 summarizes the characteristics of both approaches [48, 86]. The decentralized EV charging control is shown in Fig. 5.

Due to the simplicity of the communication network, the authors in [87] suggested that decentralized charging is a more promising approach than centralized external control. The decentralized approach, not only preserves the privacy of sensitive information but also maintains the EV user autonomy by ensuring any-time charging. Due to these benefits, it is more likely to be acceptable to users than a centralized approach. But on the other hand, decentralized control can increase the maximum aggregate demand from the grid, especially with fast charging [88].

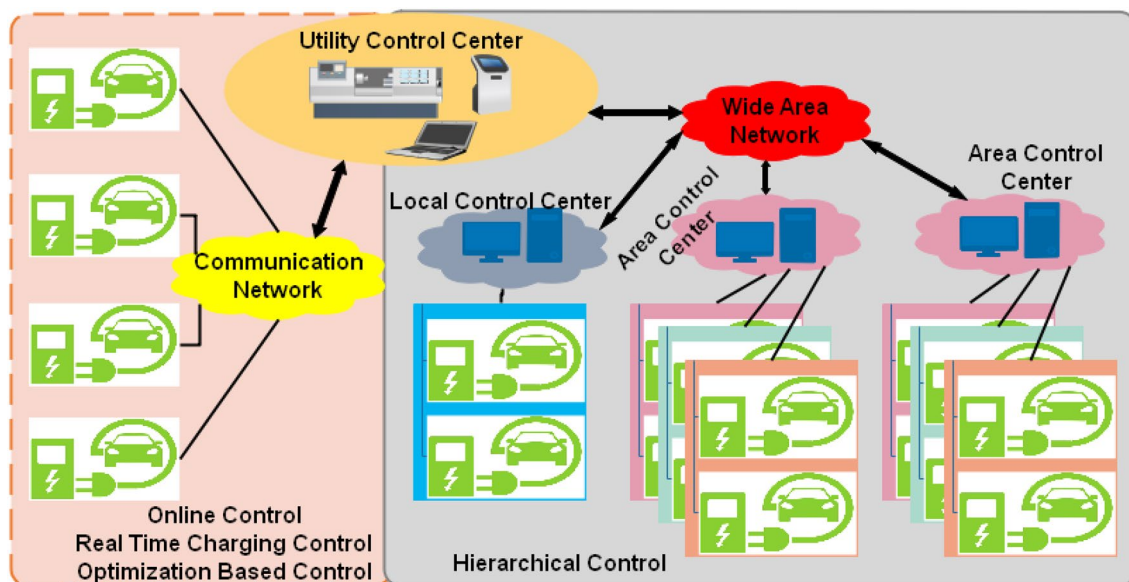


Fig. 4 Centralized control architecture for electric vehicle charging systems

Table 5 Classifications and comparison of EV charging control approaches

Control type	Advantages	Drawbacks
Centralized control	<ul style="list-style-type: none"> Provision of better auxiliary services Better utilization of network capacity Overview into the current state of operation at every network node in real time 	<ul style="list-style-type: none"> Complex and expensive communications infrastructure Significant quantity of data to process The expensive central controller and storage resources are required Complexity increases with the increased number of EVs Possible privacy violations The charging process can be interrupted anytime Provision of limited auxiliary services
Decentralized control	<ul style="list-style-type: none"> Charge control remains in the user's hands (autonomy) Less and simple communication infrastructure is required Higher consumer acceptance 	

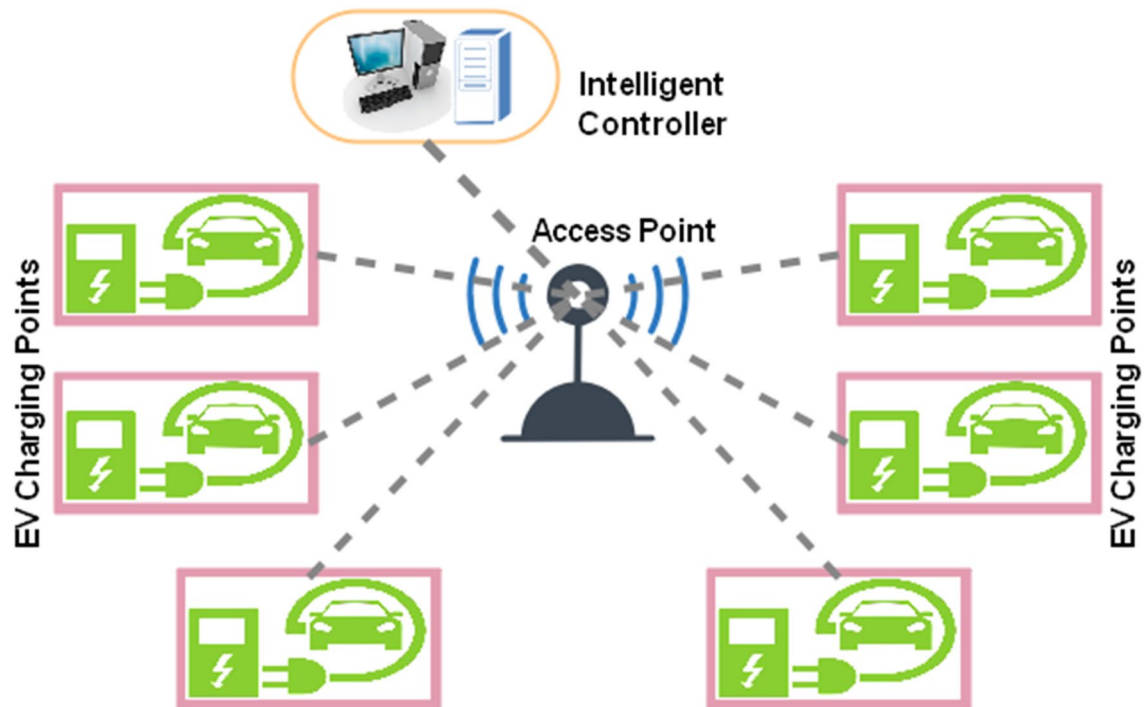


Fig. 5 Decentralized control architecture for electric vehicle charging systems

4 Electric vehicles charging systems

The EV charging system is an infrastructure that provides electrical energy for recharging. The capacity and location of such systems depend on various factors such as EV users, distribution network, and availability of generation resources [89–92]. In recent literature, the most discussed charging systems are standard grid and grid-connected renewable energy (RE) systems [15]. In the standard grid, EV charging is solely accomplished by the national utility grid [32]. On the other hand, in the case of RE-grid systems, charging can be done through the utility grid as well as RE sources. The grid-connected RE sources used for EV charging mainly include solar PV, wind, and biomass [15, 54]. However, the literature on PV systems for EV charging is far more sophisticated and varied, as it has additional technical advantages compared to windmills and biomass plants such as low maintenance and long unattended periods of operation [18, 54, 93].

4.1 Standard grid charging system

Direct charging using the standard grid is widely used because of its simplicity and availability of an unlimited energy supply. EV users may easily access charging points because the charger only needs a standard power outlet [43]. The impact of grid-connected EVs can be divided into negative and positive impacts. Excessive integration of EVs into distribution systems will affect load distribution profile, voltage and frequency imbalance, power losses, distribution system component capacity, excessive harmonic injection, and distribution grid stability [94–98]. Although excessive penetration of EVs in the power grid can cause issues like higher peak load demand, deterioration of power quality, and the power regulation problem. All of these problems are solved and managed by using advanced power management technologies. The positive effects of EV integration on the utility grid include power management, improvement in power quality, regulation supervision, and RE support [98–103].

The standard grid system needs a simple EMS for EV charging compared to the schemes designed for complex grid-connected RE systems. In grid charging, the battery of the EVs can be recharged with the help of various approaches namely: simple, delayed, and night-time [104–106]. In a simple approach, EVs immediately start recharging once connected to the standard grid. The delayed charging approach shifts the process of charging by a fixed duration of

time, such as five hours. Night-time approaches delay the charging process over the course of the night when the prices of grid electricity are at their lowest.

The delayed and night-time charging approaches are not suitable for day-time charging in office parking because EV users may lose the autonomy of charging during working hours. On the other hand, the simple charging approach can cause grid overloading; this results in distribution losses, voltage variation, and degradation in power quality [104]. The overloading problem becomes more crucial during the day-time when power demand is highest. Thus, also the simple approach is not suitable for day-time charging in office parking. However, the grid burden can be released during the charging process, if the RE source is integrated with the standard grid system [107]. The grid-connected RE sources used for EV charging mainly include solar PV, wind, and biomass [28, 54]. Nevertheless, the PV system has some additional technical advantages compared to windmills and biomass plants such as requirements for low maintenance and long unattended periods of operation [18, 54].

4.2 Grid-connected RE-based EV charging systems

The utility grid will undoubtedly be overloaded since the number of EVs is expected to expand quickly. Integrating RE systems into the utility grid is one alternative strategy to alleviate this issue [108] [109–114]. Solar PV, wind, biomass, and hybrid energy generation systems are all viable options that could be considered for this aim [115–119]. The long-term impacts of using large-scale wind energy to meet the increasing energy demand caused by EV charging have been examined in many studies [120]. Wind energy-based EV charging stations can operate in off-grid mode [121] and on-grid mode [122]. But, it should be noted that the wind energy generation system needs a suitable optimal location and a wide space to install the windmill [123]. The issue is significant in urban regions, where high buildings are major obstacles in wind paths. Furthermore, the wide variations in wind speed make it less suitable for EV charging as compared to other RE systems [124].

Biomass energy differs from wind energy in that it can be easily stored and used when necessary [125] [126]. However liquid biofuels are considered to be an alternative option for EV fuel [127]. For EV charging stations, bioelectricity offers a number of benefits [128]. Bioenergy could be produced with numerous materials of biomass feedstock such as agricultural and forestry residues, animal waste, whole tree harvesting, and woody energy crops [129–132]. Bioelectricity has higher energy returns than biofuel processes from a financial perspective. Many recent research articles have been published to investigate the potential application of biomass energy in electric transportation [133]. A 20 kW EV charging station has been designed and installed using biogas [128]. Despite these benefits, the polluted environment originated due to the production of bioelectricity makes it unsuitable for areas with high population density.

The research on the use of solar photovoltaic (PV) energy for EV charging is more developed and wide-ranging. Solar (PV) system is more flexible in terms of integrating with existing utility grids [93]. Several researchers have worked on PV-based EV charging stations [134–138]. Photovoltaic-based electric vehicle charging stations are divided into two primary categories: photovoltaic grid-connected charging and photovoltaic standalone charging [139–141]. Additionally, electric vehicle charging stations can be divided into two groups based on how long it takes to charge an electric vehicle: charging while vehicle parked and charging while driving [142, 143]. In photovoltaic grid-connected charging, if photovoltaic power generation is insufficient or inaccessible, the electric vehicle is charged from the utility grid. The photovoltaic grid-connected charging system is appropriate for work area parking lots [144, 145]. Another method to harness photovoltaic power is photovoltaic standalone charging system, which can be deployed in three ways: vehicle-integrated photovoltaic (VIPV), solar roofs and solar carports [146–148]. For electric vehicles to be charged from photovoltaic, the total energy needed to operate or drive the electric vehicle must not exceed the total energy produced by the photovoltaic modules installed in charging station [149]. In vehicle-integrated photovoltaic charging systems [150–152], photovoltaic modules are mounted on the body frame of electric vehicles. Electric vehicles can be charged while in motion by utilising the VIPV charging technology. In recent times, the Ford C-Max Solar Energy Concept Car 2014 employed the vehicle-integrated photovoltaic design. The C-Max Solar Energy Hybrid, a Ford concept automobile with roof-mounted PV modules, can generate between 300 and 350 Wp of power from an array that occupies around 1.6 square metres of the roof. Workplace plug-in charges the vehicle battery early in the day, causing significant daily solar radiation loss under standard commuting transit patterns. This effect is worst for drivers who charge at work and home, as well as utilize Level 2 charging in the workplace instead of Level 1. In this scenario, almost 80% of the total solar energy is not captured by the system [153].

Reference [154] proposed a high power electric vehicle charging station using solar (PV) powered bi-directional chargers. However, the proposed system cannot allow AC charging. For the EV charging station, reference [155]

recommended using integrated PV modules with multi-port converters. However, the grid current is severely distorted. A photovoltaic powered grid-connected EV charger through a Z-source converter is described in Reference [156]. Although the performance of the charger is better, this is not suitable for standalone operation. Reference [157] discusses the hybrid optimal management of the storage system of the photovoltaic powered EV station. Reference [158] optimizes the physical scheduling of EV charging stations.

One of the most fundamental concepts is to promptly charge electric vehicles (EVs) using the principle of "charging-while-parking," in contrast to the more prevalent "charging-by-stopping" [159, 160]. This provides opportunity to exploit solar (PV) system by installing them on the roof of parking lot [161] [162–164]. The use of standalone charging stations is an effective way to help the power grid [165]. Therefore, EVs can be efficiently and quickly charged through an integrated PV grid system, while EVs owners are participating in other kinds of activities [143]. The PV powered charging stations have various advantages [91, 166]. Considering that the charging is done during the day, when load demand and energy prices are at their highest, the cost reductions are substantial [167]. Furthermore, rooftop parking areas provide free rain and sun shelter which is advantageous in nations having warm climates. Due to these benefits, PV grid-connected systems are more efficient and popular than other RE generation systems (wind and biomass etc.). A PV-powered grid connected EV charging system is shown in Fig. 6.

A. R. Bhatti et. al. [168] presented a case-study on EV charging utilising the conventional utility power grid, grid-connected PV system, and a stand-alone PV system in the presence of the ESS. The research study concluded that PV grid systems are more profitable and economical than standard grid charging systems and PV standalone systems. Furthermore, M. Honarmand et. al. [169] analyzes the large-scale deployment of EV chargers, where PV-powered carports are installed in large car parks in a mid-sized Swiss city. The authors found that 14.0–50.0% of city's mass transit energy needs can be supplied by PV energy. However, some suggestions for PV-powered EV charging facilities are discussed in [170–172].

4.3 Comparison between standard grid and PV-grid charging systems

To quickly evaluate the features of the standard grid and PV-grid charging systems, a comparison between these two systems is provided in Table 6.

From the above discussion, it is concluded that a PV grid system can provide a more feasible solution for the daytime charging of EVs in office parking spaces than a standard utility grid system [173]. However, in order to use hybrid power sources effectively, an intelligent as well as effective EMS is required.

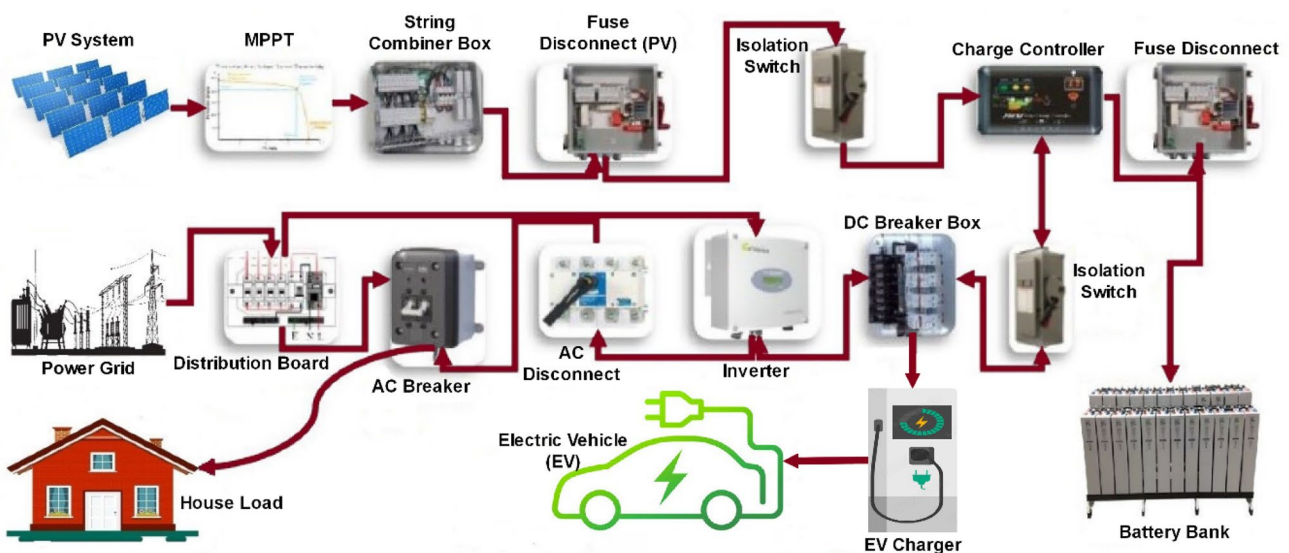


Fig. 6 Photovoltaic-powered grid-connected EV charging system

Table 6 Features of the standard grid and PV-grid charging stations

Charging system	Advantages	Drawbacks
Standard Grid	<ul style="list-style-type: none"> Easy access Availability of night-time charging Readily available Simple structure Needs a simple charging scheme Simple control structure 	<ul style="list-style-type: none"> Grid overloading problem Uncertain/variable charging price Interruptions in the charging process to reduce the burden Not suitable for day-time charging
PV-grid	<ul style="list-style-type: none"> Easy day-time charging Earning profit by selling surplus power More reliable charging system Possibilities of cheaper charging during day-time Improved grid stability Free shelter from sun and rain Saving from the electricity tariff Less grid burden 	<ul style="list-style-type: none"> Limited access Fewer chances of night-time charging Complex structure Needs a complex charging scheme

5 Energy management scheme

5.1 EMS for electric vehicle charging systems

The deployment of an EMS is very crucial for the optimization of available energy from various sources linked to the charging system [174, 175]. In the context of EV charging, optimization is defined as a method or process that supplies charging power demand consistently over time without violating the constraints under consideration [176]. Without proper energy management (EM), the grid can be overloaded and EV users may have to bear a high cost for day-time charging. On the other hand, proper EM not only reduces the grid burden but also facilitates EV users with a low charging price. Additionally, other requirements of the users (for example quicker charging, uninterrupted charging) can also be realized, without incurring the system's economic losses, by properly defining the rules of energy utilization.

Based on the requirements of users and from the perspective of the distribution networks [177], an EV can be considered as a simple load, flexible load, or distributed and mobile storage element [48, 178]. The simple load can be handled by the uncoordinated scheme. However, the flexible and mobile storage element can be controlled via valley-filling and peak-shaving smart schemes respectively [48]. In valley-filling, charging takes place during utility grid off-peak hours, whereas, in peak-shaving, the V2G operation supports the grid during peak conditions [24]. Thus, in a broader sense, the charging can be realized by uncoordinated or smart EMSs.

5.1.1 Uncoordinated charging scheme

The uncoordinated/simple scheme describes the uncontrolled behavior of charging without considering proper EM where it is expected of all customers to charge their electric vehicles as soon as they reach charging station [48, 179, 180]. Among all EV charging schemes, this one is considered to become the most expensive and may have the highest impact on the electric grid [181, 182]. Moreover, the literature indicates that uncoordinated charging of a large number of EVs will cause some distribution network issues. The issues are related to network congestion, peak power problems, grid overloading, voltage drops, and power losses [183]. During peak hours, uncoordinated EV charging can increase the power demand by up to 5% [184]. Thus, the uncoordinated scheme is not recommended to apply for the day-time charging operation. Nevertheless, the uncoordinated scheme is used as a base case to benchmark the performance of newly proposed smart EMSs [32, 115, 185].

5.1.2 Smart energy management schemes for EV charging

Smart EMSs for standard grid [82, 85, 176, 185–190] and PV-grid [32, 115, 169, 191–197] EV charging systems have been proposed by various researchers. These schemes allow the stakeholders e.g. EV users, aggregators, and distribution system operators (DSOs) to achieve technical and economic benefits [169]. The charging profiles should be scheduled by the DSO to avoid grid congestion issues [48, 198]. Based on the interests of stakeholders, smart EMSs can be categorized into three main groups, namely— aggregator based schemes (ABSs), distribution system operator based schemes (DBSs), and system based schemes (SBSs) [199–201].

5.1.2.1 Aggregator based schemes The ABSs can be derived depending on the interest of the charging station owner or EV user or both. The ABS optimize the charging schedules to achieve charging price minimization, uninterrupted charging, or increased system profit, regardless of the electric network constraints [200, 202, 203]. The group of publications [32, 169, 191–193] proposes charging using ABS. In these publications, the interests of EV users and/or station owners are handled based on top priority.

Considering management control strategies, a system integrating electric vehicles and aggregators as operators of EV charging management can utilize both centralized and decentralized schemes. A multi-level hierarchical optimizing model is introduced in the research [204]. This model focuses on the worst case state of charge (SOC) and involves decision-making by a central aggregator. The research [205] introduces a centralized energy management method for charging stations (CS) in the presence of an aggregator responsible for coordinating electric vehicle scheduling. The research in [206] presents a concept for an electric vehicle customer incentives pricing approach, which aims to enhance user comfort while simultaneously reducing their charging expenses. A centralized coordinated electric vehicle scheduling system is proposed in [207], where the objective function takes into account a combination of charging expenses and peak shaving/ valley filling. For this investigation, both methods of fast and slow charging are selected based on the level of urgency for each electric vehicle (EV) at a public CS. The authors of [208] proposed an algorithm for scheduling electric vehicles in both commercial and residential sectors, where every sector is managed by a single aggregator. The primary objective of this research is for the aggregator to maximize its profits while also meeting the demand response requirements of distributed systems and fulfilling the needs of electric vehicle owners.

Electric vehicle owners can reduce their expenses by earning revenue from exporting electricity back to the power grid through a network of one or several aggregators. A case study of this can be examined in [209], where a network of EVs is simulated. These EVs participate in the energy and the regulation market by utilizing V2G technology, all under the management of a central aggregator. This investigation focuses on optimizing the maximum income by considering the EVs battery degradation. The researchers of [210] simulated the most unfavourable scenario for the minimal electricity trading with the electric market using V2G service as one of the lower-level objectives in the multilevel optimization situation. The optimization model in [211] incorporates both V2V and V2G capabilities, taking into account real-time electricity prices.

5.1.2.2 Distribution system operator based schemes Such schemes emphasize the interests of the DSOs in maintaining the operation of the electric network with high efficiency [212, 213]. Therefore, the DBS is expected to be the most beneficial to the electric power network, as its primary goal is to shift peaks of EV charging load and fill the load valleys. The work in [115, 195, 214] is based on DBS. These schemes mainly provide charging through centralized control. Therefore, EV charging can be interrupted at any time to handle the electric network's constraints.

DSOs based schemes encounter a difficult situation due to the incorporation of distributed renewable energy sources, innovative strategies for assisting prosumers, and the adoption of other DER technologies like EVs, batteries, and demand response programs [215]. EVs may have an impact on the functioning and strategic development of local distribution networks. Their impacts can be classified as voltage and load disturbances. The presence of EVs in the distribution system can lead to an increase in active power losses, which could potentially cause congestion [216]. In order to address these concerns, DSO could be required to make investments in infrastructure enhancements, such as updating power lines or transformers, to mitigate congestion and maintain voltage within the specified limits [217]. The increasing popularity of the EVs and their integrations into electric systems have boosted the significance of DSOs [218].

Recent research has focused on smart grids with electric vehicle integration. These research studies have proposed various energy management systems that take into account various forms of electric vehicle charging as well as the duration of time it takes to charge according to the DSO perspective. Smart charging and V2G charging are essential for reducing electrical network expenses during EV parking. Smart charging is a dynamic charging method that regulates

the charging of EVs based on demand, intending to prevent network failures, particularly during periods of high demand such as rush and peak hours [219]. The authors [220] designed a model that indicates the random characteristics of the initial State-of-Charge (SoC) and starting time when charging an individual EV battery. Four residential charging scenarios were formulated: smart, late-hour, controlled and uncontrolled charging. The four scenarios consider energy market rates, indicating that smart charging is valuable for both DSO and the electric vehicle owner. The research [221] aims to establish a negotiation process between the distribution system operator (DSO) and electric vehicle (EV) aggregator. The objective is to achieve a harmonious equilibrium between the stability of the distribution system operation and the financial benefits of EV charging. The DSO uses the best power flow technique to sustain network performance, while the EV aggregator keeps charging prices to a minimum.

5.1.2.3 System based schemes SBSs offer a combination of the ABS and DBS by compromising the interests of stakeholders. The authors in [196, 197] proposed the SBS for EV charging. The SBS utilizes the objective function of ABS and incorporates limitations analogous to those used by DSOs. The primary goal of this scheme is to minimize the costs associated with charging while also meeting the needs of the DSO. This scheme can yield outcomes that meet the criteria for different entities and consumers [222]. System Based Scheme for EV charging energy management aim to optimize the coordination between electric vehicles, the charging infrastructure, and utility grid in order to achieve optimal efficiency and cost reduction. Generally, these solutions combine an automated control system, a predictive analytics model, and real-time data to effectively manage energy storage, charging time, and power distribution [223]. SBS for electric vehicle charging frequently use V2G technology. This allows EVs to supply electricity back to the utility grid during the periods of high demand, improving stability of the electric grid and lessening the requirement for extra power generation [224].

The primary obstacle in deploying system based scheme for V2G technology is how the general public perceives electric vehicles and their suitability. A significant number of electric vehicles owners have concerns regarding the potential consequences of regular charging and discharging on life-span of their batteries. EV owners also concerned about the financial and time-related risks of being involved in V2G operations [225]. Furthermore, currently EV owners have adequate information about how V2G can help both the individual EV owners and the utility grid. This could result in a reluctance to adopt these kinds of technologies, thus generating challenges to their broad utilization [226].

The SBS aims to minimize charging expenses while satisfying the DSO's requirements. Therefore, SBS is expected to produce worse results when compared with the ABS and DBS according to their respective objectives. The SBS also interrupts EV charging anytime when it is needed. Table 7 presents the comparative summary of ABS, DBS, and SBS [213].

It is clear from the above discussion that to keep users' interests on top priority. In this regard, ABS provides the most important insight. Therefore, more literature is reviewed from ABS. The adopted ideas, as well as the algorithms implemented for EM in these publications, are subsequently presented.

5.2 Energy management schemes for EV charging

The purpose of any EMS for the electrical system is to provide a sequence of the power delivery for each power source to achieve the required objectives while optimizing the available energy. An appropriate EMS allows the system to effectively share the power among powertrain components, increase components' service life, improve system performance, reduce operating costs, increase fuel economy, and reduce carbon dioxide emissions [227]. An open-source framework termed "datafev" based on Python is presented in [228] to develop and test EMS for EV charging. Highly supervisory control is another term for EMS. These control technology like SCADA and PLC are used to control the entire system [229, 230]. Highly supervisory control is further divided into two types (i) optimization-based and (ii) rule-based control strategies [231–233].

5.2.1 Optimization-based algorithms

The optimization-based algorithms aim to provide a formal approach to design EMSs. In most cases, an objective function that represents some degree of optimum energy flow is minimized [234, 235]. Two types of optimization-based control are global optimization and real-time optimization. The former is called online strategy using the intelligent transportation system (ITS) and global positioning system (GPS), indicating that it is a casual method that would not require previous information [236]. To acquire optimal and global minima for lowering fuel consumption, real-time algorithm employs different control algorithms like Pontragin's Minimum Principle (PMP) [237], decoupling control [238], and robust control technique [239, 240].

Table 7 Comparative summary of smart schemes for EV charging systems

Smart charging schemes	Advantages	Drawbacks
Aggregator Based Scheme (ABS)	<ul style="list-style-type: none"> Primary objectives are the minimization of charging prices or maximizing system profit Provides higher satisfaction level for EV users Less communication is required Can provide the lowest charging cost out of all schemes Can decrease the burden on the grid more than uncoordinated charging by providing peak shaving (V2G) or valley-filling 	<ul style="list-style-type: none"> Less or no focus on distribution-side constraints Can cause more electric network congestion
DSO Based Scheme (DBS)	<ul style="list-style-type: none"> Shifting the load peak and filling up the valleys is the primary objective Try to maximize energy delivery Most electric network friendly Network losses are small 	<ul style="list-style-type: none"> May interrupt EV charging due to network constraints Less satisfaction for EV users Interrupts charging anytime
System Based Scheme (SBS)	<ul style="list-style-type: none"> Try to account for all stakeholder's interests Make compromises to minimize charging costs while satisfying the DSO requirements 	<ul style="list-style-type: none"> More complex communication network is required Produce worse results when compared with ABS and DBS on their respective main objectives Interrupts EV charging process

On the other hand, global optimization is an offline technique that is dependent on previous information of the driving cycle and is a non-causal approach to minimizing fuel usage [241]. It can be divided into several algorithms, including stochastic dynamic programming [242], adaptive fuzzy rule-based [243], control theory approach [61], AI [227], simulated annealing (SA) [244], optimal control [245] while others are particle swarm optimization (PSO) [246], linear programming (LP) [247] and genetic algorithm (GA) [43]. The classification and characteristics of optimization-based control strategies are shown in Table 8.

Nowadays, metaheuristic optimization algorithms have gained much attention. To indicate that these algorithms are "higher level" heuristics, the Greek word "Meta" is employed, as contrasted to problem-specific heuristics (that is rule-based). Metaheuristics are widely acknowledged as successful and efficient strategies for complex optimization problems that are difficult to solve within specified constraints and with appropriate fixed methods [264]. In other words, metaheuristics are not specific to a particular issue but provide solutions (usually optimizations) to various problems. To handle complex problems, these algorithms give complementary reasoning and search strategies. These search methods involve iteration processes to find the optimized solution to problems. To have the idea of iterative behavior, the working principle of the PSO algorithm is presented as an example.

PSO is a population-based search strategy based on how flocks of birds behave [265]. It keeps a population of individuals in which every particle is a possible solution. Particles exhibit simple behaviours in which they emulate the successes of nearby particles. Particle position, x_i , is adjusted using the following expression:

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (1)$$

where velocity component (v_i), represents the step size. v_i is calculated by:

$$v_i^{k+1} = wv_i^k + c_1r_1\{P_{best_i} - x_i^k\} + c_2r_2\{G_{best} - x_i^k\} \quad (2)$$

where G_{best} is the position of the particles called global best, c_1 and c_2 are acceleration coefficients, w is inertia weight, $r_1, r_2 \in U(0, 1)$, P_{best_i} is personal best position of the particle i called personal best. Note that r_1 and r_2 are the random numbers. Inertia weight (w) is crucial for maintaining balance between local and global search. Small values of the inertia weight improve local search while high values facilitate global search. It can have the positive decreasing linear function of the iteration index k or the positive constant value which can be found as [266];

$$w = w_{max} - \left\{ \frac{w_{max} - w_{min}}{iter_{max}} \right\} \times k \quad (3)$$

where $iter_{max}$ is maximum times of iteration and w_{max} is the start of the inertia weight, set as 0.9, w_{min} is end of the inertia weight which can be set as 0.4. Figure 7 shows the typical movement of the particles in the PSO process.

Figure 8 shows the execution process of a simple PSO, which can be described and explained using the phases below [266]:

- (i) The population is randomly created in search space.
- (ii) The initial velocities of all particles are randomly generated.
- (iii) The objective function values of all particles are calculated.
- (iv) G_{best} represents the selection of the best particle in the population and the initial position of each particle is chosen as P_{best} .
- (v) Using the Eqs. (1) and (2), the particles are moved to their new positions
- (vi) A particle is replaced with its previous position if it goes outside of its permitted range.
- (vii) The objective function values of all particles are calculated.
- (viii) G_{best} and P_{best} are updated.
- (ix) Criteria for stopping are evaluated. The algorithm is terminated if it is satisfied. Otherwise, repeat steps (v)–(viii). The maximum numbers of the iterations ($iter_{max}$) is used as the stopping criterion for terminating the iterative process.

It is clear from the operation of PSO that the optimization-based algorithms reach the solutions through the iteration process— increasing the decision-making time compared to the time taken by the rule-based algorithms which have no such iterations.

Table 8 Optimization-based classification of algorithms

Serial No	Approach	Algorithm name	Characteristics
1	Real-time optimization	Pontragin's minimum principle (PMP) [248, 249] Model predictive control (MPC) [227, 236, 250, 251] Robust control approach [252, 253] Decoupling control [238] Equivalent consumption minimization strategy (ECMS) [227, 254] Linear programming (LP) [255] Genetic algorithm (GA) [69, 256, 257] Practical Swarm Optimization (PSO) [258–260] Dynamic programming (DP) [261, 262] Artificial Intelligence (AI) [84, 227, 263]	Reduce hydrogen consumption, limit the current rate of change and large current of FCS, and keep SOC within safe limits The power distribution problem in PHEVs is solved by using power input and torque curves to reduce fuel usage This method is used to reduce fuel consumption by solving the power input and torque curve of the power distribution problem in PHEVs Verifying the battery's capacity to drive, power requirements, and state of charge within the specified range It represents future engine efficiency and its use has a direct impact on the sustainability of vehicle power and strategic control efficiency Reduce the operating system's complexity. It is used to reduce fuel usage by treating it as a nonlinear convex optimization problem Organizing, evaluating, optimizing, managing, and scheduling HEVs, as well as lowering the operating costs of the cogeneration system (Power system and combined power) Sizing, scheduling, and pricing of the ESS of the PV grid-tied charging system, as well as the optimal PV array size Locate the optimal action of the PHEV engine, find the optimal power solution, and analyzed sequential decisions making to improve the consumption efficiency of fuel Used for the optimization-based method for estimating and determining the best balance between costs and systems reliability
2	Global optimization		

Fig. 7 Movement of the particles in the PSO process

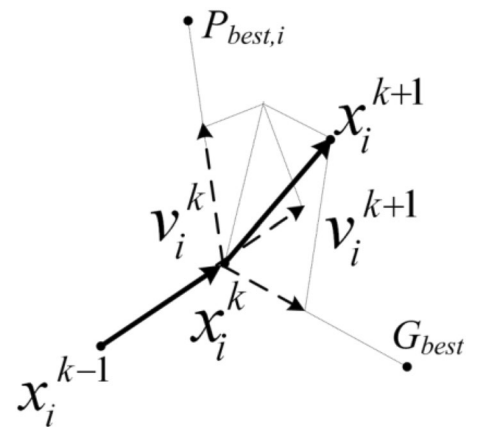
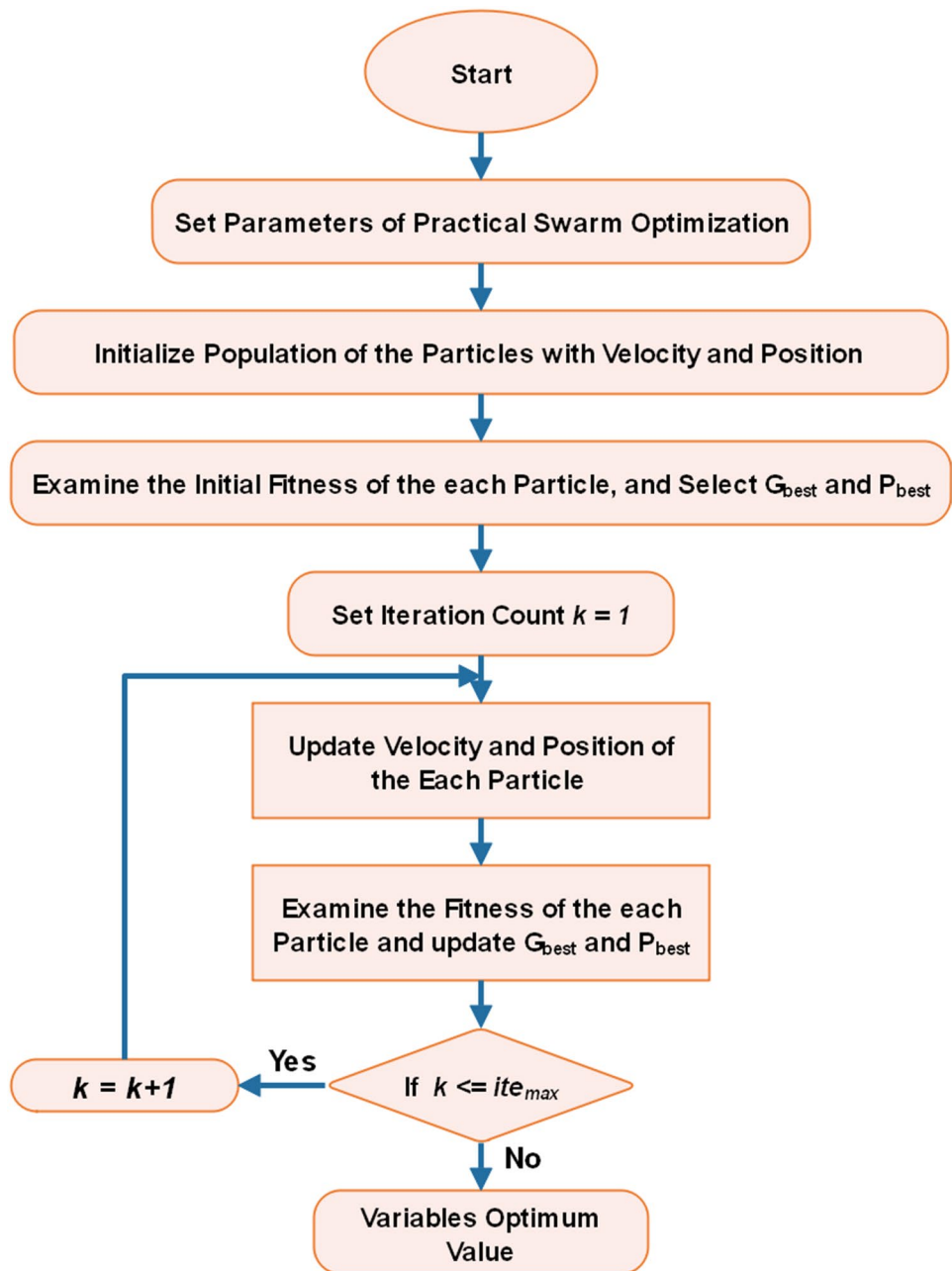


Fig. 8 Flowchart of PSO as a sample metaheuristic optimization algorithm



5.2.2 Rule-based algorithms

The industry is dominated by rule-based EM algorithms because of their rapid computation potential [231]. Due to several advantages such as the lack of complex mathematical equations, short-time solutions, and future decision-making data, these have been deemed the best available tool for making decisions in real time. [238, 267]. To create a set of rules, these algorithms dependent on human expertise and understanding of the system [268].

Deterministic and fuzzy logic are the two types of high-level control. The deterministic control strategies are divided into the following four subcategories: state machine-based strategy [61], power follower (base-line) control strategy [244], modified power follower (based on line strategy) [245], and thermostat (on/off) control strategy [269]. On the other hand, fuzzy logic techniques are divided into three subcategories: fuzzy adaptive strategy [270], convectional fuzzy strategy [227], and fuzzy predictive strategy [271]. The classification and characteristics of rule-based control strategies (high-level control) are shown in Table 9.

Deterministic algorithms function according to a set of rules those have been specified before the actual operation of the system. The fuzzy algorithms still utilize predetermined rules, but, these based on "degrees of truth" in contrast to the more common "true or false" [279]. Fuzzy rules are not suitable for controlling systems that need for the highest level of precision because they are based on approximations. The imprecision in decision-making and the complexity of rules formation further increases for a large number of system components [18, 279]. Therefore, practically, deterministic rule-based algorithm is commonly used to solve EM problems as it is computationally more efficient and generates accurate results [231, 280].

Deterministic rule-based (simply called rule-based in this research) algorithms explain exactly what would have happened in different scenarios [281, 282]. As a result, EM issues are addressed by scheduling resources only in accordance with a set of rules, where real time decisions are made without the use of optimization techniques [191]. In contrast to the optimization-based algorithms, the rule-based are problem-specific and need to be redefined for different challenges. However, data predictions are not required for the implementation of rule-based algorithms, making them suitable for real-time decision-making. Recent literature shows that many researchers have adopted the rule-based approach for EM of electrical power systems [32, 187, 193, 195, 268, 281]. Not only in power systems, the rule-based approaches have been widely applied in various other fields; for example, banking system [283], livestock farms [284], medical sciences [285], business management [286], computer tools [287], agricultural applications [288] and the manufacturing process [289].

To establish these algorithms, 'if-then' rule sets are defined according to numerous scenarios [173, 195, 268, 280, 290, 291]. The 'if' statement is linked to specific scenarios (cases/conditions) and 'then' performs a specific action of the system under the given scenario [290]. To have a conceptual understanding of this approach, a simple example of a self-explanatory rule-based algorithm is given in Fig. 9. The flowchart in this figure presents the decisions taken to balance the energy between the battery and the capacitor installed within EV [281]. Here, the diamond shapes represent various scenarios and the boxes show the operating modes.

Although the above algorithm is very general and the result is not optimal, the performance of rule-based schemes can be improved significantly by considering additional scenarios [281]. It is clear from the above example that rule-based algorithms do not have an iterative process that makes them efficient in decision-making.

5.2.3 Comparison of optimization and rule-based algorithms

The EM algorithms mentioned above have their own pros and cons. A careful examination can lead to the selection of a proper algorithm to be used in the real-time application. Thus, Table 10 shows a comprehensive comparison between these algorithms [191, 280].

It is concluded from the above discussion that the rule-based algorithms are computationally efficient as compared to the optimization algorithms. More so, in contrast to optimization-based algorithms, rule-based algorithms have no such requirements that the future journey profile is known for decision-making which makes them suitable for real-time applications. Owing to the above-mentioned advantages, the rule-based approaches in the development of EMSs for EV charging systems are more promising.

Table 9 Rule-based classification of algorithms

Serial No	Approach	Algorithm name	Characteristics
1	Deterministic rule-based method	State machine-based strategy [61, 237, 272]	Command vehicle operating mode, like an engine (ICE supercharged vehicle), boost, and charging
		Power follower (baseline) control strategy [70, 244, 273]	Turning on/off power depends on SOC, and its design depends on power requirements of the SOC and EV. It is predicated on the energy consumption and emission cost function
		Modified power follower (based on line strategy) [70, 245]	It is based on the cost function of energy consumption and emissions
		Thermostat (on and off) control strategy [269]	This control strategy is simple, reliable, and controllable, resulting in frequent switching (charging and discharging) of the power supply, which brings inconvenience to the ESS
2	Fuzzy rule-based method	Fuzzy adaptive strategy [270, 274, 275]	Improve robustness, load balance, voltage regulation, delivering peak power, and power balance controllers and driver intention predictors
		Conventional fuzzy strategy [11, 227, 276]	This is used to develop the design of fuzzy logic control and load balance by using the complex controller
		Fuzzy predictive strategy [271, 277, 278]	Determine the future state based on past data or estimate speed based on traffic situation along the route

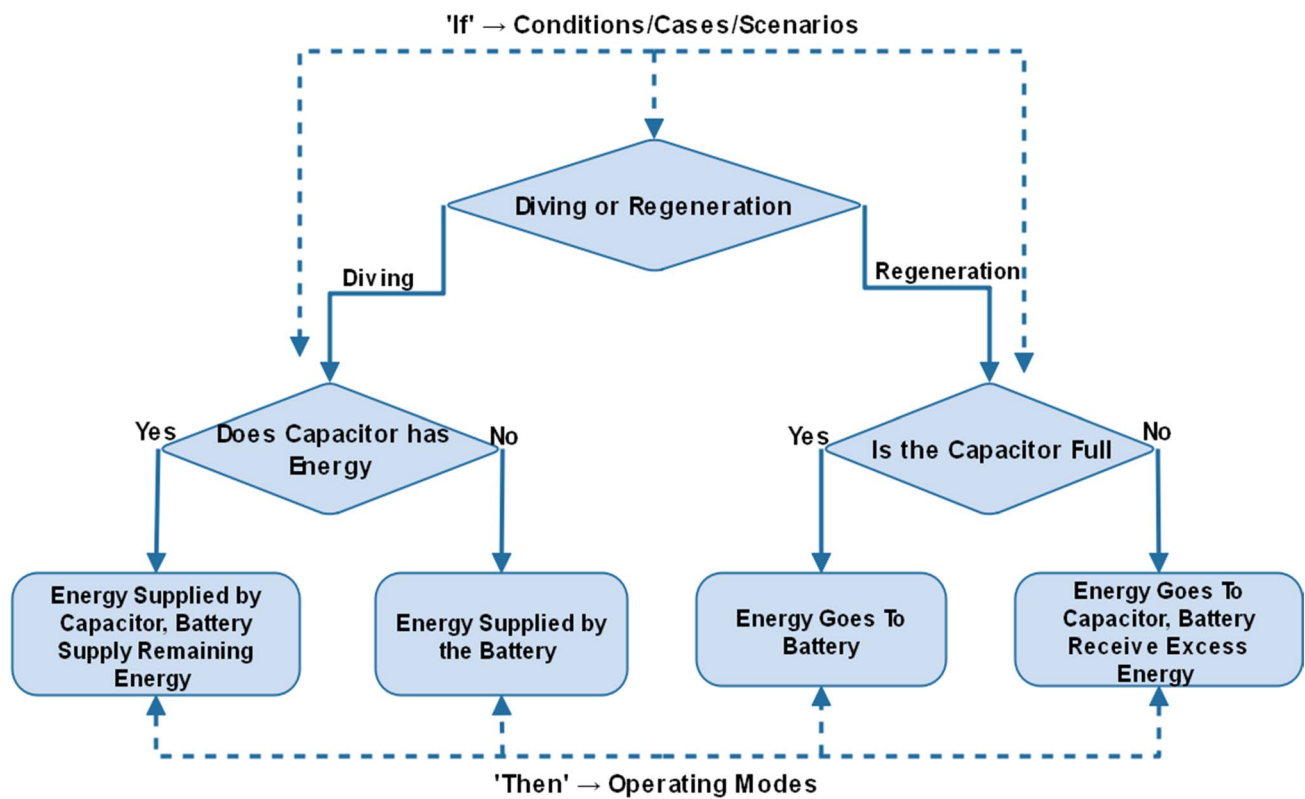


Fig. 9 An example of a simple rule-based algorithm

Table 10 Comparative summary of energy management algorithms

Algorithm type	Advantages	Drawbacks
Optimization-based (Metaheuristic)	<ul style="list-style-type: none"> Effective for hard optimization glitches Less technical knowledge is required to implement 	<ul style="list-style-type: none"> Complex mathematical expression Complexity increases with the increased number of system variables (components) High storage is required High computational time Poor constraint handling ability
Rule-based (Heuristic)	<ul style="list-style-type: none"> No need for complex mathematical equations Low computational time Small storage is required Provide an exact solution 	<ul style="list-style-type: none"> More technical knowledge is required to implement

5.3 Analysis of installed pilot EV sites

Numerous studies provide insightful data for analyzing the findings of pilot sites for electric vehicle (EV) charging stations with sophisticated capabilities and power electronics. Initial results of an EV ownership in the United States with a significant number of public and private charging stations are provided by Schäuble et al. [292]. This study sheds light on the deployment scale and the number of plug-in hybrid electric vehicles (PHEVs) involved, which can be crucial for understanding the impact of such infrastructure. Power architectures and circuit topologies for future megawatt ultrafast electric vehicle charging stations with improved grid support functions have been investigated by Wang et al. [293]. Pinto et al. [294] discuss power electronics converters for fast charging stations with storage

Table 11 Descriptions of different V2G projects around the world [298–305]

Project	Country	Year	Project description
V2G Clarity	UK	2014	This project aims to develop and evaluate a vehicle-to-grid system that allows EVs owners to engage in demand response activities and provides grid services. This project minimizes adverse impacts on battery lifespan and driving distance
V2G-SYNC	European Union	2019	To design and evaluate V2G system that can integrate energy storage systems and renewable energy sources. This project allow bi-directional energy transfer between EVs and the grid while resolving economic, technological, and regulatory issues
Nissan V2G	USA, Japan, and Europe	2012	To showcase the capacity of V2G technology to utilize EVs as a reliable backup power source and ensure stability in the power grid. It also aims to encourage the widespread use of EVs
Electric Nation	UK	2016	To assess the practicability of vehicle-to-grid technology in real-world situations and to analyse the impacts of EV charging on local power grids
V2G-SHARED	Belgium	2019	The objective is to research and experiment with V2G technologies that allow electric vehicles to contribute to the power grid by providing various services, and assess the effects of these technologies on the stability, flexibility, and sustainability of the energy system
INVENT	European Union	2018	To develop vehicle-to-grid technologies that allow EVs to actively engage in energy markets and contribute to grid services, as well as demonstrate their economic viability and sustainability
Nissan Energy Perks by EVgo	USA	2019—Ongoing	To provide electric vehicle drivers with special access to EVgo's network of V2G- equipped and fast-charging stations, as well as opportunities for participating in grid services including peak shaving, demand response, and renewable energy integration
VIGIL	UK	2020	The project objective is to develop and evaluate an intelligent system that can effectively control V2G systems and power networks
V2G Açores	Portugal	2021	Enhance the stability of the electrical system by EVs as flexible load

capacity, emphasizing efficient energy management. The novel solid-state transformer-based EV charging station concept proposed by Eshkevari et al. [295] ensures high power supply without impacting grid quality. Safayatullah et al. [296] emphasize the significance of high-power, low-cost solutions in their thorough evaluation of power converter topologies and control techniques for fast EV charging applications. Additionally, Vasiladiotis & Rufer [297] present a modular multiport power electronic transformer with integrated split battery energy storage for ultrafast electric vehicle charging stations, demonstrating flexible and efficient charging solutions. Table 11 provides comprehensive descriptions of V2G technology projects that have been completed or are currently ongoing around the world.

Analysing these research studies indicates that advancements in power architectures, power electronics converters, solid-state transformers (SST), and innovative transformer designs are crucial for improving the functionality and efficiency of electric vehicle charging stations. These technologies are crucial for meeting the growing demand for reliable and fast charging infrastructure to facilitate the broad acceptance of electric vehicles.

6 Conclusion

It is anticipated that the use of electric vehicles will increase significantly in the coming decade as a result of advancements in EV technology. Increased adoption of the EV needs the proper charging arrangement in the form of charging along with suitable EMSs for coordination among available energy and the charging demand. However, the available literature on this topic lacks in providing a comparative survey on different aspects of this field to properly guide the people interested in this area. To mitigate this gap, this research work is an effort to provide the know-how about the important aspects of the overall EV charging setup. This article reviews the achievements of EMS in terms of improving fuel consumption efficiency and reducing carbon dioxide emissions in EV systems. This article focuses on the state-of-the-art and most up-to-date standards of EV technology, EV batteries, chargers and charging power levels (levels 1, 2 & 3), and charging infrastructure. Power infrastructure in the EV charging station is discussed in accordance with type of power used, physical contacts, and the direction of power flow. In addition, charging schemes through the standard grid and RE resources have been explored. In the standard grid, EV charging is solely accomplished by the utility grid. On the other hand, in the case of RE grid systems, charging can be done through the grid as well as RE sources (such as solar (PV), wind, and biomass). This article introduces a comparative survey of the standard grid and PV-grid charging systems. It also discussed different EV charging control configurations, namely centralized and decentralized. It also introduces the comparative survey between different EMS algorithms and highlights the benefits and drawbacks of each algorithm. The PV grid system can provide a more feasible solution for the day-time charging of EVs in office parking spaces than a standard utility grid system. However, to effectively utilize hybrid power sources, an efficient and intelligent EMS is required. Rule-based EM algorithms are computationally efficient compared to optimization algorithms. The work presented in this review paper will provide a thorough understanding and in-depth knowledge of EV charging infrastructure, standards, and EV charging control configurations namely centralized and decentralized, EV charging through standard grid and RE resources. It also introduces the comparative survey between different EMS algorithms to the engineers and researchers in order to shape future research needs.

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Declarations

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