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A review of the stage-of-the-art charging technologies, placement methodologies, and impacts of electric vehicles

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ABSTRACT

The world population depends highly on fossil fuels, particularly for transportation and power generation. This dependency leads to oil price increases because of the depletion of fossil fuels. Burning of fossil fuels also increases greenhouse gas emissions that are greatly responsible for global warming. Thus, electric vehicles (EVs) are considered one of the premium solutions in the land transportation system because they can significantly reduce the dependency on crude oil and minimize transportation-related carbon dioxide emissions along with other pollutants. This study presents an extensive review of the three key areas of EV research, namely, EV charging technologies, the various impacts of EVs, and optimal EV charging station (CS) placement and sizing. Several technical publications related to EV charging technologies are highlighted, and the performance comparison of different EV technologies is discussed. A review of literature on these key areas reveals an increasing interest in these topics in the last decade, with the impacts of EV on the electric power system and the optimal placement and sizing of CS issues widely investigated. By providing an overview of these areas, this study demonstrates the current issues and challenges of widespread deployment of EVs in the market as well as the future research direction in this field. A total of 185 publications are arranged and appended for quick referencing.

Contents

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1. Introduction

In recent years, the world has realized that the Earth suffers from the effects of global warming and various problems caused by lack of care. Internal combustion engine (ICE) is considered one of the most important components in the transportation sector for creating such problems through carbon dioxide (CO_2) emissions. CO_2 is considered the main perpetrator of global warming. Depletion of fossil fuels is another concern in the transportation system. Therefore, emissions of CO_2 and other pollutants and dependency on fossil fuels should be reduced. The findings in Copenhagen revealed the high possibility of global temperature increasing by approximately 2 °C per year because of the delayed actions to reduce our carbon foot print [1]. Interestingly, electric vehicles (EVs) do not contaminate the Earth or contribute to problems of high oil prices. An EV is a forthcoming technology that has many environmental and economic benefits in the transportation and energy sectors.

Despite these advantages, the massive penetration of EVs on a traditional distribution network for recharging EV batteries poses new challenges for distribution grids and power engineers. Numerous studies on EVs are conducted all over the world. In addition, many automotive industries, organizations, and countries invest millions of dollars to develop and control EVs by predicting the challenges and opportunities of these vehicles. For instance, Google spent $10 million to conduct EV research and test on EVs, while the US government spent $2 billion for the advancement of EV batteries [2].

The present study aims to present an extensive overview of EVs with regard to EV charging technologies, the various impacts of EVs and the optimal placement and sizing of charging stations (CSs). Thus, a literature survey is conducted via journal citation reports database which is the largest abstract and citation database, including IEEE/IET/Elsevier/Springer databases. The survey spans over 10 years from 2006 to 2015. Fig. 1 statistically shows the number of published papers on EVs with regard to the three key areas of this paper, including charging technologies, the various impacts of EVs and the optimal CS placement and sizing. The figure shows the rapid growing research trend of EVs. Fig. 2 indicates the research intensity by each country in the aforementioned three main areas from 2006 to 2015.

The rest of this paper is constructed as follows: first, EV charging technologies are presented in Section 2. The various impacts of EVs are illustrated in Section 3, and the optimal CS placement and sizing are described in Section 4. The current issues, challenges and future trends of this research are presented in Section 5. Finally, the conclusions are drawn in Section 6.

2. EV charging technology

This section presents an overview of the power levels, types, and standards for EV charging.

2.1. Charging power levels and infrastructure

EV supply equipment (EVSE) is the “point-of-fueling” infrastructure uses to deliver electrical energy from an electricity source to an EV charger. EVSE is also known as an electric recharging point [3]. It incorporates cords, connectors, and interfaces into utility power to deliver energy to an EV battery. The interface between the EVSE and the utility power will be directly “hardwired” to a control device or a plug and receptacle [4]. Specific power configurations vary in each country depending on frequency, voltage, electrical grid connection, and transmission standards. The Electric Power Research Institute (EPRI), which plays a leading role, and the Society of Automotive Engineers (SAE) categorize charging levels as alternating current (AC) Level 1, AC Level 2, and direct current fast charging (DCFC) Level 3, along with the subsequent functionality requirements and safety systems [5]. However, the new revision of SAE standards classifies DCFC into direct current (DC) Level 1 and DC Level 2 [6]. The International Electrotechnical Commission (IEC) also defines four modes of EV charging, namely, AC Mode 1 (slow), AC Mode 2 (slow), AC Mode 3 (slow/fast), and DC Mode 4 (fast) based on IEC 61851-1 [7]. EPRI discloses that the majority of EV owners expect to recharge their EVs overnight at home. Therefore, AC Level 1 and AC Level 2 are the most prevalent charging levels for them [8]. The conversion from AC to DC for these charging levels occurs in the vehicle onboard charger [9]. The charging levels according to EPRI are represented as follows:

2.1.1. Charging Level 1

Level 1 uses standard 120 V AC household outlets with a current handling capacity of 15 A (12 A usable) or 20 A (16 A usable), where a 12 A charge takes twice as long as a 16 A outlet. This charging level usually uses the standard electrical outlet NEMA 5–15 R/20 R with a current-interrupting device at one end and an SAE J1772 standard connector at the other end. Level 1 can draw 1.4–1.9 kW powers depending on ampere rating [6,9]. Therefore, this charging level takes 8–16 hours to fully charge an EV battery depending on the battery type and size. This level is the cheapest and most convenient home-based charging method, but the slowest and lowest common level found in both residential and commercial buildings. For home sites, an additional infrastructure is not needed. Low off-peak rates are expected to be available at night. Residential Level 1 charger infrastructure costs are estimated approximately $500 - $880 [10].

2.1.2. Charging Level 2

Level 2 is typically defined as the primary and prominent method for both private and public facilities; this level assigns single-phase 240 V AC with a current-handling capacity of 40 A for private installation and a three-phase 400 V AC with a current-handling capacity of 80 A for public installation [5]. Most Level 2 EVSE use a dedicated 40 A (maximum 32 A usable) circuit. SAE International has developed a standard connector and receptacle for Level 2 based on the SAE J1772 standard [11]. This charging level can provide 7.7–25.6 kW power and usually takes 4–8 h to

Nomenclature

AC	Alternating current
ACO	Ant colony optimization
BSS	Battery swapping station
CC	Constant current
CO_2	Carbon dioxide
CP	Constant power
CS	Charging station
CV	Constant voltage
DC	Direct current
DCFC	DC fast charging
DCFCS	DC fast charging station
EPRI	Electric power research institute
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
GA	Genetic algorithm
GHG	Greenhouse gas
ICE	Internal combustion engine
IEC	International electrotechnical commission
PC	Pulse current
PEV	Plug-in EV
PHEV	Plug-in hybrid EV
PSO	Particle swarm optimization
RCS	Rapid charging station
SAE	Society of automotive engineers
SOC	State-of-charge
TC	Trickle current
THD	Total harmonic distortion
VI	Voltage imbalance
V2G	Vehicle-to-grid

Symbols

AP_L	Additional power loss
I_h	RMS value of the current
THDi	Total current harmonic distortion
THDv	Total voltage harmonic distortion
TPL_{EV}	Total power loss with EV load
TPL_{origin}	Total power loss without EV load
V_h	RMS value of the voltage

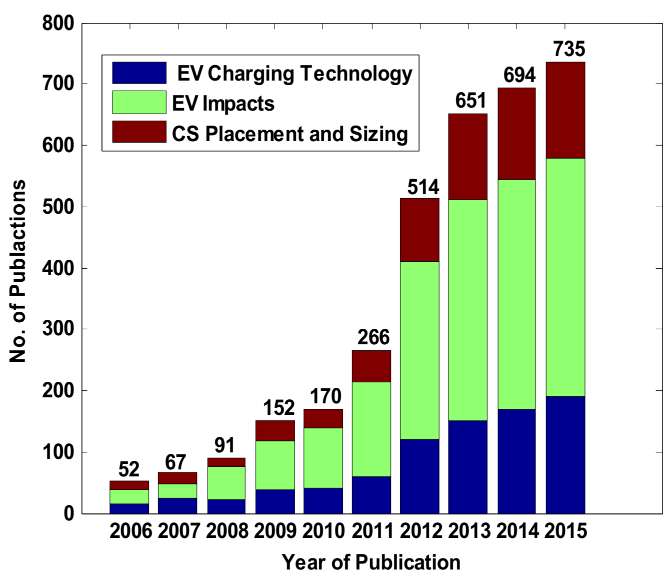

Fig. 1. Number of publications in the three main areas of EV research from 2006 to 2015. Source: JCR 2015.

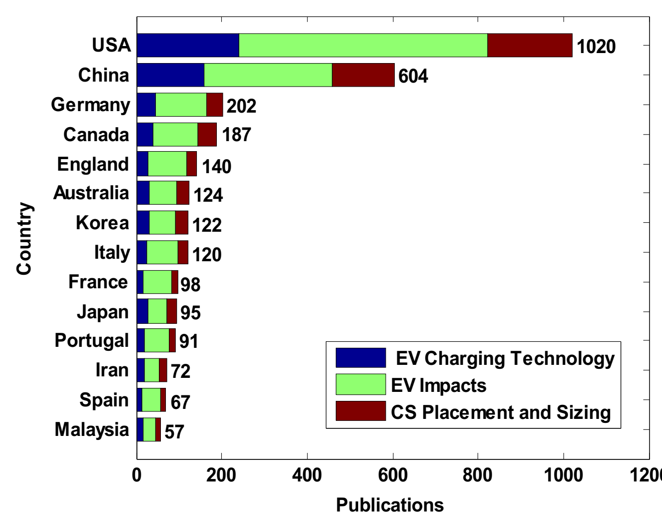

Fig. 2. Number of papers produced by various countries in the three main areas of EV research from 2006 to 2015. Source: JCR 2015.

charge an EV battery [6,9].

EV users can normally charge an EV battery overnight without affecting the home gadgets because of the availability of the 240 V AC service. Users highly affiliate themselves to Level 2 technologies because of their fast charging time and standardized vehicle-to-charger connection. Level 2 EVSE operates on the same circuits that generally run household appliances, such as electric ovens and clothes dryers/washers [12]. However, the current demand of a household can be increased by up to 25% [13]. Important procedures must be followed to ensure safe and efficient charging opportunities when installing EVSE at home. Users can also charge EV batteries outside their home through an “occasional-use cable” supplied by the manufacturer [14]. The cable itself protects over-current, and over-temperature. It also has earth detection. Residential Level 2 infrastructure installation costs are estimated at approximately $2150–2300 [10], whereas commercial public station costs are more than $15000 [11]. For example, the Tesla Roadster charging system imposes an additional cost of $3000 [15].

2.1.3. Charging Level 3

Level 3 charging is suitable for commercial and public applications and is intended to provide consumers an experience similar to a commercial filling station with oil-based fuel by performing a DC fast charge. In general, fast charging provides 80% charge in 10–15 min depending on battery type and size. In practice, DC charging is measured up to 80% because the last 20% takes a very long time to fully charge an EV battery [14]. In Level 3, the conversion from AC to DC generally occurs in an off-board charger; thus, DC power is delivered to the vehicle [9]. The off-board charger is utilized by a three-phase circuit with 208–600 V AC that can support up to 200 A to provide fast EV charging. The specifications for an off-board power source are quite challenging because this power source is not dedicated to a certain EV type. Nevertheless, an off-board charger minimizes on-board cabling,

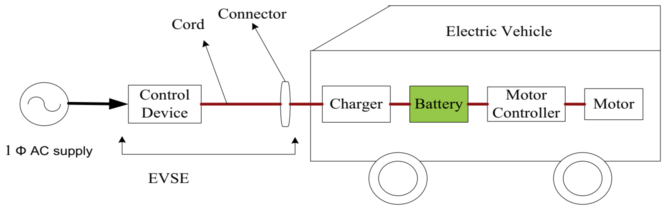

Fig. 3. EVSE arrangement for on-board AC slow charging.

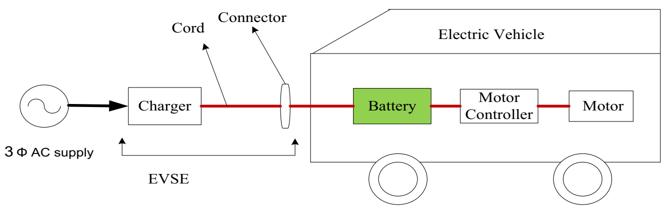

Fig. 4. EVSE arrangement for off-board DCFC.

thereby reducing the overall weight of EVs [8]. The off-board fast charging standard SAE J1772 "Combo" is gaining popularity over the Japanese CHAdeMO [14]. According to the new revision of SAE standards, DCFC is divided into DC Level 1 and DC Level 2, where the output power for Level 1 and Level 2 varies respectively from 0–40 kW and 40–100 kW [16]. DC charging is appropriate in highway rest areas, shopping mall areas, governmental facilities, restaurants, entertainment venues, airports, and city refueling points, where drivers can quickly charge an EV battery while performing other businesses [17]. CS installation cost is a potential issue. Level 3 charging infrastructure costs are reported between $50,000 and $160,000 depending on the quality and nature of the components [18]. The maintenance of a CS is another cost factor [19]. Nevertheless, the deficiency of public CSs can cause "range anxiety" or "charge anxiety" [3].

Figs. 3 and 4 represent EVSE arrangement with the on-board AC slow charging and off-board DCFC schematic, respectively.

Table 1 shows the charging levels of the SAE J1772 standard and compares the charging times of similar EV batteries. Table 2 represents the charging characteristics of different EVs.

2.2. Types of charging systems

A battery charger is a device used to transfer energy to a rechargeable EV battery by processing and controlling the electric current through it. An EV charger incorporates a rectifier to recharge an EV battery by converting AC to DC. Fig. 5 shows the basic arrangement of a battery charger. Battery charging can be categorized based on the mode of energy transfer such as conductive or inductive, and the battery swapping types [9,21,22].

2.2.1. Conductive charging

Conductive charging scheme transfers power through direct contact. This scheme uses a conductor to connect the electronic devices to the extent of energy transfer. Conductive charging is simple and highly efficient. It can be an on-board or off-board method. An on-board charger is mainly utilized for slow charging, and the charging activity is conducted inside the EV, whereas an off-board charger is installed at fixed locations to offer rapid charging service. Conductive charging is available in Nissan Leaf, Tesla Roadster and Chevy Volt [9]. Fig. 6 represents the conductive charging scheme.

2.2.2. Inductive charging

Inductive charging, also known as wireless charging, uses an electromagnetic field to transfer electricity to an EV battery. The benefit of inductive charger is that it provides electrical safety under all-weather conditions. The drawbacks of state-of-the-art inductive chargers are low efficiency and high power loss. Nonetheless, a commercial inductive charger can deliver high power at an efficiency of up to 86%. For instance, it can deliver 6.6 kW power from 7.68 kW input power [21]. Fig. 7 represents the inductive charging scheme.

2.2.3. Battery swapping

Battery swapping is a scheme by which users can swap their empty battery with a fully charged one from a battery swapping station (BSS). BSSs have several benefits, such as long battery lives, low time consuming, and comparatively minimal cost to manage, given that batteries are collected and managed in centralized locations. For instance, Tesla, a renowned car maker, swaps an EV battery in 90 s [23]. Battery swapping gives the chance to avoid the peak demand of the grid, possibly saving a significant of money [22]. Conversely, BSSs have some drawbacks, such as high investment cost and huge space, which are required for BSS construction; the current battery management system is also not good enough to ensure battery safety [24]. China has built the highest number of BSSs and charging spots in the world [25].

2.2.3.1. Battery charging techniques. Rechargeable battery is considered the main energy resource of EVs. The recent widespread deployment of EVs is the result of the significant improvement of battery technology, which has transformed from lead-acid to lithium-ion battery. At present, researchers study other types of high-energy density batteries, such as lithium-sulfur batteries, for EV applications [26]. Different charging techniques are available to charge an EV battery. The traditional charging techniques include constant current (CC), constant voltage (CV), constant power (CP),

Table 1
Charging levels of the SAE standard J1772 [6].

Level	Input voltage and current	Charger location	Maximum power (kW)	Battery size (kW h)	Charging time (h)	Typical use
AC Level 1	120 VAC-15 A (12 A useable) 120 VAC-20 A (16 A useable)	On-board 1-phase	1.44 1.92	24 (energy available 19.2)	10–13	Home or office
AC Level 2	240 VAC-40 A(32 A useable) 400 VAC-80 A(64 A useable)	On-board 1-phase/3-phase	7.7 25.6	24 (energy available 19.2)	1–3	Private or public outlets
DC Level 1	208 VAC-80 A(64 A useable) 600 VAC-80 A(64 A useable)	Off-board 3-phase	13.3 38.4	24 (energy available 19.2)	0.5–1.44	Public, commercial
DC Level 2	208 VAC-200A(160 A useable) 600 VAC-200A(160 A useable)	Off-board 3-phase	33.3 96	24 (energy available 19.2)	0.2–0.58	Public, commercial

Table 2
Charging characteristics of different EVs [16,20].

Model	Vehicle type	Battery size (kW h)	Energy available (kW h)	Range (km)	Energy consumption (kW h/kW)	AC Level 1		AC Level 2		DC Level 3	
						Demand (kW)	Charge time(h)	Demand (kW)	Charge time(h)	Demand (kW)	Charge time (h)
Nissan Leaf	EV	24	19.2	160	0.12	1.8	11	6.6	2.9	50	0.4
Mitsubishi i-MiEV	EV	16	12.8	150	0.086	1.5	9	3.6	4	50	0.26
Toyota RAV4	EV	41.8	32.18	160	0.20	1.9	17	9.6	3.35	50	0.64
Cooper (BMW)	EV	28	21.5	160	0.13	1.9	11	7.6	2.8	50	0.43
Sabaru Stella	EV	9.2	7.1	80	0.09	1.8	4	3.8	2	47	0.15
Tesla Roadster	EV	53	37.1	340	0.11	1.8	21	16.8	2.2	100	0.37
Chevrolet Volt	PHEV	17.1	13.7	64	0.21	1.4	10	3.6	4	N/A	N/A
Toyota Prius	PHEV	5.2	4.1	25	0.16	1.8	3	3.2	1.5	N/A	N/A
Buick	PHEV	8	6.4	16	0.40	1.4	4.6	3.2	2	N/A	N/A
Frisker karma	PHEV	22	17.6	80	0.22	1.8	10	3.6	5	N/A	N/A

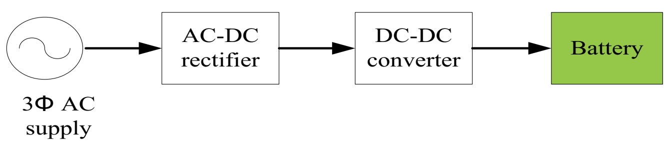

Fig. 5. Basic components of a battery charger.

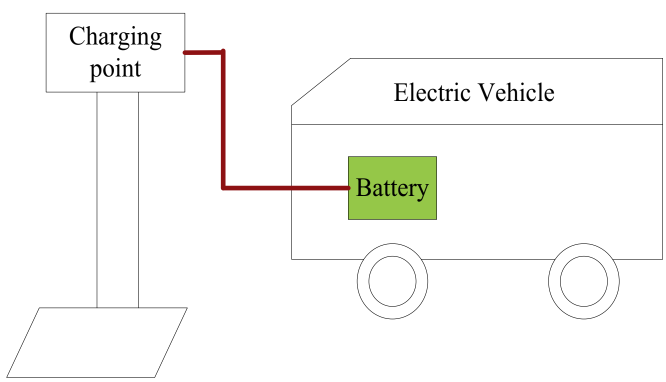

Fig. 6. Conductive charging.

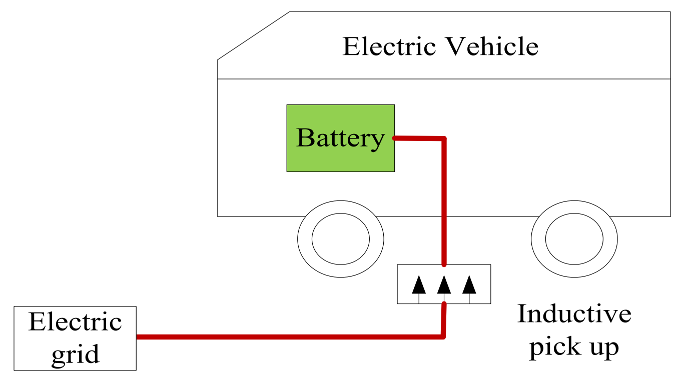

Fig. 7. Inductive charging.

trickle current (TC), and taper and float charging. An advanced charging technology recently combined the aforementioned techniques, resulting in CC-CV and pulse and reflex or negative pulse charging, which are utilized to charge batteries rapidly [27].

2.2.3.1.1. Slow charging. CC charging is the simplest technique; it employs a single low-level current to the discharged battery. In practice, the current level is set as 10% of the maximum rated capacity of the battery. This type of charging is best suited for nickel-cadmium and nickel-metal hydride batteries [28]. However, gassing and overheating may occur if the battery is overcharged. Similarly, a small current is applied to recompense for the self-discharge of a battery in TC charging [27]. Taper charging utilizes unregulated CV charging, which may results in serious damage to the cells through overcharging. On the contrary, float charging uses CV method below the upper limit of the battery. This charging system is usually used for emergency power back-up systems and is suitable for lead-acid battery [28].

2.2.3.1.2. Rapid charging. In general, CC–CV charging technique is utilized for majority of commercial chargers to charge a lithium-ion battery because this battery has higher power and energy densities than others. The advantages of the CC–CV technique include limited charging current and voltage through battery controller utilization; thus, over-voltages are prevented and thermal stress is reduced. First, a CC is applied to charge a battery until a pre-defined voltage level is achieved, and then a CV is used until a termination condition is reached. CC charging mode is faster than CV charging mode. The CV mode is used to prevent overvoltage charging, which can increase loss of battery life [29]. A method to improve the battery performance of an EV was proposed in [30]. This method included rest periods during battery charging to reduce battery temperature, which is one of the main factors affecting battery performance. The study showed that battery degradation is reduced by 14% through the proposed method compared with standard CC–CV charging; thus, the battery life is extended by 17%. However, the total EV charging time increased because rest periods were included. The CC–CV charging technique was improved in [29]. In this study, an algorithm based on integer linear programming was applied to determine the optimal charging profile of a multi-step CC–CV charging scheme. The results showed that compared with the standard CC–CV charging technique, the suggested algorithm could significantly reduce the charging time by up to 18.25% for rapid charging. Nonetheless, numerous switching actions are required to transfer from one step to another step, thereby increasing the total power losses. On the contrary, He et al. [31] proposed reconfiguration-assisted charging in lithium-ion battery systems to reduce the cell imbalance issue and increase battery charge capacity. First, the battery cells were categorized based on their real-time voltages, and then the CC–CV charging process was applied in a group-by-group manner. Both simulation and experimental results showed that the proposed method increases battery cell charging capacity by approximately 25%.

Some studies considered pulse current (PC) charging to charge an EV battery rapidly [32–34]. This charging technique uses pulses

Table 3
Standards for EV charging [7,14,36–40].

No	Standards		Scope
1	IEC 61851: conductive charging systems	IEC 61851-1	Defines cables and plug setups
		IEC 61851-23	Describes electrical safety, harmonics, grid connection, and communication architecture for DCFC station (DCFCS)
		IEC 61851-24	Explains digital communication for DC charging control
2	IEC 62196: Plugs, socket-outlets, vehicle connectors and inlets	IEC 62196-1	Explains general requirements for EV connectors
		IEC 62196-2	Describes coupler types for different charging modes
		IEC 62196-3	Defines connectors and inlets for DCFCS
3	IEC 60309- Plugs, socket-outlets and couplers	IEC 60309-1	Explains general requirements for CS
		IEC 60309-2	Describes different sizes of plugs and sockets with different number of pins based on current supply and number of phases, also defines color coded connector based on voltage range and frequency
4	IEC 60364		Describes about electrical installations for buildings
5	SAE J1772: conductive charging systems		Defines connectors for AC charging
			Describes new Combo connector for DCFCS
6	SAE J2847: Communication	SAE J2847-1	Describes the communication medium and criteria for the EV to connect to the utility for AC Level 1 and AC Level 2 energy transfer
		SAE J2847-2	Defines additional messages for DC energy transfer
7	SAE J2293	SAE J2293-1	Describes the total EV energy transfer system and allocates requirements to the EV or EVSE for the various system architectures
8	SAE J2344		Describes guidelines for electric vehicle safety
9	SAE J2954: inductive charging		Under development

Fig. 8. New SAE combo connector.

in every second to feed the charge current to the battery. Therefore, precise pulse control is important. PC technique was proposed in [32] based on optimal frequency and duty cycle searching modes. The results showed that PC charging speed is more than two times faster than the speed of the CC-CV charging system. Another study in [33] utilized hybrid sinusoidal PC to charge an EV battery, and showed that the performance of the hybrid PC charging technique is better than that of the standard PC. On the contrary, both positive and negative pulse frequency current control techniques were utilized in [34] to minimize the charge time of an EV in a fast CS. The results illustrated that the proposed technique requires 4 min less time to charge an EV battery from 20% of state-of-charge (SOC) to 80% of SOC, and the temperature rise is 1 °C less than the temperature rise in the CC–CV technique.

The charging time of a battery is one of the most important issues in the large deployment of EVs. Many studies enhanced the standard CC–CV charging technique to reduce the charging time and increase battery capacity. For the same purpose, PC-based charging technique is also used in different studies. However, the current charging systems still have some limitations. Therefore, more studies are required on this issue for enhancement.

Fig. 9. CHAdeMO connector.

2.3. Standards for EV charging

Various types of standards for EV charging are utilized in different regions of the world. Table 3 represents the EV charging standards based on IEC and SAE. SAE developed a new connector for DC rapid charging known as SAE J1772 Combo, which incorporates AC and DCFC standards in one unit. This charging standard can provide a significant solution to the charge anxiety problem and the widespread the deployment of EVs. Combo connector becomes the global standard in contrast to the previous technology known as CHAdeMO, which was introduced by Japanese automakers and Tokyo Electric Power Company [14,35]. By contrast, CHAdeMO only contains the DC standard. Figs. 8 and 9 show the Combo and CHAdeMO connectors, respectively.

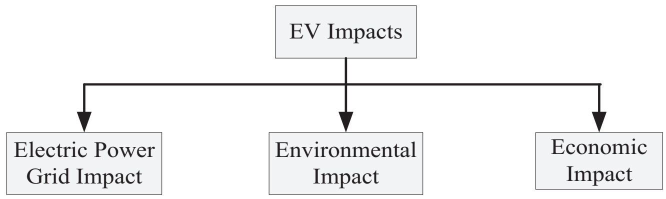

Fig. 10. Classification of EV impacts.

3. Impacts of EVs

The current growth of EVs is anticipated to lead the enormous penetration into electric power grids in the near future. The supplementary energy consumption of EVs may add extensive loads on power grids. These additional loads have numerous adverse effects on existing distribution networks. On the contrary, massive uses of EVs with smart technologies have favorable impacts on environment and economy. An EV not only reduces the emissions of greenhouse gases (GHGs) and other pollutants, but also improves the utilization of renewable energy resources [41]. Thus, EVs contribute to clean transportation and energy independence. The overall impacts of EVs can be classified into three major categories, as shown in Fig. 10. The following sub-sections provide details of these various impacts.

3.1. Impact of EV on electric power grid

Significant attention is given on EVs to tackle the global climate change challenges, given that the transportation sector is considered the second highest contributor of carbon emissions [42]. However, large scale deployment of EVs demands additional power from a traditional distribution network. This scenario indicates a wide variety of significant adverse impacts on this distribution network. These impacts may vary based on EV penetration levels, EV battery characteristics, charging patterns, charging locations, charging modes, charging times, battery SOC while charging, EV driving patterns, fleet charging profiles, driving distances, demand response strategy, and tariffs [20,43]. EVs also have noteworthy positive effects on a distribution network. The impacts of EVs on a distribution network can be categorized as follows:

3.1.1. Adverse impacts

This sub-section describes the adverse impacts of EVs on the existing distribution network such as voltage instability, increased peak demand, power quality problems, increased power loss, transformer heating, and overloading (Fig. 11).

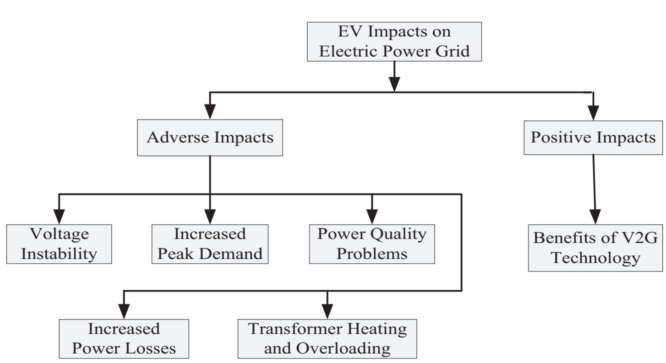

Fig. 11. EV impacts on electric power grid.

3.1.1.1. Voltage instability. Major blackouts in a power system mainly occur because of voltage instability. The reason is that the power system is operated close to the stability limits because of excessive power demands [44]. Different load characteristics also play a vital role in inaugurating voltage instability [45]. However, a stable electric power grid is imperative to ensure reliable power supply for users. EV load characteristics are different from the traditional household or industrial loads [46–48]. In particular, EV loads are nonlinear in nature and take a huge amount of power for a short period to fully recharge an EV battery. Load characteristics have a noteworthy influence on voltage stability; therefore, the effects of EV loads on grid voltage stability must be properly investigated.

The impacts of EV loads on power system voltage stability were examined in [49–53]. In [49], the authors developed an EV load model in MATLAB SIMULINK with a combination of CP and voltage-dependent and negative exponential components. The model was simulated on the IEEE 43-bus test distribution system, and then voltage stability was analyzed by considering the load margin for various circumstances, such as CS locations, number of CSs, and power factors. The study confirmed that EV charging is highly responsible for voltage instability in the power grid. In a related work [50], spatio-temporal travel patterns were utilized. In this work, power system modeling was handled in openDSS software and simulated on an IEEE 39-node test feeder system. The high charging level with massive penetration of EVs causes voltage instability in power grids. However, constrained charging strategy extensively improves power system reliability. For the same purpose, Onar et al. [51] considered an individual household as an EV load for the existing distribution network, and their model was simulated on IEEE 3-bus test system. This model identified that system voltages are responsive to disturbances and slightly stable with EV load because this load injects harmonic currents to the distribution network. A multilayer perceptron neutral network approach based on voltage stability L-index was estimated in [52]. This approach determined that system voltage stability margin fluctuates in accordance with EV smart park operation, charging, and discharging. However, the study in [53] showed that power grids can adopt many plug-in hybrid EVs (PHEVs) as constant impedance load before the occurrence of voltage instability. This study also represents that the constant impedance control charging improves system performance and shows lower loading margin than the CP method. The aforementioned models are designed and simulated irrespective of uncertainty of EV penetration, variable SOC, and variable EV types. EV loads are different from other typical loads because the power consumption of EVs cannot be anticipated in advance. Therefore, distribution constraint violations may occur if numerous EVs are connected to a distribution network. Hence, proper EV load modeling is imperative.

A wide area control method that damps out the oscillations during charging and discharging of an EV battery was suggested in [54] to overcome the voltage instability problem caused by EV penetration. Similarly, bus voltage control method via tap changing transformer was proposed in [20] to mitigate voltage instability. The authors also demonstrated that proper planning of charging infrastructure is vital to mitigate voltage instability. The main perceptions behind CS planning include proper site selection, sizing of CS, and charging time. Fuzzy logic controller was utilized in [55] by considering the real-time voltage and SOC of an individual battery to ensure proper grid operation.

3.1.1.2. Increased peak demand. Various studies have been conducted to examine the impact of EV charging on grid peak demand. The substantial peak demand imposed by the large deployment of EVs was investigated in [56]. The authors determined that uncoordinated charging with full EV penetration introduces peak demands that surpass the existing generating capacity on average load days. Therefore, at least 93% of the EV loads must be shifted to off-peak or shoulder times if no new generation is added to the power network. Similarly, Wang and Paranjape [57] showed that uncoordinated EV charging leads to increase peak demand by 53% with 30% EV penetration. Meanwhile, Putrus et al. [58] revealed that uncontrolled domestic charging contributes a large peak with 10% EV penetration. Nonetheless, Hadley [59] identified that peak demand increases under a normal EV charging condition. Thus, a smart charging concept is required.

Smart or controlled charging and time-of-use tariff plan can significantly reduce peak demand without extra generation capacity expansion [60,61]. For instance, Hajimiragha et al. [62,63] estimated that approximately 500,000 PHEVs can be charged from a distribution network at Ontario, Canada without affecting this distribution network. Similarly, Meyer et al. [64] presented that the existing grid capacity of the US can tolerate 73% PHEV penetration.

3.1.1.3. Power quality problems. The massive penetration of EVs in a distribution network can affect supply quality. Charging demand may arrive at high levels if large numbers of EVs are integrated with distribution networks [65]. The majority of the studies consider harmonics and voltage imbalance (VI) to discuss the impacts of power quality caused by EV penetration on distribution networks. Voltage sag and noise are likewise studied.

3.1.1.3.1. Harmonics. Harmonics are represented as a component of voltage and current spectrums whose frequencies are an integer multiplication of the reference frequency (i.e., 50 or 60 Hz) [66]. The undesirable voltage and current spectrums in a power system are caused by non linear loads, such as EVs. Total current harmonic distortions (*THDi*) and total voltage harmonic distortions (*THDv*) can be expressed in percentage, as shown in Eqs. (1) and (2) [67]:

$$THDi = \frac{\sqrt{\sum_{h=2}^{H} I_h^2}}{I_1} \times 100\% \tag{1}$$

$$THDv = \frac{\sqrt{\sum_{h=2}^{H} V_h^2}}{V_1} \times 100\% \tag{2}$$

where h is the harmonic order number, H is the highest number of harmonics, I_h and V_h are the RMS value of the current and voltage at the hth harmonic component, I_1 and V_1 are the RMS value of the fundamental frequency current and voltage, respectively.

The recent works that determined that EV charging produces harmonic current and voltages were presented in [68–74]. First, the detrimental effects of harmonic currents to a distribution network caused by a massive EV integration were examined by Orr et al. [68]. This study is considered one of the innovative works in relation to the effects of EVs on a power system. In this work, the authors considered five types of chargers as a sample for an EV. Charging time and SOC were considered the probabilistic parameters, and Monte Carlo simulation was utilized to analyze the system. The study determined that approximately 10% EV penetration into the distribution networks signifies the possibility of detrimental effects to customers and utility equipments. Nonetheless, other parameters, such as charging level, uncertainty of EV penetration, and initial charging time, were disregarded during the simulation. Similarly, a Monte Carlo simulation-based probabilistic harmonic approach was developed in [69] to determine the power quality impact of EVs at both reference and harmonic frequencies. This approach was regarded with random operating characteristics of EVs, such as charging time, charging duration, and EV locations. Some case studies confirmed that EV charging has a slight harmonic effect on a distribution network. However, Level-1 showed a significant rise in neutral-to-earth voltage. This scenario can be directed to stray voltage occurrences. The uncertainties of harmonic, SOC, and EV penetrations were ignored in simulating the models. In a similar work, the results of harmonic distortions caused by a plug-in EV (PEV) charging on a smart grid distribution system in Australia were presented in [70]. The simulations were performed on IEEE 30-bus test system with different charging scenarios, including different penetration levels, charging rate, and time zone scheduling. The results indicated that the harmonic distortions are in acceptable limits with low PEV penetration. However, the high penetration of PEVs showed considerable *THDv*. Similar results were presented in [71]. This study showed that with few EVs rapid charging, *THDv* reaches 11.4%, which exceeds the acceptable limit of 8%. On the contrary, the authors in [72] revealed that rapid charging of EVs produces high *THDi* in the range of 12%–24% and creates significant adverse effects on low-voltage residential distribution networks; however, the *THDi* is below the standard limit for slow charging [73]. Zamri et al. [74] performed actual harmonic measurement and analysis on conventional and modern types of EVs. They used the Fluke power quality meter, which provides voltage and current harmonic spectrums in real time. The findings showed that the *THDi* and *THDv* generated by the modern EV are lower and higher, respectively, than those generated by the conventional EV. In addition, a comparative study was conducted on harmonics, which are generated during single EV charging and a group of EVs charging. The comparative study confirmed that the summation of THD is not a linear multiplication with the increased number of EVs connected to a distribution network.

An EV charger contains nonlinear characteristics, which are highly responsible for voltage and current harmonic distortions in a distribution network. These harmonic effects usually create a powerful stress on distribution network components, such as fuses and cables [48,75]. A study was presented in [75] to determine the effect of EV charging for the period of peak demand on cable loading. The outcomes showed that the existing cable can normally handle 25% and 15% EV penetration for slow and rapid charging, respectively. Another problem, which is introduced as a consequence of harmonic distortions and voltage unbalance, is neutral wire current [69,76,77], which may become detrimental if overloaded. Simple and effective EV models were suggested in [78] to estimate the electromagnetic noise emission produced by EV traction drive. The authors determined through laboratory tests that the noise production in EVs is mainly caused by the high-speed switching of power electronic devices in the electrical traction system.

In general, a distribution network undergoes a vast number of nonlinear loads to supply the required electrical power to users. Therefore, various harmonic patterns may be produced in a distribution network because of different EV chargers. However, various load patterns can be contributed to harmonic cancellation in power networks [79,80]. The increase in the number of EV customers results in the high possibility of harmonic cancellation [48]. Harmonic effects can be overrated if the diversity of EV chargers is ignored [79]. A practical example of harmonic cancellation as a result of various phase angles and magnitudes of different EV chargers was presented in [79]. The authors determined that the existing distribution system can provide sufficient power for 20% and 15% EV penetration levels in summer and spring, respectively, before *THDv* goes beyond 5%. For the same purpose, Bentley et al. [80] showed a comparative study on four traditional PEV chargers, such as pulse width modulation, square wave, single-phase rectifier, and three-phase rectifier. The study concludes that pulse width modulation can be a promising option to lessen or eliminate the unexpected harmonics induced from different nonlinear loads. This type of charger can automatically reduce the selected harmonics or THD of the supply.

A smart grid compatible power conditioning unit was proposed in [81] to solve the power quality problems by permitting controlled charging to an EV. This power unit was experimented in terms of battery charging, discharging, capacitive, and inductive operating conditions. The obtained results determined that the proposed power conditioning unit can mitigate power quality issues by improving voltage quality, decreasing THD, and providing reactive power compensation for an EV battery. The authors suggested off-peak charging, which is not desirable to users, to control EV charging. The installation of filtering components at the head of the supply system is considered one of the solutions for high *THDi* [82–84]. For instance, Balcells and Garcia [82] tested single-phase and three-phase chargers with an additional series reactor as a filter. The results showed that the reactor has no noteworthy effect for single-phase chargers, but can improve *THDi* about 50% for three-phase chargers. A shunt active filter was also used to cancel higher-order harmonic components, and this method showed that the active filter can significantly reduce the neutral current from 56 A to 5 A because of reduced harmonic currents. Nonetheless, network parameters and charging scenarios were not discussed clearly to achieve deep insight. In Masoum et al. [83], smart appliance passive filter banks were placed to improve the overall power quality. Particular harmonic suppression filters were installed in [84]. In this work, fifth and seventh harmonic single-tuned filters were installed and showed that both filters can provide good remedy. The authors also suggested that, in general, no harmonic measurement is needed for small-sized CSs; however, occasionally, only fifth harmonic measurement is required for medium-sized CSs.

3.1.1.3.2. Voltage imbalance. Voltage variation in a three phase system is a condition in which the differences between voltage magnitudes or phase angles are not equal. It occurs only in a polyphase (e.g., three-phase) system because of unequal loads in distribution lines. The VI can be calculated as shown in Eq. (3) [67]:

$$VI = \left|\frac{V_-}{V_+}\right| \times 100\% \tag{3}$$

where V_- and V_+ represent the negative and positive sequences of the voltage, respectively.

In the research of Shahnia et al. [85], the sensitivity of VI in consideration of the locations and levels of charging and discharging of PEVs were analyzed in a low-voltage distribution network. The findings proved that EVs have a negligible impact at the beginning of the low-voltage feeder. However, the same EVs have a major impact at the end of the feeder. This work also showed that at approximately 34%, VI surpasses the allowable limit, which is restricted to 2% for low-voltage networks [66]. In a related work, Li et al. [86] showed that the voltage starts to decline at the end of the feeder when EV penetration rate increases by more than 50%. Leou et al. [87] proposed stochastic and deterministic EV load models based on actual measurement and survey data. Monte Carlo simulations and roulette wheel selection concept were utilized to create uncertainties of EV penetration, SOC, and charging time. The study showed that compared with deterministic approach, stochastic approach determines many under-voltages and over-currents and presents significant security risk information. Nevertheless, the diversity of SOC and charging levels is also important for stochastic approach to evaluate VI accurately. Similarly, Jimenez and Garcia [88] developed a PEV load model that incorporates a voltage-controlled converter and a battery pack. The model was simulated on an IEEE 13-node test system, and the results showed that the percentage of imbalance in the bus voltages increases when EV acts as a load. However, another study [89] showed that AC single-phase EV charging creates tremendous phase imbalance because of unequal load distribution in the three-phase system.

A smart charging plan was suggested in [86] to lessen the VI. This strategy can also significantly alleviate security problems even with large adaptation of EVs. On the contrary, the authors in [88] mentioned that the percentage of imbalance in bus voltage decreases when EV provides active power into a distribution network.

3.1.1.3.3. Voltage sag. Voltage sag is not a complete interruption of power; it is a reduction of RMS voltage at the power frequency for a period of 0.5 cycles to 1 min [66]. Voltage sag in a distribution network normally occurs because of short circuit, overload, or starting of electric motors. To estimate voltage sag with the integration of EVs in a distribution network, Lee et al. [90] modeled an EV charger and power converter utilizing an electromagnetic transient program. The model was simulated on the distribution system of Korea Electric Power Corporation, and the results were compared with IEEE standards [91]. The comparative study showed that the voltage sag exceeds the limits at 20% EV penetration. Only the uncertainty of EV penetration was considered during simulation. Another study [92] also investigated voltage sag by considering different charging scenarios and penetration levels. The results determined that the existing distribution networks can safely operate at the EV penetration level of 10% and 60% respectively for uncontrolled and controlled charging without any adverse impact on the distribution system voltage. Similarly, the grid effects of on-board EV charging on the grid were tested in [93] on the massively loaded unbalanced Flemish three-phase distribution network. This test was conducted based on voltage droop charging and EV-based peak shaving charging model. Charging time and driving distances were considered the key parameters to evaluate the EV effects. The results showed that voltage droop charging considerably lessens the voltage sag, thereby providing negligible effect on the total EV charging time.

Smart grid with load management strategy provides tremendous prospects that can considerably improve the voltage sag and the overall power quality of the distribution networks [94].

3.1.1.4. Power loss. The massive penetration of EVs can affect the distribution networks and increase power losses. Power loss (P_L) in a feeder of a distribution system can be calculated as [95]:

$$P_L = \sum_{i=1}^{N_B} I^2 R_i \tag{4}$$

where I is the current, R_i is the resistance of feeder i, and N_B is the number of feeder of a distribution system.

Additional power loss (AP_L) due to EV charging can be expressed as shown in Eq. (5) [96]:

$$AP_L = TPL_{EV} - TPL_{origin} \tag{5}$$

where TPL_{EV} is the total power loss when EVs are connected to a distribution network with the original load and TPL_{origin} is the total power loss with no EV load connected.

To measure the power loss in terms of high penetration of EVs, Papadopoulos et al. [97] utilized a probabilistic approach that includes uncertainties of EV charging rates, charging time, and duration of charging. Simulations were conducted on the UK generic distribution network based on EV users' data. The results showed that a high penetration of EVs will increase power losses. In Pieltain et al. [98], large-scale distribution planning model was simulated considering 85% EV charging at off-peak hours and the rest of the EVs charging at peak hours, regardless of their arrival times and charging patterns. The results determined that energy loss can increase up to 40% in off-peak hours when 60% of PEVs are in charging mode. Similar results were obtained in [86,99], where a higher penetration of EVs increased the power system losses. The study in [99] clearly revealed that penetration levels of PEVs, charging mode, and charging time have significant impacts on system power losses and voltage profiles.

Uncoordinated charging can result in great power losses and unacceptable voltage deviations. For this reason, in [100], an objective function based on coordinated charging was proposed to reduce the system power loss. In this study, stochastic programming was introduced to obtain an optimal solution because an accurate forecasting of load was unfeasible. Similarly, Deilami et al. [101] and Sortomme et al. [102] suggested that a coordinated charging strategy significantly minimizes power system losses. In [99], Deilami again demonstrated that uniformly distributed charging can substantially reduce power losses. EV charging with nearby power generation is another approach to minimize system power losses [96].

3.1.1.5. Transformer overloading. Widespread penetration of EVs in a distribution network produces extra pressure on the distribution transformers. The stress on distribution transformers owing to the large penetration of PHEVs in a medium voltage distribution system was described in [75]. A PHEV distribution circuit impact model was proposed to randomly distribute the PHEV loads throughout the circuit. IEEE standard C57 [103], that provides a function for translating hot spot temperature into an aging factor, was utilized to determine the loss of transformer life. The findings showed that the annual accelerated aging of a fully loaded 10 KVA transformer was almost negligible due to the cool weather in Vermont; however, this aging could be larger with higher ambient temperature. Similarly, thermal aging of power distribution transformers was tested in [104] using the UK's generic low-voltage distribution model and real load demand. The results indicated that transformer life anticipation mainly depends on ambient temperature, EV penetration levels, and charging start time, and that 10% EV penetration has no detrimental impact on transformer life. However, heating due to harmonic current and eddy current loss was not considered to calculate the thermal aging. Similarly, Razeghi et al. [105] showed that Level 1 slow charging has a negligible impact on the transformer lifespan; however, the high penetration of EVs with Level 2 charging causes transformer failure because of excessive temperature. In a related study, the authors in [106] showed that a distribution transformer becomes overloaded at 20% and 10% PHEV penetration for Level 1 and Level 2 charging, respectively. Through some case studies, they concluded that distribution transformers are the bottleneck for the extensive adoption of EVs because of overloading during uncontrolled charging [97]. By contrast, an EV model was proposed in [48] to measure the effect of harmonics on a distribution transformer life. The study revealed that a direct connect-and-charge scheme can be harmful for transformer life in terms of massive loads and high temperature. Finally, the authors suggested that the THD should be restricted to 25–30% for better operation of the transformer. However, random features of EV and charging time were disregarded to determine the actual effect of harmonics on transformer life.

EV integration to a distribution network may significantly increase the transformer loading. Hence, proper selection of the transformer, network planning, and load management are important to reduce the negative impacts of EVs. The smart metering approach was presented in [94,104] to maintain better power quality and reduce THD in the distribution network to enhance transformer life. In [94], the K-factor derating method was utilized to diminish the transformer operating power as a precaution, thus enhancing transformer life.

3.1.2. V2G technology as a positive impact

V2G technology is the most auspicious opportunity to embrace an EV in power systems owing to its particular characteristics of discharging stored energy back to the distribution network [107]. This technology increases the reliability and lowers the system costs of the power system. In general, EV batteries store energy during charging when connected to a distribution network. However, they can also perform as a generating source when they are parked and V2G is enabled. Thus, EV owners can obtain revenues for their participation in V2G services. The benefits of V2G services bring the privileges not only for EV owners but also for power grids [108–114]. Studies in [108,109] discussed that battery storage energy is effective in mitigating voltage fluctuations in distribution networks and can contribute to power quality improvement and frequency control for a decentralized power supply. In related studies, Ohtaka et al. [110] and Wade et al. [111] concluded that V2G systems can provide sufficient voltage support to subsequently moderate the use of voltage regulators at distribution networks. V2G can also greatly reduce distribution line loss, circumvent voltage drop, and achieve protective relay tripping [112]. Similarly, Ruther et al. [113] pointed out that V2G technology has the potential to stabilize grids in terms of peak-load shaving. Ma et al. [114] also demonstrated that V2G can considerably reduce power system operating costs and secure distribution networks. However, the battery life cycle will be extremely affected because of frequent charging and discharging in the V2G service. Intelligent charging systems can extensively extend battery life. This issue has recently gained great interest from researchers [13].

3.2. Environmental impacts

The power demand of EVs is provided from a power grid rather than employing fuel-based traditional technologies, thus reducing carbon emissions. In addition, the expanded integration of alternative and renewable energy systems to charge an EV battery can promote further reduction of pollutant emissions [115]. As an effort, numerous countries are introducing photovoltaic-based CSs [116,117].

To calculate the emissions of CO_2 and other contaminants per km in relation to a smart electric derive, Donateo et al. [118] proposed a methodology that includes electricity consumption and electricity generation mix for each recharging event and emission level. The study represents the advantages of electric derive in terms of CO_2, carbon monoxide, nitrogen oxide, and particulate matter emissions. The study also concludes that EV has low well-to-wheel emissions. The well-to-wheel is a parameter used to calculate the emissions over the entire life of a vehicle. On the other hand, the life cycle assessment method, which combines production and well-to-wheel phases, was utilized in [119] to calculate the environmental impacts of EVs. This study found that EVs are the least carbon-intensive vehicles. A model that assesses the GHG emission impacts for massive adoption of PEVs was investigated in [120] for a specific city. The impacts were calculated for two specific years with a 10-year interval between them. For the former year, the study revealed that EV charging during off-peak or valley-filling hours resulted in greater GHG emissions due to a higher percentage of coal power generation. Contrary to the previous year, analysis of the latter year showed that the distribution network faced significant operational challenges because of massive EV penetration. However, the GHG emissions during off-peak hours were greatly reduced due to the removal of coal power generation. CO_2 emissions also decreased to 85% in the transportation sectors in Denmark by integrating electric power and EV transportation [121]. Lund and Kempton [122] showed that even without the integration of wind energy in the generation capacity, the use of EVs can significantly mitigate CO_2 emissions. In a similar study, Hadley [59] confirmed that the addition of EVs in the transportation sector in the US alleviates CO_2 emissions by approximately 10% compared to gasoline vehicles. Notably, in the US, around 65% of total generation capacity comes from fossil fuel plants. To estimate the CO_2 emissions in the three regions of China, three EVs were examined in [123] considering four penetration scenarios. For all scenarios, CO_2 reduction occurred for all three regions, although coal power plants contributed 79% of the total generation capacity. The study in [124] investigated the impact of larger EV deployment in an urban environment. In the study, the authors considered three deployment rates and found that the reduction of nitrogen oxide and nitrogen dioxide happens for all three deployment rates. Results showed that nitrogen oxide and nitrogen dioxide are reduced by 15% and 5.5%, respectively, when 50% of the vehicles are replaced with EVs.

However, EV charging from an electric power grid based on coal or other polluting fuels may increase GHG emissions. For example, power generation based on mixing coal and natural gas showed higher CO_2 emissions from EVs compared to ICE [125]. Similarly, Ma et al. [126] mentioned that CO_2 emissions from electricity generation are high due to the large penetration of EVs at peak hours, a result of using gas or coal plants that contribute more CO_2 emissions. However, the proper integration of renewable energy can potentially reduce the emissions of CO_2 and other pollutants from both transportation and power generation [13].

The advanced lithium-ion batteries do not contain any caustic chemicals those are found from lead-acid and nickel-metal batteries. However, dead lithium-ion battery when through in landfills can pollute the groundwater because at present very limited numbers of companies are able to fully recycle the lithium-ion batteries [127]. Hence, government should create facilities that can ensure safe and sound environment by managing and recycling the batteries. Reuse of lithium-ion battery can help to reduce the "peak oil" or "peak lithium" demand in the US [127].

3.3. Economic impacts

The economic impacts of EV can be observed from two perspectives: the EV owners and the utility company [128]. From the EV owners' view, the fuel and operating costs of EVs are comparatively less than the ICE because of the higher efficiency of electric motors [129]. The typical ICE vehicle efficiency is 15–18%, whereas the EV efficiency is as high as 60–70% [130]. The enhancement of battery technologies improves the lifecycle economics of EV batteries. On the other hand, EV prices are still high in comparison with ICE vehicles. Mass production of EVs and energy trading policies can significantly reduce the high initial price of an EV [27]. The V2G concept first introduced by Kempton and Letendre [131] demonstrated that EV owners can profit if they transfer their battery stored energy into the distribution network.

From the power grid perspective, the integration of EVs to a distribution network increases system costs and other losses; however, proper charging strategy can greatly minimize those adverse impacts [132,133]. For instance, Kiviluoma and Meibom [132] calculated that smart charging can save $227 per year per vehicle compared to a simple charge plan. Similarly, controlled charging can cut system costs more than 50% and reduce peak demand compared to uncontrolled charging [133]. System costs and peak demand can be further reduced by integrating renewable energy sources in the distribution network. Peterson et al. [134] and Sioshansi and Denholm [135] showed that an EV fleet can result in fundamental power system cost savings of $200-$300 per year per vehicle. By using EVs, residential customers can have enough ability to partake in demand response programs as discussed in [136]. Such programs may assist to counterbalance any adverse impact that arises from EV charging. Demand response programs can likewise support EV users by reducing the EV charging costs. The capability of the Spanish electric grid to manage demand with different levels of EV penetration and its impact in spot electricity market price for various seasons in a year was investigated in [137]. Meanwhile, Salah et al. [138] found that the distribution network can operate in normal conditions with current electricity prices and 16% EV penetration.

The above discussions show that EV has significant positive and negative impacts. Table 4 summarizes the negative impacts of EVs with corresponding remedies, while Table 5 summarizes the positive impacts with corresponding benefits.

Table 4
Negative impacts of EVs and corresponding remedies.

No.	Negative impacts	Remedy
1	Voltage instability	• Apply wide area control method to damp out the oscillations [54] • Adopt the tap changing transformer to control the voltage [20]
2	Increased peak demand	• Use smart charging [60,61] • Introduce controlled charging [60,61]
3	Power quality problems	• Apply smart grid compatible power conditioning unit for controlled charging [81] • Install harmonic filter at the supply system [82] • Install smart appliances passive filter banks [83] • Introduce smart grid with load management strategy [94]
4	Increased power loss	• Apply coordinated charging [100–102] • Introduce uniformly distributed charging [99]
5	Transformer overloading	• Introduce smart load management strategy [104] • Apply K-factor derating method [94]

Table 5
Positive impacts of EVs and corresponding benefits.

No.	Positive Impacts	Benefits
1	Benefits of V2G	• EV can as act as a power source for the electric grid • Increases the reliability and lowers the system costs of power system [107] • Reduce the distribution line losses, voltage drops [112] • Reduce frequency fluctuations in power grids as well as contribute to improve power quality [96] • Stabilize the grid voltage [113]
2	Environmental	• EV acts as a greener solution in road transportation system • Significantly reduce the CO_2 and other pollutants emissions [59,120–122].
3	Economic	• Users can be benefited if the energy is transferred from EV into a distribution network [131] • Lower operating cost [134,135]

4. Optimal placement and sizing of CS

CS is an element in an infrastructure that supplies electrical energy for recharging an EV battery. Appropriate site selection and sizing of CS is important to reduce the adverse impacts on EVs. The CS placement can be mainly categorized into two types, namely, slow and rapid. The following sub-sections describe the slow and rapid CS placement and sizing in detail.

4.1. Slow EV charging station

Slow CS is related to charging Level 1 and Level 2 which use AC voltage and take 4–16 h to charge an EV battery. Users can easily charge an EV battery from home or work or a parking place without affecting the distribution networks. In these cases, EV charging is considered a household appliance, such as an electric oven, and clothes dryer/washer [12] because of its low charging power. Limited studies have been found in literature on slow CS placement. For example, Frade et al. [139] introduced a slow charging facility location model to optimize the demand covered within an acceptable level of service. The authors emphasized on population (households) and employment (jobs) for the optimal location of slow CS. Taking into consideration slow charging modes, Jia et al. [140] proposed a model for the placement of CS by considering charging piles for EV charging at residential areas.

4.2. Rapid EV charging station

EV users need a public charging infrastructure similar to a filling station for quick charging. In recent years, various studies have focused on optimal placement and sizing of rapid CS (RCS). These studies consider two aspects: one is focused on economics, and the other is directed on power grid-related concepts. The placement and sizing of RCS by only considering economic benefits are not reasonable and practical. Therefore, the ultimate goal is to determine the optimal location and sizing of RCS by utilizing optimization techniques that minimize the total cost while maintaining power system security. Various heuristic optimization algorithms have recently been utilized to solve the placement and sizing problems of RCS. The benefit of heuristic algorithms is that they can find the global or near-global optimal solution even though the problem is very complex. Other techniques have been explored for the same purpose. The following sections provide a detailed review of various RCS placement methods.

4.2.1. RCS placement considering only economic benefits

This RCS placement method incorporates various cost functions, such as land cost, fixed cost, construction cost, operating cost, and transportation cost, for optimal placement and sizing of RCS. Genetic algorithm, particle swarm optimization, integer programming, and other techniques have been applied to determine the optimal RCS placement and sizing.

4.2.1.1. Genetic algorithm. Genetic algorithm (GA) is an evolutionary algorithm that obtains solutions to optimization problems by utilizing techniques motivated by natural evolution, such as inheritance, selection, mutation, and crossover. The benefit of GA is its ability to search and determine a global optimal solution within the optimization process [141]. Numerous studies have utilized standard and modified GA to solve the optimal CS placement and sizing problems [142–148]. For instance, GA was used in [142] to optimize the CS placement for an existing city traffic network that aims to minimize the transportation cost while considering traffic density and station capacity as constraints. However, cost functions, such as land cost, fixed cost, and operating cost were disregarded in optimizing the system; thus, its outcome is not a global optimal solution. A similar algorithm was utilized in other studies. In [143], the authors developed a cost model predicting the total number and distribution of EVs. Conversation theory was demonstrated based on regional traffic flows that consider EVs within each district as a fixed load point of CSs. Finally, GA was applied to optimize the model. For the same purpose, Kameda and Mukai [144] developed an optimization routine for locating CS depending on taxi data and a focused on-demand local bus transportation system. GA was again proposed to optimize the route of the on-demand bus transportation system. The result was mainly based on computer simulation without justification on a practical network. In [145], a modified GA was used to optimize CS location that considers an objective function based on investment and transportation cost. By contrast, Bendiabdellah et al. [146] and You and Hsieh [147] employed a hybrid GA to determine the optimal number and size of public CS. The hybrid GA found the optimal location by minimizing the investment and travelling cost. Other costs, such as operating and charging costs, were ignored in optimizing the system. On the other hand, a two-stage GA was utilized in Yan [148] to solve a multi-objective optimization model and minimize investment and travelling costs. The authors demonstrated that the layout of CS is obtained by the charging demand of various locations as well as charging time constraints, whereas the scale of CSs is interrelated to the number of EVs, layout of CSs, and charging duration at peak hours. However, GA requires long computational time to find the optimal location and sizing of CS. Another drawback is caused by premature convergence.

4.2.1.2. Particle swarm optimization. Particle swarm optimization (PSO) relies on the simulation of social behavior among particles flying through a problem space, wherein an individual particle represents a solution to the given problem. The benefit of PSO is its ability to obtain a global optimal solution with higher possibility and efficiency compared to other optimization methods. Unlike GA, PSO is easy to implement and makes faster convergence owing to the absence of evolution operators, such as crossover and mutation [149]. For instance, Zi-fa et al. [150] utilized PSO to declare an optimal location of CS based on construction cost (e.g., land price) and running cost and considering geographic information and traffic flow as constraint conditions. Similarly, Tang et al. [151] developed an optimal planning model of CS incorporating the global searching ability of PSO and a weighted Voronoi diagram. The defined area was partitioned by the weighted Voronoi diagram, and then PSO was employed to determine the optimal CS locations. For the above cases, the authors did not discuss CS sizing. The main shortcomings of PSO are low precision and easy divergence, thus making solutions of CS non-optimal.

4.2.1.3. Integer programming. Integer programming is a mathematical optimization program in which some or all of the variables are defined as integers. Linear integer programming is a term in which objective functions and constraints are linear. Ip et al. [152] employed linear programming to find the optimal CS location considering certain constraints and cost factors. A two-step model was introduced in which the first step congregated the road information into "demand clusters" by hierarchical clustering analysis. In this work, travelling cost on the way to the CS was neglected. Meng and Kai [153] modeled the CS placement problem by first using game theory, and later transformed it into a linear programming model. Finally, the model was solved using a primal-dual path-following algorithm to simplify and clarify the process while maintaining viability. Important factors such as traffic flow, road network, structure, and capacity constraints of the distribution network were not taken into account during problem modeling.

Mixed integer programming is a method wherein some variables are restricted to an integer. An integer programming model was designed in [154] to find the optimal set of routes and CS locations. The model aims to minimize the total transportation, charging, and CS placement costs. Andrews et al. [155] also developed a mixed-integer programming model to find the CS locations by considering diminishing the range anxiety and minimizing the travelling distance from the EV to the CS. This model was implemented in Chicago and Seattle, and the results showed that user convenience increases promptly while increasing the number of CSs. In this work, only travelling distance from EV to the CS was minimized. Furthermore, Kockelman et al. [156] utilized mixed integer programming to optimize the CS placement problem as a function of parking demand and user travelling costs to access the CS. The parking demand was predicted on the basis of site accessibility, local jobs and population densities, trip attributes, and other approaches. The method only identified optimal zones for CS placement. Specific CSs within recognized zones were not determined. The shortcoming of integer programming is that it cannot solve the stochastic characteristics related to CS.

4.2.1.4. Other techniques. Other techniques have also been used to find the optimal location and sizing of CS. A CS model was developed by Chunyang et al. [157] on the basis of three stages, such as demonstration, public promotion, and commercial utilization, considering interval distance ratio, charge capacity, and charging power redundancy. However, this study did not implement optimal sizing of CSs. Wang et al. [158] represented a multi-objective expandable planning model for CS considering feasible improvements of EVs, CS's features, EV user's manners, distribution of the charging demand, community planning, and other factors. An algorithm process was also designed depending on the demand preference and re-use of gas stations. Sweda and Klabjan [159] utilized an agent-based decision technique to identify the EV ownership patterns and driving activities in a residential area of Chicago, and thus find the optimal location of CSs. The method considered a fixed plan for CS placement without any dynamic or iterative modification. On the other hand, Wirges et al. [160] relied on socio-demographics, land use, and mobility to introduce temporal-spatial models for the development of EV charging infrastructure in the metropolitan region of Stuttgart, Germany. Simulation results determined that the number of public CSs required to provide improved service for that region is relatively small. A mathematical optimization method was suggested in [161] based on a geographical information system model to solve the location optimization problems. The results indicated that the proposed method and model can select the proper locations with good neighbor security and adequate distribution network capacity. On the other hand, commercial CPLEX software was used in [140,162,163] to determine optimal CS locations. In [163], the authors modeled a transportation network with the help of graph theory to find the shortest distance from vehicle location to allocated CS. The method also optimized station sizes at each location based on charging demand. The established model, which minimized the overall cost, was solved by using CPLEX software. This software was also applied in [140] to solve the optimization problem and the P-center location, and allocation models were utilized to abate the investment and charging costs. Nonetheless, the disadvantage of commercial software is that users cannot modify the parameters of the software.

Meanwhile, the principle of queuing theory was applied in [164] to optimize the capacity of CS by minimizing the travelling and investment costs of CS. In this study, authors suggested a CS planning model for an urban area, taking into account road network, traffic information, structure, and capacity as constraints of a distribution network. In a similar study, an active-set algorithm was applied in [165] to determine the optimal location of a given number of CSs among the cosmopolitan areas to maximize the social welfare. Different factors, such as charging demands, performance and charging period of a battery, the system of energy supply, locations, and the environment of CSs, were found to have significant impacts on the layout of CSs, as demonstrated in [166]. However, this study did not consider any mathematical model for the layout of the CS. Rastegarfar et al. [167] established a cost model with reference to total investment and operation cost; the model considered geographic conditions, traffic, and local access to find optimal CS locations. A computer program was developed in MATLAB to calculate the costs and determine the optimal combination of CS. On the other hand, Lam et al. [168] utilized a greedy algorithm to minimize the total construction cost, which was based on the user's convenience and CS coverage. The weakness of this method is that the obtained solutions are usually suboptimal. In Zambrano et al. [169], flow-capturing methodologies were employed to find the optimal locations of CSs. First the methodology followed the classical flow-capturing location-allocation model to maximize the traffic flow that would be captured by CS. Then, an advanced flow-capturing location-allocation model was used to minimize the setup costs of CSs. For the same reason, the authors in [170] proposed an extended flow refueling location model to obtain the optimal location of CSs and charging pads. However, the proposed model was restricted to handle small-scale networks.

4.2.2. RCS placement considering power grid impacts

CS placement methods that consider grid impacts include different power system issues and various cost functions to find the optimal placement and sizing of RCS. Similar to the methods that consider only economic benefits, the overview of optimal RCS placement and sizing problems considering power grid issues based on different optimization techniques are represented as follows:

4.2.2.1. Genetic algorithm. A GA was proposed in [171] to solve the optimal sizing problem. In this study, the authors suggested an optimal sizing model of CSs in relation to power loss and voltage drop. Traffic and distribution networks were taken into account to find the optimal locations for CSs. However, the model was not quite realistic because the cost parameters were ignored while designing the model. On the other hand, an improved GA was utilized in [172] to solve a multi-objective, multivariate optimal planning model. The model was developed based on investment costs and feeder energy losses with other constraint conditions and tested on IEEE 33-node distribution system. The study showed that the improved GA successfully solves the difficulties of blind search and overcomes the low efficiency in the basic GA.

4.2.2.2. Particle swarm optimization. PSO was utilized in [173] to find the locations and capacities of CS for regional EVs. In this study, the authors proposed a cost model based on the operating costs of CS, network loss, and investment costs of a distribution transformer. This model comprises various constraints, such as distance between substation and EV location, installed costs of CS, and number of EVs. PSO was utilized to optimize the system. The forecasting of charging demand was disregarded in optimizing the model. On the other hand, Prasomthong et al. [174] used PSO with time varying coefficient for V2G CS placement and sizing in the distribution grid at peak period. The simulation results showed that V2G CS maximizes the total benefits comprising power loss minimization, peak power saving, and reliability enhancement while maintaining system operating constraints.

4.2.2.3. Ant colony optimization. Ant colony optimization (ACO) is another heuristic optimization method used to evaluate optimal CS placement. For instance, ACO was used to find the best location of CSs in the distribution grid [95,175]. The proposed methods minimized the total costs and real power loss while maintaining the power system security and traffic flow as constraints. In a related study, Dharmakeerthi et al. [176] developed an EV model that combines constant power and voltage-dependent load to determine the best CS locations using ACO in a power grid based on voltage stability margins, grid power loss, and cable flow ratings. The weakness of this technique is that it is very slow in comparison with other optimization techniques.

4.2.2.4. Other techniques. Aside from heuristic techniques, other techniques are also used to solve CS placement and sizing

Table 6
Comparison of different optimization techniques in CS placement and sizing schemes.

No.	Algorithm	Benefits	Drawbacks
1	GA	Easy to implement, suitable for placement problems as it is originally a describe algorithm [141]	Takes a long time to solve the placement and sizing problem [148,172]
2	PSO	Simple computation and ability to find near optimal solution [149]	Premature convergence, higher possibility to get struck in local optima [150,174]
3	ACO	Positive feedback accounts for rapid discovery of good solutions [95]	Time to convergence is uncertain [175]
4	Greedy algorithm	Fast and guaranteed to produce feasible solution	The obtain solution normally is a sub-optimal solution [168]
5	Integer (linear) programming	Simple and solve many diverse combination of problems [152]	Only works with linear variables and cannot potentially solve stochastic problems [100]

problems. For instance, a modified primal-dual interior point algorithm that considers environment factors and maximum coverage of service was adopted in [177] to solve the optimal CS placement problem. The algorithm also solves a cost function associated with power system loss cost to determine the optimal sizing of the CSs. Masoum et al. [178] designed a new smart load management control scheme based on peak demand shaving, voltage profile improvement, and power loss minimization for coordinating multiple EV chargers while considering daily residential load patterns. This approach was tested on the 31-bus distribution system. Similar to the previous study in [164], queuing theory was utilized in [179] to minimize transportation wastage cost and optimize CS allocation. In this study, the CS model was proposed for a new city traffic network in relation to construction cost, operation cost, maintenance cost, and power loss cost. Hence, the planning model is not realistic for an existing city road structure. Meanwhile, Wang et al. [180] introduced a traffic constrained poly objective pattern by considering the traffic system and power loss for optimal CS placement. This method utilizes data employment analysis to determine the best candidate solution and cross-entropy algorithm to solve the optimization problem. These techniques effectively reduce the power loss and voltage deviation as well as travel distance to the CS.

All the aforementioned techniques can find the optimal location and sizing of CS. However, a comprehensive study is still required to enhance performance. Table 6 summarizes the benefits and drawbacks of various optimization techniques used in solving the RCS placement and sizing problems.

5. Current issues, challenges, and future outlook

5.1. Issues and challenges

EV is considered a promising forthcoming option toward the road transport system for the next generation. Threats of fossil fuel depletion, increasing price of crude oil, and abrupt climate changes are always promoting users to find alternative energy sources in transportation systems. In contrast to the ICE vehicle, the EV is more energy proficient and environment friendly because it barely produces carbon emissions. However, the existing power networks and intelligent EV management systems are not sufficiently updated to avoid adverse impacts on electric power networks. Therefore, comprehensive studies need to be conducted before fully launching the EVs in the market. Some current issues and challenges that can obstruct the widespread deployment of EVs are presented in [181–183].

Presently, EV price is still high compared to ICE vehicles because of the high initial cost of EV batteries. Although remarkable enhancements in batteries have been made in the last few decades, the current lithium-ion battery is restricted to lower energy density and limited life cycle. Owing to its low life cycle, the battery requires maintenance every one to two years. In addition, the battery is one-third or more of the vehicle weight and size. Therefore, advanced research is required to improve the economic and technical performances of an EV battery.

On the other hand, the current battery charger has restrictions and is not technically sound for V2G implementation. Hence, additional attention should be given to advancements in the design of bi-directional chargers. At the same time, research should be conducted to introduce new policies to encourage EV users to participate in the V2G program. Otherwise, it may be a massive blockade for the implementation of V2G if EV users are not interested. High investment costs are likewise required to upgrade the power system to implement the V2G. Furthermore, due to frequent charging and discharging of its battery, V2G can increase energy and conversion losses, which is another inauspicious issue in the power system.

Given that EV charging is time consuming, RCS is urgently necessary to abate users' anxiety. RCS is implemented to solve the long charging time of conventional slow chargers and can perform similarly to a commercial filling station. Currently, RCS facilities have not been commonly available and accessible everywhere. For example, the USA, UK, Australia, and other countries have limited numbers of RCSs for EV rapid charging, while Malaysia has no available RCSs [184]. However, the optimal placement and sizing of RCS is another challenge.

The emission performance of EVs mainly depends on the power generation mix. EV may have less importance when the generation mix is mainly dominated by dirty power plants (e.g., coal or nuclear energy). For example, in the US and China, around 65% and 79% of total generation capacity comes from fossil fuel and coal plants, respectively [59,123]. An increased deployment of EVs in such areas may cause adverse impacts on the environment because emissions from the power plant may need to be increased to generate sufficient electricity to power them. A study at a North Carolina state university claimed that EVs will not decrease America's polluting air emissions even if 42% of all passenger vehicles are replaced with EVs [185]. However, the employment of renewable energy generation with a smart grid can be facilitated to protect the environment.

At present, existing power grids are not efficient enough to provide additional and sufficient power for the upcoming massive numbers of EVs. For instance, the western part of the Lithuanian grid is insufficient to deliver power for massive numbers of EVs [41]. As the number of EVs increases, a higher possibility exists for the occurrence of adverse impacts on distribution networks. These impacts may include voltage instability, increased peak demand, power quality problems, increased power loss, and transformer overloading. The adoption of renewable energy sources in electric power can alleviate these negative impacts. However, renewable energy sources have drawbacks in energy and power density that are not desirable for today's EVs charging patterns. The creation of an efficient power management system is also challenging because of the difficulty of coordinating multi-power sources. It may hamper the system stability, uninterrupted power supply, and power quality of the supply system. Advancement of intelligent control techniques is required to properly integrate multi-power sources and transfer controlled energy to an EV battery. Thus, the EV battery can be intelligently optimized at the user point through controlled charging.

5.2. Future trends

On the basis of the aforementioned discussions, future research trends are suggested as follows.

EV has numerous benefits in terms of environment, economics, and smart grids. However, EV users are still concerned about cost, longevity, driving range, charging time, and safety. The advanced lithium-sulfur battery offers promising benefits over lithium-ion batteries, such as higher energy density, extensive temperature range, improved safety, and lower costs due to the availability of sulfur. However, the lithium–sulfur battery has not been extensively commercialized. In addition, this battery faces self-discharge and capacity declines because of higher charging and discharging cycles. Advanced battery modeling is important for safe charging and discharging, reduction of weight and size, and optimal utilization of the battery. Therefore, further investigations need to be conducted on this issue.

In recent times, the development of the smart grid has modernized the power system and enhanced the use of EVs in the V2G technology. In a smart grid, EV is also considered one of the important solutions to balance power fluctuations arising from a higher integration of unpredictable and inconsistent renewable energy sources. Nevertheless, the enormous integration of EVs acts as additional loads on the power grid during battery charging, and these extra loads may create unwanted congestions, voltage collapses, and various adverse impacts in the distribution network. All these issues create new challenges for power system operators. Therefore, smart charging and discharging (i.e., bidirectional V2G) solutions are imperative to ensure EVs become an asset to the smart grid instead of a simple traditional load. However, for smart charging and discharging systems, smart metering, security, and smart communication systems between an EV and a smart grid will inevitably incur additional costs. The enhancement of smart charging technologies is worthwhile for future research.

Alternative sources and smart charging can significantly reduce the negative impacts induced by EV charging. However, optimal placement and sizing of RCSs are also important to reduce the power grid-related adverse impacts and increase the economic benefits [20,96]. To determine the optimal placement and sizing of CSs, actual cost functions and good optimization techniques are imperative. Although heuristic optimization techniques can efficiently solve the optimal CS placement and sizing problems, noting that each technique has its benefits and drawbacks is important. For example, GA can successfully solve the CS placement and sizing problems, but it requires a high computational time. A higher possibility exists for getting stuck in the optimization results in local minima in PSO. Therefore, research could be carried out on the enhancement in cost functions and optimization techniques to make these issues more effective in CS optimization problems.

6. Conclusion

This paper presented a comprehensive review on EVs in terms of charging technology, various EV impacts and optimal CS placement and sizing. Charging technology plays an important role in energy transfer for an EV battery. To provide enhanced understanding about this technology, this study presented different energy transfer modes, charging levels, and techniques in addition to the standards currently being utilized for EV charging worldwide. A comparison was likewise made on various types of EVs with regard to battery size and energy availability, electric range, energy consumption, charging power levels, and charging time. In addition, the impacts of EVs were classified and discussed with remedies for negative impacts and benefits for positive impacts. Various optimization techniques that tackled the CS placement and sizing problems were also outlined and critically discussed with their benefits and drawbacks. Some noteworthy works have already been done in the above areas, but many issues remain for further research. This paper also highlighted the current issues and challenges of EVs for large-scale deployment in the market, as well as a future research outlook. Therefore, this work will help provide most relevant and significant information about existing studies. It will also provide an opportunity to research further on battery performance optimization and intelligence systems related to the integration of multi-power sources, stability, reliability analysis of distribution networks, and location and sizing optimization of CSs in consideration of power quality issues.

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