A Comprehensive Review of Fast Charging Infrastructure for Electric Vehicles

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ABSTRACT
The idea of electrified transportation is envisioned to be a promising approach to alleviate the issue of climate change. However, a cost-effective commercialization and wide acceptance of electrified transportation necessitates the development of an economical, reliable, and fast charging infrastructure. The incorporation of a well-defined electric vehicle (EV) fast charging infrastructure in the smart grid can offer numerous potential opportunities, particularly from the perspective of vehicle to grid (V2G) technology as well as a solution to the renewable energy intermittency issue. This work reviews the state-of-the-art technology for fast charging of electric vehicles with a comprehensive coverage of the research work done related to the challenges and road blocks to be encountered in its implementation. A comparison of conductive and inductive charging systems is presented followed by an overview of the charging standards and a discussion on the topologies presented in the literature for fast charging stations. A detailed account is presented concerning the issues and opportunities on integration of fast charging infrastructure with grid. The economic aspects of fast charging infrastructure along with an overview of prospective areas for future research in this field are also presented.

1. Introduction
Nowadays, the interest in electric vehicle (EV) technology is growing because of their reduced fuel emissions, and their numbers are expected to grow rapidly in the near future [1], [2]. This necessitates a consistent development in their charging facilities, particularly fast charging infrastructures, which are intended for commercial and public applications to operate like filling stations [3], [4]. The availability of fast charging facilities can alleviate the problems of charging time and range anxiety, which can be considered to be the two most important barriers standing in the way of wide acceptance of EVs. Deployment of such efficient and reliable fast charging infrastructures at short distances would support an unrestricted range for EVs [5]. Connecting the electric vehicles to the electricity grid presents some challenges in terms of infrastructure planning, power quality aspects, network loading etc., along with certain opportunities in the form of ancillary services, reactive power support, and load balance [6]. In [7] and [8], the technological challenges related to the integration of the EV charging infrastructure with the grid
are discussed. The uncoordinated or random EV charging can result in losses in the distribution system, voltage deviations, and poor power quality [9]. Further issues include the problem of instability and reduction of transformer life because of overloading [10].

Numerous demand side management strategies are implemented to minimize these effects, including the use of energy storage systems (ESS) and integration of renewable energy sources (RESs) with the charging systems [11] and [12]. The advantages offered by the implementation of energy storage systems in reducing the adverse effects of EV charging on the grid are presented in [13] and [14]. Further detailed analysis with modeling and experimental results is presented in [15]. Use of renewable energy as alternate source for EV charging is also being considered with focus on solar PV [16–18]. An emerging concept of Vehicle-to-Grid (V2G) power flow is also being introduced to support the grid [19]. In [20], the authors have presented the development in solar-powered electric vehicle charging infrastructure and in [21] the authors discussed a regional (Germany)-based development in EV standard. However, the [18] and [19] missed the regress analysis on fast charging infrastructure, such as standard and implementations, the power electronic role in the fast charging development, the fast charging integrated energy management system, the various converter topologies in fast charging mechanism, fast charging impact on grid stability and its role to support the regulation, and the mathematical model to present the vehicle to grid technology.

This paper covers different aspects with regard to the fast charging infrastructure for EVs (that have been ignored by [20], [21]), including the standards developed around the world for EV charging, topologies for charging stations, and challenges and roadblocks being confronted in its implementation along with different strategies developed to overcome those challenges. This paper is categorized into ten sections. Section II gives an overview of the conductive and inductive EV charging systems. Section III deals with the standards of EV charging. Section IV gives a comparative account of the fast charging station topologies available in the literature. Sections V and VI discuss, respectively, the key barriers and potential solutions with regard to the integration of charging station with the grid. Section VII discusses the role of V2G technology from the perspective of power market operations. The economic aspects and future trends are discussed in sections VIII and IX, respectively. Finally, conclusion is presented in section X.

2. Charging Systems for EVs

EV charging systems can be broadly classified as conductive and inductive charging systems. Conductive charging systems are well established and more common in use than inductive systems, which are under research stage and are yet to gain wide acceptance in the field of electrified transportation.

2.1. Conductive Charging Systems

In conductive charging, a direct contact is made to the vehicle in order to transfer power. This method of charging is modest as well as efficient. Conductive charging can be classified into two broad categories as on-board charging and off-board charging. On-board method is primarily used for slow charging, wherein the charging activity is confined within the vehicle, while an off-board method is used to provide quick charging facility. In off-board charging, the charger is shifted outside the vehicle. EVs like Tesla Roadster, Nissan Leaf, and Chevy Volt use conductive method of charging [22]. Figure 1 represents the conductive on-board and off-board charging systems. The Society of Automotive Engineers (SAE) and Electric Power Research Institute (EPRI) have categorized EV charging levels as AC Level-1, AC Level-2, and DC fast charging or Level-3 charging, along with the subsequent functionality requirements and safety systems [23].

2.1.1. Level-1 Charging

Level-1 charging is the slowest type of EV charging which utilizes a standard 120 V AC domestic outlet having a current carrying capacity of 15 or 20 A. This type of charging uses the typical electrical outlet NEMA 5–15 R/20 R at one end and a standard SAE J1772 connector at the other end. Level-1 charging draws power in the range of 1.4–1.9 kW depending on the current rating and takes 8–16 h for a full charge subject to the battery type and size [24]. Level-1 is the most expedient home-based EV charging method for which no additional infrastructure is required. Low off-peak rates available during night hours make it an economic method for charging. Estimated Level-1 charging infrastructure costs for residential applications approximately range between $500 and $880 [25].

2.1.2. Level-2 Charging

Level-2 is generally considered as the most prominent charging scheme for private as well as public facilities. This level uses a single-phase 240 V AC outlet having a current carrying capacity of 40 A for private systems and a three-phase 400 V AC connection having a current carrying capacity of 80 A for public installations [23]. Most Level-2 supply equipment uses a dedicated 40 A circuit. Standard connector and receptacle have been developed for Level-2 charging by SAE International based on SAE J1772 standard [26]. Level-2 charging provides power at 7.7–25.6 kW and takes 4–8 h to fully charge an EV [24]. Estimated Level-2 charging infrastructure installation costs range approximately between $2150 and $2300 [25].
2.1.3. Level-3 Charging

Level-3 or DC fast charging is the most appropriate charging method for commercial or public charging facilities which is envisioned to deliver customers an experience like that of a commercial filling pump with oil-based fuel. Fast charging offers charging up to a level of 80% in about 10–15 min depending on EV battery type and size. DC fast charging is practically considered up to 80% SOC level because last 20% charging requires a long time [27]. AC to DC conversion in Level-3 charging takes place in an off-board charger and DC power is supplied to the vehicle through a standard connector [22]. The off-board supply equipment consists of a three-phase circuit supplied from 208–600 V AC which can carry up to 200 A current to offer fast charging. An off-board charger reduces on-board circuitry, thus leading to a reduction in the overall weight of the vehicle [28]. SAE J1772 Combo and Japanese CHAdeMO standards are gaining worldwide acceptance for fast DC charging [27]. As per the revised SAE standards, DC fast charging is classified as DC Level-1 and DC Level-2, where the power output for DC Level-1 and Level-2 varies from 0–40 kW and 40–100 kW, respectively [29]. Level-3 charging infrastructure cost is estimated between $50,000 and $160,000 depending upon the quality and nature of the components [30]. Maintenance of the charging station is another cost factor [31]. However, the availability of public charging stations can eliminate the problem of range anxiety [32].

2.2. Inductive Charging Systems

Inductive or wireless charging method utilises an electromagnetic field for transferring power with no physical contact between the power supply and the vehicle. Inductive charging has an edge over conductive charging in terms of electrical safety. However, high power loss and low efficiency are some of the shortcomings of this method of charging [33]. Wireless charging allows the automated charging of EV that can be realised under three different modes shown in Figure 2: (1) Static wireless charging [34]–[35], (2) Dynamic charging [36]–[37], and (3) Quasi-Dynamic charging [38].

Figure 3 gives a schematic view of wireless charging for electric vehicles. Static charging provides the benefit of eliminating the shock hazard owing to wires and can be set up in suitable locations such as parking lots and home garages [39]. The dynamic wireless charging system has the ability of continuously charging the vehicle while in motion through specified charging tracks on the path, also increasing the driving range and reducing battery size of the EV [40]. The Quasi-dynamic wireless charging system charges the vehicle as it stops for short period of time, as on traffic signals, which extends the driving range and also allows for reductions in energy storage for the EV [41]. Inductive or wireless power transfer with 230 V AC (Level-2) charging at a power rating of 7.2 kW...
all over the world [49]. These standards with maximum required power and current ratings are listed in Table 1.

4. Topologies for Fast Charging Stations

There are different topologies mentioned in the literature for fast charging stations which can be broadly classified into three categories as described below.

4.1. Topology with Back to Back AC/DC/DC Converters

Topologies of this type comprise AC to DC front-end converters linked with the power system through distribution transformers, harmonic filters, and a DC bus that is used to feed all DC to DC converters that are connected to this DC bus [50]. The presence of this DC bus makes these topologies modular in nature and many subsystems like systems for energy storage and renewable energy systems can be integrated with these topologies along with the chargers [50]. This feature makes this kind of topologies perfect in minimizing the intermittent nature of renewable resources [51] and also makes them suitable for minimizing the potential negative impacts of fast charging on the distribution network by employing battery energy storages and renewable energy sources [52]–[53]. Also, operations like vehicle-to-grid (V2G) and station-to-grid (S2G) can easily be performed by means of bi-directional converters [54]. This type of topology for charging station also eliminates the need for any communication between the centralized front-end converter and individual charger units as the magnitude and direction of power exchange between the station and the network depends on the voltage levels of the grid and the DC bus [55]. A general topology for this type of charging station is shown in Figure 4.

4.2. Multiport Stations with Common AC-Link

In such a topology, individual charger is connected with the low-voltage grid through a unity ratio line frequency transformer which acts as an isolating device. The front end converter is used to convert the three-phase AC voltage at 50 Hz into DC voltage which is then converted into high frequency AC voltage at about 25 kHz. The high frequency AC voltage so obtained is then applied at the input of the EV charger through coreless coils. This topology is shown in Figure 5. A multiport bi-directional charging station with this type of topology is proposed in [56] with capability of vehicle-to-grid operation. However, there are certain limitations of this topology such as requirement of large number of equipment which increases the number of devices and control circuits for each charging unit and also reduces the efficiency as well as reliability of the

Figure 3. Schematic diagram of wireless EV charging.

Figure 4. General topology of charging station with back to back AC/DC/DC converters.

Figure 5. Multiport charging station with common AC-link.

Table 1. EV charging standards [24], [122], [3].

| Level of charging | Maximum power rating (kW) | Maximum current rating (A) |
|-------------------|---------------------------|----------------------------|
| AC Charging       |                           |                            |
| Level-1           | 4–7.5                     | 16                         |
| Level-2           | 8–15                      | 32                         |
| Level-3           | 60–120                    | 250                        |
| Fast DC charging  | 100–200                   | 400                        |
| SAE Standard      |                           |                            |
| DC Charging       |                           |                            |
| Level-1           | Above 20                  | 80                         |
| Level-2           | 90                        | 200                        |
| Level-3           | 240                       | 400                        |
| CHAdeMO           |                           |                            |
| Fast DC charging  | 62.5                      | 125                        |
medium voltage distribution network (4.8 kV) with each phase consisting of several AC to DC and DC to DC converters resulting in a multilevel converter. Moreover, a battery storage is used instead of a capacitor bank at the DC side which is allowed to charge when EV charging is not in progress [58]. The results presented in [58] show that fast charging can be achieved along with simultaneous active power filtering (APF) using this topology. A similar topology has been used in [59] with DSTATCOM. Stability and performance analysis for this topology is done in [60]. Analysis related to the efficiency, reliability, and cost for this topology is yet to be performed. Moreover, a 4.8 kV distribution network is required for operation with this type of topology which not very common in the existing infrastructure.

Another transformerless topology is presented in [61] and [62], which can be connected to 11 kV grid which is common in use. This type of topology is shown in Figure 7. This topology does not utilize a common DC bus and uses a split-type battery energy storage instead of a single energy storage employed in the previous topology shown in Figure 6. Each three-phase module contains DC/DC converters whose outputs are connected in parallel, which allows the charging power drawn by the charger to be shared among the three phases. This leads to a balanced distribution of power between the three phases. One more advantage of such a topology is that for higher charging power requirements, two or more modules can be used. However, the absence of a common DC bus makes the system less flexible and modular [63]. Also, the control complexity is increased with this topology as compared to the topology shown in Figure 6 above.

Transformerless topology using a battery energy storage system instead of using capacitor storage is presented complete system. Moreover, the possibility of incorporation of renewable energy and energy storage systems with charging station is not explored in detail [57].

4.3. Transformerless Charging Stations

In these type of topologies, the line frequency transformer on the input side is removed in order to increase the power density of the charging station [58]. Two types of options have been reported in the literature for connecting the front end converter without using the line frequency transformer. The first type uses a direct connection of the charging station to the low-voltage grid which results in high conduction losses because of large current drawn from the grid. This limitation is overcome in the second type of charging stations which feed directly from medium voltage grid as reported in [59], [60]. This second type of topology is shown in Figure 6 which uses cascaded multilevel inverters for the interconnection. As evident from Figure 6, the charging station is connected directly to a medium voltage distribution network (4.8 kV) with each phase consisting of several AC to DC and DC to DC converters resulting in a multilevel converter. Moreover, a battery storage is used instead of a capacitor bank at the DC side which is allowed to charge when EV charging is not in progress [58]. The results presented in [58] show that fast charging can be achieved along with simultaneous active power filtering (APF) using this topology. A similar topology has been used in [59] with DSTATCOM. Stability and performance analysis for this topology is done in [60]. Analysis related to the efficiency, reliability, and cost for this topology is yet to be performed. Moreover, a 4.8 kV distribution network is required for operation with this type of topology which not very common in the existing infrastructure.

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during this time. However, the capability for this topology in integration with renewable energy resources is yet to be explored. Moreover, a large number of components to be used in inverters along with their drive and control circuits add to the complexity of this topology.

Table 2 summarizes the desired features of a charging station for the topologies discussed. For selecting the best topology, a compromise has to be made between features like modularity, power density, and complexity.
5. Fast Charging Station Integration with Grid

There are many challenges that have been discussed in the literature pertaining to the integration of EV charging station with the grid [10], [8]. The high power demanded by the charging station has many negative effects on the power system in the form of voltage deviations, increased distribution losses, and power quality degradation [65]. Issue of increased network loading also arises on integration due to the volatile nature of EV charging [6]. Moreover, the concern of decreased lifetime of the transformer because of overloading have to be taken into account. A fast charging station even with four slots for charging, would need charging capacity in the megawatt range. Thus, there are a number of requirements that have to be fulfilled so as to have a functional fast charging station integrated with the grid.

5.1. Impact on Network Loading

The interconnection of fast EV charging station with the utility grid leads to some negative impacts on the distribution system [66]. One of the main effects that is encountered is that of increase in the peak load of the network [67]. Due to the volatile nature of the charging load, it seems hard to restrict the EV charging behavior to low peak hours, which may lead to larger system peak differences [68]. This would further lead to lower operational efficiency of the distribution network equipment. This may also lead to a rise in energy losses [70] and adversarial effects on voltage profile and distribution transformers [69]. The effect of fast EV charging on the distribution transformers is studied in [70]. Further impacts in the form of overloading of conductors, cables, low voltages on the customer end, and violation of planning limits are noticeable if the charging is not coordinated [71]. Uncontrolled EV charging leads to large voltage deviations and power quality problems to such an extent that even ten percent of further penetration cannot be tolerated [72]. Thus, an approach of Valley filling of the network load curve is presented which can release the strain on the transmission system. These effects can also be minimized to a large extent if the time and duration of EV charging are controlled and the process of EV charging is well regulated [73]. Regulatory changes must be introduced from time to time in the implementation of charging strategies in order to alleviate distribution network overloading [74]. Apart from these methods, a smart multiagent metering system is suggested in [75] in order to mitigate the problem of network loading.

5.2. Issues with Power Quality

Fast charging of electric vehicles has detrimental effects on the power quality of the network. The main problems contributing to the degradation of the power quality include harmonics in line currents, phase imbalance,
voltage deviations, dc offset, phantom loading, and stray fluxes [76]. Nonlinear nature of EV chargers introduces higher order harmonics in the line current drawn by the them [77], [78]. These problems are bound to affect the performance as well as endurance of the distribution network equipment. Moreover, the component of harmonic current induces additional IR losses in the windings of the power transformers and cables. A lot of research has been done concerning the power quality problems caused by the AC/DC converters used in EV chargers. The impact of different charging rates of the batteries used in EVs on the power quality of the distribution system is studied in [68]. The effect of the harmonic currents on the system with fast charging of multiple EVs is studied in [8]. Due to the presence of these harmonic components, the commercially available on-board chargers give poor power quality [79]. The presence of lower order harmonics in the line current leads to low power factor operation and ineffective use of the volt-ampere rating. The problem of harmonic distortion deteriorates with increase in charging load. A solution to the high harmonic current injection in the distribution network is proposed in [80]. Some standards have been formulated to regulate the amount of harmonics that can be injected into the system such as IEEE 519–1992, IEC 61000–3–12/2–4, and EN 50160:2000 [81]. The quality of the input current can be enhanced by incorporating certain modifications in the control system of the charger by using an interim voltage source inverter (VSI) which prevents the harmonic currents to be fed back in the feeder. Moreover, the current control of the converters is more effective as compared to the voltage control in ensuring enhanced power factor operation and in suppressing the transients in current [82]. Also, some level-3 chargers with greater efficiencies are anticipated to mitigate the power quality issues [79].

5.3. Effect on Voltage Profile

A large deployment of plug-in electric vehicles (PEVs) may also lead to the violation of statutory voltage limits and a mismatch in supply–demand [83]. The impacts of EV charging on the voltage profiles and the voltage stability in the transmission system are analyzed in [84] concluding that charging large number of EVs would not lead to voltage collapse, but low values of voltage in the transmission system are expected. The impact of a DC fast charging station on an IEEE 34 node test feeder is analyzed in [85] which shows that coordinated modes are required to minimize the effect of fast charging stations on the network peak load, and there is a rise in the voltage drop of the network up to five percent in uncoordinated mode of charging. Fast charging can also result in an upsurge in the energy losses and network congestions along with low network voltages. However, if EVs are equitably spread between the three phases, the imbalance in voltage is not likely to surpass the statutory limits. Applied dual tariff charging policies can increase the EV integration capability of the system by fourteen percent while approach of smart charging can lead to an increase in the integration capability of the network by 52 percent [86].

6. Role of Demand Side Management Strategies

Various demand side management schemes have been devised to tackle the high-power required by fast charging stations, for example, using energy storage systems, along with the implementation of certain strategies to attain better load profile at the point of coupling of grid and the charging station. One approach is to use dynamic pricing scheme for charging operations. This approach is already in use with customers who pay increased prices during peak load timings. The second method is that of using some sort of controllable plug which can be used to either disconnect or to reduce the power level during peak load times using a signal from the utility or grid equipment [87]. Though these strategies are effective in decreasing the power consumption, they rely on complex communications and controls, which add to the overall cost of the charging stations. More commonly used strategies include the use of energy storage systems and renewable energy sources (RESs) along with the charging stations.

6.1. Energy Storage Systems for Fast Charging Stations

The rise in the demand peaks by the addition of charging load can be met partly by implementing energy storage units (ESUs). Various strategies for energy storage have been proposed in the literature to be used along with charging stations [88]. Storages in fast charging stations let accumulation of the energy to be used for charging EVs at high power. Energy storage approaches can be mainly classified into two types. The first method targets at optimization of the power to be demanded from the grid along with the optimization of capital investment in procuring the storages. The second method targets at the accumulation of energy at times when there are low tariffs. The second approach needs storages of high capacity but also provides some ancillary services, like injecting reactive and active power and providing voltage regulations. Storages using flywheel and super capacitor-like devices are common in use [89]. Hybrid energy storage systems (HESS) can also be used. A fast charging station with battery energy storage (BES) and superconducting magnetic energy storage (SMES) is proposed in [90] which limits the power change rate and power magnitude of the fast
charging station by HESS compensation. A power balancing scheme based on flywheel storage is presented in [91] for a fast charging station to minimize the impact of fast charging on the power grid by ramping the power peak. In [92] an approach is presented to determine the optimal size of the storage system for a fast charging station by considering EV characteristics and driving patterns of the vehicle owners.

6.2. Integration with Renewable Energy Systems

With anticipated fast growth in the number of electric vehicles, it is certain that the power system would be highly burdened. The integration of renewable energy sources into the grid is one way to minimize this problem [93]. Solar, wind, and biomass energy are possible options that may be used for this purpose. Various studies have been carried out to observe the extensive, longstanding effects of using wind energy in order to meet the excess energy demand put forth by charging of EVs [94], [95], [96]. However, the installation of windmills necessitates the availability of suitable locations and large premises which is a major challenge in urban areas. Moreover, the unstable nature of wind speed also makes it less attractive for charging applications as compared to other renewable sources. Biomass energy is different from the wind energy in this respect as it could be conveniently stored and used whenever required [93]. The possibility of using biomass energy for electric transportation is explored being [97], [98]. In spite of some advantages that are offered by bioelectricity its use is limited as it gives rise to a highly polluted environment that makes its utilization incompatible for highly populated areas. The prospects of using solar energy for this purpose are very high and diverse as the energy production from solar PV offers greater flexibility for integration with the existing system. One approach is to charge the vehicle directly implementing the concept of ‘charging-while-parking‘, instead of using the more common practice of ‘charging-by-stopping’ [99], [100]. This gives rise to the idea of utilizing the solar PV by installing them on the rooftop of the car park [101], [102] so that the vehicle gets charged by the integrated PV-grid system. Some benefits of the PV integrated charging station have been presented in [103], [104]. A case study presented in [105] on EV charging using only grid, grid-PV integrated system and standalone PV system with battery energy storage shows that grid-PV integrated system is better in terms of economy when compared with the grid charging and standalone PV systems. Owing to various benefits offered by the grid-PV integrated system, solar PV is more favored as compared to other renewable energy based systems. Further, a large-scale placement of EV chargers for an entire city along with solar car-ports is studied in [106] which shows that up to 50% of the city’s public transport energy need could be delivered by solar PV. A method to determine the cumulative capacity that can be provided by a PV-grid is proposed in [107]. In [108] the application of PV electricity and storage in EVs to supply peak energy to the grid is discussed. There are already some demonstration projects to assess the impacts and feasibility of the EV interaction with the RES. The ‘Zem2Alle-mobility’ pilot project inaugurated in April 2013 in Spain featured 23 CHAdeMO DC fast charging points including six bidirectional chargers capable of providing V2G functionalities. The project comprised of 200 EVs (Nissan Leafs & Mitsubishi iMiEV) compatible with the CHAdeMO DC-fast charging standard [109]. More importantly, the EVs will support the integration of the intermittent renewable sources by absorbing the excess power produced by the RES and supply back to the grid at the times of peak demand (i.e. V2G). This will demonstrate the real life scenario for the interaction of the EVs with electric power system incorporating the RES and fast charging for the V2G services.

7. Role of V2G Technology

EVs can certainly be treated as potential independent distributed energy sources which can serve the power grid. Many research studies have shown that most of the vehicles remain parked idly for about 95 percent of their time. This way, they may be left connected to the grid and can deliver the stored energy within their batteries to the grid by implementing the vehicle to grid (V2G) concept presented by Kempton [110]. The implementation of the V2G concept can assist in resolving many of the prevalent grid related problems in a smart grid environment. V2G strategies have provided a promising solution to the power market. Most of the current studies on the deployment of V2G concept have focused on the deregulated electricity market operations. Various researches have been dedicated to reducing the cost of charging, optimizing the price variations, and cost of investments on V2G and distribution infrastructures and V2G transactions have been shown to be economically and technically viable and feasible [111], [112]. Participating in the electricity reserve market can provide benefit in terms of economy to the EV aggregator as well as to the consumer. The aggregator of the EV charging station can get maximum profit by optimizing the cost function of trading revenue mentioned in Equation (1). An optimization model based on this cost function is given in [113].

\[ \max \{ r_{\text{cap}} + r_{\text{up}} - c_{\text{cap}} - c_{\text{regdn}} \} \]

where, \( r_{\text{cap}} \) represents the Day Ahead (DA) revenue of energy market, \( r_{\text{up}} \) represents the DA regulation market
The DA revenue of energy market, \( r^{em} \) can be expressed as:

\[
r^{em} = \Delta t \sum_{t \in T} \sum_{v \in V} \lambda^{DA}_t (\eta^{dis}_v \cdot (P_{reg}^{emdg} - P_{reg}^{emdg} + \Phi^{a} + \Phi^{d})) = p \cdot y
\]

where, \( \lambda^{DA}_t \) is DA energy market price, \( \eta^{dis}_v \) is battery discharge efficiency, \( P_{reg}^{emdg} \) and \( P_{reg}^{emdg} \) represent discharging and charging powers, respectively.

The revenue \( r^{cap} \) is obtained as:

\[
r^{cap} = \sum_{t \in T} \sum_{b \in B} \left[ (w^{up}_{t,b} \cdot \lambda^{up}_{t,b}) \pi^a p^{up}_t + (w^{dn}_{t,b} \cdot \lambda^{dn}_{t,b}) \Phi^d p^{dn}_t \right]
\]

(3)

where, \( \lambda^{up}_{t,b} \) and \( \lambda^{dn}_{t,b} \) are DA regulation-up and -down capacity prices, respectively; power \( p^{up}_t \) and \( p^{dn}_t \) are regulation-up and -down capacity offers to the market; \( \pi^a \) is the probability of acceptance and deployment, respectively, for up-regulation; \( \Phi^d \) is the probability of acceptance and deployment, respectively, for down-regulation; \( w^{up}_{t,b} \) and \( w^{dn}_{t,b} \) are the segment activation of the price-quantity for capacity and real-time energy probability curves in period \( t \) and segment \( b \).

Cost for regulation up service \( c^{regup} \) can be expressed as:

\[
c^{regup} = \pi^a (1 - \pi^d) \sum_{t \in T} \sum_{b \in B} \left( v^{up}_{t,b} \lambda^{RT}_{t,b} \right) (p^{up}_t - \pi^a p^{up}_t)
\]

(4)

Similarly, cost for regulation down service is expressed as:

\[
c^{regdn} = \Phi^d (1 - \Phi^d) \sum_{t \in T} \sum_{b \in B} \left( v^{dn}_{t,b} \lambda^{RT}_{t,b} \right) (p^{dn}_t - \Phi^d p^{dn}_t)
\]

(5)

In order to participate in DA market, proper load forecasting is essential. Numerous techniques have been developed for load forecasting like Simplistic Benchmark methods, Seasonal ARMA modeling, Periodic AR models etc. [114]. For simplistic benchmark method, the forecast function is given as:

\[
y_{t}(K) = y_{t+k-S_t}
\]

(6)

where \( y_t \) represents the demand in period \( t \), \( k \) is the forecast lead time (\( k \leq s_t \)). Second simplistic benchmark does simple averaging of the corresponding observations in the past for forecasting. The forecast function for this method is given in Equation (7) for four observations.

\[
y_{t}(K) = \left( y_{t+k-s_1} + y_{t+k-2s_1} + y_{t+k-3s_1} + y_{t+k-4s_1} \right)/4
\]

(7)

The uncertainties involved in the EV fleet characteristics, DA electricity market operations as well as in generation, transmission, and load may be represented by Monte Carlo simulation. Risk involved with the financial as well as economic aspects of the EV aggregator in uncertainty environments can be managed by conditional value added risk analysis (CVaR) as given in Equation (8).

\[
\text{Maximize}_{c^{reg}} \text{CVaR} = \zeta - \frac{1}{(1 - \alpha)} \sum_{s=1}^{NS} Pr^s \cdot \delta^s
\]

(8)

A detailed risk analysis based on the above method is given in [115].

8. Economic Aspects of Fast Charging Infrastructure

Total investment cost required for the establishment of charging infrastructure for EVs includes the cost of equipment to be used, installation costs, and operation and maintenance costs. With increase in penetration of EVs in the next few years, number of EV chargers will increase and hence the equipment cost is expected to decrease. There is large variation in the EV charging equipment cost among different manufacturers. Besides the initial equipment cost, installation cost is required for installation of the charger and interconnection with grid. The installation cost includes cost of civil works, transaction cost regarding distribution system operator permission, and other related costs depending on factors like requirement of a new grid connection or upgradation of the existing connection. In case there is a pre-existing connection, the installation cost may greatly reduce. Some other parameters that influence installation cost include number of simultaneous installation of many chargers which may reduce cost on account of common labor and grounding costs, mutual components etc. For semi-private/semi-public places where low or medium power level chargers are required, cost varies between 500 € (Rs 36,431) and 1200 € (Rs 87,435) [116], [117]. For public places where high power level chargers are required, installation cost is relatively higher ranging between 2400 € (Rs 1,74,871) to 3600 € (Rs 2,62,306) [117]. Apart from the equipment and installation costs, there is a requirement for continuous maintenance over the running period. For that operation and maintenance cost is to be added, which may be taken to be 10% of the total installation cost (including equipment cost) [118], [119].

9. Potential Future Research and Development

In a smart grid environment, EVs can be considered to be an important asset. They can be considered as a solution in balancing the power fluctuations arising as a result of increased penetration of unpredictable and inconsistent renewable energy sources. However, a massive integration
of EVs would act as an additional load on the power grid which would lead to unwanted congestions, voltage collapse, and other adverse impacts on the distribution system. This issue gives rise to different challenges to the power system operators. Smart charging and discharging (i.e. bidirectional V2G) solutions incorporating smart metering, security, and smart communication between EVs and smart grid are indispensable to ensure that EVs become an asset to the smart grid instead of becoming a conventional load. Thus, the enhancement in smart charging technology is advisable for future research. Apart from this, an optimal placement and sizing of charging stations is also significant in reducing the grid-related issues and maximizing the economic benefits using good optimization techniques [120], [121]. Thus, research may be done related to the optimization techniques and cost function enhancement in charging station optimization problems.

10. Conclusion

The interest in EV technology has grown in recent times due to the environmental benefits offered by them. However, the technological advancements in EV charging technology require an intensive research on this topic as well as efforts for their worldwide deployment. This paper provides an in-depth review on growing advancements in the fast EV charging infrastructure, charging technologies, and developed international standards with a comprehensive coverage of the challenges encountered as well as the opportunities offered. Despite the economic and environmental benefits, integration of EVs with the power grid can introduce certain adverse impacts on the operation of the existing electricity network with respect to the network loading, voltage deviations, and power quality. These negative impacts are discussed in detail along with the remedies proposed in the literature to counter these effects. Various demand management strategies such as use of energy storage units and renewable energy sources with the charging systems are also discussed. Furthermore, V2G technology along with its future prospects is mentioned. On the basis of this discussion, it can be concluded that it is necessary to develop and extend the fast charging infrastructure all over for the benefits of the users and the manufacturers. This would alleviate the problem of range anxiety, which is the most common concern with EVs. However, various challenges are still associated with the EVs charging infrastructure. The energy management system of EVs needed a more specific framework to deal the multilevel uncertainties associated with renewable energy sources, arrival and departure pattern of xEVs and variable market price etc. From the market framework point of view, there is a potential in researching EV market design. New market models that enable active and reactive EV-power system services such as load shifting, peak shaving, valley filling, voltage regulation, and reactive power control at the distribution system level can be investigated. The development of an accurate load model to represent EV load for the power system stability studies is essential. The energy storage system fast DC charging infrastructure is in under development and needs in-depth research. Most of the EV EMS works based on price signal strategies are focused on minimizing operational cost or EV charging cost; thus, there is room for developing new methodologies with the main objective of avoiding new peaks. Moreover, aspects regarding battery degradation issues are topical subjects that should also be taken into account in optimization methodologies for the EV charging/discharging coordination. This work is expected to deliver most relevant and significant information about the existing researches in the field of EV fast charging and encourage a further research on the topic.

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