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Review on Optimal Siting of Electric Vehicle Charging Infrastructure

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Concerns about the need for clean energy and the need to reduce green-house gases have led researchers and engineers to explore adoption of electric vehicle technology. Electric vehicles hold a promising future due to their efficiency, low maintenance cost and zero carbon emission. Unfortunately, due to metric range drawbacks associated with electric vehicles, large scale adoption of electric vehicles still remains relatively low. To solve this issue of range anxiety, optimal placement and sizing methods of electric vehicle infrastructure is essential. This paper presents a review of optimal siting of electric vehicle charging infrastructure. It discusses impacts of electric vehicle charging loads on the distribution network and how large scale electric vehicle penetration would affect the grid. Further, the benefits of electric vehicles on the distribution network as well as the integration of renewable energy resources are presented.

Keywords: Electric vehicles; charging infrastructure; charging stations; optimal location; renewable energy integration.

1. INTRODUCTION

With rising concerns over environmental pollution as well as diminishing oil reserves, research into electric vehicles (EVs) is becoming increasingly popular [1,2]. EVs also have the added advantage of being easy to maintain, efficient and are cost effective in the long run [1]. Even

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though during the manufacturing stage of EVs, greenhouse gases are produced, their carbon footprint is much lower than (only about 40%) internal combustion engines (ICEs) [2-4]. These reasons make EVs an ideal and realistic alternative to ICE vehicles in the near future. As promising as EVs may seem, they have some major obstacles to overcome such as high initial cost, limited driving range and limited charging infrastructure [1,2,5–7].

Driver range anxiety is the concern the driver has about running out of power before reaching desired destination [8]. Several factors that affect the range of EVs include temperature, battery charge, terrain, travelling speed, etc. [8]. Limited driving range may likely discourage potential consumers from adopting EVs [9]. In order to tackle such problems (and many more), charging infrastructure is critical to the development and full-scale deployment of EVs. These charging infrastructure include battery charging stations and battery exchange stations.

For EVs to be a viable option, it is important to have an adequate amount of optimally distributed and sized charging stations. Given the electric or transport network of a particular area, optimal placement and sizing of electric vehicle (EV) infrastructure is a multi-objective multi-constraint problem [2]. The most common objectives are maximizing the covered demand or service coverage of EV charging stations and minimizing costs (initial investments, operating costs, maintenance costs) [2,10]. With respect to the electric grid, significant challenges will arise as a result of increased installation of charging infrastructure. Power loss, voltage profile and system reliability are all factors that must be taken into consideration for successful planning of EV infrastructure [10]. Therefore, optimal siting of EV charge infrastructure becomes essential to the success of EV deployment.

Optimal siting of charging infrastructure has been reported in literature and various methods used [1,2,7–10]. This paper reviews some of the works previously reported on optimal siting of EV infrastructure.

2. OPTIMAL SITING OF EV CHARGING INFRASTRUCTURE

The deployment of EV Charging infrastructure is vital to the development of EVs. These charging infrastructure must contend with growing population, change in market trends and other factors that directly affect EV adoption.

The EV infrastructure location problem has been widely discussed in literature [1,2,8-20]. Optimal siting of charging infrastructure is usually a minimization of the cost, maximizing coverage of charging stations or a combination of both [2].

From the literature reviewed, optimal location of EV charging infrastructure is generally modeled by considering the transportation network, the electricity distribution network or a hybrid of both [20].

2.1 Optimal Siting of Charging Infrastructure Using Transportation Network Based Model

Optimal siting of charging infrastructure using transportation network can be further divided into: flow-based demand model and point-based demand model. In this approach optimal siting is focused on the transport network alone.

2.1.1 Flow-based demand model

Flow-demand models try to maximize the vehicle flows along certain paths. Flow Capturing Location Model (FCLM), Flow Capturing Refueling Model (FCRM) and Maximal Covering Location Model (MCLM) are path-based approaches for optimal placement of charging station problem. Dimitrios Efthymiou et al. [2] presented a Genetic Algorithm (GA) approach. Origin destination (OD) data from conventional vehicles was analyzed with necessary assumptions made. A tool developed in *R* and based on the GA was used to identify optimal locations for charging stations in the city of Thessaloniki, Greece. The downside of this method is that the OD data used was from conventional ICE's and not EVs. Also the tool used was an open source program which may face certain difficulties in the face of computational complexities. In [21], Ren et al. established a location model to minimize total social cost using GA to solve the quantity and location of charging stations. The paper details grey decision-making scheme to calculate quantity and location of charging stations. Unlike earlier studies the paper considered both quantity and optimal placement of charging stations. Unfortunately, the proposed method is such that when carrying out index evaluation scoring for a site selection scheme, its result depends on the subjectivity of the expert. Barış Yıldız et al. [22] proposed an urban model for recharging infrastructure design problem (RIDP) with stochastic recharging demands, capacitated facilities and deviation tolerances. These problems were solved by formulating a two stage stochastic programming formulation. In the first stage, an efficient branch-and-cut algorithm to solve large RIDP instances was obtained. In the second stage a novel characterization for the feasible solutions of the capacitated flow capturing problem was derived.

2.1.2 Point-based demand model

Points are nodes in transportation networks and are intersections of geographic zones. A point is modeled as a node-based facility location problem where facilities are placed at nodes based on the demand at nodes. It has the advantage of low data requirements as only the population and road network data is necessary.

Zheng & Peeta [8] studied the EV routing and optimal charging station location problems. In the optimal charging station location problem (CSLP) each OD pair was defined within a feasible range and EVs recharged a limited number of times. This was modeled as a mixed integer mixed commodity problem which involves many binary variables making it difficult to solve. The authors developed a novel algorithm based on Benders decomposition which was able to determine the exact solution. Traffic congestion was not taken into consideration which will likely be a big factor in the shortest path problem. Similarly, Brandstätter et al. [23] modeled the problem as a time-dependent integer linear program where a heuristic algorithm was developed to solve it given stochastic demand forecast. Computational studies carried out on the set of graph grid-based tests analyzed the influence of different parameters on the overall performance. The study focused on car-sharing systems for optimal CSLP. However the model assumes that the potential location for charging station is at maximum capacity (i.e. max number of charging stations) and that cars should be fully charged before a trip. For a faster convergence, Hu et al. [24] proposed a hybrid heuristic algorithm based on Genetic Algorithm (GA) and Binary Particle Swarm Optimization (BPSO) for the optimal CSLP. The model was derived by forecasting future data of EV quantities using a unique Nonlinear Autoregressive Neural Network. Results presented show that GA-BPSO converges faster and reaches better objective value than traditional GA [24]. This is because BPSO has a better random search ability which gives the GA-BPSO greater diversity, meaning it is less likely to fall into a local minimum or maximum. Through the hybridization, GA also helps with the slow convergence of the BPSO.

2.2 Optimal Siting of Charging Infrastructure Using Distribution Network-Based Model

To reduce the adverse effect on the power grid, optimal placement of EV charging infrastructure is necessary [20]. Some issues like voltage stability, reliability and power losses are addressed while selecting the optimal locations of EV charging infrastructure with respect to the distribution network [20]. Here only the electric distribution network is considered.

Shinde and Swarup [25] presented a locational marginal pricing-based approach to solve the charging station location problem. The location marginal pricing was calculated at different load buses and based on that optimal placement was done using a Non-Dominated Sorting Genetic Algorithm (NSGA) and Multi-Objective Particle Swarm Optimization. When compared to random placement of charging infrastructure the two optimization techniques saved charging costs [25]. In [10], Mohsenzadeh et al. presented a Genetic Algorithm solution to the EV infrastructure placing and sizing optimization problem. The problem was viewed from the perspective of the electric distribution network where changes in system reliability, power loss, voltage drop, and costs associated with the installation of EV infrastructure were considered. The EV charging infrastructure, namely parking lots, were considered as distributed generation sources due to their potential for electricity exchange. The optimal placing and sizing of parking lots include different levels of charging stations. Using the proposed method, the results show improvements in the power loss levels, voltage profile, system reliability and costs even though increase in EVs causes financial and technical challenges in the electric distribution network.

2.3 Optimal Siting of Charging Infrastructure Using Transportation and Distribution Networks-Based Models

A Geographic Information System (GIS) based multi-objective Particle Swarm Optimization (PSO) technique was used in [26]. PSO was applied to analyze the relationship between upfront and operating costs and service coverage of the charging stations. Taken into account were charging infrastructure influence on the loads of power grid as well as the conveniences of the charging station. Here, the GIS was used to overlay the traffic system and electric power grid together to find EV charging infrastructure sites. Wang et al. [27] presented a traffic constrained multi-objective planning of EV charging stations using a novel method. The IEEE 33 bus radial network representing the model electric distribution network and a 25 node road network were superimposed together. Similarly, the authors in [28-31] all presented optimal allocation of charging stations using a superimposed distribution and road network. They all either used IEEE's test network or real electric grid in a locality to model the distribution network.

3. IMPACT OF EV CHARGING STATION LOADS ON THE ELECTRIC DISTRIBUTION NETWORK

In the future it is expected that there will be high penetration of EVs due to the concerted effort by governments around the world to reduce greenhouse gases (GHGs) [17]. The transportation sector plays a key role here as it is the second highest contributor to GHGs [17]. The increase in number of EVs, while solving some challenges, pose a whole new set of problems especially as it concerns the electric power grid. An increase in EV charging station loads will lead to rise in peak demand, power loss, voltage instability, transformer life reduction and power quality problems (due to harmonics, voltage sag and unbalance) [32–50].

In addition, EV charging effects on the electric grid depend on the state of charge (SOC) and capacity of the battery, load profiles of existing feeders and charging modes of the EV. This makes operation and planning of electric grid more complex with the rise in EV penetration [5]. The EV charging parameters are usually modeled using stochastic methods to capture the uncertainties.

3.1 Voltage Instability

Voltage instability may cause very low voltage in an electric grid as a result of excess power demand by the loads, which is beyond the grid's capability. A stable electric distribution network is essential for steady and reliable power supply. Power outages may be caused as a result of voltage instability due to excessive power demand. EVs have nonlinear load characteristics and may draw large amounts of current in a short amount of time [17]. Studies have shown that different load profiles of EVs have an effect on the voltage stability [17,32,33]. This makes studying the effects that EVs have on voltage stability ever more important. Several methods have been suggested to tackle the issue of instability [34,35]. Rajakaruna et al. [34] proposed a voltage control method via tap transformer to reduce instability. Mitra et al. [35] proposed a wide area control method to dampen out the oscillations in EVs while charging and discharging to mitigate voltage stability.

3.2 Increase in Peak Demand

An increase in EV penetration may lead to a corresponding increase in the grid peak demand if there is uncontrolled charging [36,37]. In [36] McCarthy et al. determined that a substantial amount of EV loads must be shifted to off-peak hours for demand to be stable assuming generation is not increased. The problem of increase in peak demand can be resolved without necessarily increasing generation by using smart charging and time of use (TOU) tariff plan [38,39].

3.3 Harmonics

The nonlinear nature of EVs leads to high frequency components of voltage and current which are integer multiples of a reference frequency. These high frequency components are undesirable and are known as harmonics [17]. Harmonics has many negative effects, these include [17,40]:

i. Distortion of component waveforms leading to poor power quality.
ii. It can cause stress in distribution network equipment (e.g. cables and fuses).
iii. Can lead to current flow in neutral wire.

The total amount of voltage or current harmonics can be expressed as total voltage harmonics distortion (THD_v) and total current harmonics distortion (THD_i), given in (1) and (2).

$$THD_v = \frac{\sqrt{\sum_{h=2}^{H} V_h^2}}{V_1} \times 100\% \tag{1}$$

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

Where, H is the highest harmonic number, h is the harmonic order number, V_h is the RMS voltage measured in volts, V, I_h is the RMS current measured in amperes, A, V_1 is the RMS value of the fundamental frequency voltage measured in volts, I_1 is the RMS value of the fundamental frequency current measured in amperes.

Boynuegri et al. [41] proposed various operating modes to eliminate power quality problem in a smart grid-compatible system. The results showed a significant improvement in voltage quality and a reduction in the total harmonic distortion.

3.4 Voltage Unbalance

Voltage unbalance or voltage imbalance is a power quality problem that only affects three-phase systems. Voltage unbalance happens when the magnitudes of the line or phase voltages are different, the phase angles are different (from a balanced system) or both [42]. Voltage unbalance is caused by unequal loads in the distribution lines. IEEE defines voltage unbalance as the phase voltage unbalance rate (PVUR) given in (3).

$$\%PVUR = \frac{\max voltage\ deviation\ from\ avg.phase\ voltage}{avg.phase\ voltage} \times 100\% \tag{3}$$

However the true definition of voltage unbalance (VU) is given as the ratio of negative sequence voltage component (V-) to the positive sequence voltage component (V+), both measured in volts, V, shown in (4).

$$VU = \frac{V_-}{V_+} \times 100\% \tag{4}$$

Shahnia et al. [43] showed that EVs have little impact at the beginning of a low voltage feeder, but have a major impact at the end of the feeder. Li et al. [44] also showed that with more than 50% EV penetration voltage starts to reduce at the end of the feeder. They also suggested a smart charging plan to mitigate the effect of voltage unbalance [44].

3.5 Voltage Sag

Voltage sag or voltage dip is a reduction in the RMS voltage value for a short duration (half a cycle to one minute) of time caused by starting of electrical machines, overload and short circuit. Tie et al. [45] and Lee et al. [46] showed the effect of EV penetration on voltage sag limit. Tie et al. [45] showed that up to 60% EV penetration can be achieved if proper charge control strategies are used. Without any charge control strategies, only 10% EV penetration would be acceptable without exceeding the voltage sag limit.

3.6 Power Loss

Power loss is the loss of electrical power supply. Large EV penetration into the electric grid can cause huge power losses. Power loss (P_{LOSS}) in a distribution network feeder is given in (5).

$$P_{LOSS} = \sum_n^N I^2 R_n \tag{5}$$

Where N is the total number of feeders in a system, I is the current measured in amperes, A, and R_n is the resistance across feeder n, measured in ohms, Ω. P_{LOSS} and extra power loss (P_{LE}) are both measured in watts, W. The P_{LE} caused by EVs can be mathematically expressed as given in (6).

$$P_{LE} = P_{LEV} - P_{LO} \tag{6}$$

Where P_{LEV} is the total power lost when EVs are connected to the electric grid and P_{LO} is the total power lost when the EVs are not connected to the electric grid, both measured in watts. Fernandez et al. [47] showed that power loss to the electric grid could be as high as 40% if 60% of the EVs in UK were connected at the same time. Without coordinated charging schemes the loss could grow even more.

3.7 Overloading of Transformers

Overloading of transformers occur when its voltage or current ratings have been exceeded. Transformer overloading causes excess heat which affects the insulation of the transformer leading to reduction of transformer life [48]. Although in areas with low ambient temperature, studies show transformer loading has little effect on its aging [48].

Integration of EVs to the electric grid may increase overloading of transformers. Therefore, proper transformer selection, network planning and load management are necessary to mitigate the negative effects of EVs. Some smart metering schemes have been suggested to increase transformer lifespan [49,50].

4. BENEFITS OF ELECTRIC VEHICLES ON THE ELECTRIC DISTRIBUTION NETWORK

4.1 Vehicle-to-Grid (V2G) Technology

V2G is a service where EVs can provide power back to the electric grid. Power flow can either be unidirectional or bidirectional. For bidirectional power flow extra equipment are needed to supply power to the grid from the EV as well as other protection issues related to grid connections. This technology can increase reliability and potentially reduce peak demand when necessary [51]. EV users can gain financially from the V2G technology by selling some of their stored power to the grid. Arita et al. [52] and Sasaki et al. [54] showed the impact of V2G in limiting voltage fluctuations and improving power quality in the electric grid. In related studies [54-56], the authors noted that the V2G technology can provide voltage support to minimize the use of voltage regulators, reduce distribution line loss and voltage drop. Constant charging and discharging can have adverse negative effects on the battery life. It is therefore important that intelligent charging systems are employed to reduce this effect [51].

Prasomthong et al. [57] presented optimal placement of V2G enabled charging station in a radial distribution network and considered the net benefit of the V2G model. Khalkhali et al. [58] proposed an optimal placement method for a V2G enabled charging station in electric grid. The results showed an improvement in the voltage profile and reduction in active power loss.

4.2 Smart Grid

Smart Grid technology incorporates communications with decision making to make the electric grid ‘intelligent’. This technology paves the way for many solutions to the problems of EV integration into the electric grid. Reliable power supply, advanced control methods, better integration of renewable energy resources, V2G and coordinated charging schemes are all advantages of smart grids.

5. INTEGRATION OF EV CHARGING INFRASTRUCTURE WITH RENEWABLE ENERGY RESOURCES

Integration of EVs and renewable energy is a promising area due to the need to add distributed generation to reduce excess stress on the electric grid. Parking lots, rooftops, public buildings are all potential sites for either Photovoltaic (PV) panel or wind turbine placement. EVs parked under these structures can conveniently charge using these sources while EV users carry out other activities. Though, there are other forms of renewable energy resources, this work focuses on wind and solar PV.

5.1 Wind Energy

A number of studies present the impact that EVs have on the electric grids integration with wind energy. Fernandez et al. [47] showed that V2G technology can increase the penetration of wind energy by up to 59%. Similarly, Turton et al. [59] derived a model that forecasts impact of integration of EVs with a V2G enabled grid. Their findings show that there is increased renewable energy capacity as a result of the EVs storage and discharge capability in the V2G scheme. Borba et al. [60] modeled the electric grid in a 20-year span and assumed a huge increase in wind energy generation. The exact size of the hybrid EVs that could be powered by the excess wind energy was then calculated. They estimated that 1.6 million cars will be able to be powered during the optimal seasonal conditions (from January to June). Bellekom et al. in [61] studied the combined and separate effect of EVs and wind energy. The study showed that 4 GW of wind energy can be added without EV penetration, and 10GW with 1 million EVs. Ekman et al. [62] discussed the relationship between energy produced and consumed, and EV charging load patterns. EVs with smart charging capabilities were shown to reduce excess wind generation and could decrease the backup capacity required. All these studies show that EVs are likely to play a big role in increasing the wind energy penetration by capturing energy that would have been wasted.

5.2 Solar Photovoltaic

EVs and solar PV integration has been widely discussed in literature [63]-[66]. Dallinger and Wietschel [63] considered both solar PV and wind energy with 50% capacity by 2030 in Germany. The results show that EVs can absorb about 50% of excess solar PV and wind energy yearly. The author in [64] proposed installing solar panels on parking lot rooftops. Using New Jersey as a case study, their findings showed that during summer, given the solar irradiation, module efficiency and parking space, most driving needs would be met. This was not the same case for winter where average energy production dropped drastically. The paper however did not mention the economic viability of such systems. Gibson et al. in [65] and Zhang et al. in [67] discussed the feasibility of EV battery charging using solar PV. Using on-site generated energy, many losses associated with electric grid were avoided. These losses include, transmission losses and DC-to-AC conversion losses. The study proves the viability of the method. The authors in [67] proposed a method in which solar PV is integrated with EVs and heat pumps in Japan. Their finding showed that with a 30GW solar capacity installed, that would take the overall production excess to about 10 TWh annually. 5 million EVs and heat pump would absorb all the excess energy. Only about 30% of excess energy would be absorbed if 1 million EVs and heat pumps were added to the grid. These studies show that integration of solar energy with EVs would assist in capturing excess energy.

6. CONCLUSION

This paper presents a general overview of EV charging infrastructure and impacts of EV on the distribution grid. Low emission and high efficiency among others are considered as some of the major benefits of EVs. Despite these benefits, driver anxiety, costs, increase in demand of EVs and by extension new technical challenges to the electric distribution networks are some of the major impacts. For this reason it is important for EV charging infrastructure to be optimally placed and sized. Optimal siting based on the transport network, distribution network or a combination of both were discussed. Then, the impact of EV charging loads on the electric grid were discussed with various papers proposing solutions to the challenge. The benefits of EVs to the grid were presented, notably V2G technology was one of the major benefit that could be derived from this method. It is still clear that V2G technology is an area for future studies as it makes EVs an asset as opposed to just an ordinary load. Finally, the integration of solar PV and wind energy has huge potentials for EVs to absorb excess energy. The integration of these renewable energy resources also helps lift some of the burden from the electric grid.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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