Hosting Capacity Assessment of Electric Vehicles Integration in Active Distribution System

Sagarika Rout¹, GyanRanjan Biswal²
¹,²Department of Electrical Engineering & EEE, VSSUT, Burla, Odisha-768018
¹routsagarika90@gmail.com

Abstract: The current article aims to assess the effects of electric vehicles (EV) integration in distribution networks, considering the initial state of charge (SOC) and charging level type. The increase engagement for the incorporation of larger numbers of EVs in low voltage (LV) networks causes a significant overload and voltage fluctuation in the system because of the synchronization condition of domestic load peak time and EV charging time. The effect on the system is analyzed by determining the total hosting strength of the LV active network for a different level of EV penetration. Two different load models for slow and fast charging EV are considered along with an initial state of charge (SOC) condition. The hosting capacity is affected not only by the penetration level of EV but rather; it also depends upon SOC condition and type of charger. Moreover, the methodology is proficient enough to give sufficient and reliable information so as to flexible for the control in real time scenario in the smart grid execution.

Keywords: Electric Vehicles, electric vehicle integration, EV load model, Hosting Capacity, LV grid.

1. INTRODUCTION:

Transportation is the major areas regarding consumption of huge amount of energy and has impacted heavily on the electrical distribution network. Additionally, so many load types that exist in the power system whose characteristics were studied. The Electric Vehicle (EV) is recent and different type of load in the system, which is going to be a common load in distribution sector. Green environmental and clean energy issues have led to transfer the effort from the internal combustion engine (ICE) vehicle to electric vehicles. The increased integration of EV load will impose a considerable demand on the system, and thus, the distribution system will be impacted. The main power source of EV is a rechargeable battery and charging condition. So, to accommodate the large proliferation of EVs in power distribution networks, it very much depends on EV load characteristics, battery capacity and the charging behavior of EVs. EV load characteristics and conventional loads characteristics are different from each other. It based on some precariousness parameters like driving pattern, location, the initial SOC, time, level of charging, type of EV and number of EV.

The technologies for EV charging are identified as AC and DC and further as level 1-3. [1]. In home the level of charging is 1 and 2 which are known for slow level of charging and level 3 is used for faster charging used commercially. The Vehicle load is different from the conventional load type. Many papers analyzed how EV affect the the low voltage distribution sector by using an aggregated stochastic approach for EV charging load model [2–6]. These studies indicate EV charging load has a considerable effect on the system. In [7], a static model for the EV as a charging load is presented by considering the initial SOC based on daily driving distance. In the literature, as mentioned above, it is assumed that power consumed by the EV charging is basically constant current and constant voltage.
phenomenon. The battery charging time in [8] depends on SOC and charging characteristics. The work in the literature presented above considers the EV load as constant power load (CP) in the power flow simulation, which considers the Vehicle load model is unaffected by feeder voltage. The electrical load model is categorized as static load models and dynamic load models. In static load model, the load characteristics are defined as the voltage dependent and frequency dependent [9]. The battery in normal charging mode is presented by the EV characteristics, which is defined as an exponential load model by testing in laboratory [10]. The authors in [11, 13] have modeled the EV charging load but in [11] the author have not considered initial SOC and how it affect the load model, and in [13] a slow charging EV load model is defined. From the study, it is seen that few authors have contemplated and analyzed the EV charging behavior and the feeder voltage fluctuation for fast-charging EV load modeling. However, the characteristics of EVs under voltage dependent power flow analysis considering the SOC is not been discussed and assessed.

For uncoordinated EV charging, LV grid is significantly affected because of concurrently between the residential power load peak time and the EV load charging time. The maximum number of EV load that can be injected to the grid without imperiling the stability and quality of the system is defined as the hosting capacity of the vehicle in that network. The increased penetration of EVs on the distribution networks has negative impacts. Many papers have introduced the enhancement strategy for EV penetration like network reconfiguration [14, 15], on load tap changers, switched shunt capacitors, energy storage [16, 17] without system reinforcement. However, the above study does not indicate any effect of the charger model in the network hosting capacity.

The impression of EVs when integrate to low voltage active network has to be quantified. Therefore, this article is going to analyze the EV hosting capacity (HC) by considering faster level of charging and slow charging level load model of EV. The load model is also expressed exponentially with static load base and fast charging battery model and analysis is done by considering the voltage magnitude deviation due to EVs charging as the constraint. The EV is described in normal charging mode at a rate about 1.2-3.7 KW. These EVs are consuming low power in a range of 120-240 V at home and public place. So, the balanced system is considered to analyze the impact of EV load on the LV distribution section for various level types.

The article is arranged as follows; the load model of EV is discussed in section 2; the methodology for HC analysis is briefly explained in Section 3, and the simulation result is explained in Section 4 for different types of EV Charging. Finally, in section 5 the conclusion is given.

2. ELECTRIC VEHICLE LOAD MODEL:

The load model in the electrical system is the mathematical interpretation based on the frequency or the node voltage magnitude relation for that network. The apparent load power (KVA) considered real power and watts power components separately. The voltage dependent load model is defined by the exponential mathematical expression at each bus as in [9].

\[ P_{LK} = P_{LK0} \left( \frac{V_k}{V_{ko}} \right)^{n_p} \]  
\[ Q_{LK} = Q_{LK0} \left( \frac{V_k}{V_{ko}} \right)^{n_q} \]

(1)
(2)

Where, \( S_{LK} \) indicate the apparent load power, \( P_{LK} \) is the active component and \( Q_{LK} \) represents the reactive component of power. \( V_{ko} \) is the magnitude of nominal bus voltage where, \( n_p \) and \( n_q \) represents indices for different load type.
The batteries in the EVs are chemical storage representation and the charging/discharging behavior of the battery is the chemical process which can be describes in mathematics as exponential function over time. The vehicle battery charging status in active power requirement is defined as in [18].

\[ P_{EV}(t) = P_{EVMAX}(1 - e^{-\alpha t/t_{max}}) + P_{EV0} \]  

(3)

The constant parameter is calculated experimentally in [18] and value as \( \alpha = 6.9077 \). The time taken by the vehicle to charge the battery fully is very much depends on its real power status. It is considered that the EV needs \( t_c \) hours to full charge its battery.so, the real power demand of each EV is describes as

\[ P_{EV} = P_{EVMAX}(1 - e^{-\alpha t/t_{max}}) \]  

(4)

Again, the power factor of the system is taken as unity; so that the reactive power demand component becomes \( Q_{EV} = 0 \).

2.1. Slow charging Model:

For slow charging EV load model, the relationship is expressed as an algebraic function by exponential characteristics. When the EV is charging from the grid the power factor has an important role in the modeling and will be considered at this instant as given below.

\[ P_{EV} = S_0 \times k_p \times \left( \frac{V_k}{V_{k0}} \right)^{n_p} \]  

(5)

\[ Q_{EV} = S_0 \times k_q \times \left( \frac{V_k}{V_{k0}} \right)^{n_q} \]  

(6)

Where, \( S_0 \) is the apparent load kva at nominal voltage \( V_{k0} \). \( k_p \) is the power factor(pf) of the load and can be calculated as \( k_q = \sqrt{1 - p_i^2} \). \( n_p = 2.59, n_q = 4.06 [10] \). The EVs were specified as normal slow charging load model of the battery charger.

2.2. Fast Charging Model:

By considering the fast charging behavior of the battery of EV, the existing voltage dependent load model is modified for the analysis purpose. The model given in the literature [19] closely resembles the analytical expression for fast charging EV model.

\[ \frac{P_{EV}}{P_0} = a_p \left( \frac{V_k}{V_{k0}} \right)^{n_p} + b_p \]  

(7)

Where, \( P_0 \) is the consumed real power at the nominal voltage level \( V_0 \). \( a_p, n_p, b_p \) are the indices of the load model expressed exponentially for the active power component which are depends on the SOC of the battery of EV and determined experimentally.

3. METHODOLOGY:

The hosting capacity strength of EVs in the LV section defined as the number of EV that can be injected to the network for charging purpose without affecting stability and reliability of the system. It is defined by considering the indexes described below.

3.1. Voltage deviation index (VDI):

The enhanced load in the network affects each bus voltage in the system. VDI is used to analyze loading effect on the bus voltage. A good level of system voltage is indicated by a low value of VDI. It is defined as

\[ VDI = \sum_{k} \frac{V_k^{ref} - V_k}{V_k^{ref}} \]  

(8)
Where, $V_k$ is the load voltage at node $k$ and $V_{k}^{ref}$ is the voltage reference which is defined as 1 p.u. under normal conditions.

3.2. Total power loss:

The active and reactive powers in the transmission line between two connecting nodes $k$ and $k+1$ is calculated as

$$P_{Ls}(k, k+1) = R_k \times \left( \frac{P_k^2 + Q_k^2}{V_k^2} \right)$$

$$Q_{Ls}(k, k+1) = X_k \times \left( \frac{P_k^2 + Q_k^2}{V_k^2} \right)$$

(9)

(10)

The aggregate real power loss ($P_{\text{loss}}$) and aggregate wattles power loss ($Q_{\text{loss}}$) of the network is summarized. The whole total loss and voltage at each node is analyzed by using an efficient voltage dependent power flow method.

4. RESULTS AND CALCULATIONS:

The IEEE bus 33 radial distribution test system set up is taken for the analysis and to estimate the proficiency of each type of EV load. The test system model is modified from conventional load model to voltage controlled load model. The system load flow algorithm is performed in MATLAB m-file for the analysis. Two DGs are installed in an optimal position by considering the voltage stability index and total system demand. Two scenarios are considered for hosting capacity calculations with EV penetration rate: 100%, 50% with different SOC for different EV load type. The EV charging power of 3680 Watt (corresponding to 16 amps) is considered. This is typical value for the home charger. A 3680 watt charger is capable to charge an EV from flat to full in 6-8 hours. The total load demand of the network is used as constraint for different scenario to find the number of vehicle that can be hosted in the distribution network in addition to the residential load.

![Figure 1. Voltage level for various SOC in slow charging EV load.](image)

The simulation is done for both slow charging EV load and fast charging EV load separately with different penetration levels in the network considering the initial SOC. Figure 1 shows the voltage magnitude for slow charging EV load is very sensitive for various SOC levels.
Figure 2. Voltage Magnitude comparison between slow and fast charging EV load type

| Charging Type | Penetration (in %) | SOC (in %) | VDI | real power loss (KW) | Reactive power loss (KVAR) | %VDI | %P   | %Q   |
|---------------|--------------------|-----------|-----|----------------------|---------------------------|------|------|------|
| EV (SLOW CHARGING) | 100                | -         | 0.07 | 97.3 | 67.6 | -66.66 | -62.97 | -63.90 |
|                | 80                 | 0.16      |      | 277.08 | 196.54 | -23.80 | 5.43   | 4.93   |
|                | 50                 | 0.24      |      | 404 | 286 | 14.28 | 53.72 | 52.69   |
|                | 20                 | 0.33      |      | 513 | 391 | 57.14 | 95.20 | 108.75  |
|                | 50                 | 0.27      |      | 333 | 309.65 | 28.57 | 65.04 | 66.32 |
| EV (FAST CHARGING) | 100                | -         | 0.59 | 360 | 330 | 180.04 | 36.98 | 76.18 |
|                | 50                 | 0.37      |      | 303 | 217 | 76.333 | 15.29 | 15.85 |

The results obtained are analyzed with the indices defined in percentage. The gross real power loss, VAR loss and VDI for different load types by taking Constant power load as the reference is shown in Table 1. The indices indicate as lower the value lesser is the impact in the grid. That means if the value is less then, the system is least affected by that factor. Interestingly, the result shows that the above mentioned indices are insignificant to the voltage index and aggregate power loss of the system if the EV load is modeled without considering taking the initial SOC condition of the battery. So when the load model of EV considers the effect of the initial SOC, it is significant to the network. It is also shown that the fast charging model is much more affected than the slow charging model.
The fast-charging EV load type is insignificant to the SOC; rather, it depends on the voltage level during charge. Figure 2 indicates the fast charging load is more sensitive to the voltage level of the network than the slow charging load type. But for the same penetration level and SOC, voltage is not affected in all nodes rather for some nodes.

### Table 2. Hosting capacities for different SOC for normal charging EV model

| PENETRATION | SOC (%) | CHARGER LOAD (KW) | HOSTING CAPACITY (in number) |
|-------------|--------|-------------------|-----------------------------|
| 100%        | 20     | 3860              | 0                           |
|             | 50     |                   | 22                          |
|             | 80     |                   | 301                         |
| 50%         | 20     | 3860              | 22                          |
|             | 50     |                   | 292                         |
|             | 80     |                   | 590                         |

Furthermore, Table 2 indicates the hosting capacity for normal charging EV load type is depended on SOC as well as the EV penetration level in the network. Whereas in fast charging load type, hosting capacity is reduced significantly as compared to slow charging EV load, which is shown in Table 3. The hosting capacity is insignificant to the SOC in the fast charging load model.

### Table 3. Hosting capacities for the fast-charging EV model

| PENETRATION | CHARGER LOAD (KW) | HOSTING CAPACITY (in number) |
|-------------|-------------------|-----------------------------|
| 100%        | 3860              | 42                          |
| 50%         | 3860              | 315                         |

5. **CONCLUSION:**

This article analyzed the hosting capacity assessment of single phase EV charger in the LV active distribution network. The hosting capacity strength of the network turns out to be the most significant in terms of the percentile of EV used and to the power availed per charger. The percentile is noted as an index for the network operator that how much risk can be taken or allowed in the planning stage. It has been seen that with the increase in penetration level hosting capacities reduces significantly and also vary much sensitive towards the SOC. Two scenarios were considered. In the case of a fast-charging load type of EV, the system voltage magnitude is not very much affected by the initial condition of SOC of the battery; rather, it is affected by the penetration level of the EVs. But, for slow charging EV load type, it is sensitive toward both conditions. So, for the fast charging network, if the penetration level is increased, the network will incline towards more under-voltage condition for each node. Furthermore, the proper management of EVs with coordinated charging will reduce its impact in the network and enhance the stability.
Reference:

[1] Yilmaz M and Krein P T May 2013, “Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles”, IEEE Transactions on Power Electronics, vol. 28, no. 5, pp. 2151-2169.

[2] Papadopoulos P, Skarvelis-Kazakos S, Grau I, Cipcigan L M and Jenkins N Sept 2012, “Electric vehicles’ impact on british distribution networks”, IET Electrical Systems in Transportation, vol. 2, no. 3, pp. 91-102.

[3] Arias A, Granada M and Castro C A Sept 2017, “Optimal probabilistic charging of electric vehicles in distribution systems”, IET Electrical Systems in Transportation, vol. 7, no. 3, pp. 246-251.

[4] Neaimeh M, Wardle R and Jenkins A M, 2015, “A probabilistic approach to combining smart meter and electric vehicle charging data to investigate distribution network impacts”, Appl. Energy, vol. 157, pp. 688–698.

[5] Li G and Zhang X, Mar 2012, “Modeling of plug-in hybrid electric vehicle charging demand in probabilistic power flow calculations”, IEEE Transactions on Smart Grid, vol. 3, no. 1, pp. 492-499.

[6] Shafiee S, Fotuhi-Firuzabad M and Rastegar M, Sept. 2013, “Investigating the impacts of plug-in hybrid electric vehicles on power distribution systems”, IEEE Transactions on Smart Grid, vol. 4, no. 3, pp. 1351-1360.

[7] Zhang P, Qian K, Zhou C, Stewart B G and Hepburn D M, Aug. 2012, “A methodology for optimization of power systems demand due to electric vehicle charging load”, IEEE Transactions on Power Systems, vol. 27, no. 3, pp. 1628-1636.

[8] Hafez O and Bhattacharya K, Jan. 2018, “Queuing analysis based pev load modeling considering battery charging behavior and their impact on distribution system operation”, IEEE Transactions on Smart Grid, vol. 9, no. 1, pp. 261-273.

[9] Kundur P, 1994, Power System Stability and Control; New York, NY, USA, McGraw-Hill.

[10] Hajagos L M and Dana B, May 1998, “Laboratory measurements and models of modern loads and their effect on voltage stability studies”, IEEE Transactions on Power Systems, vol. 13, no. 2, pp. 584-592.

[11] Dharmakeerthi C, Mithulananthan N and Saha T, 2014, “Impact of electric vehicle fast charging on power system voltage stability”, Int. J. Electr. Power Energy Syst., vol.57, pp. 241–249.

[12] Haidar A M, Muttaqi K M and Haque M H, 2015, “Multistage time-variant electric vehicle load modelling for capturing accurate electric vehicle behaviour and electric vehicle impact on electricity distribution grids”, IET Gener. Transm. Distrib., vol 16, no.9, pp. 2705–2716.
[13] Haidar A M and Muttaqi K M, 2016, “Behavioral characterization of electric vehicle charging loads in a distribution power grid through modeling of battery chargers”, IEEE Trans. Ind. Appl., vol.52, no.1, pp. 483–492.

[14] Pinto Y G, Trindade F C L, Cebrian J C, and Teixeira W W, Sep. 2017, “Investigation of infrastructural solutions to mitigate the impacts of EV recharging at LV networks”, IEEE PES Innov. Smart Grid Technol. Conf.-Latin America (ISGT Latin America), pp. 1-6.

[15] Melo D F R, Leguizamon W, Massier T, and Gooi H B, Sep. 2017, “Optimal distribution feeder reconfiguration for integration of electric vehicles,” IEEE PES Innov. Smart Grid Technol. Conf.- Latin America (ISGT Latin America), pp. 1-6.

[16] Procopiou A T, Quirós-Tortós J and Ochoa L F, May 2017, “HPC-based probabilistic analysis of LV networks with EVs: Impacts and control”, IEEE Trans. Smart Grid, vol. 8, no. 3, pp. 1479-1487.

[17] Deilami S, Masoum A S, Jabalameli N, and Masoum M A S, 2013, “Optimal scheduling of load tap changer and switched shunt capacitors in smart grid with electric vehicles and charging stations”, Proc. 8th Int. Conf. Elect. Electron. Eng. (ELECO), pp. 162-166.

[18] Shukla A, Verma K. and Kumar R, Dec 2018, “Voltage-dependent modelling of fast charging electric vehicle load considering battery characteristics”, IET Electrical Systems in Transportation, vol. 8, no. 4, pp. 221-230.

[19] Cundeva S, Mateska A K and Bollen M H J, 2018, “Hosting capacity of LV residential grid for uncoordinated ev charging”, 18th International Conference on Harmonics and Quality of Power (ICHQP).pp. 1-5.

[20] Quijano D A, Wang J, Sarker M R and Padilha-Feltrin A, Dec 2017, “Stochastic assessment of distributed generation hosting capacity and energy efficiency in active distribution networks”, IET Generation, Transmission & Distribution, vol. 11, no. 18, pp. 4617-4625.