EV Hosting Capacity Analysis on Distribution Grids

Preprint

Priti Paudyal, Shibani Ghosh, Santosh Veda,
Deepak Tiwari, and Jal Desai

National Renewable Energy Laboratory

*Presented at the 2021 IEEE Power and Energy Society General Meeting
July 26–29, 2021*

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-75639
August 2021

EV Hosting Capacity Analysis on Distribution Grids

Preprint

Priti Paudyal, Shibani Ghosh, Santosh Veda, Deepak Tiwari, and Jal Desai

National Renewable Energy Laboratory

Suggested Citation
Paudyal, Priti, Shibani Ghosh, Santosh Veda, Deepak Tiwari, and Jal Desai. 2021. *EV Hosting Capacity Analysis on Distribution Grids: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-75639. https://www.nrel.gov/docs/fy21osti/75639.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-75639
August 2021

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

EV Hosting Capacity Analysis on Distribution Grids

Priti Paudyal, Shibani Ghosh, Santosh Veda, Deepak Tiwari, Jal Desai
National Renewable Energy Laboratory
15013 Denver W Pkwy, Golden, CO, 80401
Email: Priti.Paudyal@nrel.gov

Abstract—**The increasing trend in electric vehicle (EV) adoption can cause challenges to traditional electric grid operations if utilities are not equipped with tools and methods to effectively manage these fleets. Growing EV charging loads will alter the magnitude and duration of conventional peaks in demand profiles and even significantly shift them, potentially causing operational violations in the distribution grid. This paper presents the development and results of an EV hosting capacity tool to quantify the impacts of injecting large numbers of EV charging loads and to determine the available capacity of existing distribution feeders to continue providing reliable and affordable grid operations. Tools like the hosting capacity analysis would enable utilities to better prepare for grid operations in the near future while exploring the impact and effectiveness of strategies to manage these loads, such as peak pricing and smart charging. This paper evaluates the hosting capacity of some real-world feeders to accommodate EV charging loads, including extreme fast-charging options.**

Index Terms—**Hosting capacity, electric vehicle (EV), distribution grid, extreme fast-charging (xFC), voltage limit, thermal overload.**

I. Introduction

Given the continuing trends in the decreasing costs of battery energy storage and in improving electric vehicle (EV) technologies, there is increased adoption of EVs [1]. The increasing penetration level of EVs could cause challenges with equipment overloading, voltage regulation, and congestion in the network. Controlled or coordinated charging of EVs could be one solution for grid operators to address these network issues [2]. The presence of EV fleets presents unique challenges because EV adoption concentrated in clusters in specific parts of the electric grid could cause local voltage and thermal overloading violations. Higher power levels at the charger level relative to the rest of the home electrical loads and aggregate charging behavior driven by user preferences (e.g., charging after commuting home from work) could further exacerbate these impacts.

Hosting capacity analysis could be a primary tool to estimate the amount of distributed energy resources (DERs) the grid can allow without the need for major upgrades. This static parameter can be defined as the amount of new production/consumption that can be connected to the grid without risking reliability or voltage quality for other customers [3]. Hosting capacity is a location-dependent concept—in other words, hosting new distributed generators or EV loads can be accommodated in some locations to varying extents [4]. There are two types of hosting capacity studies: system level and node level. In [5], the authors discussed the photovoltaic (PV) hosting capacity using a statistical approach. A Monte Carlo-based methodology was used in [6] to analyze the PV hosting capacity considering the impact on operational limits such as overvoltages, thermal capacity, and transformer overload. Most previous work included a snapshot of a worst case to determine hosting capacity. In [7], the authors considered quasi-static time-series simulations to study the PV hosting capacity.

EV hosting capacity analysis is performed to evaluate how much EV load each node of the feeder can accommodate without violating the operational limits. In [8], the authors proposed maximizing EV hosting capacity by calculating the maximum charging load on each node in terms of chargeable region; however, the impact on voltage quality was not discussed. In [9], the authors calculated the optimization-based marginal hosting capacity for EV integration into the smart grid. A probabilistic method was used in [10] to determine the distribution network EV hosting capacity. System-level EV hosting capacity was estimated by considering different combinations of the nodes with EV charging and checking the voltage violations. The results demonstrated that the location of EV charging load has a considerable impact on the EV hosting capacity of the network. In [9] and [10], the authors did not consider thermal violation constraints. The authors of [11] analyzed the impacts of EV charging (slow charging: 3.7 kW; and fast charging: 22 kW) in a low-voltage distribution network. The results quantified the increased peak load and power losses, transformer and line overloads, reduced voltage, and increased voltage asymmetry as the impacts of EV charging, specifically fast charging. The authors in [12] assessed the EV hosting capacity, explored the impacts of increasing EV penetration levels, and proposed an optimal location for fast charging in a Norwegian distribution grid. In [13], the impacts of EV charging on residential distribution systems were analyzed, and mitigation approaches were discussed. The literature mostly discusses Level 1 (up to 1.8 kW AC charging) and Level 2 (up to 19.2 kW AC charging) EV charging loads, and a few discussed Level 3 (50 kW–150 kW DC charging) charging. But the potential of higher power chargers, such as extreme fast-charging (xFC) (350 kW and above), and their

This work was supported by Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

impact on the distribution grid has not yet been explored. The high-power xFC option is expected to further increase EV adoption in the near future.

This paper investigates EV hosting capacity by focusing on xFC of EV charging loads. The main contribution of this paper includes the development of an EV hosting capacity tool—specifically, an xFC hosting option—that provides insight into network capabilities and conditions. This can help utilities plan for optimal system upgrades to facilitate future needs and greatly reduce the cost of EV integration. Both the voltage limit and thermal overload are evaluated to identify actual hosting capacity. The overall approach is to identify representative feeders of the utility distribution network in a certain region. This paper presents the outcomes of an EV hosting capacity assessment on three different real-world utility distribution feeders representing varying compositions of residential, commercial, and industrial customers.

The rest of this paper is organized as follows: Section II describes the feeders used here to assess hosting capacity. Section III provides the EV hosting capacity assessment methodology. Sections IV and V discuss the case studies and simulation results. Section VI discusses network upgrade requirements. Finally, Section VII presents the conclusion.

II. Feeder Description

Three representative Minnesota feeders were selected for the analyses presented in this work. The selection of these feeders was based on an analysis of future EV adoption scenarios performed by the National Renewable Energy Laboratory. This study identified specific locations that are expected to host a large number of passenger EV fleets in the near future and the corresponding feeders that serve these locations. The list of feeders was further narrowed by considering factors such as existing phase imbalance; relative loading levels; opportunity for public charging infrastructure; and different customer mixes, such as commercial, industrial, or residential. These feeders have different features, such as varying length, capacity, peak load, and peak times. Feeder 1, Feeder 2, and Feeder 3 have 197, 213, and 157 three-phase nodes, respectively.

III. EV Hosting Capacity Assessment

EV hosting capacity assessment refers to the evaluation of the maximum available capacity of a given feeder network to host the EV charging loads up to the point at which the existing system needs to be upgraded. The system performance should comply with acceptable standards, such as voltage within a range from 0.95 p.u. to 1.05 p.u. [14] and line loading less than 100% of nominal ampere rating. EV hosting capacity is estimated in terms of voltage and thermal limits; these limits determine the adequacy of grid operations. There are different ways to estimate the hosting capacity, and different approaches result in different capacities because there are always several uncertainties. A simple but effective methodology is used to estimate the theoretical maximum EV charging capacity. This approach is an iterative process wherein the load in each node of the network is increased in a predefined step and the snapshot load flow analysis is performed. The performance limits are checked at each iteration until the violation occurs; the last loading level before the violation occurs is the hosting capacity for that particular node. The algorithm for the hosting capacity assessment conducted in this work is presented in Algorithm 1.

Algorithm 1: Hosting capacity assessment algorithm

1 Select the performance parameters and their limits for the network based on the acceptable standards.

2 Make the available peak load values as the initial loads in the network.

3 For each performance check parameter in the network:
For each node in the network:
a. Increase the load by a predefined step (keeping loads at other nodes constant) and solve the power flow simulation.
b. Compare the chosen performance parameters through the network against the standard allowable limits.
c. If they violate the limits, then the previous loading level is the hosting capacity of that node. But if the parameter values are within the limits, then go to step 3a and repeat the process.
d. Record the hosting capacity for this node, and change the load to the initial value.

The hosting capacity analysis is conducted considering the voltage and thermal limits as the performance check parameters, and the lowest hosting capacity between these two performance limits will be taken as the actual EV hosting capacity for the network. The standard voltage limit is [0.95 to 1.05] p.u. [14]. The thermal limits are defined by the normal ampere ratings of the conductors in the network, and they are available from the utility data. The conductors and equipment might have an emergency ampere rating that indicates short-term overloading limits. For planning purposes, the loading should not exceed the normal ampere ratings. In this work, we analyze the available capacity of the given feeders to host different power levels (xFC: DC charging; Level 2: AC charging; and Level 1: AC charging) of EV charging load.

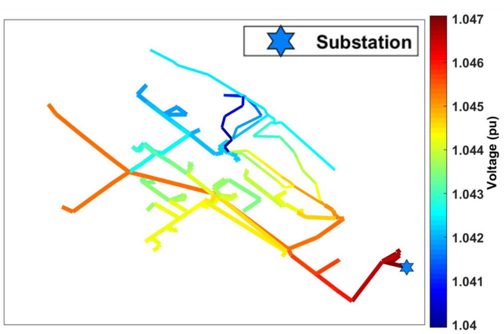
IV. Case Study

Hosting capacity on a nodal basis depends on several factors, including the location, and it is a network-specific quantity. Because of the lack of sufficient and accurate data about the feeders to be modeled, there can be uncertainties in the hosting capacity assessment process. In this work, we conduct a case study for the EV hosting capacity assessment of three feeders from Minnesota, described in Section II. Two different performance parameters are considered for the EV hosting capacity estimation: voltage and thermal limits. The normal ampere ratings of the conductors determine the thermal loading in the network. The acceptable thermal limit is 100% of the normal ampere ratings, whereas the acceptable voltage limits are determined to accommodate model data inaccuracies. In this study, three scenarios are created to evaluate the EV hosting capacity considering different network uncertainties, and the results are compared.

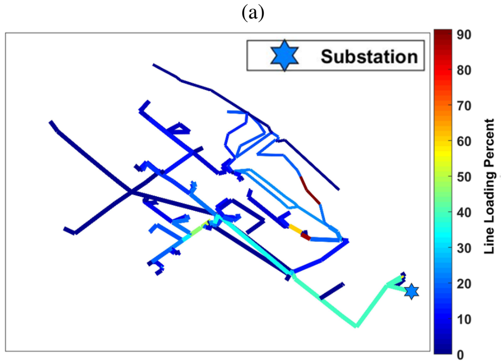
- Scenario 1: Perfect feeder information—In this scenario, it is considered that we have complete and perfect feeder information. Permissible voltage range is [0.95, 1.05] p.u.
- Scenario 2: No secondary modeling of the network—This scenario takes into account that only the primary distribution network models are considered here. Considering the secondary drops, when the primary feeder voltage hits 0.95 p.u., it can create voltage violations downstream, i.e., at the secondary nodes. Therefore, in order to account for any secondary voltage drops, the acceptable voltage limit is increased by approximately 2% for this scenario.
- Scenario 3: Account for some uncertainties and assumptions—In the considered feeder modeling, there are some unknown system parameters, such as transformer connection type, reactance, line length, and imperfect load profile data; thus, typical values are assumed for the unknown parameters. The voltage drop depends on some of these factors such as service/secondary line lengths, conductor materials, and connected loads. The acceptable voltage limit is further increased by approximately 1% for this scenario, to account for the missing data and assumptions.

The EV hosting capacity results from these scenarios are compared for both performance parameter criteria. Further, this case study identifies the number of xFC (350 kW), Level 2 (7.2 kW), and Level 1 (3.3 kW) EV charging loads that each feeder has the potential to host.

V. Results and Discussion



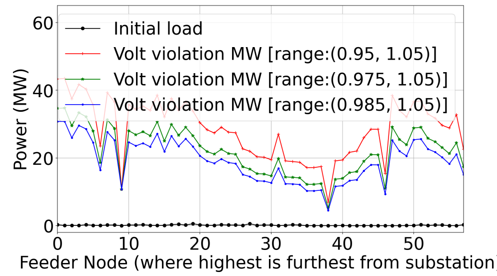
(a)



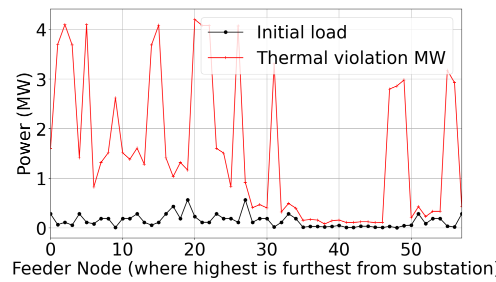
(b)

Fig. 1. Heat map representing (a) the voltage and (b) the line loading throughout the network for the existing peak load condition of Feeder 1.

The network voltage for the existing peak load condition for Feeder 1 is presented in Fig. 1a. The maximum voltage is 1.047 p.u. and the minimum is 1.0398 p.u. for the existing peak load condition. The line loadings at the existing peak load condition for Feeder 1, Fig. 1b, suggest that the maximum line loading is approximately 90% for this feeder, whereas some lines are minimally loaded.

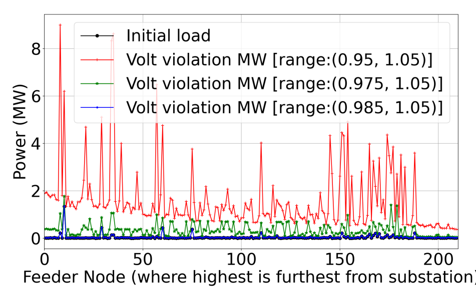


(a)

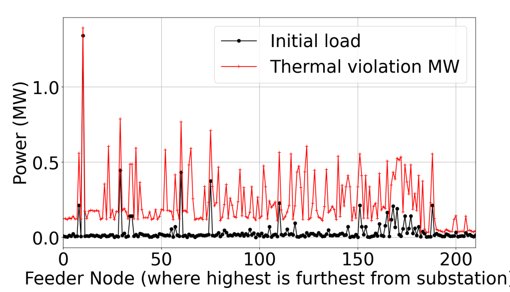


(b)

Fig. 2. Hosting capacity of the nodes of Feeder 1 according to the increasing distance from the substation considering (a) the voltage limit criteria and (b) the thermal limit criteria.



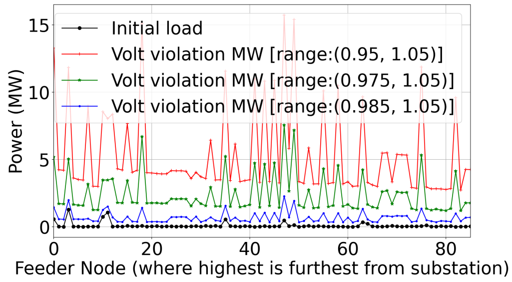
(a)



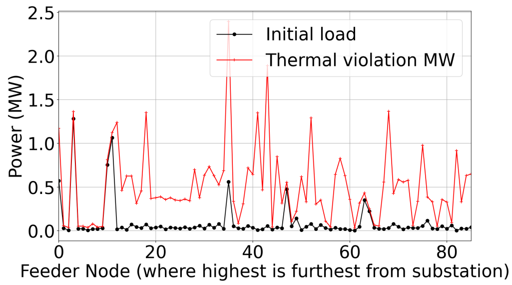
(b)

Fig. 3. Hosting capacity of the nodes of Feeder 2 according to the increasing distance from the substation considering (a) the voltage limit criteria and (b) the thermal limit criteria.

The EV hosting capacity of Feeder 1 considering the three scenarios with different voltage limits and the thermal limits is presented in Fig. 2. First, the hosting capacity simulation



(a)



(b)

Fig. 4. Hosting capacity of the nodes of Feeder 3 according to the increasing distance from the substation considering (a) the voltage limit criteria and (b) the thermal limit criteria.

is run keeping the voltage limits as the stopping criteria regardless of the thermal limits. The resulting hosting capacity limited by undervoltage is presented in Fig. 2a. Then, only the thermal limit is considered in the simulation. Fig. 2b represents the resulting hosting capacity limited by thermal overload. It shows that Feeder 1 has a higher hosting capacity considering the voltage as the performance-limiting parameter, Fig. 2a, than the thermal limit, Fig. 2b. A comparison of the three scenarios in Fig. 2a shows that the capacity is higher for Scenario 1, i.e., the voltage range [0.95, 1.05]. Because the voltage decreased with the increasing load, the lower voltage limit guided the hosting capacity. With the increase in lower voltage limit from Scenario 1 to scenarios 2 and 3, the hosting capacity reduced further. In Feeder 1, the thermal violation occurred before the voltage limit considering all scenarios, so the thermal limit curbs the EV hosting capacity of this feeder.

Similarly, Fig. 3 and Fig. 4 portray the results of the EV hosting capacity assessments on Feeder 2 and Feeder 3, respectively. In these two feeders, the hosting capacity decreased significantly from Scenario 1 to Scenario 2 and Scenario 3 considering the voltage limit criteria. Also, for these two feeders, the voltage decreased with increasing load, and the lower voltage limit was violated. For the second feeder, the minimum voltage at the initial condition was 0.978 p.u., which was already less than the limit in Scenario 3, so there was no available capacity in Feeder 2 considering Scenario 3. Thus, for Feeder 2, we compare the hosting capacity results from Scenario 1, Scenario 2, and the thermal overload criteria. In the first and third feeders, it can be observed that the thermal limit completely restricts the additional feeder capacity before the voltage limit, whereas for the second feeder, the capacity is limited by undervoltage or thermal overload.

According to the hosting capacity estimation, the available capacities for the EV charging loads in each of the three feeders are presented as heat maps in Fig. 5. The dark red nodes represent the lowest capacities (less than 0.3 MW), whereas the dark blue nodes represent the highest additional capacities (more than 3.5 MW). These heat map plots clearly show that Feeder 1 has the highest EV hosting capacity compared to Feeder 2 and Feeder 3, whereas Feeder 2 has the lowest; thus, each feeder has different EV hosting capacities depending on its existing network condition. Fig. 6 shows the three feeder networks highlighting the nodes that are capable of hosting at least 1 xFC. The figure shows that each node in Feeder 1 can host more than 1 xFC EV loads compared to the other two feeders. A single node of Feeder 1 can host 11 number of xFC EV loads, and there are 7 such nodes in Feeder 1; thus, Feeder 1 has greater potential to host more xFCs without any additional change in the network.

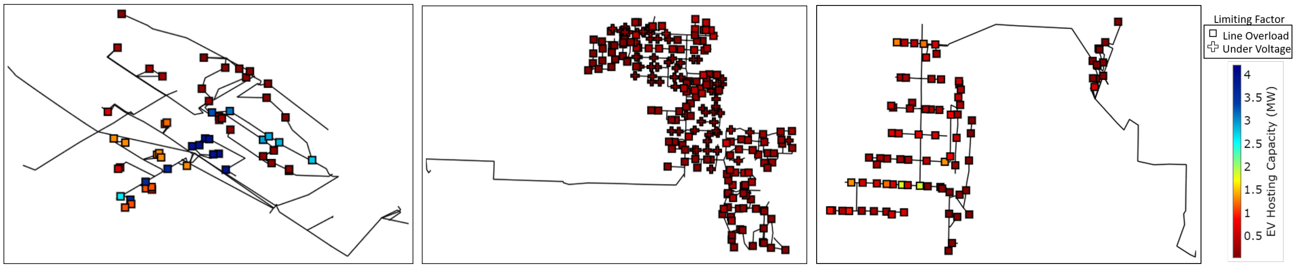
Table I shows the differences in the three feeders in terms of type of customers served, feeder size, total peak load, and estimated EV hosting capacity. Feeder 1 serves mostly industrial and commercial customers and a small portion of residential customers; Feeder 2 has a comparatively higher percentage of residential customers; and Feeder 3, the smallest feeder, is basically an industrial feeder. The table shows that even though all three feeders have almost the same total peak load, they have very different EV hosting capacities. This analysis focuses on the xFC charging, so the total number of xFC charging that each node can host is calculated first, then the number of Level 2 charging that the node can host is identified, and then only the remaining capacity of the node is allocated for Level 1 charging. For example, if the hosting capacity of a node is 400 kW, it can host one xFC charging (1 X 350 kW), six Level 2 charging (6 X 7.2 kW), and two level 1 charging (2 X 3.3 kW). Feeder 1 can theoretically facilitate more xFCs. These three feeders can host a significant number of Level 2 EV charging loads as well.

VI. Network Upgrade Requirements

Hosting capacity analysis provides a realistic assessment of how much load a node can accommodate until network violations start to occur. But EV adoption typically has a clustered pattern wherein such violations might start to appear earlier than the theoretical maximum capacity for each node. These violations also have a temporal nature depending on the variations in the base load. To identify and mitigate these violations in a realistic EV integration scenario, detailed studies need to be conducted in the time-series domain. Required network upgrades, when properly identified, can help utilities plan ahead with static resource allocation for projected EV adoption scenarios. As a future extension of the hosting capacity study, network upgrade options will be conducted that would identify necessary network asset upgrades, such as lines, transformers, and voltage regulation devices.

VII. Conclusion

This paper investigated the EV hosting capacity—specifically, xFC integration—for three feeders from Min-



(a) (b) (c)

Fig. 5. Heat map showing the available EV hosting capacity of the nodes in (a) Feeder 1, (a) Feeder 2, and (a) Feeder 3.

(a) (b) (c)

Fig. 6. Feeder circuit showing the nodes capable of hosting xFC EV load for (a) Feeder 1, (a) Feeder 2, and (a) Feeder 3.

TABLE I
DIFFERENCE IN COMPOSITION, EXISTING LOADING, AND THE HOSTING CAPACITY OF THE THREE FEEDERS

	Total peak load (MW)	Customer type			Feeder length (Km)	EV hosting capacity evaluation			Average distance from SS for XFC location (Km)
		Residential	Commercial	Industrial		No. of xFC	No. of Level 2	No. of Level 1	
Feeder 1	8.02	20%	26%	54%	5.88	204	1241	28	2.28
Feeder 2	8.58	62%	12%	26%	5.7	17	4282	183	4.78
Feeder 3	8.04	12%	18%	71	3.86	58	2137	29	3.27

nesota. Voltage limit and thermal limit constraints were considered as the performance parameter criteria. A case study was designed considering three scenarios for the voltage violation criteria to account for different uncertainties in the network. The results show that the available additional capacities of the three feeders are different and that each feeder has the capacity to host a number of xFCs without any alterations to the existing system. In addition, it was interesting to observe that the feeder that mainly comprises industrial and commercial customers was theoretically capable of hosting more xFCs than the heavily residential feeder and the heavily industrial feeder. Further detailed study is required to identify any necessary network upgrades to accommodate the increasing numbers of uncoordinated EV charging loads. Additionally, a future study can be conducted to estimate the system level EV hosting capacity incorporating the coincidence of EVs at different nodes in a particular time.

REFERENCES

[1] "The grim state of electric vehicle adoption in the U.S." https://www.citylab.com/transportation/2018/10/where-americas-charge-towards-electric-vehicles-stands-today/572857/, accessed: 2019-08-30.

[2] E. Sortomme, M. M. Hindi, S. D. J. MacPherson, and S. S. Venkata, "Coordinated charging of plug-in hybrid electric vehicles to minimize distribution system losses," *IEEE Transactions on Smart Grid*, vol. 2, no. 1, pp. 198–205, March 2011.

[3] M. H. J. Bollen and S. K. Rnnberg, "Hosting capacity of the power grid for renewable electricity production and new large consumption equipment," *Energies*, vol. 10, no. 9, p. 1325, Feb 2017.

[4] S. M. Ismael, S. H. A. Aleem, A. Y. Abdelaziz, and A. F. Zobaa, "State-of-the-art of hosting capacity in modern power systems with distributed generation," *Renewable Energy*, vol. 130, pp. 1002 – 1020, 2019. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0960148118307936

[5] F. Ding, B. Mather, and P. Gotseff, "Technologies to increase PV hosting capacity in distribution feeders," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, July 2016, pp. 1–5.

[6] R. Torquato, D. Salles, C. Oriente Pereira, P. C. M. Meira, and W. Freitas, "A comprehensive assessment of pv hosting capacity on low-voltage distribution systems," *IEEE Transactions on Power Delivery*, vol. 33, no. 2, pp. 1002–1012, April 2018.

[7] A. Jain, K. Horowitz, F. Ding, N. Gensollen, B. Mather, and B. Palmintier, "Quasi-static time-series PV hosting capacity methodology and metrics," in *2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 02 2019, pp. 1–5.

[8] J. Zhao, J. Wang, Z. Xu, C. Wang, C. Wan, and C. Chen, "Distribution network electric vehicle hosting capacity maximization: A chargeable region optimization model," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 4119–4130, Sep. 2017.

[9] M. Alturki and A. Khodaei, "Marginal hosting capacity calculation for electric vehicle integration in active distribution networks," in *2018 IEEE/PES Transmission and Distribution Conference and Exposition (T D)*, April 2018, pp. 1–9.

[10] S. Wang, C. Li, Z. Pan, and J. Wang, "Probabilistic method for distribution network electric vehicle hosting capacity assessment based on combined cumulants and gram-charlier expansion," *Energy Procedia*, vol. 158, pp. 5067 – 5072, 2019.

[11] A. Bosovic, M. Music, and S. Sadovic, "Analysis of the impacts of plug-in electric vehicle charging on the part of a real low voltage distribution network," in *2015 IEEE Eindhoven PowerTech*, 2015, pp. 1–5.

[12] M. Lillebo, S. Zaferanlouei, A. Zecchino, and H. Farahmand, "Impact of large-scale EV integration and fast chargers in a norwegian LV grid," *The Journal of Engineering*, vol. 2019, no. 18, pp. 5104–5108, 2019.

[13] A. Dubey and S. Santoso, "Electric vehicle charging on residential distribution systems: Impacts and mitigations," *IEEE Access*, vol. 3, pp. 1871–1893, 2015.

[14] *American National Standard for Electric Power Systems and Equipment Voltage Ratings (60 Hertz)*, NEMA ANSI C84.1-2011, 2011.