Electric Vehicle Hosting Capacity Study

Jillian Zitcovich
Dept. of Electrical and Computer Engineering
University of Pittsburgh
Pittsburgh, PA
jpz15@pitt.edu

Robert Kerestes
Dept. of Electrical and Computer Engineering
University of Pittsburgh
Pittsburgh, PA
rjk39@pitt.edu

***Abstract*—The integration of electric vehicles (EV) into distribution systems presents considerable challenges in maintaining stable voltage levels. The growth and increasing trend of EV adoption can cause significant alterations to conventional demand peaks [1]. This study investigates the hosting capacity of a distribution system to accommodate the addition of EV chargers, specifically using the IEEE 13-node system in OpenDSS. A Python script was developed to randomly distribute a varying number of level 2 EV chargers across the system and evaluate their impact on voltage levels at different buses. The results indicate that voltage issues, including both overvoltage and undervoltage, become noticeable when approximately 227 chargers are added. These findings call attention to the need for potential grid enhancements, such as infrastructure updates, smart charging control, and vehicle-to-grid (V2G) technologies to effectively support the anticipated growth in EV adoption [2]–[4].**

***Index Terms*—electric vehicles, hosting capacity**

I. Introduction

As electric vehicle (EV) adoption continues to rise, the demand for EV charging infrastructure has increased significantly, placing substantial pressure on existing distribution systems [1]. Hosting capacity refers to the maximum amount of Distributed Energy Resources (DER), such as EV chargers, that can be integrated into the grid without causing adverse impacts on power quality or reliability [4]. This study examines the hosting capacity of the IEEE 13-node system in the context of EV integration at the residential level. Using OpenDSS and Python, various scenarios are modeled to assess the impact of adding EV chargers on voltage stability. The primary goal is to identify the point, or capacity, at which the system begins to experience voltage deviations, such as overvoltage or undervoltage, indicating the system's limits in supporting additional chargers.

II. Methodology

A. System Model

The system model used in this study was the IEEE 13-node distribution system, which includes various components such as buses, transformers, and lines. The model is set up using OpenDSS, a widely used tool for simulating and analyzing power distribution systems. To integrate it with Python, the py_dss_interface library is used, providing direct access to OpenDSS functionality. This setup makes it easier to manipulate the system —such as adding EV charging loads— using familiar Python logic, and to generate plots for analyzing results more efficiently.

The system is set up in OpenDSS using its default configuration, with typical loads assigned to each bus to represent normal conditions. Before adding any EV chargers, this baseline setup is used to establish a reference point. From there, Python is used to modify the system and simulate how it reacts as more chargers are introduced, making it easy to test different scenarios and track the impact.

B. EV Charger Integration

The EV chargers are modeled as ZIP loads (constant impedance, current, and power), which is a common representation of the charging behavior of EVs in a distribution system. Initially, the intention was to utilize the built-in distribute command in OpenDSS, which is designed to randomly place loads across the system. However, due to difficulties encountered when attempting to overwrite the default load model, which assigns load model 1 to each bus, it became challenging to directly implement the load model 8, ZIPV model, for the EV chargers and ensure proper behavior.

To address this limitation, a custom implementation of the distribute command was developed using Python. This script enables more precise control over the placement of EV chargers and ensures that the correct ZIP load model is applied to each bus. The number of chargers varies between 0 and 320 to allow for an in-depth view of each additional charger added to the system.

Each EV charger's power demand ranges from 3.3 kW to 19.2 kW, with a power factor of 0.95 lagging, which is typical for level 2 residential and commercial EV chargers. Specifically, the load model used in OpenDSS is load model 8, ZIPV. The ZIPV coefficients used to define the charger's behavior are as follows [5]:

```
zipv_coeffs = (0.1824, 0.9949),-0.1773
              ( 8.917),-12.91, 4.993),
              (0.85)
```

The coefficients are organized as:

- The first three inputs represent the real power coefficients for the ZIP components. These coefficients should sum to 1.

- The next three inputs represent the reactive power contributions from each component. These should also sum to 1.
- The final input in the ZIPV model is the voltage threshold in p.u., which is set to a relatively lower value to prevent the load from transitioning into a purely constant impedance model. If the voltage crosses the threshold set by the final input, the load will behave as a constant impedance model. This would no longer align with the dynamic behavior typically seen in EV charging scenarios, and therefore, would not accurately reflect the charging conditions in this study. Therefore, a low value is selected as a precaution against the possibility of misbehavior.

After distributing the chargers using this custom approach, OpenDSS solves the circuit, and the bus voltages are monitored to assess the impact of the chargers on the system's voltage stability. The primary objective is to determine the threshold at which voltage issues, such as over-voltage and under-voltage, begin to emerge, indicating the system's limits in supporting additional chargers.

C. Simulation Setup

The simulation is performed in the following steps:

a) Grid Model Setup: The IEEE 13-node system is imported from OpenDSS, and the base system configuration, including existing loads and bus voltages, is compiled.

b) EV Charger Placement: The Python script takes the desired number of EV chargers as a function input and randomly selects candidate buses, assigning each one a power demand within a predefined range to represent level 2 charger penetration. Once the chargers are placed, the script writes their load characteristics to a DistLoads.dss file. OpenDSS then references this file when solving the circuit, allowing the system to simulate the specific impact of the newly added chargers for each run.

The script runs iteratively, adding chargers one by one and analyzing the simulation results to assess their effect on voltage levels across the system. Voltage stability is closely monitored, with a particular focus on over-voltage and under-voltage conditions, to evaluate the system's response as the number of chargers increases.

c) Data Collection: After solving the circuit with the newly added EV chargers, the bus voltages are read from the IEEE13Nodeckt_VLN_Node.Txt file, which is generated by OpenDSS after solving the system with the updated loads for each iteration. This file contains the p.u. voltage data for each bus in the system. The voltage values are then sorted and organized into a table. This table is used to track voltage stability, and the number of over-voltage and under-voltage occurrences is monitored as the number of chargers increases.

The voltage data is stored for further analysis, with the final results of each iteration being printed to an HTML file for visualization. This file contains the voltage levels at each bus, providing a clear record of how the voltage profile changes with the integration of EV chargers.

d) Voltage Stability Analysis: After each simulation iteration, the system's voltage levels at each bus are compared to predetermined thresholds. The voltages are compared to the acceptable range of ±5% (as defined by ANSI C84.1). Any deviations outside this range are flagged as either over-voltage ($>$1.05 p.u.) or under-voltage ($<$0.95 p.u.) [6].

While reading in the voltages from the IEEE13Nodeckt_VLN_Node.txt file generated by OpenDSS, simple code logic is applied to filter out and detect these over-voltage and under-voltage violations. These violations are tracked and flagged for further analysis. The voltage levels that fall within the acceptable range are printed in green, while those outside the range (over-voltage or under-voltage) are printed in red in the HTML output file for clear visualization.

D. Evaluation Metrics

To evaluate the hosting capacity of the grid, the following metrics are used:

Voltage Deviations: The system's voltage levels at each bus are compared to the acceptable voltage range of ±5% (as defined by ANSI C84.1). Deviations outside this range are tracked for further analysis [6].

Over-voltage and Under-voltage Counts: The number of buses experiencing over-voltage ($>$1.05 p.u.) or under-voltage ($<$0.95 p.u.) is monitored as the number of EV chargers increases. This helps assess the system's overall ability to accommodate additional chargers.

Hosting Capacity Threshold: The threshold for hosting capacity is determined by the number of chargers that can be added before the voltage violations become excessive. This threshold marks the point where the system can no longer support additional EV chargers without significant voltage instability or oscillation.

III. Results

a) Voltage Deviation Analysis: The addition of EV chargers to the distribution system caused voltage deviations at various buses, which were recorded during each simulation. Figure 1 presents the over-voltage and under-voltage counts as a function of the number of chargers added. These counts are plotted to show how voltage issues escalate as more chargers are added to the system. The results reveal that voltage stability began to degrade, or oscillate, when approximately 227 chargers were added to the system. Beyond this point, over-voltage and under-voltage conditions became increasingly frequent.

b) Over-voltage and Under-voltage Counts: As the number of chargers increased, the number of buses experiencing over-voltage and under-voltage also increased. Figures 2 and 3 visualize the HTML output for a stable and unstable system after the addition of EV chargers. These figures demonstrate how the voltage levels at each bus are color-coded to indicate their status within the voltage range. Green indicates stable voltage (within the acceptable range), while red flags over-voltage and under-voltage conditions (outside the ±5% range as per ANSI C84.1) and displays which threshold the voltage crosses.

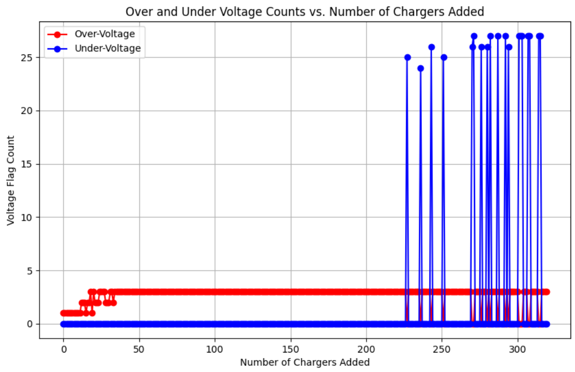

Fig. 1. Voltage Violations Versus Chargers Added

Figure 2 presents the bus voltage table after the addition of 5 EV chargers, where the system is still stable, and most buses are within the acceptable voltage range. This figure illustrates the early stage of EV charger integration, where voltage stability is not yet significantly affected.

Figure 3 shows the bus voltage table after adding 227 EV chargers, where the voltage deviations become more prominent. Many buses experience overvoltage or undervoltage, highlighting the system's inability to accommodate this magnitude of additional EV charging loads. This figure helps visualize the point at which voltage instability becomes significant, with several buses exceeding the ±5% voltage range.

Bus	Phase A	Phase B	Phase C
SOURCEBUS	0.99999	0.99997	0.99995
650	0.99994	0.99996	0.99991
RG60	1.04980	1.04990	1.05600 ⚠ OVER
633	1.01800	1.01940	1.00760
634	0.99564	1.00070	0.98691
671	0.99898	1.01370	0.97951
645	---	1.01510	---
646	---	1.01250	---
692	0.99898	1.01370	0.97951
675	0.99661	1.01300	0.97647
611	---	---	---
652	---	---	---
670	1.01310	1.01830	0.99896
632	1.02060	1.02180	1.01020
680	0.99898	1.01370	0.97951
684	---	---	0.97707

Fig. 2. Bus Voltage Table After 5 EV Charger Addition

c) Hosting Capacity Threshold: The hosting capacity threshold of the system was determined to be around 227 EV chargers, as this was the point where voltage instability

Bus	Phase A	Phase B	Phase C
SOURCEBUS	0.99992	0.99989	0.99988
650	0.99985	0.99987	0.99981
RG60	0.99969	0.99971	0.99963
633	0.94794 ⚠ UNDER	0.94655 ⚠ UNDER	0.92387 ⚠ UNDER
634	0.91230 ⚠ UNDER	0.91361 ⚠ UNDER	0.89097 ⚠ UNDER
671	0.91743 ⚠ UNDER	0.93563 ⚠ UNDER	0.88499 ⚠ UNDER
645	---	0.94009 ⚠ UNDER	---
646	---	0.93638 ⚠ UNDER	---
692	0.91743 ⚠ UNDER	0.93563 ⚠ UNDER	0.88499 ⚠ UNDER
675	0.91323 ⚠ UNDER	0.93360 ⚠ UNDER	0.88033 ⚠ UNDER
611	---	---	---
652	---	---	---
670	0.93979 ⚠ UNDER	0.94456 ⚠ UNDER	0.91106 ⚠ UNDER
632	0.95217	0.95106	0.92808 ⚠ UNDER
680	0.91743 ⚠ UNDER	0.93563 ⚠ UNDER	0.88499 ⚠ UNDER
684	---	---	0.88014 ⚠ UNDER

Fig. 3. Bus Voltage Table After 227 EV Charger Addition

(both overvoltage and undervoltage) became significant. This indicates that the IEEE 13-node system can support up to 227 level 2 EV chargers before voltage issues reach unacceptable levels. Beyond this threshold, the grid would likely require enhancements, such as upgraded voltage regulation equipment or advanced charging controls, to maintain stability [1], [2].

IV. Discussion

An increase in the adoption of electric vehicles is escalating concerns for utilities regarding the maintenance of voltage stability and thermal limits on distribution networks. Stress on hosting capacity, in particular, is becoming an area of concern with higher EV penetration. Thankfully, recent research has provided some solutions, especially in the case of high EV penetration, which are discussed below.

To address the first concern, shifting charging periods to off-peak hours is a key strategy that smart charging algorithms aim to achieve [1]. Additionally, various systems are being incorporated to implement a vehicle-to-grid (V2G) charging system that plays an important role in discharging power back to the grid at peak times, thus aiding dynamic balancing of voltage and power flows [2]. Standards such as IEEE P1729 are being continuously developed to create formal techniques for assessing the hosting capacity of DERs, thereby facilitating clear integration planning [6]. Also, case studies in [1], [3], [4] serve with equal importance when discussing upgraded voltage regulation devices such as increased rating of transformers or capacitor banks and their role in enabling higher penetration of EVs without violating voltage limits.

References

[1] A. Dubey and S. Santoso, "Electric Vehicle Charging on Residential Distribution Systems: Impacts and Mitigations," *IEEE Access*, vol. 3, pp. 1871–1893, 2015, doi: 10.1109/ACCESS.2015.2476996.

[2] X. Yang *et al.*, "V2G Potential Evaluation Method Considering Spatiotemporal Transfer Features of Electric Vehicles," in *Proc. 2022 IEEE 4th Int. Conf. on Power, Intelligent Computing and Systems (ICPICS)*, Shenyang, China, 2022, pp. 306–311, doi: 10.1109/ICPICS55264.2022.9873541.

[3] S. Sirisumrannukul, P. Sihawong, P. Charoenpanon, O. Rattananatthawon and N. Sabpayakom, "Determining Hosting Capacity of Low-Voltage Distribution System with High Penetration of Electric Vehicles by Monte Carlo-Based Quasi-Dynamic Simulation Approach," in *Proc. 2024 11th Int. Conf. on Power and Energy Systems Engineering (CPESE)*, Nara City, Japan, 2024, pp. 396–401, doi: 10.1109/CPESE62584.2024.10841253.

[4] P. Paudyal, S. Ghosh, S. Veda, D. Tiwari and J. Desai, "EV Hosting Capacity Analysis on Distribution Grids," in *Proc. 2021 IEEE Power & Energy Society General Meeting.*

[5] W. H. Kersting and R. Kerestes, *Distribution System Modeling and Analysis with MATLAB® and WindMil®*, 5th ed., Boca Raton, FL, USA: CRC Press, 2022. doi: 10.1201/9781003261094.

[6] (PESGM), Washington, DC, USA, 2021, pp. 1–5, doi: 10.1109/PESGM46819.2021.9638170. IEEE Standards Association, "IEEE Draft Guide for Hosting Capacity Analyses for Distribution Systems," IEEE Std P1729/D1.4, 2023.