

EVALUATING THE IMPACT OF EV INTEGRATION ON DISTRIBUTION NETWORKS USING A VOLTAGE, RELIABILITY, AND POWER LOSS FRAMEWORK

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Abstract

Electrical Vehicles have the potential to transform the energy sector, bringing with them advantages for sustainability and new chances for grid optimization. However, the stability, reliability, and effectiveness of distribution networks are also put at risk by this transformation. Therefore, it is crucial to perform thorough analysis of how EV integration may affect distribution networks. The vital importance of impact analyses for EV integration into distribution networks is highlighted in this paper. These evaluations are essential for comprehending and controlling the complex impacts of EV charging on the distribution system. The paper also highlights how impact evaluations help with effective infrastructure planning, improving the integration of renewable energy according to regulatory requirements, and making the most use of already existing assets. This paper examines how the EVs adoption affects distribution network based on three important parameters: voltage instability, power losses and reliability. The IEEE 33 bus test system for ten different scenarios is used for the whole investigation. Additionally, a method for placing EV charging stations on distribution networks based on the analysed grid parameters is proposed. The outcomes show that the VRP (Voltage, Reliability and Power loss) is effective to decide the optimize location for charging station.

Keywords: Charging Stations; Distribution System; Electric Vehicles; Power Loss; Reliability; Voltage Stability

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Nomenclature

VSF	=	Voltage Sensitivity factor
VRP	=	Voltage, Reliability and Power
THDI	=	Total Harmonic Distortion
GA	=	Genetic Algorithm
PHEV	=	Plug-in Hybrid Electric Vehicle
V2G	=	Vehicle-to-Grid
RES	=	Renewable Energy Sources

Introduction

The need of assessing EVs' effects on distribution networks increases as the electrification of transportation continues to gain momentum (Karim *et al.*, 2024). The smooth integration of EVs is ensured by a well-executed impact assessment, which also helps to reduce possible problems and, in the end, promotes a robust and sustainable energy ecology (Firouzjah, 2022; Inci *et al.*, 2024; Kumar *et al.*, 2025).

The multifaceted implications of EV integration have been the focus of a range of research in the past. Load analysis, grid stability, appropriate charging methods, infrastructure design, grid resilience, regulatory concerns, integration of renewable energy sources, and communication/control approaches are all subjects of investigations (Deb *et al.*, 2021; Roslan *et al.*, 2024). There is a deliberate effort to build a charging infrastructure to support electric vehicles (EVs), even in a poor country like Bhutan (Pandey *et al.*, 2024). However, the power grid is put under more demand as a result of the expansion of charging stations. Fast EV charging stations' significant charging demands could compromise the distribution network's ability to function normally. Uncoordinated EV charging has negative effects on voltage profiles, increases peak loads, and raises harmonic distortions. The negative impact of EV charging loads on distribution network characteristics includes voltage profiles (Zeb *et al.*, 2020; Lin *et al.*, 2023; Belany *et al.*, 2024; Rani *et al.*, 2024; Sepehrzad *et al.*, 2024; Sujatha *et al.*, 2025; Singh *et al.*, 2025), harmonics (Khalid *et al.*, 2021; Mojumder *et al.*, 2022; Yap *et al.*, 2022; Malik *et al.*, 2024), and peak loads (Jones *et al.*, 2021; Eid *et al.*, 2022; Hartvigsson *et al.*, 2022; Fernandez and Pérez, 2024; Bilal and Rizwan, 2025), as illustrated in a wide range of articles.

Researchers have paid close attention to the possible impact of EV charging station loads on distribution network voltage profiles. An investigation of the effects of EV charging station loads within a European low-voltage distribution network under various EV penetration scenarios

was done (Zeb *et al.*, 2020). According to their investigations, the network is resilient enough to handle a 1-2% EV intake. The voltage profile did, however, show considerable deterioration at nodes with several charging stations, with heavy charging station loads adversely influencing the voltage profiles of the system's weaker buses. The impact of EV charging on distribution networks has been analyzed in studies such as Singh *et al.* (2025) (13-node network) and Belany *et al.* (2024) (14-bus network), revealing a decrease in transient voltage stability with higher EV penetration; this trend is corroborated by Rani *et al.* (2024). While networks possess some capacity for EV integration, it has been suggested that older distribution networks, specifically those from a decade ago, may be unable to handle substantial EV loads (Lin *et al.*, 2023). A comprehensive evaluation of the combined effect of charging station loads on the aforementioned characteristics (voltage stability, reliability, and power loss) simultaneously is notably missing in the literature. Existing approaches often isolate one or two parameters for analysis. This study aims to overcome this limitation by proposing a holistic VRP framework (Rani *et al.*, 2024).

Researchers have recently focused considerable attention on harmonic analysis, a crucial effect of integrating EVs. Mojumder *et al.* (2022) examined the impact of EV charging loads on harmonic voltages in distribution systems using a statistical analytical methodology. Based on their classification of chargers according to Total Harmonic Distortion of current (THDI), harmonic distortion in summer was hardly noticeable even at a 45% EV penetration rate. Studies also indicate that EV charging introduces harmonic distortion that degrades distribution-network power quality. Khalid *et al.* (2021) suggested that such distortion may shorten the lifespan of network assets, while Malik *et al.* (2024) reported that harmonic levels could reach up to 50% in severe cases. Probabilistic Monte Carlo methods have been employed to model these harmonics-particularly those originating from plug-in hybrid electric vehicle (PHEV) chargers-while accounting for uncertainties. Furthermore, residential Level 1 chargers (1.8 kW) have been shown to significantly affect power quality, as highlighted in a critical synthesis of recent studies, particularly those using the IEEE 33-bus system and those focusing on multi-objective optimization for EV placement (Inala *et al.*, 2020).

Prior research have in-depth examined a number of adverse effects resulting from EV charging station loads, including voltage instability, harmonic distortion, and power losses within

distribution networks. A comprehensive evaluation of the combined effect of charging station loads on all the aforementioned characteristics simultaneously, however, is notably missing in the literature. Existing approaches often isolate one or two parameters to study. With the goal of completely addressing the interaction of these elements, this study makes an effort to overcome the limitations indicated above that are currently existent in the literature. The main outcomes of this paper are described in the section as follows:

- To analyze the impact of EV charging loads on distribution network voltage stability.
- To examine the effects of EV charging loads on reliability indices, from both consumer and energy perspectives.
- To compare the impacts of EV charging loads on voltage stability, reliability, and power losses within the distribution network.
- To strategically place EV charging stations within the distribution network using the VRP index.

The remaining sections of the paper are organized as follows. The methodology employed in impact analysis is described in Section II. Section III highlights the VRP index. Different results analysis is given in Section IV and respective discussion is included in Section V. Finally, the main conclusion of the chapter is drawn in Section VI.

Methodology

Reliability, Voltage stability, and power losses are the primary operational characteristics important in a distribution network. This section offers a more comprehensive elucidation of the approach employed to assess these factors: reliability, voltage stability, economic losses, and power losses within the distribution network. Furthermore, this section details the computational approaches taken to investigate the adverse impacts of EV charging station loads on the distribution network. The computational methodology, which incorporates the VRP index, is illustrated in the flowchart shown in Figure 1.

Voltage Stability

Voltage stability has been a source of concern for power system engineers for a very long time. Voltage stability tends to the power system's capability to keep constant, acceptable voltages at all of the system buses both during normal operation and in the presence of external interruptions

(Grigsby, 2007). The voltage of the bus in the network steadily and uncontrollably decreases when instances of voltage instability happen. Power system operators utilise advanced monitoring and control systems, voltage control devices, and sophisticated modelling and analysis tools to assess and maintain voltage stability. These measures aim to ensure the power system can operate within acceptable voltage limits, mitigate the risk of voltage instability, and provide consumers with a reliable electricity supply. Although voltage stability is a general phenomenon, it can result in a major voltage breakdown. In this work, VSI and VSF are used for voltage stability analysis.

VSF (Voltage Sensitivity factor): Voltage stability, due to its slow-changing nature, is typically assessed using static methods. The Voltage Stability Factor (VSF) is often estimated via power-voltage curves. However, traditional load flow methods like Newton-Raphson face challenges in radial distribution networks due to their high resistance-to-reactance (R/X) ratios. This is because distribution lines have significantly lower inductance compared to transmission lines, making the R/X ratio more influential. Due to the high R/X ratio, the Jacobian matrix of the system becomes singular. Due to this reason, the forward and backward sweep algorithm is taken to determine the bus voltages. Figure 2 illustrates the PV curve, demonstrating that as active power load increases, voltage starts decreasing until the peak of active power (P_{max} , $V_{critical}$). The critical operational state, referred to as the limit of stable operation, is precisely situated at that particular point. The ratio of voltage changes to loading change is known as VSF. Mathematically, it is expressed as:

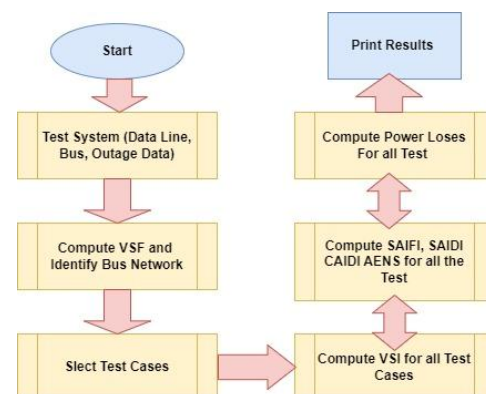


Figure 1. Diagram outlining the computational approach for assessing the influence of EV charging station load on the distribution network

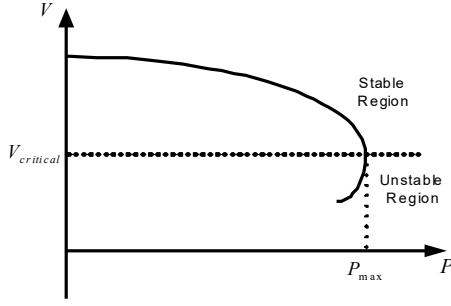


Figure 2. P-V Curve

$$VSF = \left| \frac{dV}{dP} \right| \forall P < P_{max} \quad (1)$$

If the VSF value increases, then the voltage drop also increases at that bus; thus, that particular bus is weak, and if the VSF value decreases, then Bus will be strong. Thus, a high VSF value means that for the considerable change in loading, there is a large amount of voltage drop, and hence bus becomes weak. The steps demonstrating the methodology of calculation of VSF are described below:

Step 1: Enter IEEE 33 bus line data and bus data.

Step 2: Use the forward-backwards method for the distribution load flow of the bus.

Step 3: Use Equation (1) for the calculation of VSF.

Step 4: Identify different loading conditions and increase gradually in steps.

Step 5: Again run distribution load flow analysis for the test system.

The above study is performed on the IEEE 33 Bus network, shown below in Figure 3.

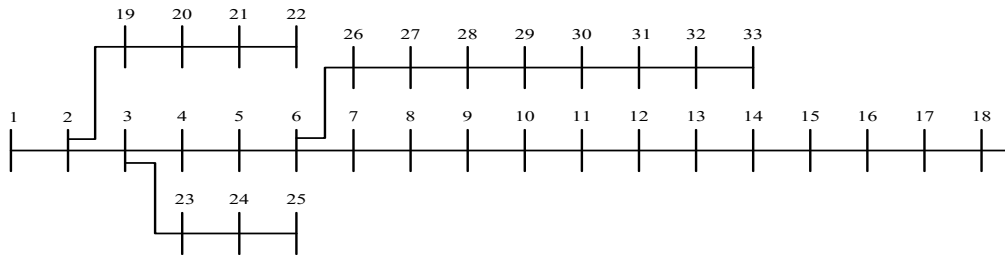


Figure 3. IEEE-33 bus network

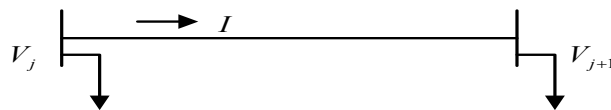


Figure 4. Two bus system

VSI (Voltage Stability Index): A distribution network's bus that is most prone to voltage collapse is calculated using the voltage stability index. The stability index is developed using the distribution line's transferred reactive and active power equation, and all that is needed a power flow solution for the system under any operating circumstance (Kim *et al.*, 2024).

Figure 4 illustrates a simple two-bus system for the mathematical formulation of the distribution system voltage stability index where j and $j + 1$ are the two buses of the system. Current I , active and reactive power flow through the branch of the above two bus system having line resistance r and reactance x , can be express as Equation (2)-(3). $V_{j+1} \angle \delta_{j+1}$ and $V_j \angle \delta_j$ are the voltage at bus $j + 1$ and bus j , respectively.

$$I = \frac{V_j - V_{j+1}}{r + ix} \quad (2)$$

$$P_{j+1} - iQ_{j+1} = V_{j+1}^* I \quad (3)$$

Equation (4) is obtained after putting the value of I in Equation (3) and equating real parts:

$$V_{j+1}^4 + 2V_{j+1}^2(P_{j+1}r + Q_{j+1}x) - V_j^2V_{j+1}^2 + (P_{j+1}^2 + Q_{j+1}^2)|Z|^2 = 0 \quad (4)$$

We can obtain transferred reactive power in Equation (6) and transferred active power in Equation (5) after solving Equation (4):

$$P_{j+1} = \frac{M \pm \sqrt{N}}{|Z|} \quad (5)$$

Where $M = -\cos\theta_z V_{j+1}^2$, and $N = \cos^2\theta_z V_{j+1}^4 - V_{j+1}^4 - |Z|^2 Q_{j+1}^2 - 2V_{j+1}^2 Q_{j+1}x + V_j^2 V_{j+1}^2$.

$$Q_{j+1} = \frac{P \pm \sqrt{Q}}{|Z|} \quad (6)$$

Where $P = -\sin\theta_z V_{j+1}^2$, and $Q = \sin^2\theta_z V_{j+1}^4 - V_{j+1}^4 - |Z|^2 P_{j+1}^2 - 2V_{j+1}^2 P_{j+1}r + V_j^2 V_{j+1}^2$.

The inequalities for the transferrable reactive power and transferrable active power existence are given below in Equation (7):

$$N \geq 0 \text{ and } Q \geq 0 \quad (7)$$

Putting the values of Q and N and adding them to make the inequality which defines the stability condition of the used system:

$$2V_j^2 V_{j+1}^2 - 2V_{j+1}^2 (P_{j+1}r + Q_{j+1}x) - |Z|^2 (P_{j+1}^2 + Q_{j+1}^2) = VSI \geq 0 \quad (8)$$

In radial distribution networks, the value of Equation (8) is utilised to determine the stability index for each line receiving end bus. The amount of voltage at each system node is known, completing a load flow analysis. Because P and Q at each line's receiving end can easily calculate, Equation (8) may be used to determine each node's voltage stability index. This standard is used to evaluate voltage stability. With the rise in active power, VSI will decline. Beyond a certain point, raising the active power will make the system unstable. The node most vulnerable to voltage collapse is the one where the stability index value is the lowest.

The steps demonstrating the methodology of calculation of VSI are described below:

Step 1: Input IEEE 33 test bus system line and bus data.

Step 2: Use the forward-backwards method for load flow analysis to calculate the voltage at each bus.

Step 3: Calculate VSI by Equation (8) using Bus and voltage data.

Step 4: Increase real loading and calculate bus voltage again and VSI.

Step 5: If $VSI > 0$, repeat the above steps for another load.

Power Loss

There are two forms of power loss in the distribution system: technical losses and nontechnical losses. Technical losses in power systems typically account for 22.5% of total losses and are directly influenced by the network

properties and style of operation. A power system's primary and secondary distribution networks account for most losses. In contrast, only 30% of the losses are linked to transmission and sub-transmission lines (Khalid *et al.*, 2021).

Technical losses in electrical systems arise from persistent and changing causes. Persistent losses include corona, dielectric, leakage, open circuit, and continuous load losses on measurement and control components. Variable losses consist of Joule, impedance, and contact resistance losses. Due to increased loads, introducing EV at any distribution system bus causes variable losses to rise. Losses change as a result of the fact that EV load is not constant throughout time. Losses are calculated for situations in this thesis using the same methods as VSI calculations. A typical $I^2 R$ losses of the line referred to power loss of the distribution system. The line losses for the system shown in Figure 4 are given below:

$$P_j = |I|^2 R \quad (9)$$

Where; $I = (V_j - V_{j+1})/(r + ix)$

Sum of power losses for each line of the system

$$P_t = \sum_{j=1}^n P_j \quad (10)$$

From Equation 9, it can be seen that power loss increases even if a single charging station is placed on a bus. Power losses can be calculated easily for each case using Equation (10).

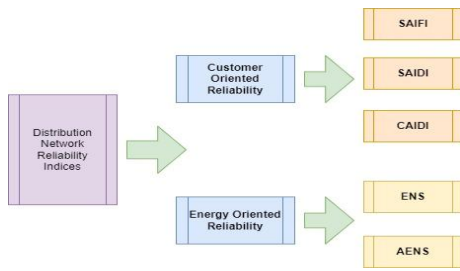
Reliability

The ability of a system to perform its intended function under specified conditions and for a defined period is its reliability (Gönen *et al.*, 2024). For a power system to be reliable, generation, transmission, and distribution must all function effectively. Evaluating distribution network reliability indices requires the collection of data regarding failure and repair rates, average outage durations, and the number of consumers connected to each load point (Bhadra and Chattopadhyaya, 2015; Zhang *et al.*, 2021). Reliability indicators fall predominantly into customer-oriented indices, as illustrated in Figure 5. This category includes SAIDI, SAIFI, and CAIDI. ENS and AENS, conversely, belong to energy-oriented reliability indices, Such as shown in Table 1 of significance of these indices.

The frequency and duration of power interruptions determine the relationship between SAIFI and SAIDI. CAIDI provides a measure of

Table 1. Definition and physical significance of different reliability indices

Index	Definition	Formula	Physical Significance
SAIDI	Duration of average interruption per customer	$\frac{\sum U_j N_j}{\sum N_j}$	A system condition in terms of the duration of the interruption
SAIFI	Interruption experienced by a Customer at a particular time	$\frac{\sum F_j N_j}{\sum N_j}$	A system condition in terms of interruption
CAIDI	Duration of average interruption by a customer experienced in a year.	$\frac{\sum U_j N_j}{\sum F_j N_j}$	Average output duration experienced by a customer
ENS	Energy is not supplied by the system.	$\sum L_j U_j$	System energy deficiency indicator
AENS	Average energy not supplied by the system.	$\frac{\sum L_j U_j}{\sum N_j}$	During a particular time period amount of energy not served

**Figure 5. Reliability Indices Classification**

customer dissatisfaction resulting from these interruptions. AENS represents the average energy not supplied due to service interruptions (Xiangning *et al.*, 2007; Shaheen *et al.*, 2021; Kumar *et al.*, 2023). The cause of the interruption is as follows:

- Power Outage due to damage to distribution lines and Equipment failure.
- Load shedding due to the sudden increase in load and Interruption is due to scheduled maintenance of lines and substations and
- Damage to distributing infrastructure due to extreme weather conditions.

A fundamental criterion for electrical power systems is Reliability. Power system expansion planning has long required measuring the reliability of power systems in order to determine their capacity to deliver a sufficient and secure supply of electrical energy.

For further detail, the following steps for computation are shown below:

Step 1: Select the test system.

Step 2: Calculate SAIDI, SAIFI, AENS and CAIDI for all the buses.

Step 3: Calculate $\sum SAIDI_j$, $\sum SAIFI_j$, $\sum AENS_j$, and $\sum CAIDI_j$.

Step 4: Change the loading at the buses for different cases illustrated previously.

Step 5: Again, calculate SAIDI, SAIFI, AENS and CAIDI for all the system buses.

VRP (Voltage, Reliability and Power) Index

There are three main operating parameters in a power system for proper operation, i.e., reliability, voltage stability, and power loss. Based on these operating parameters, an index called VRP (Reliability, Voltage stability, and Power loss) index is formed. If any disturbance occurs in the distribution network, then this index can give information about that disturbance.

The prime objective of this index:

- To find the best location for a fast-charging station in the distribution network
- To make a proper plan for the distribution network with distribution generation
- To analyse microgrid planning and To make possible changes in the distribution network with the increase in demand

Mathematical formulation of VRP Index:

$$VRP = w_1 A + w_2 B + w_3 C \quad (11)$$

$$A = 1/a \quad (12)$$

$$a = \frac{VSI_l}{VSI_{base}} \quad (13)$$

$$B = w_{21} \frac{SAIFI_l}{SAIFI_{base}} + w_{22} \frac{SAIDI_l}{SAIDI_{base}} + w_{23} \frac{CAIDI_l}{CAIDI_{base}} \quad (14)$$

$$C = \frac{P_{loss}^l}{P_{lossbase}} \quad (15)$$

The primary objective of placing charging stations in the distribution network is to do so efficiently, minimising the impact on operational parameters.

$$\min (VRP) \quad \text{where } VRP = f(d, f, s) \quad (16)$$

Where d = Buses at which the charging station is placed, f = Buses at which Fast Charging is placed, and s = Buses at which slow charging is placed.

Initially, the test cases are simulated, and the load of the EV chargers is modelled. Subsequently, the impact of the EV charging station load is evaluated in terms of reliability, voltage stability, and power loss for each test case.

Results

Reliability, voltage stability, and power loss are operational parameters that may deteriorate when demand exceeds the capacity of a distribution network. This section briefly discusses the findings of the EV-penetration study on the IEEE 33-bus

system under various scenarios. The study was conducted using the IEEE 33-bus test system shown in Figure 3, which comprises 32 branches and 33 buses. The branch, line, and reliability data for this network were compiled from the literature (Bhadra and Chattopadhyay, 2015; Shaheen *et al.*, 2021).

Different cases and VSF

The Voltage Stability Factor, calculated using equation (1), was used to determine weak and strong buses. The Power Voltage Curve for the IEEE 33-bus system, shown in Figure 6, illustrates voltage changes with varying loads. Table 2 provides the VSF values for each bus under these load conditions. Specifically, the VSF of bus 2 rose from 0.1243 to 0.13892, and that of bus 19 from 0.23404 to 0.22937, as loading increased. These values demonstrate that higher loading results in a higher

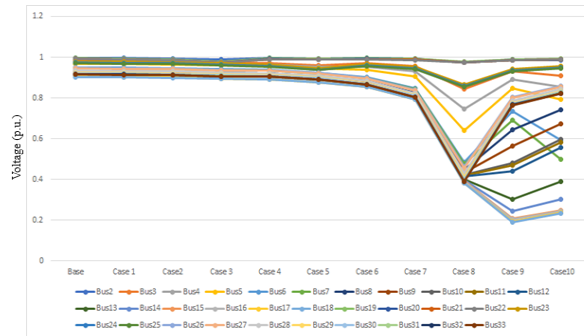


Figure 6. PV curve at different loading conditions on different buses

Table 2. VSF on different loads for various cases

Bus	VSF1	VSF2	VSF3	VSF4	VSF5	VSF6	VSF7	VSF8	VSF9	VSF10
Bus2	0.1214	0.1237	0.1389	0.1286	0.1276	0.1429	0.1517	0.2865	0.369	0.5643
Bus3	0.1277	0.1287	0.1315	0.8227	0.841	0.922	0.9725	1.8826	2.5052	3.6454
Bus4	0.1232	0.1215	0.122	0.8406	0.8229	1.5217	1.5868	3.1165	4.2257	6.0942
Bus5	0.125	0.1224	0.1223	0.8194	0.8163	2.0486	2.1769	4.4247	5.9966	8.2778
Bus6	0.1319	0.1259	0.1263	0.8403	0.8367	3.3194	3.5238	6.2406	12.092	14.868
Bus7	0.1462	0.1321	0.1288	0.9308	0.8786	3.6923	3.7143	6.4151	16.004	19.677
Bus8	0.1462	0.1357	0.1301	0.9462	0.8929	3.7462	3.7786	6.6342	6.8357	22.177
Bus9	0.1319	0.1293	0.129	0.8611	0.8571	3.4167	3.6293	6.6129	8.5782	25.111
Bus10	0.1319	0.1327	0.1304	0.8681	0.8639	3.4375	3.6565	6.7124	10.966	30.444
Bus11	0.1301	0.1284	0.13	0.8562	0.8581	3.3904	3.6351	6.7078	11.331	30.925
Bus12	0.1319	0.1327	0.1304	0.8681	0.8673	3.4444	3.6667	6.7527	12.303	33.125
Bus13	0.1389	0.1327	0.1317	0.875	0.8741	3.4722	3.6973	6.8616	17.82	42.229
Bus14	0.1449	0.1354	0.1328	0.913	0.8924	3.6304	3.7847	6.958	21.066	48.174
Bus15	0.1319	0.1327	0.1317	0.875	0.8776	3.4861	3.7143	6.9315	22.401	48.5
Bus16	0.1319	0.1327	0.1317	0.875	0.8776	3.4931	3.7211	6.957	22.527	48.84
Bus17	0.1389	0.1327	0.1331	0.8819	0.881	3.5	3.7313	6.9946	22.728	49.375
Bus18	0.1348	0.1306	0.1323	0.8936	0.8866	3.5745	3.7698	7.0337	23.021	50.582
Bus19	0.234	0.2268	0.2294	0.1277	0.1271	0.1489	0.1546	0.2362	0.1134	0.4113
Bus20	0.234	0.2268	0.2294	0.1277	0.1271	0.1418	0.1546	0.2375	0.1134	0.4113
Bus21	0.234	0.2268	0.2297	0.1277	0.1271	0.1418	0.1546	0.2375	0.1134	0.4113
Bus22	0.234	0.2302	0.2297	0.1348	0.1306	0.1489	0.1546	0.2375	0.1168	0.4113
Bus23	0.1277	0.1237	0.1215	1.1418	1.1237	0.9291	0.9759	1.5547	0.7663	2.6312
Bus24	0.1667	0.1395	0.1285	1.4907	1.2752	1.213	1.1047	1.6398	0.8682	3.4537
Bus25	0.1667	0.1395	0.1285	1.5	1.2791	1.2222	1.1124	1.6469	0.8721	3.4722
Bus26	0.125	0.1259	0.125	0.8333	0.8367	3.4722	3.6837	6.5497	3.068	10.063
Bus27	0.125	0.1259	0.125	0.8403	0.8367	3.4792	3.6939	6.5914	3.0714	10.097
Bus28	0.1319	0.1293	0.1277	0.8542	0.8503	3.5278	3.7483	6.7836	3.1088	10.25
Bus29	0.1377	0.1319	0.1301	0.8986	0.875	3.7174	3.8681	6.9837	3.2049	10.819
Bus30	0.1462	0.1357	0.1315	0.9538	0.9036	3.9615	3.9964	7.1233	3.3107	11.531
Bus31	0.1407	0.1368	0.132	0.9259	0.8947	3.837	3.9474	7.1524	3.2702	11.17
Bus32	0.1473	0.1362	0.1317	0.9612	0.9104	4.0155	4.0358	7.2263	3.3405	11.698
Bus33	0.1319	0.1327	0.1304	0.8681	0.8673	3.6042	3.8333	7.0874	3.1735	10.486

VSF, correlating with decreased bus stability. Similarly, if the same loadings were applied at different buses, for example, at bus 3 and bus 23, then the VSF values increase at a much higher rate and system stability further decreases. For cases 9 and 10, fast charging is placed at bus no. 14 and 15. The VSF values for bus 14 and 15 is 21.066, 48.174 and 22.401, 48.5, which are very high. Very high VSF values mean the bus is weak, and loading must not exceed the limit.

Light-duty EV chargers, with power ratings between 3.6 kW and 11.5 kW, were included in the analysis, with a significant emphasis on Level 2 chargers rated at 7.2 kW and 9.6 kW. EV battery capacities, reflecting both current and projected models, ranged from 5 kWh to 95 kWh. Fast charging was predominantly modeled using 50 kW chargers (Adaikkappan and Sathiyamoorthy, 2022; Adetunji *et al.*, 2022; Jones *et al.*, 2021; Keser and Poyrazoglu, 2020; Varghese *et al.*, 2024). Using this 50 kW fast-charger rating, different scenarios were developed to assess impacts on the IEEE 33-bus system at various locations, as detailed in Table 3.

Initially, the entire system analysis is done without placing any charging station; after that, case 1 is considered, in which rapid chargers are placed at buses 2 and 19. Bus 2 has 30 serving points in the strongest bus of the system. Considering that each charger consumes 50kW, the charging station can charge 30 electric vehicles simultaneously. Similarly, case 2 and case 3 considered with 2 charging stations and 5 charging stations placed at each bus 2 and 19 with 60 serving points and 150 serving points, respectively. The entire analysis was done considering the same chargers and serving points at different locations of the IEEE 33 bus. The case 9 and case 10 charging stations were placed at the weakest buses 14 and 15 of the system, with one charging station at each bus in case 9 and 2 charging stations at each bus in case 10. Other cases 4, 5, 6, 7 and 8 were also considered at different locations of the system to see the effect of the fast charging station on the entire system.

Impact due to load of EV Charging on Distribution System

An analysis was conducted to determine the effect of EV charging stations on voltage stability, reliability, and power losses within the distribution network for each case listed in Table 3. The results of this analysis are presented in the following subsection.

Impact due to load of EV Charging on Voltage Stability: This section examines how EV charging station load affects voltage stability in the IEEE 33-bus network. The data in Table 4, analyzed using the methodology in section 2.1.2, shows that the highest Voltage Stability Index (VSI) values were observed in cases where fast charging stations were located at buses 2 and 19 (cases 1-3). Conversely, the lowest VSI values were found in cases where fast charging stations were located at buses 14 and 15 (cases 9 and 10). A low VSI indicates lower bus stability, and a high VSI indicates higher stability.

Bus voltages for different charging scenarios (Table 3) are detailed in Table 5, including the base case without fast charging. At bus 2, the base case voltage is 0.9970 pu, and it decreases to 0.9953 pu, 0.9935 pu, and 0.9882 pu in cases 1-3. For bus 14, the corresponding voltages are 0.909 pu (base case), 0.907 pu, 0.9051 pu, and 0.8992 pu. All these values remain within acceptable voltage limits. Now if we see case 9 and case 10, the voltage at bus 2 and other strong buses are within tolerable limits, but at bus 14 and bus 15, voltages are 0.2442 pu, 0.2089 pu and 0.3032 pu, 0.2487 pu, which are extremely low from the tolerable limit. In cases 4, case 5, case 6, case 7 and case 8, fast charging stations were placed at buses 3, 23 and, 6, 26. The range of a fast charging station is 1500 kW to 7500 kW, and in Table 5 if we observe that the voltage of each bus is within the tolerable limit except for case 8, which consists fast charging station of 7500 kW at bus 6 and a bus 26. In case 8, voltage drops because such a large fast charging station withdraws a large amount of power from the system.

Table 3. Cases for analysing the impact of Fast Charging Stations on the distribution system

Cases	Fast Charging Station Placed at	Increase in Load (kW)	Number of Serving Points
Case 1	2 and 19	1500	30
Case 2	2 and 19	3000	60
Case 3	2 and 19	7500	150
Case 4	3 and 23	1500	30
Case 5	3 and 23	3000	60
Case 6	6 and 26	1500	30
Case 7	6 and 26	3000	60
Case 8	6 and 26	7500	150
Case 9	14 and 15	1500	30
Case 10	14 and 15	3000	60

Table 4. Impact due to load of EV Charging on Voltage Stability Index (VSI)_j

Bus	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Bus2	1.9879	1.9811	1.9739	1.9529	1.9807	1.9486	1.9799	1.9704	1.9042	1.9565
Bus3	1.9200	1.9064	1.8926	1.8518	1.8681	1.6503	1.8620	1.7950	1.3541	1.6972
Bus4	1.8372	1.8241	1.8107	1.7706	1.7517	1.4092	1.7127	1.5743	0.7898	1.3777
Bus5	1.7819	1.7691	1.7560	1.7164	1.6976	1.3603	1.6036	1.4118	0.4530	1.1439
Bus6	1.6881	1.6751	1.6626	1.6239	1.6055	1.2778	1.4310	1.1684	0.1918	0.7784
Bus7	1.6115	1.5986	1.5865	1.5485	1.5307	1.2110	1.3094	1.0130	0.1070	0.5142
Bus8	1.5493	1.5368	1.5247	1.4878	1.4702	1.1572	1.2535	0.9637	0.0903	0.3922
Bus9	1.4885	1.4764	1.4643	1.4282	1.4109	1.1043	1.1986	0.9155	0.0753	0.2636
Bus10	1.4498	1.4379	1.4257	1.3901	1.3731	1.0706	1.1636	0.8850	0.0664	0.1474
Bus11	1.4293	1.4175	1.4055	1.3699	1.3531	1.0530	1.1454	0.8690	0.0619	0.1013
Bus12	1.4216	1.4099	1.3979	1.3625	1.3458	1.0467	1.1387	0.8630	0.0603	0.0848
Bus13	1.3968	1.3849	1.3731	1.3381	1.3216	1.0252	1.1163	0.8436	0.0551	0.0355
Bus14	1.3711	1.3591	1.3478	1.3130	1.2967	1.0030	1.0934	0.8236	0.0500	0.0109
Bus15	1.3600	1.3483	1.3367	1.3022	1.2860	0.9935	1.0835	0.8150	0.0479	0.0052
Bus16	1.3505	1.3393	1.3275	1.2931	1.2770	0.9856	1.0751	0.8078	0.0461	0.0036
Bus17	1.3399	1.3284	1.3169	1.2825	1.2665	0.9764	1.0655	0.7994	0.0441	0.0030
Bus18	1.3321	1.3207	1.3096	1.2750	1.2590	0.9701	1.0588	0.7936	0.0428	0.0026
Bus19	1.6199	1.6024	1.5851	1.5322	1.5693	1.3551	1.4380	1.2390	0.2795	0.0706
Bus20	1.9556	1.9298	1.9042	1.8275	1.9415	1.8788	1.9395	1.9204	1.8211	1.9103
Bus21	1.9404	1.9147	1.8893	1.8126	1.9263	1.8641	1.9248	1.9054	1.8063	1.8954
Bus22	1.9347	1.9091	1.8834	1.8069	1.9203	1.8582	1.9188	1.8999	1.8010	1.8899
Bus23	1.8853	1.8659	1.8462	1.7886	1.8168	1.5348	1.8274	1.7614	1.4162	1.7248
Bus24	1.8083	1.7949	1.7817	1.7420	1.6917	1.2438	1.7129	1.6061	1.0907	1.5475
Bus25	1.7715	1.7583	1.7453	1.7059	1.6563	1.2133	1.6773	1.5714	1.0621	1.5135
Bus26	1.6864	1.6738	1.6609	1.6226	1.5895	1.2094	1.4722	1.2457	0.3078	1.1182
Bus27	1.6022	1.5900	1.5773	1.5401	1.5221	1.2030	1.2891	0.9845	0.0874	0.8229
Bus28	1.5545	1.5423	1.5298	1.4932	1.4753	1.1616	1.2463	0.9470	0.0757	0.7886
Bus29	1.4900	1.4778	1.4658	1.4296	1.4123	1.1057	1.1884	0.8964	0.0614	0.7424
Bus30	1.4513	1.4394	1.4276	1.3919	1.3749	1.0725	1.1539	0.8663	0.0536	0.7151
Bus31	1.4277	1.4160	1.4039	1.3687	1.3519	1.0522	1.1328	0.8480	0.0491	0.6986
Bus32	1.4131	1.4014	1.3895	1.3546	1.3379	1.0397	1.1198	0.8368	0.0464	0.6884
Bus33	1.4101	1.3984	1.3865	1.3516	1.3350	1.0370	1.1170	0.8343	0.0459	0.6863

Table 5. Impact due to load of EV Charging on Voltage Profile

Bus	Base	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9
Bus2	0.997	0.9953	0.9935	0.9882	0.9952	0.9933	0.995	0.9926	0.9758	0.9891
Bus3	0.9829	0.9811	0.9793	0.9739	0.9713	0.9593	0.9699	0.9546	0.8434	0.9315
Bus4	0.9753	0.9736	0.9718	0.9663	0.9637	0.9516	0.9543	0.9296	0.7453	0.8912
Bus5	0.9679	0.9661	0.9643	0.9588	0.9561	0.9439	0.9384	0.9039	0.6387	0.8487
Bus6	0.9494	0.9475	0.9457	0.94	0.9373	0.9248	0.9016	0.8458	0.4851	0.7353
Bus7	0.9458	0.9439	0.9421	0.9364	0.9337	0.9212	0.8978	0.8418	0.4775	0.69
Bus8	0.9321	0.9302	0.9283	0.9226	0.9198	0.9071	0.8834	0.8263	0.4478	0.6438
Bus9	0.9258	0.9239	0.922	0.9162	0.9134	0.9006	0.8766	0.8191	0.4338	0.5642
Bus10	0.9199	0.918	0.916	0.9102	0.9074	0.8945	0.8704	0.8124	0.4205	0.4815
Bus11	0.919	0.9171	0.9152	0.9093	0.9065	0.8936	0.8695	0.8114	0.4186	0.4675
Bus12	0.9175	0.9156	0.9136	0.9078	0.905	0.892	0.8679	0.8097	0.4151	0.4405
Bus13	0.9113	0.9093	0.9074	0.9015	0.8987	0.8856	0.8613	0.8026	0.4008	0.3032
Bus14	0.909	0.907	0.9051	0.8992	0.8964	0.8833	0.8589	0.8	0.3955	0.2442
Bus15	0.9073	0.9054	0.9034	0.8975	0.8947	0.8815	0.8571	0.7981	0.3916	0.2089
Bus16	0.9059	0.904	0.902	0.8961	0.8933	0.8801	0.8556	0.7965	0.3883	0.2026
Bus17	0.9039	0.9019	0.9	0.894	0.8912	0.878	0.8535	0.7942	0.3835	0.1929
Bus18	0.9032	0.9013	0.8994	0.8934	0.8906	0.8774	0.8528	0.7935	0.382	0.19
Bus19	0.9965	0.9932	0.9899	0.9798	0.9947	0.9928	0.9944	0.992	0.979	0.9907
Bus20	0.9929	0.9896	0.9863	0.9762	0.9911	0.9892	0.9909	0.9884	0.9753	0.9871
Bus21	0.9922	0.9889	0.9856	0.9754	0.9904	0.9885	0.9902	0.9877	0.9746	0.9864
Bus22	0.9916	0.9883	0.9849	0.9748	0.9897	0.9878	0.9895	0.9871	0.974	0.9858
Bus23	0.9793	0.9775	0.9757	0.9703	0.9632	0.9466	0.9662	0.9509	0.8641	0.9422
Bus24	0.9726	0.9708	0.969	0.9635	0.9565	0.9397	0.9595	0.9441	0.8565	0.9353
Bus25	0.9693	0.9675	0.9657	0.9602	0.9531	0.9363	0.9561	0.9406	0.8527	0.9318
Bus26	0.9474	0.9456	0.9437	0.9381	0.9354	0.9228	0.8974	0.8391	0.4601	0.8025
Bus27	0.9448	0.943	0.9411	0.9355	0.9327	0.9202	0.8947	0.8362	0.4544	0.7994
Bus28	0.9334	0.9315	0.9296	0.9239	0.9211	0.9084	0.8826	0.8232	0.4287	0.7858
Bus29	0.9252	0.9233	0.9214	0.9156	0.9128	0.9	0.8739	0.8138	0.4098	0.7759
Bus30	0.9216	0.9197	0.9178	0.912	0.9092	0.8963	0.8701	0.8097	0.4016	0.7717
Bus31	0.9175	0.9156	0.9136	0.9078	0.905	0.892	0.8657	0.805	0.3918	0.7667
Bus32	0.9165	0.9146	0.9127	0.9069	0.9041	0.8911	0.8647	0.8039	0.3897	0.7656
Bus33	0.9163	0.9144	0.9124	0.9066	0.9038	0.8908	0.8644	0.8036	0.389	0.7653

Table 6. Impact on different reliability indices

Case	SAIDI (Interruption/Year)	CAIDI (hours/Interruption)	SAIFI (Interruption/Year)	AENS (kWh/Year)
BASE	0.5014	5.1041	0.0982	1.9304
CASE1	0.7016	5.274	0.133	5.2509
CASE2	0.892	5.3431	0.1669	10.5274
CASE3	1.4156	5.4496	0.2598	31.2236
CASE4	0.7274	5.6258	0.1293	5.5976
CASE5	0.9211	5.7256	0.1609	11.0974
CASE6	0.7308	3.4704	0.2106	5.9182
CASE7	0.9592	5.9557	0.1611	12.2449
CASE8	1.5956	6.2782	0.2541	37.2982
CASE9	0.6707	4.1806	0.1604	4.8698
CASE10	0.8423	5.8675	0.1435	9.7022

Table 7. Impact on different reliability indices

Case	Power Loss (pu)	Case	Power Loss (pu)
BASE	0.0223	CASE6	0.1531
CASE1	0.0499	CASE7	0.1314
CASE2	0.0487	CASE8	0.2828
CASE3	0.0476	CASE9	2.9731
CASE4	0.0451	CASE10	3.4660
CASE5	0.0623		

Impact due to load of EV Charging on Reliability: In this section, an examination was conducted to assess the influence of EV chargers load on the distribution system's reliability, considering all the scenarios. The repair rate, failure rate, and outage duration resulting from the load increment were determined using a unitary method (Bhadra and Chattopadhyay, 2015). This data helped to calculate all the reliability parameters like SAIFI, SAIDI and CAIDI.

Table 6 shows the impact on reliability indices for different considered cases. The base case represents the data when no fast-charging station is connected to the system. SAIDI, SAIFI, CAIDI and AENS for base case are 0.5014, 0.0982, 5.1041 and 1.9304, respectively. These values are less than all the other cases listed in Table 6. For case 3, SAIFI, SAIDI, CAIDI and AENS are 0.2598, 1.4159, 5.4496 and 31.2236, which are much higher than the base case beyond the tolerable limit. Similarly, case 8 has values beyond the limit. All the other cases have less reliability indices as compared to case 3 and case 8.

Impact due to load of EV Charging on Power Loss: The power losses were analysed for the case mentioned in Table 3 for IEEE 33 bus system when EV fast charging station was connected to the system. Equation (10) calculates power losses in the distribution system. Table 7 shows the power loss's magnitude due to different charging station placement cases. The power loss of the distribution was high when the charging station connected to the system compared to the base case when no charging station was placed. Power losses of the distribution

network increase when loading increases, but losses can be tolerable for cases 1 to 8. Among all the cases, the power loss is highest in case 9 and case 10, which have magnitudes of 2.9731 pu and 3.4660 pu. So, placing charging stations on buses 14 and 15 is undesirable as power losses were very high.

Comparative Analysis based on Reliability, Voltage Stability, and Power Loss: The graphical representation of the Voltage Stability Index (VSI) for different fast-charging placement scenarios within the distribution network is shown in Figure 7. This figure indicates that buses 14, 15, and 16 experience consistently low VSI values, whereas buses 2, 3, 19, 21, and 22 exhibit high VSI values. Figure 8 displays the power losses associated with these different charging station placements, revealing low power losses for cases 1, 2, and 3, and high power losses for cases 9 and 10. Figure 8 shows reliability indices for different cases of charging station placement. The reliability indices of case 1 and case 2 are the least compared to other cases. Comparing all the parameters, we cannot place the charging station on bus 14 and 15 due to high power loss and also, the charging station could not place at bus 10 to 16 due to low VSI. EV fast charging station cannot be used for case 3 and case 8 as the AENS value is very high and the system is less reliable.

Table 8 compares the impact of EV charging station load on distribution network indices. It shows that installing charging stations at strong buses (cases 2, 4, 5, 6) negatively affected reliability indices more than power loss or voltage stability. However, cases 8 and 10, with charging stations at

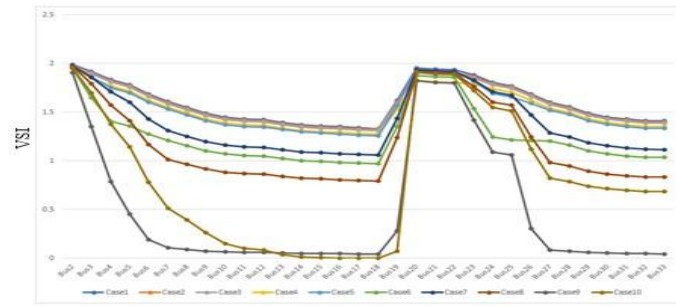


Figure 7. EV charging station load Impact on VSI

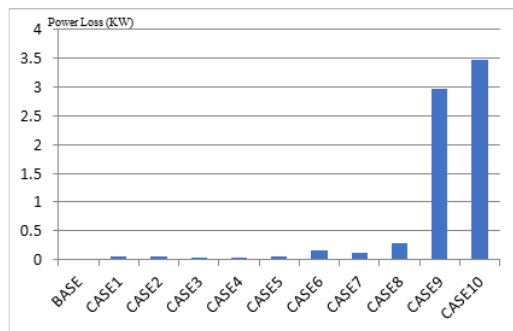


Figure 8. Power Loss for different cases

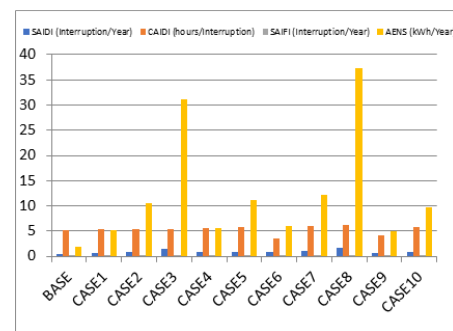


Figure 9. Reliability Indices for different cases

Table 8. Impact on different reliability indices

Cases	Change in system parameter				
	VSI	Power Loss	SAIDI	SAIFI	CAIDI
2	0.438	0.0264	0.3906	0.0687	0.239
4	2.192	0.0228	0.226	0.0311	0.5217
5	2.251	0.04	0.4197	0.0627	0.6215
6	11.194	0.1308	0.2294	0.1124	1.6337
8	13.591	0.2605	1.0942	0.1559	1.1741
10	25.936	3.4437	0.3409	0.08385	0.7634

Table 9. Impact on different reliability indices

Parameter	w1	w2	w3	w21	w22	w23	nfastCS	nslowCS
Value	0.2	0.6	0.2	0.3	0.2	0.1	2	3

buses 14 and 15, experienced the highest power loss impact. Power loss for case 4 and 5 is less affected than reliability indices, as seen in Figure 9 and Figure 10. On the other hand, the percentage change in power loss for case 2 is 11%, as shown in Figure 10.

VRP Index for Optimal Placement of Charging Stations.

In the preceding subsection, the effects of EV charging station load on the distribution network were investigated. This included an examination of voltage stability (subsection 4.2.1) and an analysis of reliability and power loss for each scenario presented in Table 3. The subsequent section will focus on identifying the best locations for EV charging stations within the distribution network, employing the VRP index and utilizing the input

parameters detailed in Table 9. Utilizing the VRP index, Table 10 provides the recommended locations for EV fast charging stations within the IEEE 33-bus system. Specifically, bus 2, identified as the strongest bus, can support 2 fast charging stations and 3 slow charging stations. Similarly, bus 19, the second strongest bus, can also accommodate 2 fast and 3 slow chargers. The optimization problem was solved using a Genetic Algorithm (GA).

Table 10. Impact on different reliability indices

Bus no.	Slow Charging station	Fast Charging Station
2	3	2
19	3	2
20	2	1

Discussion

The electrification of the transportation industry can significantly contribute to the development of smart cities. Building well-thought-out and effective charging infrastructure is highly desirable as electric vehicles (EVs) become more commonplace on the road. In contrast to level 1 and level 2 charging stations, level 3 chargers can charge EVs incredibly quickly. However, because there is a chance that critical system criteria could be broken as a result of level 3 chargers' excessive power consumption, their widespread installation is neither technologically nor financially feasible. This article has covered the effects of EV fast charging stations on the distribution network in great depth in our article. When the amount of charging infrastructure increases, the IEEE 33 bus has been utilised to analyse critical distribution networks parameters such as reliability, voltage stability, and power loss. The outcomes of this paper are discussed below:

1. Although the IEEE 33 bus, such as a level 1 or level 2 charger, is very powerful to resist small charging loads at any bus, the system contains some strong and weak buses. The strongest bus 2, however, can only handle a maximum of four level 3 charging stations before the SAIDI rises by 77.90%. Therefore, a system upgrade is required for bus 2 in order to increase the number of fast charging stations beyond a particular threshold.

2. The positioning of the rapid-charging station on the vulnerable bus compromised the system's security. Installing just one charging station on the weakest bus significantly decreased its voltage, reaching 0.2442 per unit. Moreover, locating fast charging infrastructure at these weak buses led to a notable reduction in reliability indices. Additionally, it was observed that power losses surged by 132% when a single station of EV chargers was installed at buses 14 and 15, which are recognised as the weakest buses in the network. Nevertheless, installing a 19.2 kW station of slow EV Chargers was feasible even on weak buses.

3. Distributing the charging facilities among numerous buses proved superior to concentrating them on one bus. Additionally, under some circumstances, if a strong bus of the distribution system of the road network with high traffic density converges, the roads lead to a bus beyond the stability limit.

Conclusion

Electric vehicles (EVs) serve as a viable solution for reducing emissions from transportation. As the penetration of EVs grows, the development of

charging stations has become necessary. However, it is important to analyse the potential negative impact of increased load on the distribution system. This study extensively examines the effects of EV charging station on different network parameters (voltage stability, reliability indices, and power losses) in the IEEE 33 bus test system. The findings reveal that installing rapid charging stations at weak buses negatively affects the efficient operation of the power distribution network.

On the other hand, placing charging stations at robust buses proves beneficial. Additionally, this article proposes a method to determine the proper locations for stations of EV chargers in the distribution network based on the calculated VRP index. By utilising a Genetic Algorithm (GA) and incorporating the VRP index as the objective function, an effective solution to the charger position problem is achieved, identifying optimal charger locations within the IEEE 33 bus test network. While demonstrated on the IEEE 33-bus system, the same process calculating the indices for a given network and solving the optimization problem can be directly applied to any other radial distribution network, given its line data, reliability data, and load profile. This research can prove invaluable to power system engineers, providing valuable insights and aiding in developing efficient distribution networks to address the growing demands of EV charging. We explicitly state that applying this method to a real-world, larger network is a primary objective of our immediate future work.

Limitations and Future Work

Despite the comprehensive insights provided by this study, several limitations should be acknowledged, which also delineate clear pathways for future research. The current analysis is primarily static and deterministic, based on specific snapshot scenarios rather than capturing the dynamic, probabilistic nature of real-world EV charging demand, load profiles, and renewable generation variability. Furthermore, the model assumes unidirectional power flow (G2V) and does not explore the potential of Vehicle-to-Grid (V2G) technology to enhance grid stability. The optimization is also conducted from a purely technical perspective, omitting the crucial economic and cost-benefit analyses necessary for practical implementation, and the distribution network is treated in isolation from the broader transmission and generation system. To address these constraints, future work will focus on developing a time-series probabilistic model using Monte Carlo simulations to generate realistic charging profiles for a more accurate

annualized impact assessment. Additionally, expanding the VRP framework to incorporate the benefits of bidirectional V2G power flow and conducting a thorough economic analysis will be essential steps toward providing a holistic tool for future-proof and economically viable grid planning amidst the transition to electric mobility.

Declaration of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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