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Electric vehicle charging stations load impact on the distribution network

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Abstract
Integrating large numbers of electric vehicles will lead to operational and planning difficulties for distribution networks. The installation of electric vehicle charging stations (EVCS) increases power losses, affects stability, and degrades the reliability of the distribution network, resulting in dissatisfaction among customers. This work describes the impacts of the integration of electric vehicle charging stations on power losses, voltage stability index, and the main reliability indices as a function of the position and size of electric vehicle charging stations. This investigation was carried out on the IEEE 33 bus test system. According to the results, a high concentration of EVs increases peak demand, leading to greater energy losses, adversely affecting stability, and degrading reliability indices of the distribution network. The choice of installation points for EVCS is therefore very important, as some points induce greater energy losses than others and affect stability and reliability more than others. Measures to mitigate the effects of EVCS installation on distribution networks are crucial.
Keywords: Distribution Network, Charging Station, Power Loss, Reliability, Voltage Stability.

1. Introduction

The growing adoption of electric vehicles (EVs) has led to the creation of a large number of charging stations, which in turn poses significant challenges for electrical distribution networks. These challenges are mainly due to the additional load imposed by EV chargers, which are often grouped together in specific locations. The impact of this load is noted in key areas such as power losses, voltage stability, and reliability indices, necessitating a reevaluation of the design and operation of traditional grids.

In fact, the installation of EV charging stations in the distribution network leads to an increase in power losses, as EVCS increase electrical demand on distribution networks, particularly during peak hours or in areas with high EV penetration. This increased loading is reflected in higher line currents, amplifying power (resistive) losses in the network. Such losses not only reduce energy efficiency, they also put additional strain on transformers and cables, which can lead to premature ageing of equipment. Note that a single charger can consume as much energy as a household, and if the number of chargers is multiplied, the cumulative impact on energy losses becomes significant. To remedy these losses, it is often necessary to modernize the infrastructure or implement load management strategies.

Voltage stability is also a key concern in distribution networks affected by electric vehicle charging stations. When an EVCS or several EV chargers are operating simultaneously, the localized load can generate significant voltage drops, especially in networks with restricted reactive power compensation or long radial feeders. These voltage variations can lead to non-observance of regulatory standards and affect the quality of electricity delivered to all end users. In addition, rapid fluctuations in load, for example, when several vehicles start charging simultaneously, can aggravate stability problems. Guaranteeing voltage stability in such cases often requires the implementation of advanced technologies such as voltage regulators, reactive power compensation devices, or distributed energy storage systems.

Several different metrics are commonly adopted to evaluate the reliability of distribution networks: System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), and Energy Not Supplied (ENS) can be affected by the unpredictable nature of EV charging loads. Networks can suffer overloads or failures due to high demand, resulting in more frequent and more lengthy outages. In addition, the irregular distribution of charging stations can cause stress points to appear locally in the network, increasing the potential for outages. To attenuate these effects, network operators may need to adopt advanced monitoring and control systems and optimize the location and operation of charging infrastructure.

Integrating EV charging stations into electricity distribution networks requires careful planning and innovative solutions to minimize negative impacts. To overcome power losses, it may be necessary to optimize network design or adopt energy-efficient technologies. Voltage stability problems can be alleviated by adopting advanced network control tools and localized compensation devices. Improving reliability involves a combination of predictive analytics, network upgrades, and more intelligent load balancing. As EV penetration continues to grow, understanding and attenuating the impacts of charging station loads will be essential to maintaining resilient and efficient power distribution systems. Solutions may include optimizing charging schedules, upgrading infrastructure, and integrating smart grid technologies.

2. Methodology

Power losses, voltage stability, and reliability are the three most important criteria for the performance of the distribution network. In this section, a brief overview of the method used to calculate power losses, voltage stability, and reliability of the distribution network is presented. In addition, the overall calculation approach applied to assess the impact of EV charging stations on the distribution network is also outlined in this section.

2.1. Power Losses

Power losses in a distribution network relate to the energy dissipated in the form of heat, mainly in the conductors and other components of the electrical system during power transmission and distribution. These losses are mainly due to lines resistances and are a key factor in reducing the efficiency of electrical systems. The expression for computing the active power line losses is as given as follows [1]:

$$P_L(i) = r_i |I_i|^2 = r_i \frac{(P_i^2 + Q_i^2)}{V_i^2} \tag{1}$$

Consequently, the total power loss of the system can be calculated as follows: [1]:

$$\sum_{i=2}^{N_{bus}} P_L(i) = \sum_{i=2}^{N_{bus}} r_i |I_i|^2 = \sum_{i=2}^{N_{bus}} r_i \frac{(P_i^2 + Q_i^2)}{V_i^2} \tag{2}$$

Where

- r_i line resistance between node *i-1* and node *i;*
- *I* current of branch *i*;
- V_i node *i* voltage;
- P_i and Q_i active and reactive power supplied by node *i*.

2.2. Voltage Stability

Voltage stability in distribution networks is the system's capacity to sustain tolerable voltage levels under both normal operating conditions and after perturbations such as load variations, faults, or system reconfigurations. It guarantees the continuous, reliable supply of electrical power without voltage collapse or degradation, which can result in power outages, component damage, or inefficient system performance.

It should be noted that voltage stability is affected by many factors, such as load demand, reactive power control, network reconfiguration, and the positioning of distributed generation units. To maintain stability, it is necessary to ensure a perfect balance between power generation and load demands while simultaneously providing adequate reactive power.

Voltage stability indices are one of the most effective ways of supervising the power system. However, some of them are less accurate and insensitive to certain types of disturbance, particularly when the power system is operating close to its load capacity limit. These include the P-V and Q-V curves [12][13] or simply PQ curve [6], the Line Stability Index (Lmn), the Fast Voltage Stability Index (FVSI), the Simplified Fast Voltage Stability Index (SFVSI), the Innovative Line Stability Index (NLSI) and the Line Stability Factor (LQP). In this document, we will limit the study to the voltage stability index (VSI).

2.2.1. Voltage Stability Index (FVSI)

Murthy et al. [3] developed a voltage stability index (VSI) to find the bus most susceptible to voltage collapse in radial distribution system. The VSI is set as follows at each node:

$$VSI_{i+1} = \frac{4X_i}{V_i^2}\left(\frac{{P_{i+1}}^2}{Q_{i+1}} + Q_{i+1}\right) \qquad (3)$$

where

VSI_i is the bus *i* stability index, P_i and Q_i are total active and reactive power load connected to bus *i*, V_i is the bus *i* voltage, X_i is reactance of the branch *i*.

To assure stable operation in a radial distribution system:

- **T**he value of the voltage stability index (VSI) must remain below unity.
- A lower ISV indicates better voltage stability.
- Keeping the ISV of all buses closer to zero minimizes the risk of voltage collapse.

This strategy ensures efficient power distribution while maintaining system stability.

2.3. Reliability

Power system reliability analysis assesses the system's ability to consistently deliver electrical power to consumers under standard operating conditions. It aims to ensure uninterrupted power delivery by examining system performance, forecasting failures, and implementing measures to reduce outages.

2.3.1 Reliability Indices

Reliability indices are metrics to quantify system reliability. They are classified into production, transmission, and distribution indices, with distribution indices being the ones most commonly investigated due to their direct impact on end users.

A. Distribution Indices

To evaluate the reliability indices of a distribution network, specific statistical data is essential:

- **Failure rate**: Indicates how often failures occur.
- **Repair rate**: Reflects the speed at which faults are fixed.
- **Average outage duration**: Represents the mean time consumers experience power interruptions.
- **Number of consumers**: Provides the load or demand data related to specific buses or load points.

Reliability indices are categorized into customer oriented and energy oriented reliability indices. Figure 1. The three main customer-oriented reliability indices are SAIFI, SAIDI, and CAIDI. On the other hand, energy-based reliability indices can be subdivided into ENS and AENS indices.

B. Customer-oriented reliability indices

1. **System Average Interruption Frequency Index (SAIFI)**: Measures the average customer's frequency of outages.

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customers\ served} = \frac{\sum \lambda_j N_j}{\sum N_j} \quad (4)$$

2. **System Average Interruption Duration Index (SAIDI)**: Measures the average downtime per customer over a year.

$$SAIDI = \frac{Sum\ of\ all\ customer\ interruption\ durations}{Total\ number\ of\ customers\ served} = \frac{\sum U_j N_j}{\sum N_j} \quad (5)$$

3. **Customer Average Interruption Duration Index (CAIDI)**: Average time required to restore service after an interruption.

$$CAIDI = \frac{SAIFI}{SAIDI} \quad (6)$$

C. Energy oriented reliability indices

Energy-based reliability indices quantify the reliability of a power system in terms of power delivered versus power interrupted.

1. **Expected Energy Not Supplied (EENS) :** Represents the amount of energy demand that the system fails to meet during a given period.

$$EENS = \sum_{i=1}^{N} P_i D_i \quad (7)$$

- *Pi*: Probability of failure for state *i*
- *Di*: Energy demand not supplied in state *i*

- N : Total number of system states

2. **Average Energy Not Supplied Index (AENS):** Total energy not supplied divided by the annual number of customers disconnected.

$$AENS = \frac{Total\ energy\ not\ supplied\ by\ the\ system}{Total\ number\ of\ custemer\ served} = \frac{\sum EENS_i}{\sum N_i} \qquad (8)$$

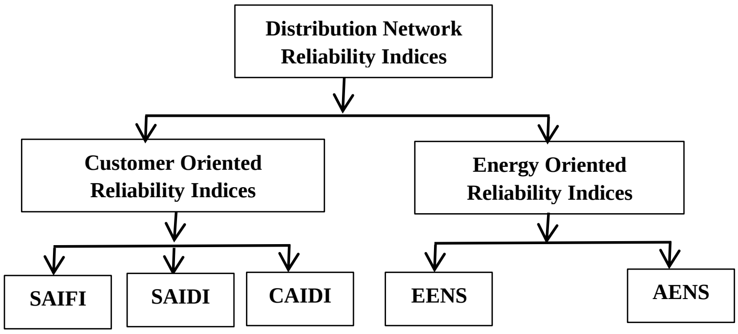

Figure 1. Distribution Network Reliability Indices.

3. Results And Discussion

The widespread growth of electric vehicles (EVs) is significantly impacting the distribution network through increased load demand. This higher demand can deteriorate the operating parameters and pose problems for the reliability and efficiency of the power grid.
This paper presents an analysis of the impact of electric vehicle charging station loading on power losses, voltage stability, and distribution network reliability as a function of the position and size of electric vehicle charging stations in the distribution network. The analysis was carried out on the IEEE 33 bus test system.Charging station is assumed to consumes 500 kW, 1000 kW, and 1500 kW.

3.1.Test System Description

In this study, the analysis was carried out on the IEEE 33 bus test Figure 2, it is a 12.66 kV radial distribution system consisting of 33 nodes and 32 branches (lines), the total system load is 3.715 MW and 2.3 MVAr, the total active power loss 202.677 kW, and the minimum voltage is 0.9038 p.u (bus 18).

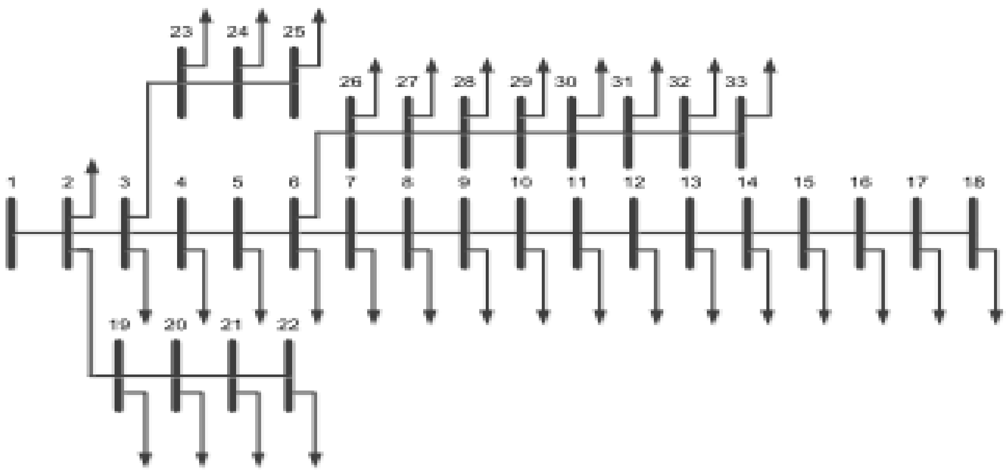

Fig.2. IEEE 33-bus distribution network diagram.

3.2. Power Losses

The impact of the EVCS on the distribution network in terms of power losses is evaluated by varying the position of the EVCS from bus two to bus thirty-three and for three EVCS sizes: 500 kW, 1000 kW, and 1500 kW. The results obtained are shown in Figure 3.
Before deployment of the EVCS, active power losses were equal to 202.667 kW. The introduction of EVCS results in an increase in power losses, with the greatest values being reached exactly when EVCS is on bus 18. Power losses when the EVCS is on bus 18 are 225.111 kW, 225.114 kW, and 225.117 kW, respectively, for EVCS sizes of 500 kW, 1000 kW, and 1500 kW.

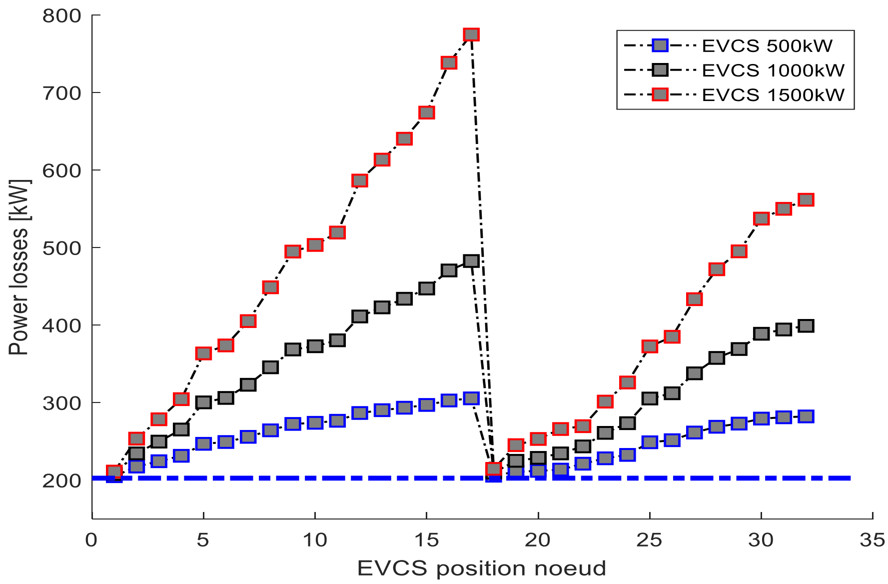

Fig. 3 The impact of installing EVCS on each bus in terms of power losses for the 33-bus test system.

3.3. Voltage Stability

One of the many indices used to check the safety level of the electrical system is the voltage stability index (VSI) [3], which is used to determine which bus is most sensitive to voltage collapse in the system. Nodes with the highest VSI values are the most sensitive [3]. To reduce the risk of voltage collapse, the VSI of all buses should be close to zero. Before the EVCS was installed on the 33-bus system, bus 6 had the highest voltage stability index in the network, equal to 0.0082 (making it the most sensitive bus to voltage collapse).The maximum values of the voltage stability index after the installation of an EVCS on all network buses, one by one, are presented in Figure 4.
It can be seen that after an EVCS has been installed on the electrical network, the maximum value of the VSI increases, reaching its highest value when the EVCS is on bus 18. Once the EVCS is installed on bus 18, the highest value is recorded on bus 18 and is equal to 0.0393, 0.1347, and 0.3131 for an EVCS load of 500 kW, 1000 kW, and 1500 kW, respectively.
It can therefore be clearly stated that the integration of an EVCS leads to a deterioration in network stability.

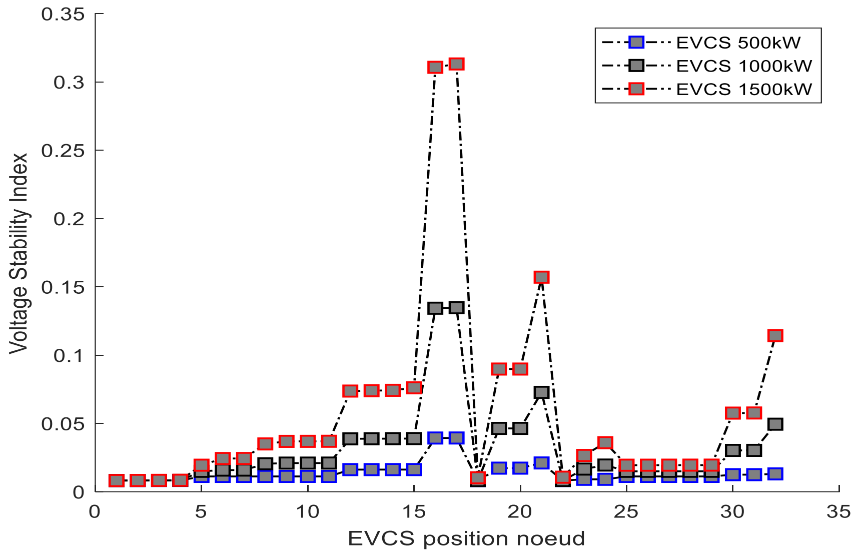

Fig. 4 The 33 bus system Voltage Stability Index

3.4. Reliability

In this section, the main objective is to provide a detailed examination of the impact of the installation of EVCS on the reliability of the IEEE 33 bus system. Reliability indices are calculated for all buses and for three sizes of EVCS. Customer information, such as failure rate, repair rate, and number of customers for the 33-bus system, are listed in Table 1.

The introduction of the EVCS charge leads to an increase in the average failure rate (λ_i) and average annual downtime (U_i). The new values for λ_i (new) and U_i (new) can be calculated as follows [14]:

$$\lambda_i(new) = \frac{\lambda_i(P_i + \Delta P_i)}{P_i}$$

$$U_i(new) = \frac{U_i(P_i + \Delta P_i)}{P_i}$$

where Pi and ΔPi are the actual load and increment in the load at that load point i.

The reliability index values for the base case (no EVCS installed) are as follows: SAIFI 0.0982 int./client/year, SAIDI 0.5048 h/customer/year, CAIDI 5.1385, EENS 1780 kWh/year, and AENS 1.9369 kWh/customer/year.

The results in Figs. 5 to 9 show that all indices increase with distance from the substation. Moreover, they also increase with increasing EVCS size. This clearly implies that the utility has suffered from the deployment of EVCSs.

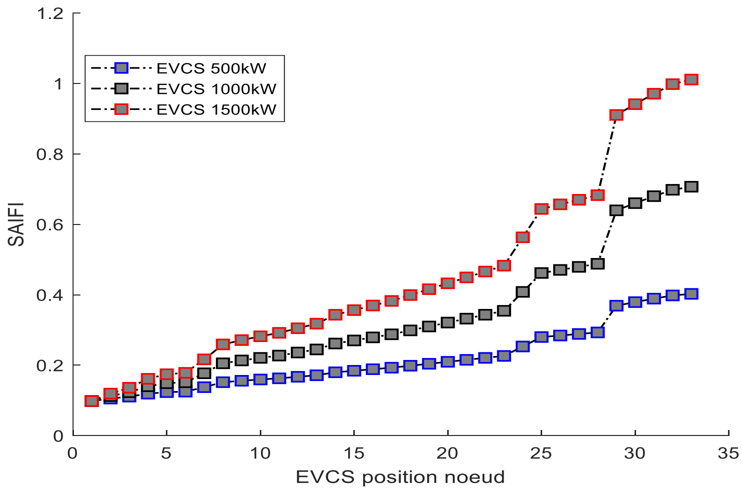

Fig. 5 SAIFI as a function of EVCS position

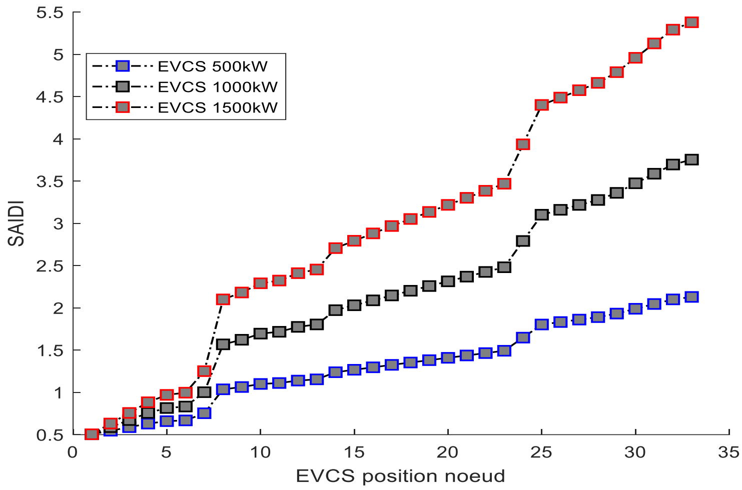

Fig. 6 SAIDI as a function of EVCS position

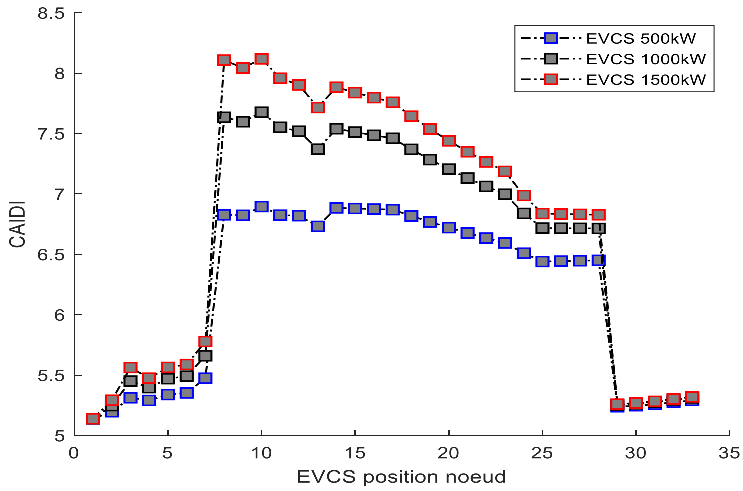

Fig. 7 CAIDI as a function of EVCS position

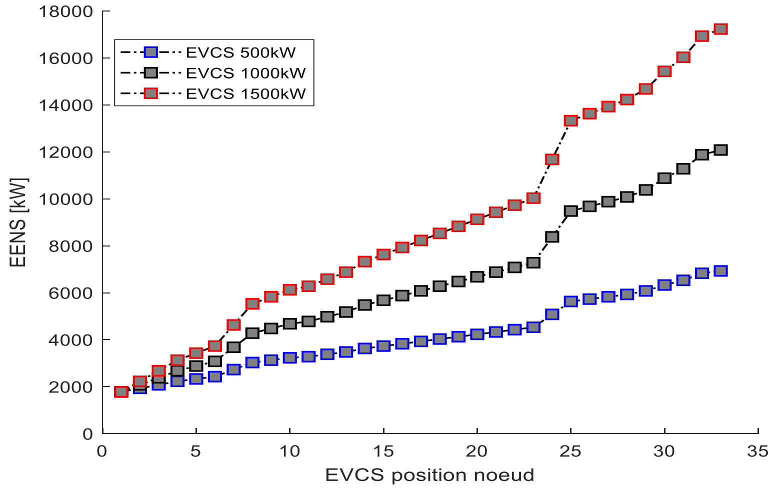

Fig. 8 Expected energy not supplied as a function of EVCS position.

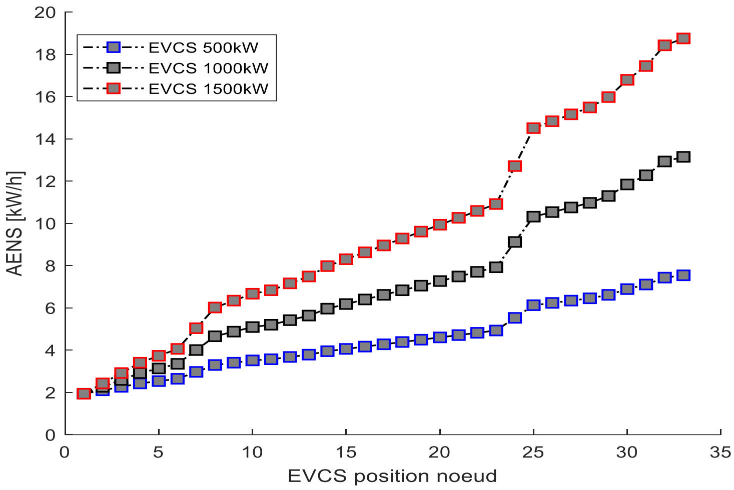

Fig. 9 Average energy not supplied as a function of EVCS position.

TABLE 1. Statistical parameters for 33 bus system [14].

Load points	Failure rate λi (f/yr)	Repair rate U(hr/yr)	Number of customers	Load [kW]
2	0.05	0.3	26	100
3	0.04	0.3	23	90
4	0.06	0.3	31	120
5	0.03	0.2	16	60
6	0.03	0.2	16	200
7	0.09	0.6	52	200
8	0.03	0.6	52	60
9	0.03	0.2	15	60
10	0.02	0.2	15	45
11	0.03	0.1	12	60
12	0.03	0.2	16	60
13	0.06	0.2	16	120
14	0.03	0.3	31	60
15	0.03	0.2	16	60
16	0.03	0.2	16	60

17	0.03	0.2	16	60
18	0.04	0.2	23	90
19	0.04	0.2	23	90
20	0.04	0.2	23	90
21	0.04	0.2	23	90
22	0.04	0.2	23	90
23	0.04	0.2	23	90
24	0.19	1.1	109	420
25	0.19	1.1	109	420
26	0.03	0.2	16	60
27	0.03	0.2	16	60
28	0.03	0.2	16	60
29	0.54	0.3	31	120
30	0.09	0.5	25	120
31	0.07	0.4	39	150
32	0.1	0.6	35	210
33	0.03	0.2	16	60

4. Conclusion

The challenges of integrating charging stations into the existing distribution network are considerable, since EVCS loads have a negative impact on the network in terms of power losses, stability, and reliability. This study examines the impact of EVCS on performance in terms of power loss, stability, and reliability of the IEEE 33-bus test system. The results showed that the installation of recharging stations, particularly on buses 18 and 17 (weak buses), was to their disadvantage. This makes the choice of installation points for EVCS very decisive, as some points generate greater energy losses than others and impact stability and reliability greater than others. Actions to reduce the effects of EVCS installation on distribution networks are therefore extremely vital. However, the integration of decentralized generation systems proved to be an effective solution.

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