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Performance Assessment and Impact of Electric Vehicles Penetration in Active Distribution Grids

Evaluación del rendimiento e impacto de la penetración de los vehículos eléctricos en redes de distribución activas

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KEYWORDS:
electric vehicles, EV charging methods, load modeling, voltage drop, line loading, load flow calculation.
vehículos eléctricos, métodos de carga de vehículos eléctricos, modelado de carga, caída de voltaje, carga de línea, cálculo de flujo de carga

ABSTRACT: Because of the ongoing discussion about global warming, many nations have developed several approaches to address this problem. Some strategies are: renewable energy integration, agricultural robotic solutions, and electric vehicle penetration. The last strategy, the electric vehicle (EV), has gained considerable attention due to the paradigm shift in the transport sector driven by internal combustion engines and EV penetration can also achieve e icient operation of power grids. However, there are numerous challenges associated with the penetration of these technologies within active distribution networks. It is necessary to analyze the increased amount of electricity consumption in these grids, the degradation in the voltage profile in these networks and the hosting capacity assessment of electric vehicle integration in these grids. This paper analyzes the influence of EV penetration on a 34-bus active distribution system through five EV stations and proposes two alternatives for improving the introduction of these technological elements. Specifically, it analyzes the voltage levels at the system nodes and proposes an intelligent management of resources through capacitor banks and transformer taps. From the results, the effects on the network were voltage drop on some bus bars and an increase or decrease of the loading on lines depending on the EV penetration. It is also evident that 9% of the bus bars were not working under acceptable voltage ranges in the worst-case scenario.

RESUMEN: Debido al calentamiento global se han creado estrategias para combatir este problema. Algunas estrategias son: integración de energías renovables, soluciones robóticas agrícolas y la penetración de vehículos eléctricos. La última estrategia, los vehículos eléctricos (VE), genera un cambio de paradigma en el sector del transporte tradicionalmente impulsado por motores de combustión interna. La penetración de VE puede lograr una operación eficiente de las redes eléctricas, sin embargo, la penetración de estas tecnologías en las redes de distribución activas plantea numerosos retos. Es necesario analizar el aumento del consumo de la electricidad, la degradación de las tensiones o la evaluación de la capacidad de integración de VE. En este trabajo se analiza la influencia de la penetración de VE en un sistema de distribución activo de 34-barras a través de cinco estaciones de carga VE y se proponen dos alternativas para mejorar la incorporación de los VE. Específicamente, se analizan los niveles de tensión en los nodos del sistema y se propone una gestión inteligente de los recursos a través de condensadores y derivaciones de transformadores. A partir de los resultados, se evidencia caídas de tensión en algunas barras y un aumento o disminución de la carga en las líneas en función de la penetración del VE. También es evidente que el 9% de los nodos no funcionaban en rangos de tensión aceptables en el peor de los casos.

1. Introduction

The transportation is one of the most important sectors of society; personal vehicles, public transportation, planes, and ships are all methods used daily by society. However, this has led to an increase in air pollution levels in urban environments [1]. According to [2] y [3] cars are responsible for 26.3% of total road CO2 emissions, with this sector being heavily reliant on fossil fuels. This dependence has contributed to the growing popularity of electric vehicles (EVs) in recent years. Between 2016 and 2021, the number of battery EVs worldwide increased from 1.2 million to 11.3 million [4]. Various vehicle manufacturers, including Audi, Porsche, Volkswagen, and Hyundai, have been producing and promoting these EVs [5]. Similarly, numerous countries have promoted the adoption of EVs through policies and financial assistance. Therefore, it is expected that the EV penetration will increase the load demand and that the EV charger characteristics will impact power networks. Some of the previously examined concerns include voltage variation, power system inefficiencies, rising peak demand, overloads, and harmonic distortions. [6].

Many authors have studied the impacts of EVs on power grids. For example, the authors in [7] have studied power losses, voltage stability and reliability indices as well economic losses in distribution networks considering various levels of EV penetration. However, the authors solely concentrate on the placement of charging stations to mitigate the impacts mentioned above. In [8], the authors conducted a sensitivity analysis using Monte Carlo simulation to assess the level of EV penetration, charger types, driving habits, electric vehicle types, grid configuration, EV locations, and load duration curves. Despite presenting a comprehensive analysis, they do not consider the voltage levels in the network or suggest improvement strategies for the aforementioned aspects. Conversely, in [9], a study was proposed to analyze the impact of EVs using two electricity price components: the grid charge for the low voltage grid and electricity generation costs. Moreover, the authors evaluate these impacts considering the penetration of EVs as controlled and uncontrolled loads. Despite its novelty, the study falls short in proposing strategies to mitigate the power grid impacts caused by EVs. In their work, Rahman et al. [10] conducted a comprehensive review and impact analysis of integrating projected EV charging loads in low-voltage distribution systems. They examined the voltage profile in these grids with higher EV penetration levels and evaluated the impact of EV charging on load curves in these systems. The authors also discussed various strategies aimed at optimizing grid performance with EV charging loads, including peak load management in load curves, increased penetration of renewable energy, and the provision of ancillary services by EVs to enhance grid stability. Despite analyzing the voltage profile at the distribution system nodes, a critical element in the operation of these systems, the authors did not address strategies such as transformer taps or the optimal location of reactive compensation.

Several methods or studies have been introduced to evaluate the aforementioned impacts of EVs on power systems [7, 8, 10]. Specifically, these studies model the penetration of EVs using hypotheses through mathematical methods to evaluate the adverse effects of these technological elements within distribution networks. These modeling approaches can be classified into three primary categories: deterministic, data-driven and uncertainty-based [11]. In the first group, authors have proposed the use of measurement-based load modeling approaches to estimate the load model for electric vehicle fast-charging stations [12]. Essentially, the authors utilize a ZIP-based methodology to model the penetration of EVs into AC distribution grids. The second category involves machine learning methods such as k-Nearest Neighbors [13], linear regression [14], and random forest [15] to model the interaction between EVs and power systems. Data-driven methods primarily handle large datasets to model realistic EV charging behaviors. The third category encompasses methodologies that address the random behaviors of EV users. This includes the use of various probability distributions (such as Gaussian [16], Weibull [17], or lognormal [18] distributions), stochastic processes [19], and Monte Carlo simulation-based approaches [8, 20]. All three approaches offer innovative modeling methodologies for assessing the impacts of EVs on distribution networks. However, data-driven and uncertainty-based methods require substantial data for conclusive modeling of EV penetration and are computationally intensive. Therefore, polynomial-based load models (ZIP-based methodologies) may be an appealing alternative for analyzing the impact of EVs on active distribution networks.

Another important element in the analysis of the penetration of EVs in power systems is the type of charger, which is little contemplated within the studies that evaluate the impact of EVs within these power grids. EV chargers primarily consist of power electronic converters, which can exhibit different behaviors compared to traditional loads in a power system [21]. There are three established methods for charging EV batteries: battery exchange, conductive charging, and inductive charging [2, 22]. Conductive charging involves directly connecting the vehicle to the power system using a charger. Inductive charging, on the other hand, uses magnetic fields to transfer power through the air gap between the coil in the ground and the coil in the vehicle [23]. The third method, battery exchange or battery swapping, entails replacing the discharged battery with a charged one [24]. This article focuses solely on conductive charging.

The increase in the adoption of electric vehicles poses significant challenges for charging infrastructure and the electrical grid. Reference [25] highlights the need for a greater number of charging stations to meet the growing demand for electric vehicles and underscores the importance of strategic planning for their location and availability. Furthermore, references [26] and [27] emphasize the importance of upgrading the electrical grid to efficiently manage the charging of electric vehicles and minimize their impact on the grid. These upgrades may include the implementation of energy management technologies and the improvement of electrical distribution infrastructure. Addressing

these infrastructure challenges comprehensively in a study on the adoption of electric vehicles could significantly improve understanding of the infrastructure requirements needed for a successful transition to electric mobility [26]. Integrating considerations for additional charging stations and upgrades to the electrical grid in a comprehensive study would enhance its completeness and help identify the best strategies to address these challenges [27].
This paper discusses the effects of EVs on active distribution networks, focusing on voltage profiles and conductor loadability as analytical elements. It also proposes improvement strategies to address these impacts. To achieve this, a ZIP load modeling approach was used to represent EV charging stations, building on the methodology outlined in [28]. It is worth noting that ZIP load models are suitable for both static and dynamic studies. The paper considers two types of charging stations within this modeling framework. AC and DC fast charging stations were considered. Only these charging stations are analyzed because they prove to have a more significant impact on a power system [29]. These EV charging stations were implemented on an active distribution system that includes wind and solar generation, where the EV penetration was increased gradually until the limit was reached. This analysis was done by connecting 5 EV stations at different EV charging station capacities: one station was considered as a DC Super-fast charging station (>50 kW per vehicle), two stations were DC fast charging stations (50kW per vehicle) and the last two were AC fast charging stations (each at 7.4 kW per vehicle). Once the limit of the system was reached, solutions were provided in order to stabilize it to acceptable conditions. Specifically, manual and intelligent managements of resources through capacitor banks and transformer taps were contemplated as solutions, showing that the optimal solution using intelligent management is the most economical strategy.

This paper is organized as follows. Section 2 presents the materials and methods used to analyze and improve the impact of EVs in an active distribution network. Additionally, the network to be used and where the EV charging stations were located are shown. On the other hand, Section 3 presents the results and their discussion of the penetration of EVs in the contemplated network. Finally, conclusions and future work are presented in section 4.

2. Materials & Methods

2.1 Materials

2.1.1 Charging electric vehicles

As mentioned previously, there are three conductive charging methods [22]; however, the fundamental concept involves using EV chargers, which convert alternating current from the grid into direct current through power converters [30]. There are two types of converters used for these vehicles: onboard and offboard converters. The onboard EV charger, as the name implies, is integrated into the vehicle. The AC/DC converter in this setup is limited by the vehicle's size, resulting in a slower conversion rate. In contrast, the offboard EV charger performs AC/DC conversion outside the vehicle, delivering DC directly to the EV battery. Because these converters are not constrained by the vehicle's dimensions, the efficiency is higher, reducing the charging time for the batteries [31]. As mentioned earlier, there are three charging methods:

- Level 1 or AC trickling charging
- Level 2 or AC fast charging
- Level 3 or DC fast charging

Level 1 and 2 charging utilize the onboard charger, while Level 3 charging employs the offboard charger. Level 1 charging, which utilizes the onboard charger, is the only method that does not require additional installation; the EV is directly connected to the existing household installation [32]. Typically rated up to 3 kW, the charging time can range from 11 to 20 hours depending on the battery type and its current state of charge. Similar to Level 1, Level 2 charging also uses the onboard charger but requires special installation, usually in residential or work areas, and is typically rated between 7 kW to 22 kW. The charging time for Level 2 is between 3 to 4 hours, depending on the previously mentioned factors. The rated voltage for this type of charging ranges from 208V to 240V. Level 3 charging is the only type that utilizes the offboard EV charger. It requires special installation and is typically not installed in residences due to the high current and voltage requirements, and not all vehicles are equipped with the technology for this charging method. This charger can deliver between 50 kW to 350 kW, depending on the vehicle. Because the AC/DC conversion occurs outside the vehicle, the charging time can vary from 30 to 60 minutes. Level 3 charging has been shown to have a greater impact on the grid, including voltage deviations, issues with system reliability, and power transfer losses [29]. It also increases demand and can shorten the lifetime of transformers.

As said before, in this paper, only levels 2 and 3 were analyzed due to these two having the most effect on an electrical system. In order to analyze the effect of these charging methods this paper used a ZIP load model to represent the EV stations. The analysis was done by connecting five EV charging stations to a 34 feeder displayed in 1. This system is supported by an external grid and is further supported by wind turbines and photovoltaic panels. It consists of 34 bus bars and 32 lines. The nominal voltage for the three-phase bus bars is 24.9 kV, six single-phase branches at a rated voltage of 14.37 kV and one branch at 4.2 kV where photovoltaic panels are connected.

EV station 1 was connected to bus-bar 808 and represents a level 3 DC fast charger with a capacity of 100 kW per vehicle. EV stations 2 and 3 represented level 3 DC fast charging stations with a capacity for 50 kW per vehicle; they were connected at bus-bars 816 and 822, respectively. Stations 4 and 5 are level 2 AC fast charging stations with a capacity of 7.4 kW per vehicle and were connected at bus bars 854 and 862, respectively. The number of vehicles was divided according to the potential of the branch where they were connected. Six cases were studied by increasing the number of vehicles in each station gradually until the limit of the power system was reached. A power flow analysis was done for each case and data was recorded to compare the starting position of the power system. After each case was analyzed, differences and issues were analyzed and presented in graphical form.

EV Stations	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
1(Level 3)	0	300	700	1100	1500	1900
2(Level 3)	50	350	650	950	1250	1500
3(Level 3)	50	350	650	950	1250	1500
4(Level 2)	7.4	7.4	14.8	22.2	29.6	37
5(Level 2)	7.4	7.4	14.8	14.8	14.8	14.8
# vehicles	4	19	37	54	71	88

Table 1 EV penetration represented in kW

In Table 1, there is a clearer view of what each station represents and how many vehicles were connected in each station in each case. Only the active power demand of the vehicles is represented and the reactive power used by the EV chargers is not taken into account. There were seven cases in total, including the starting position, which does not include any EV penetration. In the following chapter, an explanation of the method used to make an accurate representation of the EV stations is provided.

2.1.2 Active Distribution Network Characteristics

In this study, a distribution network proposed by [33] was used, which was modified to introduce distributed generation at nodes 840, 848 and 890 as is shown in Figure 1. Using this network, five charging stations were considered, as described above in Table 1. The grid parameters can be obtained in [33] and the characteristics of the distributed generators are as follows: two wind generators of 859kVA each, and a solar farm of 500kVA.

2.2 Methods

2.2.1 Load modeling

ZIP load modeling was utilized to simulate the characteristics of an EV charging station accurately. These models are defined as mathematical representations of the relationship between power and voltage at a load bus. They are commonly used in power system analysis, planning, and control. Load models are generally categorized into two types: static load models and dynamic load models [34]. The ZIP model can be employed in both static and dynamic studies, representing the relationship between voltage magnitude and power using a polynomial equation that combines constant impedance (Z), current (I), and power (P) components. Only the active power of the EVs is simulated. The mathematical equation for a polynomial load model is presented as follows:

$$P = P_0 \left[p_1 \hat{V}^2 + p_2 \hat{V} + p_3 \right], \qquad (1)$$

where P_0 stands for Active Power when the supply voltage corresponds to 1 p.u; p_1, p_2 and p_3 are model parameters, when the approach to 1, it implies that the load behaves as a constant impedance, constant current or constant power. The independent parameter V is the per unit supply voltage.

The parameters of Equation(1) that models each EV charging station are given in Table 2, and were determined using the least-squares method as mentioned in [21, 34].

Type	p_1	p_2	p_3
AC Fast Charging	0.0034	-0.1199	1.086
DC Fast Charging	0.0620	-0.2199	1.156
DC Super Fast Charging	-0.1326	0.1816	0.951

Table 2 EV charging modeling parameters.

2.2.2 Optimal Capacitor Placement and Tap Adjustment

This section describes the methods used for the intelligent management of tap adjustment and the optimal capacitor placement (OCP). The cases were studied to support the affected component after the EV penetration.

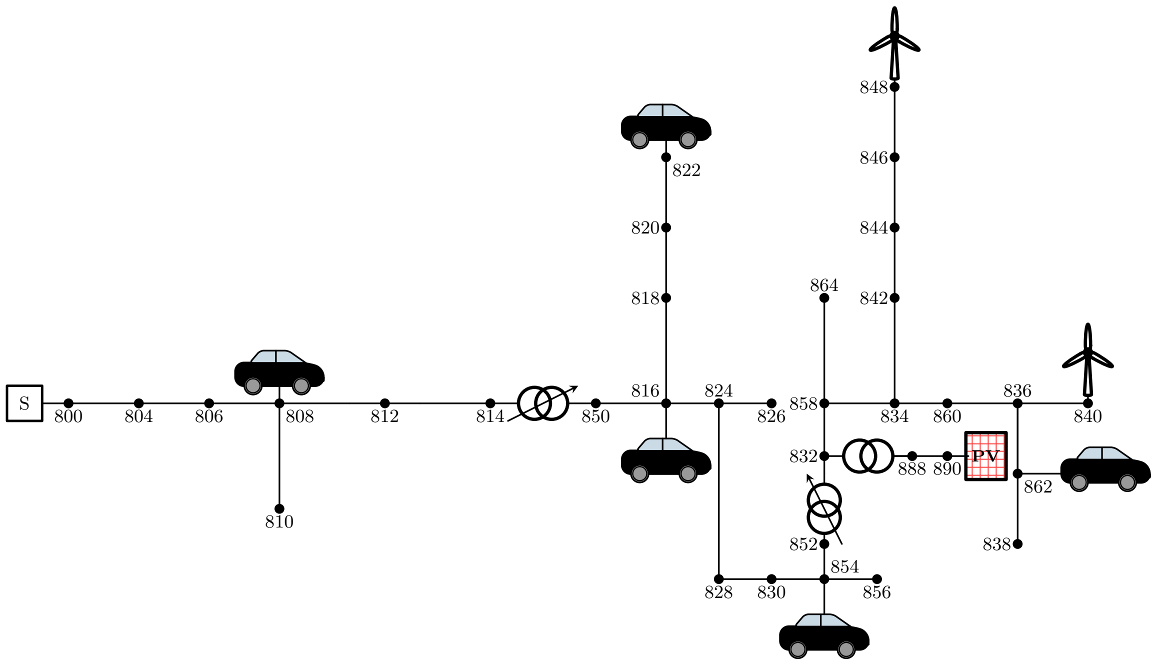

Figure 1 34-bus test active distribution network

- Optimal Capacitor Placement

OCP is an intelligent algorithm viewed as an optimization problem that minimizes the cost of losses subject to voltage constraints in power networks by proposing the installation of new capacitors at terminals along selected feeders. A suggestion for capacitor placement is only made when the total energy loss and voltage constraints are greater than the investment needed for new capacitors. The OCP algorithm minimizes the total annual cost C (see Equation (2)), which is the sum of the costs for grid losses, installed capacitors, and the penalty cost of voltage violations. The OCP objective function is as follows:

$$C = C_{\text{losses}} + \sum_{i=1}^{n}(C_{C_i}) + \sum_{i=1}^{m}(V_{V_i}) \tag{2}$$

Where C_{losses} is the annual cost of grid losses. This is technically the I^2R losses of all the elements in the system. C_{C_i} is the annual cost of the Capacitor entered by the user, and n is the total number of installed capacitors. Lastly, V_{V_i} is the fictitious cost used to penalize a bus-bar voltage deviation, and m is the total number of buses with voltage violations. This method was to study the minimal investment needed in order to correct or support the presented issues.

There are two possible situations for the calculation of V_{V_i}. The first is presented in Equation(3). In this situation, the voltage is within the allowed voltage band but deviates from the nominal voltage of 1 p.u. The second situation can be summarized in two options, as shown in Equation (3). For this situation, the voltage is outside the allowed voltage band; that is, the computation of V_{V_i} is given as,

$$V_{V_i} = \begin{cases} W_1 * |V_i - V_n| & V_{min} \leq V_n \leq V_{max}, \\ W_2 * (V_i - V_{max}) + W_1 * |V_i - V_n| & V_n \geq V_{max}, \\ W_2 * (V_i - V_{min}) + W_1 * |V_i - V_n| & V_n \leq V_{min}, \end{cases} \tag{3}$$

where W_1 and W_2 are the penalty values, V_i is the operation voltages of each bus, V_n is the nominal voltages, V_{max} is the allowed maximum voltage and V_{min} is the allowed minimum voltage.

A second algorithm used was the automatic tap adjustment of the voltage regulator transformers. A tap changer voltage regulator can raise or lower the output voltage depending on the number of taps with which the transformer is built [35]. The output voltage is regulated by altering the number of turns in one winding and thereby changing the turns ratio of the transformer. This is done by enabling the Tap Adjustment function when running a power flow. Automatic tap adjustment is an automatic algorithm that minimizes the sum of the voltage differences on each bus, Δ_V (see Equation (4)), where j is the number of buses. Equation (5) shows the tap position constraint of each transformer, where TAP_i is the position TAP of each transformer, TAP_{max_i} is the maximum position TAP of each transformer and TAP_{min_i} is the minimum position TAP of each transformer.

$$\Delta_V = \sum_{i=1}^{j}(|V_n - V_i|), \tag{4}$$

$$\text{TAP}_{min_i} \leq \text{TAP}_i \leq \text{TAP}_{max_i}. \tag{5}$$

3. Results and Discussion

Six cases were analyzed and later compared to the initial state of the system. The study was conducted to observe the voltage deviation caused by the EVs and the behaviors of the rest of the components. Five EV stations were connected to the system, and the number of vehicles was slowly increased until the limit of the system was reached. In this case, analyzing the effect on transformers was not possible due to the fact that the 34 Feeder only had voltage regulator transformers, which were not affected by the EV penetration. After the study was conducted, two main issues were presented after the implementation of electric vehicles in the system.

3.1 Impact of Electric Vehicle Penetration

The first observation was a significant drop in the rated voltage on the bus bars, and the second change was in the loading of the lines. As the EV penetration increased, the voltage on all bus bars decreased, especially in a single-phase branch. It should be noted that the single-phase branch was close to the voltage deviation limit, which was previous to any EV penetration. The nature of voltage deviation can be explained as inequality in magnitude or phase angles of voltages in three-phase, under-voltages, or over-voltages, and it can occur in both urban and rural distribution networks. When the voltage deviates negatively, it can lead to current unbalance due to low negative impedance in a power system. On the other hand, if the voltage deviation is caused by an increase in voltage levels on components, an excessive flow or phase current may overload the components and shorten their life span. Some effects of voltage deviation are increased losses, heating effects, and the vulnerability of the system, causing an unbalanced system that is not capable of feeding loads properly [36]. As expected, the voltage on most bus bars decreased respectively as the EV penetration increased. In the worst-case scenario (case 6), 9% of the bus bars reached a voltage value below the acceptable voltage range, and 41 % reached the lower limit for voltage deviation. In the grid, 88 vehicles were connected without violating operating limits in the distribution network. An under-voltage deviation can be directly observed in Figure 2 where between bus bars 818 and 822, the voltage reached a value below the accepted range. The voltage is given on the vertical axis and the bus bars on the horizontal axis. The voltage deviation started in the third case, where only two vehicles were connected to EV station 4. It is important to bear in mind that level 2 charging occurs in a residential area, and anyone can have this installation in their houses or businesses. This causes anyone to connect their vehicle at any time (uncontrolled EV charging), causing the voltage on the branch to collapse easily. It only took five vehicles (each charging at 7.4 kW) to cause a voltage drop of 1.1 kV. The branches that present these issues need stabilization of the voltage. After observing the voltage profile in the distribution network, the loading on the lines was analyzed. While there was a change in the loading after each EV penetration in this system, the lines never surpassed 80% of the loading. For the first four cases, the loading dropped below their initial state. For the last two cases, the loading increased, almost reaching 80%. The loading of the line can, therefore, increase or decrease depending on the state of the cable. Increasing the EV penetration was no longer possible due to the voltage drop on the bus bars: even so, the lines never reached an unstable level. This was interpreted to mean that the loading on the lines was not a point of concern, due to the fact that reaching the maximal EV penetration did not surpass the stability of the lines, and even decreased the loading on the lines in some cases. It must be considered that the loading on the lines does increase and that not every transmission system behaves as the 34 FEEDER. Therefore, it is necessary to prepare possible solutions prior to the future increase of EV penetration. Those will be analyzed in the next section.

Additionally, in all these future analyses, it is necessary to take into account that the management of electricity demand, load balancing, and peak demand management are key aspects in the incorporation of electric vehicles because they impact the electrical grid in several ways. Firstly, the increase in electricity demand from electric vehicles can cause peaks in the electrical grid, especially during peak usage hours. These peaks can overload the existing electrical grid, resulting in power outages and other reliability issues if not managed properly [37]. Additionally, load balancing is crucial for evenly distributing the electricity demand throughout the day. Effective load balancing can help avoid overloading certain areas of the electrical grid, optimizing its utilization and reducing the need for costly investments in additional infrastructure [38]. Lastly, peak demand management can help reduce the operating costs of the electrical grid by minimizing the need for additional electricity generation sources during high-demand periods. This can improve the overall efficiency of the electrical grid

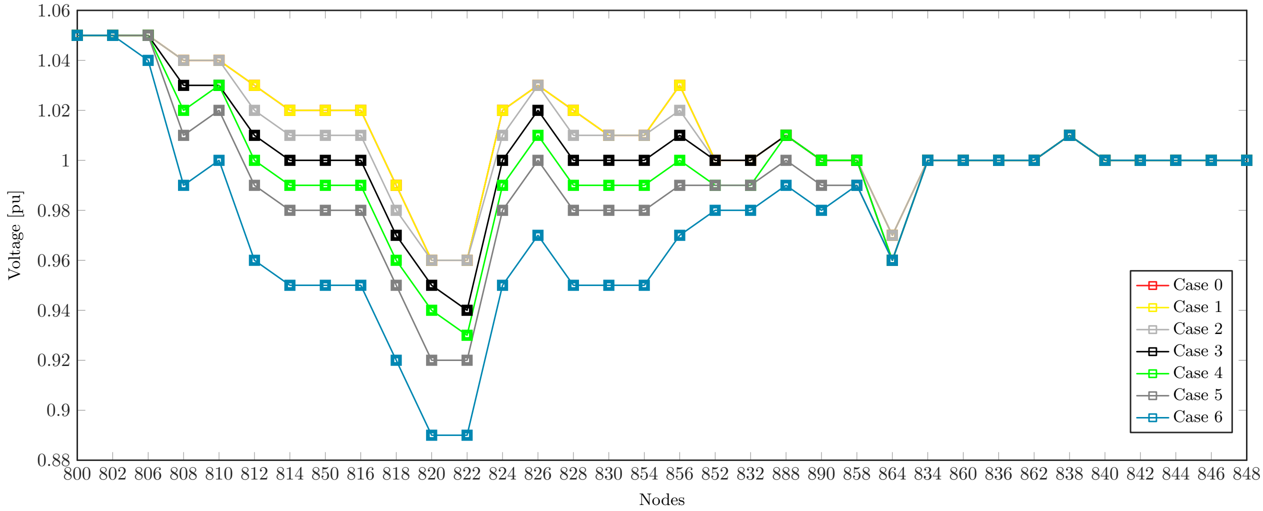

Figure 2 Rated Voltage on buses

and contribute to its long-term stability and reliability [39].

3.2 Active Power Grid Management to reduce the impact of EVs penetration

The primary challenge highlighted in the integration of electric vehicles (EVs) into the grid is the voltage drop experienced on the bus bars. It is crucial to note that this assessment solely considers the active power consumption of EVs, overlooking the reactive power demands of EV chargers. While the proliferation of EVs is inevitable, their connection to the grid must be preceded by comprehensive studies and analysis of the system's condition. The significant voltage drop induced by EVs necessitates proactive measures to stabilize the power system; failure to do so would incur penalties. In this section, we only propose two potential solutions to mitigate voltage deviations and ensure the seamless integration of EVs into the grid, that is,

- Power factor correction with capacitor banks.
- Tap Adjustment of the voltage regulator transformers.

However, there are several solutions available to mitigate voltage drops within certain nodes of the system. These include integrating energy storage technologies and renewable energy sources into the distribution network. For instance, batteries can capture and store excess renewable energy during off-peak periods, which can then be utilized during peak demand or low renewable energy generation periods. This enhances grid flexibility and reliability [40]. Additionally, demand response technologies empower consumers to adjust their electricity usage based on grid conditions and price signals [41]. Advanced grid management solutions, such as predictive analytics and real-time monitoring, enable grid operators to anticipate and address potential disruptions more efficiently [42]. Lastly, vehicle-to-grid (V2G) technologies facilitate bidirectional energy flow between electric vehicles and the grid, effectively turning EVs into mobile energy storage units [43]. These alternatives collectively offer promising strategies to address voltage drops and ensure the smooth integration of electric vehicles into the grid.

3.2.1 Power factor correction with Capacitor Banks

Power factor is the ratio between the active power (kW) and the total reactive power (kVA) consumed by an electrical system. Power factor correction refers to the method used to improve the power factor to near unity. The objective is to carry out the correction in a cost-effective manner. Adding capacitors to the electrical system is the typical approach to power factor correction. These capacitors are used to offset the reactive power requirements of the loads and to boost the voltage. The capacitors in the power factor correction equipment cause a current that leads the voltage, resulting in a leading power factor. Whereas if the capacitors are connected to a system that operates at a nominally lagging power factor, the extent to which the system lags is reduced proportionally. For this investigation, the power factor correction was implemented using four methods.

The first method was connecting one capacitor bank at the most affected bus bars, increasing the value until all bars had an optimal value. In this case, one 5 Mvar capacitor was connected to bus bar 816. 5 Mvar was

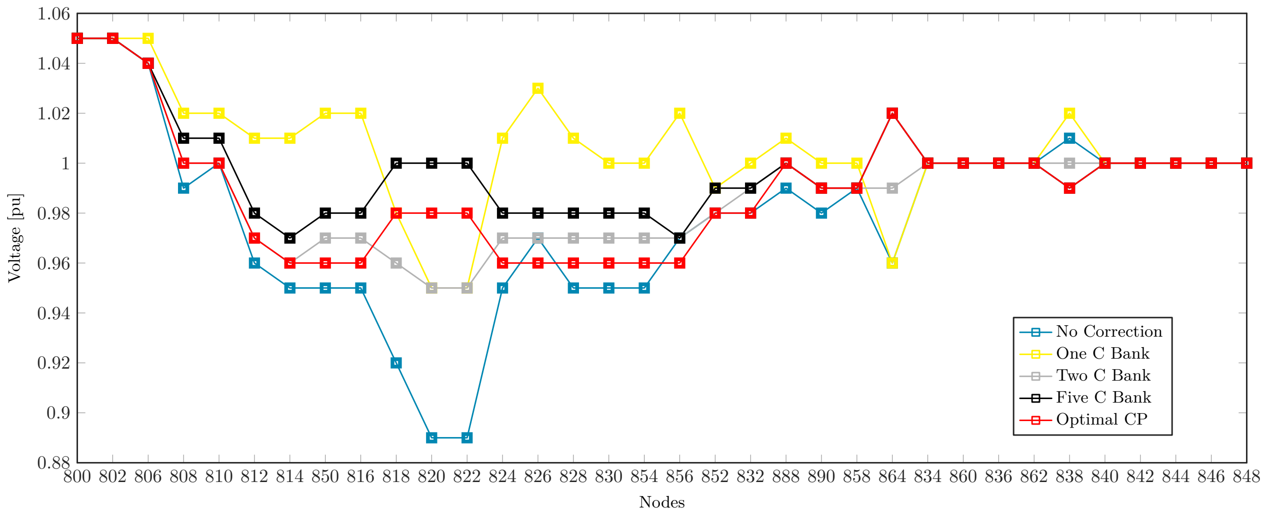

Figure 3 Rated Voltage with different reactive power compensations for case 6.

Method	Reactive power (Mvar)	usd$
1	5	1291266.67
2	0.25 * 5	1224219.80
3	0.45 & 0.25	218388.05

Table 3 Price for the power factor correction.

the limit due to the lines previous to the bus bar 816 being overloaded when the reactive power increased only in one bar. In Figure 3, it can be noted that the yellow line represents the outcome of this method. Some of the bus bars, especially at the beginning of the system, were even reaching the positive voltage deviation range, while the most affected branch barely made the limit for negative voltage deviation. It was concluded that while power factor correction using one capacitor bank at the weakest or most affected bar does help, certain branches will need more support to work in a healthier state. The second method was connecting a small capacitor bank close to every EV station. For this analysis, five capacitors were connected, each with a reactive power capacity of 0.45 Mvar. Those were connected to bus bars: 808, 816, 822. 854 and 862. This is represented in Figure 3 with the black line. As for the previous method, the voltage on all bus bars was supported, but it did not elevate the voltage on the first bus bars as much as in the previous case, while elevating the voltage on the weakest branch to a more healthier state. The third method was connecting two capacitor banks, one on the weakest single-phase branch and one on the most affected three-phase bus bar. These were connected at bus bars 816 with a reactive capacity of 0.45 Mvar and at 822 with 025 Mvar. It is represented in Figure 3 with the grey line. Similar to the previous cases, all the bus bars reached the voltage limit, but as in the first case, the bus bar where EV Station 4 was connected reached the minimum voltage deviation possible; thus, connecting one more vehicle could cause the voltage to drop below the limit again.

With this graph, it was visible that all methods were efficient in raising the rated voltage. The first method (1 capacitor bank) elevates the voltage in all bus bars, but there was a limit to how big the capacitor bank is considering that the lines did reach a dangerous level when the reactive power supply increased. The second method (5 capacitor banks) elevated all bus bar voltages to a more healthy state, where even the weakest branch reached an ideal voltage range. The third method (2 capacitor banks) also elevated all the bus bar voltages, with the weakest branch reaching the minimum acceptable voltage range. With both methods two and three, the reactive power can increase some more without harming the transmission lines. The second aspect that was analyzed was the effect that increasing the reactive power in the system had on the transmission lines. As the reactive power increased, the loading on the lines decreased. The second method of connecting five small capacitor banks shows the lowest line loading, followed by the first method connecting one big capacitor and the last two capacitor, respectively. An explanation for this could be that as the voltage increases, the current that flows through the line decreases. Even so, all methods lowered the line loading in comparison to the original case. While, in this case, this was not necessarily a priority for other systems where the lines do reach an unhealthy state, this could be a method used to release pressure on the lines. Another aspect to consider is the economic investment needed for each method. In Table 3, prices for each method is given. With the help of online electrical equipment seller Larson Electronic, an approximate cost for all methods was calculated. With this table, it can be concluded that the two-capacitor bank connection is the least expensive method and achieves the desired result while increasing the voltage on the weakest branch to a much more healthier state. After connecting the capacitors manually to reach an acceptable voltage range on every bus bar, one more method was tested: the four method. This method used the algorithm shown in section 2.2.2 called Optimal Capacitor Placement (OCP). OCP is an algorithm that automatically reduces the expense of losses in a distribution network by suggesting the installation of new capacitors at specific points on chosen feeders. The input data includes the type and size of the capacitor. This algorithm takes into account the annual cost of the capacitors and suggests the installation of new capacitors only if the cost is justified by the energy savings and voltage improvements that they provide. The capacitor specifications remain the same as those used in previous scenarios. The algorithm proposed to connect only one single-phase capacitor (0.45 Mvar) to EV station 4 (Busbar 854), where the voltage lowered below an acceptable voltage range. Before optimization, the power losses due to voltage violations costed 2049784.81 USD due to power losses. After optimization, 122109.07 USD were saved using one capacitor connected to the weakest branch at the point where the EV station was connected. The result can be seen in Table 4. After connecting this capacitor with an investment of 43788.90 USD, all the bus bars reached an acceptable voltage range, being the less expensive method in comparison to the previously mentioned. Further, increasing the amount of capacitors was not possible because the price of the capacitors was more significant than the costs due to the energy losses and voltage constraint.

Costs	Power losses $	Capacitor $	Total
Before Opt.	12049784.81	-	2049784.81
After Opt.	1927675.73	43788.90	1971464.63
Saved Costs	122109.07	-	78320.17

Table 4 Results for Optimal Capacitor placement.

3.2.2 Tap adjustment of the voltage regulator transformers.

A second inexpensive method to raise the voltage was using a Step-Up/Down AC voltage regulator using a transformer with Tap changer possibility. FEEDER 34 had 6 voltage regulator transformers, three connected in parallel between bus bars 814-850 and three equally connected between 852-832. A tap changer voltage regulator can raise or lower the output voltage depending on the number of taps with which the transformer is built [35]. The output voltage is regulated by altering the number of turns in one winding and thereby changing the turns ratio of the transformer. The results for this are shown in Figure 4. As in the previous examples, the tap adjustment was only implemented in case 6. If the tap changer transformers are already installed, this method is free of cost. With this tap adjustment, all bus bars reach an acceptable range, with voltages on bus bars 820 and 822 going from 12.8 kV to 13.70 kV and from 0.89 to 0.95 in per unit values. The only disadvantage is that this method has a limit; therefore, if this is reached, another method to support the voltage will be necessary. This can become a problem once the EV penetration increases, which causes the voltage drop to become a problem again. It is recommended to prepare for a situation where adjusting the taps is not enough by, for example, using both the tap adjustment and a power factor correction when needed. It can be concluded that using the tap changer transformer elevates the voltage to a certain point, and for this case, it was enough to regulate the voltage on all bus bars.
Tap adjustment can be adjusted both manually as done prior or by selecting the Automatic Tap Adjust of Transformers possibility when executing a Load Flow Calculation. The number of taps and the additional voltage per tap depended on the specifications of the chosen or available transformers. The power factor correction method was also used to improve network voltage conditions. These two methods are used to regulate the voltage to a voltage level between 95% and 105% of the ideal voltage. Before these adjustments, the limit of the system was 88 vehicles, 19 charging on level 3 Super Fast DC charging stations, 62 between two DC Fast charging stations, and 7 between two AC fast charging stations. After these adjustments, the grid supported 97 vehicles, 20 charging on level 3 Super Fast DC charging stations, 68 between two DC Fast charging stations, and 9 between two AC fast charging stations.

4. Conclusion

In this paper, we demonstrated the utilization of ZIP load models to effectively simulate electric vehicle stations within DigSILENT, enabling the analysis of their influence on the electrical grid. Two primary impacts emerge as the number of EVs in the grid increases. Firstly, the voltage on bus bars decreases, with some dropping to unacceptable levels. Notably, the weakest branch, linked to a single-phase branch hosting an EV station, saw a significant drop from 0.96 to 0.89 rated voltage. This loss is more apparent when comparing in kV, with a decrease from 13.80 kV to 12.80 kV in the worst-case scenario, attributed to

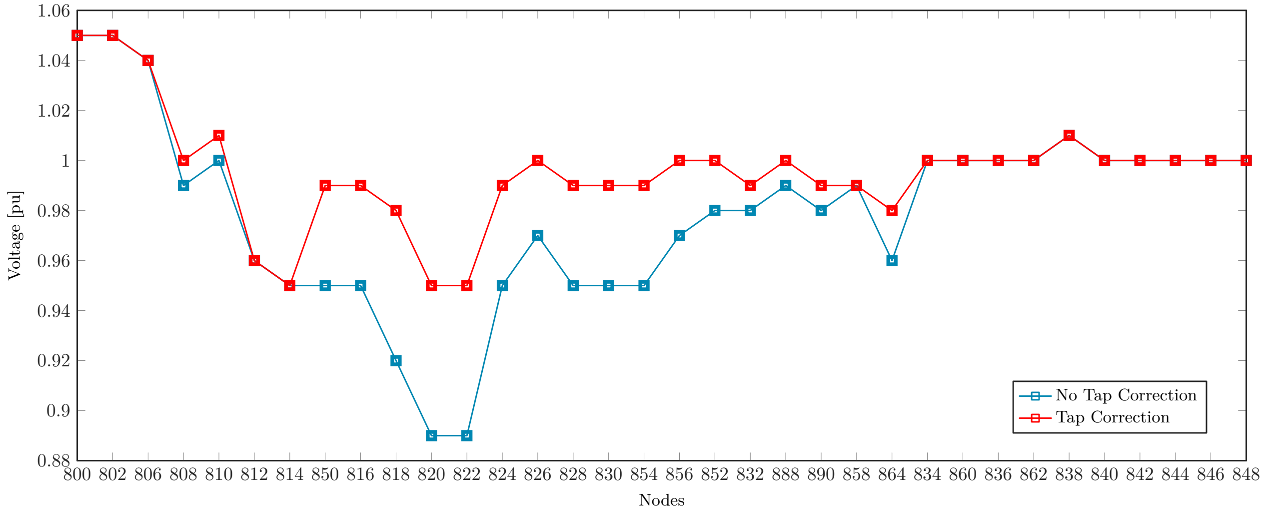

Figure 4 Rated Voltage with Tap correction

just 5 vehicles charging at 7.4 kW each. Secondly, the line loading increases with higher EV penetration, although the line never reached an unstable state even under worst-case conditions. To address unstable voltage levels, two solutions were tested. The first involved power factor correction using capacitor banks, tested across four approaches. The second solution was adjusting the tap changer of voltage regulator transformers already installed in the feeder used for analysis. Both techniques successfully raised voltage levels throughout the system while decreasing line loading. This paper highlights the impact of EV charging, particularly at levels 2 and 3, on both voltage and line loading. Near EV stations, voltage drops were observed, with some reaching unacceptable levels even with few vehicles connected. For instance, just 5 vehicles charging at level 2 caused a total voltage drop of 1 kV, posing significant destabilization to the distribution system. Despite this, the loading on the lines remained within reasonable limits, showcasing the manageable impact of EV penetration on line loading in the feeder. As future works, we recommend carrying out within the optimization problem to improve the voltage profiles, and to incorporate associated challenges with deploying EV charging infrastructure in urban areas. For example, it is necessary to propose smart charging algorithms that optimize the utilization of limited space by intelligently scheduling charging sessions based on factors such as electricity demand, grid capacity, and user preferences.

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7. Author contributions

C. D. Z. R. - S. D. S. Z. Conceived and designed the analysis. G. R. Collected the data. C. D. Z. R. - S. D. S. Z. - G. R. Contributed data or analysis tools. G. R. Performed the analysis. C. D. Z. R. - S. D. S. Z. - G. R. Wrote the paper.

8. Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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