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Impact of Electric Vehicles in a Grid-to-Vehicle Mode on Voltage Stability

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Abstract — **With a rapid development and a massive deployment of electric vehicles, the power system is facing many challenges regarding power quality and voltage stability. This paper deals with the impact of electric vehicle in grid-to-vehicle mode depending on different EV penetration levels and point of connection on static voltage stability impact of a real low-voltage distribution network. Based on nine variations created, results showed that connecting vehicles closer to the beginning of the feeders creates a smaller voltage drop, therefore more vehicles can be connected. However, going farther from the feeder causes voltage to go below 0.9 p.u. and eventually leads to instability.**

Keywords—electric vehicles, grid-to vehicle, static voltage stability.

1. Introduction

Power system stability can be defined as the ability of the system to remain in an equilibrium state under normal operating conditions and to regain that equilibrium state after being subjected to a physical disturbance [1]. According to [2] power system stability is defined as a term applied to alternating – current electric power systems, denoting a condition in which the various synchronous machines of the system remain in synchronism, or „in step“, with each other. On the opposite side, instability is defined as a condition involving loss of synchronism or falling „out of step” [2]. However, instability can also occur without the loss of synchronism [1].

Electric vehicles (EVs) are considered to be a promising solution both for reducing air pollution and also as being introduced as a new form of distributed generation when working in a vehicle-to-grid (V2G) mode. Many countries are offering incentives and by doing so, motivating EV owners to charge their vehicles in scheduled times, to help flatten the daily peaks [3].

In the stability calculations, the behavior of the system under the effect of a transient disorder is of interest. Equipment reacts as a system response to a disorder. In each situation, only part of the protection reacts, therefore, the problem must be simplified and the key factors for each type of instability must be defined.

In this project, the problem of voltage stability is investigated in a LV distribution network involving 46 buses and 42 loads. According to different penetration levels of (EVs) and point of connection across the network, nine scenarios were modeled and examined for voltage instability.

1.1 Voltage stability

Voltage stability is the ability of the system to maintain acceptable voltage values on all busbars in the system, both in normal operating conditions and after the effects of the disruption. Voltage instability occurs when a disorder, which can be caused by an increase in consumer demand or a change in operating conditions, causes a progressive and uncontrollable voltage drop. The main cause of voltage instability is the inability of the system to respond to reactive power requirements. The core of the problem is usually a decrease in the voltage in the flow of active and reactive power through inductive reactances representing the transmission network [1].

The criterion for voltage stability is that on all busbars in the system, under certain operating conditions, the bus voltage is increasing as injection of reactive power on the same buses is increasing. Therefore, the system is unstable if voltage level is decreasing as reactive power is increasing, at least on one busbar in the system. Voltage stability is a local phenomenon, but its consequences may have a widespread impact.

A voltage collapse is far more complex than voltage instability and according to [4], can be explained as an inability of the power system to supply the reactive power or as an excessive absorption of reactive power by the system itself. It can also be defined as a process in which voltage instability causes very low voltage levels in a substantial part of the system. A local voltage collapse can and will lead to a widespread collapse of the power system [4].

2. Literature review

Electric vehicles have experienced a warm welcome by pollution-aware society. Their non-polluting nature helped them gain popularity and become one of the most sold cars in Norway, according to the Norwegian Road Federation [5]. However, deploying large fleets of electric vehicles impacts the load profile of the network since EVs are introduced as additional loads when being connected for charging [3].

A study in [6] focused on the static voltage stability impact of EV charging stations. A cluster load model equivalent to 20 sets of EV chargers was taken into consideration along with the different probability distributions of state of charge (SOC) of the batteries. The authors concluded that charging stations are most likely to cause voltage instability due to the variableness of power during the charging process.

Research conducted in [7] focused on the static voltage stability of plug-in EVs with respect to different charging methods. The results showed that voltage stability is closely related to the proportion of the constant impedance and the constant power load. Since EVs were considered as constant power load, the less the initial voltage drop percentage, the more EVs will be allowed to access the distribution network.

Authors of [8] investigated the power quality and dynamic stability aspects of vehicle to grid connection of EVs which uses a bidirectional power flow and allows the EVs to give back to the grid if needed. Their conclusion was that charging and discharging state of the PEV does not affect negatively neither the voltage stability nor frequency since they remain within allowed limits.

A study in [9] investigated the impact of high PV penetration in a low-voltage distribution network on voltage stability. In the paper, PV curves were used to analyze the static voltage stability in a test node of an important and possibly critical line. It was shown that the node situated near the end of the network had the weakest PV characteristics due to power loading and the distance from the feeder. However, they concluded that integrating photovoltaic units with 40% penetration level would optimize the voltage stability of that node.

Research conducted in [10] analyzes voltage stability with aid of PV curves on an example of a real transmission network. EVs included in the study were all charged during the daily peak load with a six-hour charge time. Results showed that high levels of EV penetration, with the expected annual increase, leads to unacceptably large voltage variations.

A new method for analyzing the impact of PEVs in distribution networks was proposed in [11]. As in many other papers, this study confirmed that a small number of vehicles does not create stability issues whereas a large fleet of vehicles causes a greater effect on the grid. Charging strategies as the overall conclusion was highlighted in this paper.

A study in [12] investigated an impact of EV charging on voltage variations and unbalance in a real low voltage distribution network. Different scenarios were created to depict several EV penetration levels and load distributions across the network. Results confirmed the work of other papers, showing that point of connection plays an important role to the level of impact of EVs to two analyzed power quality parameters.

An analysis, similar to [9], will be conducted in this paper, using PV curves to determine the critical busbars along the two feeders of the low-voltage distribution network. Section III explains the modeled network and created variations, Section IV draws results and Section V draws conclusions.

3. Methods

3.1 Problem formulation

Electric vehicles in this project are treated as single-phase loads connected to the network, in a grid-to-vehicle (G2V) mode. Because of the increasing number of EV charging stations being integrated to the power system, analysis of their clustering effect and influence on the static voltage stability have become important and necessary. In this project, analysis of an impact of EV charging on voltage stability is performed on a real example of a part of a distribution network.

3.2 P-V Curves

In voltage stability studies, characteristics of interest are the relationships between transmitted power P, receiving end voltage V and reactive power injection Q. P-V and Q-V curves are traditional forms of displaying these relationships. In this project, P-V curves are analyzed. Power-Voltage analysis process includes increasing transfers of power (MW) and monitoring what happens with voltages in the system. This is done by increasing the power system load and, at each increment, power flows are recomputed (P-V curve is non-linear and full power flow solutions are required) until the nose of the PV curve is reached, that is, the maximum transferred power [13]. That point represents the critical voltage because after that, rapid decline of voltage occurs. Therefore, reaching maximum power is highly avoided because operating at or near stability limit risks a large – scale blackout. Power margin between the current operating point and critical voltage is used as voltage stability criterion [14].

3.3 LV Distribution Network Modeling and Variations

In this paper, the analysis was done using the model of 46 – bus LV distribution network, with total of 42 loads distributed along two feeders, modeled in DIgSILENT Power Factory. Modeled network is provided in Appendix 1. Length of the first feeder is 371 m while the length of the second feeder is 253 m. Nine variations were modeled, including: low, medium and high EV penetration levels, at the beginning, in the middle and at the end of the network. List of variations is provided in Table 1. Numbers of EVs included in each variation are presented in Table 2 and Table 3.

Table 1. Network variations (penetration-point of connection)

Network Variations	Case no.
1.1 Low-beginning	1
1.2 Medium-beginning	
1.3 High-beginning	
2.1 Low-middle	2
2.2 Medium-middle	
2.3 High-middle	
3.1 Low-end	3
3.2 Medium-end	
3.3 High-end	

Table 2. Number of EVs in Variations

Variation No.	Network Variations		
	Penetration Level	Number of EVs	Percentage of penetration level
1.1 2.1 3.1	Low	6	≈15%
1.2 2.2 3.2	Medium	12	≈30%

Table 3. Number of EVs in Variations cont'd

Variation No.	Network Variations		
	Penetration Level	**Number of EVs**	**Percentage of penetration level**
1.3 2.3 2.4	High	21	50%

4. Results

4.1 Case 1 - EVs distributed at the beginning

First three variations were modeled so that electric vehicles are placed near the beginning of the two feeders. Each variation had a different penetration level of EVs as explained in Table 1. After the load flow calculation was performed, Transmission Network Toolbox was activated, and PV curves were calculated. To see which busbars stay within the allowed limits and which do not, several busbars were selected from the beginning, middle and end of each of two feeders and included in the resulting PV graph. The obtained graphs for Case 1 variations are presented in Figure 1, Figure 2 and Figure 3, respectively.

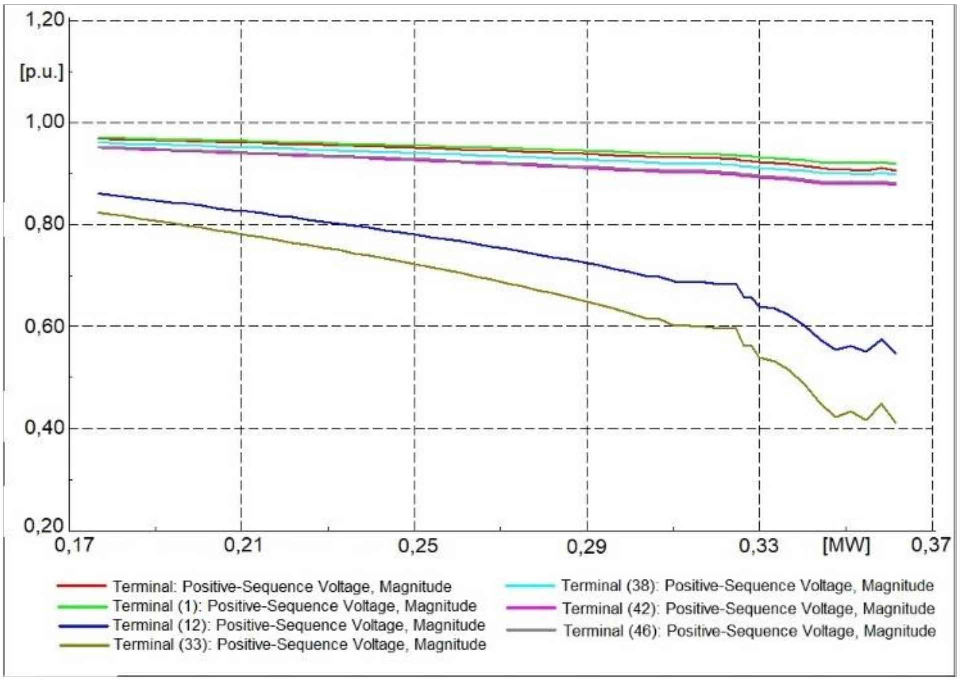


Fig. 1. PV curves for Variation 1.1

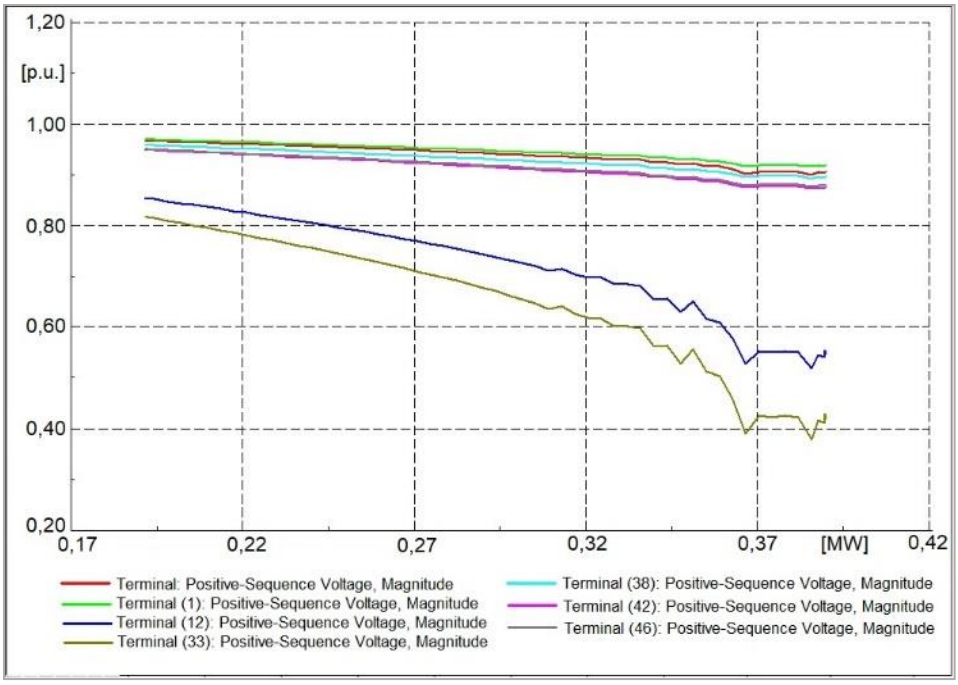


Fig. 2. PV curve for Variation 1.2

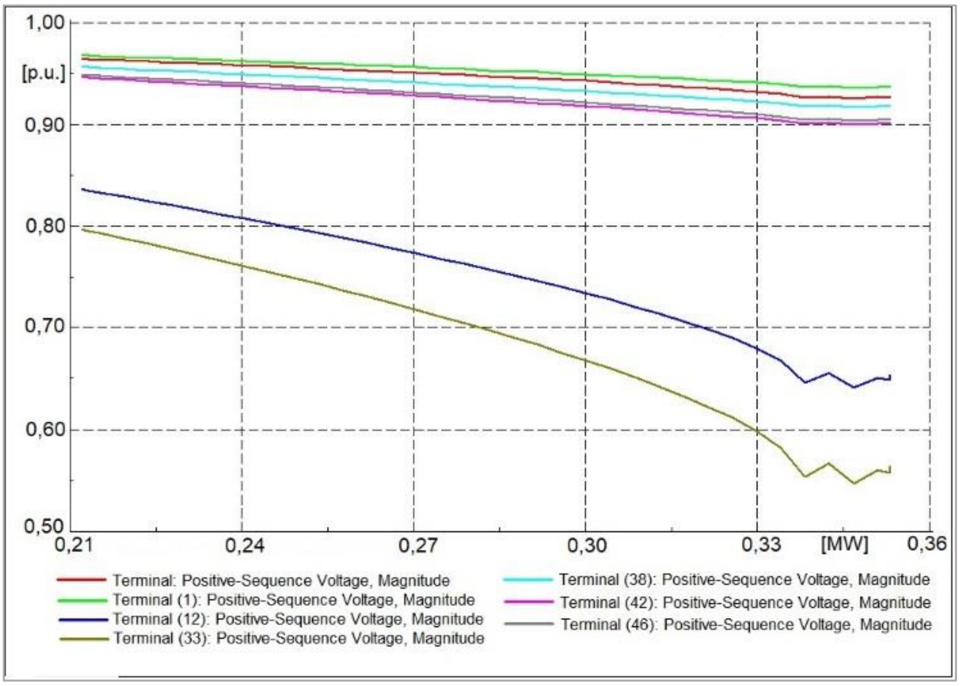


Fig. 3. PV curve for Variation 1.3

All busbars whose PV curves are above the voltage value of 0.9 p.u. are acceptable and stable, while those below 0.9 p.u. are not stable and therefore not acceptable. As presented in the graphs, two busbars, plotted in blue and grey, have values below 0.9, which makes them unstable. These two busbars are from the first feeder, situated in the middle and at the very end of the feeder. All busbars from the second feeder stayed within allowed limits, as well as the busbar from the beginning of the first feeder.

4.2 Case 2 – EVs distributed in the middle

Three variations examined for the impact of EV charging and placement around the middle of the two feeders were 2.1, 2.2 and 2.3 Number of EVs connected to the feeders are with respect to Table 1. Several busbars were selected and included in resulting PV graph, to depict the voltage stability across the two feeders, that is, to show how stable are busbars from the beginning, middle and end of the two feeders. Results for the abovementioned variations are shown in Figure 4, Figure 5 and Figure 6.

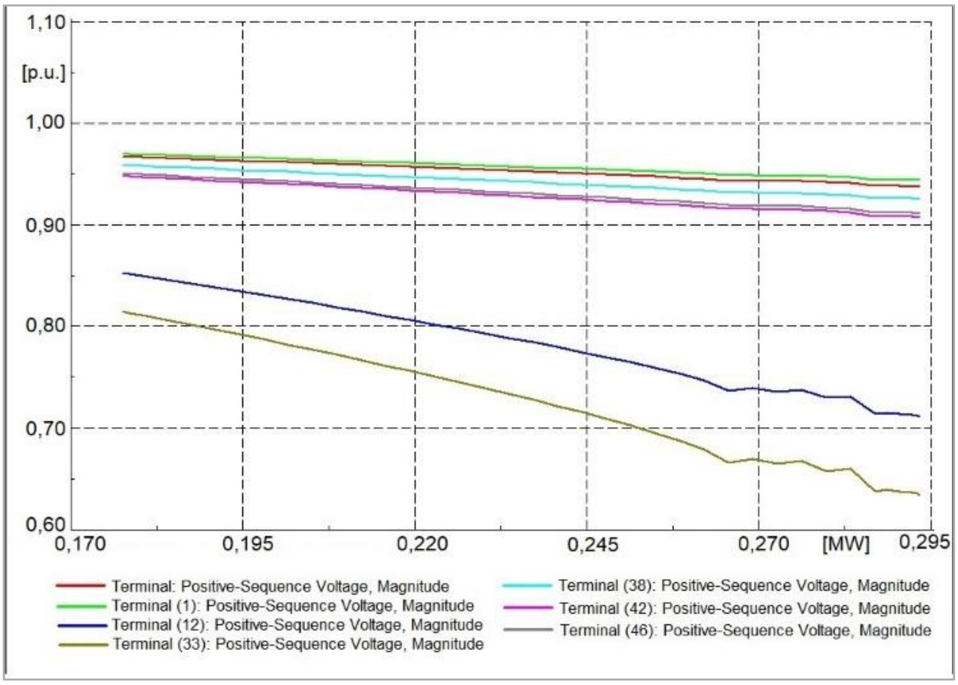


Fig. 4. PV curve for Variation 2.1

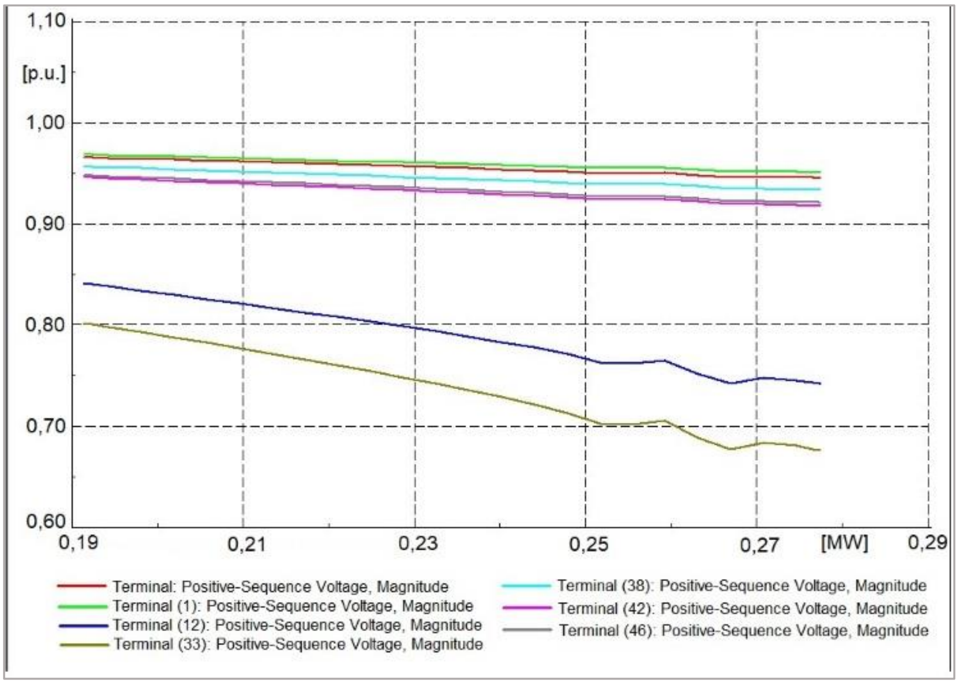


Fig. 5. PV curve for Variation 2.2

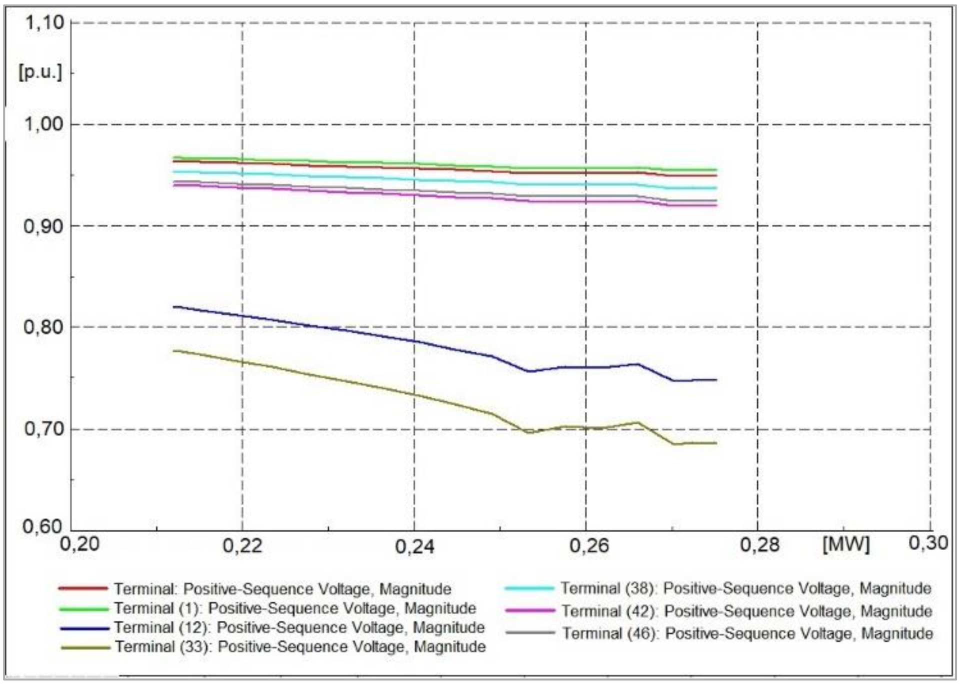


Fig. 6. PV curve for Variation 2.3

According to results obtained from the PV graph, conclusions similar to those in previous variation can be drawn. All busbars from the second feeder and only the busbar from the very beginning of the first feeder stay within allowed limits of stability, that is above 0.9 p.u. value of voltage, shown in the y-axis. Two busbars from the middle and at the end of the first feeder show instability.

4.3 Case 3 – EVs distributed at the end

Last three variations from Figure 2 were modeled to investigate how much EVs connected near the end of the feeders will affect voltage instability of selected busbars across the two feeders. Number of connected vehicles per variation is shown in Table 1. Selected busbars remained the same as those used in the previous six variations. Results obtained are shown in Figure 7, Figure 8 and Figure 9.

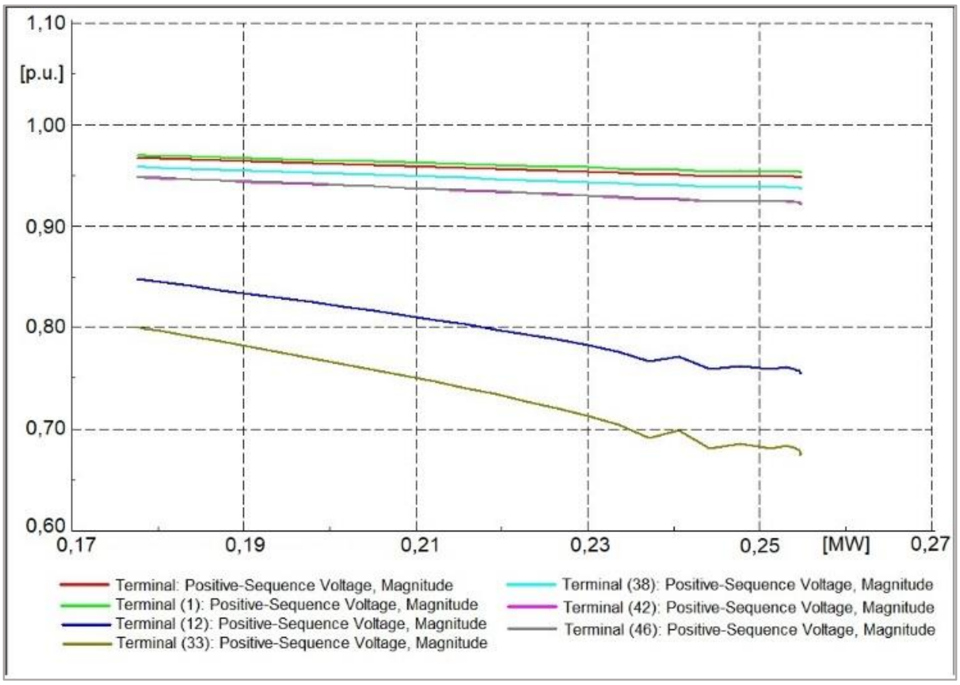


Fig. 7. PV curve for Variation 3.1

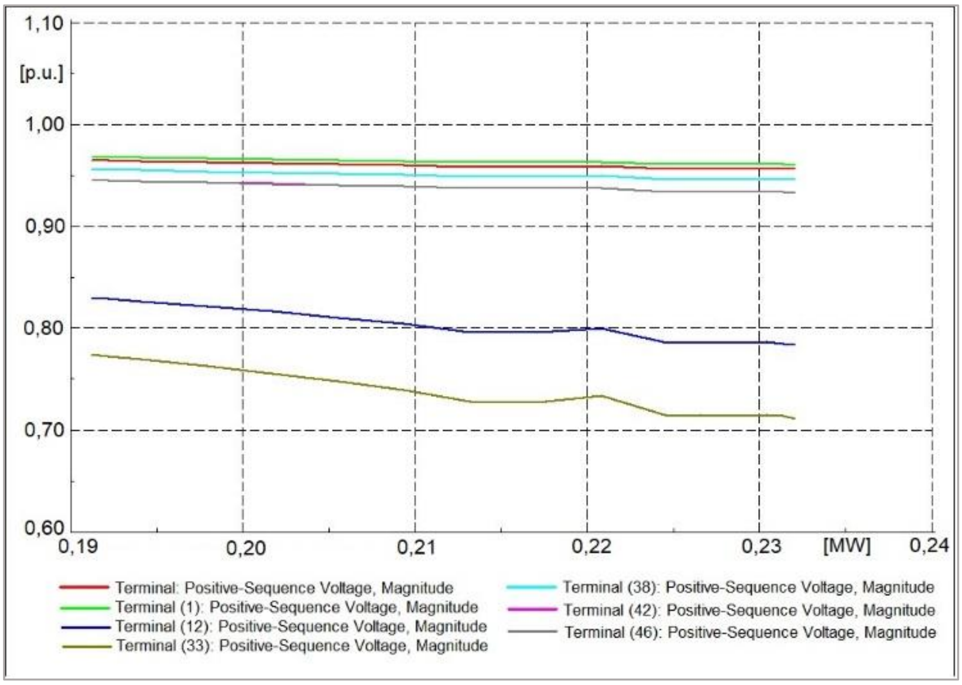


Fig. 8. PV curve for Variation 3.2

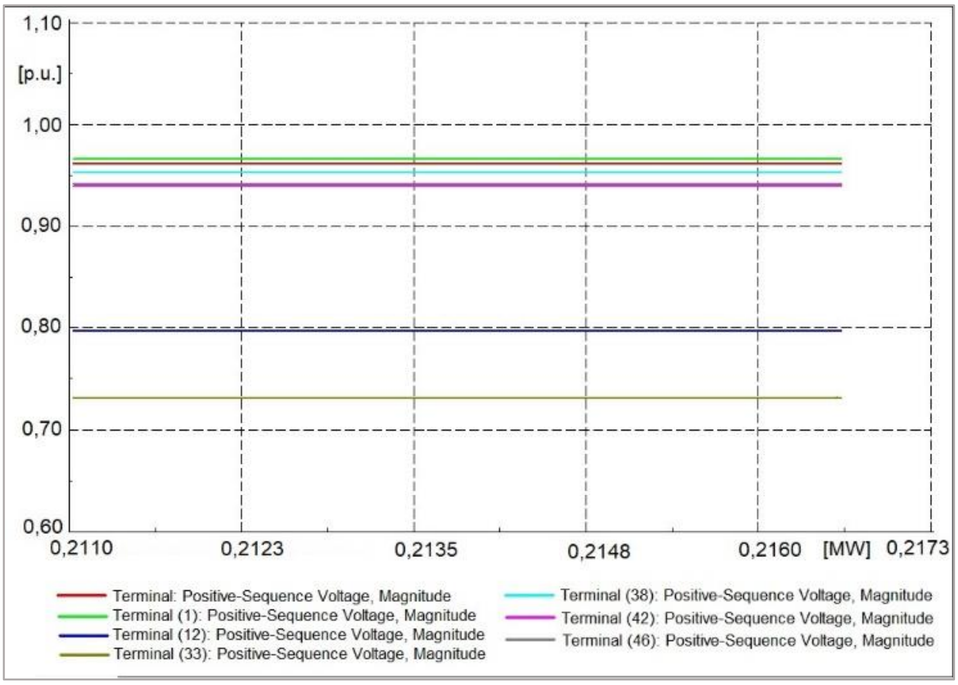


Fig. 9. PV curve for Variation 3.3

Results from the obtained PV graph of the last tested variations show that voltages of the two terminals from the middle and end of the first feeder experience a drop below 0.9 p.u. but gets a more constant value when compared to results of previous variations. All busbars from the second feeder and only one from the very beginning of the first feeder have values greater than 0.9 p.u., making them well within allowed limits of voltage stability.

5. Conclusion

The purpose of this paper was to analyze the impact of different EV penetration and points of connection on voltage stability of a distribution network. Load flow analysis was performed on all nine scenarios followed by a PV curve calculation in Transmission Network Toolbox of DIgSILENT. Then, a static voltage stability analysis was performed using PV curves for a number of selected busbars from the beginning, middle and end of the two feeders. The criterium was that all curves above 0.9 p.u. value of voltage were acceptable, and all below show voltage instability.

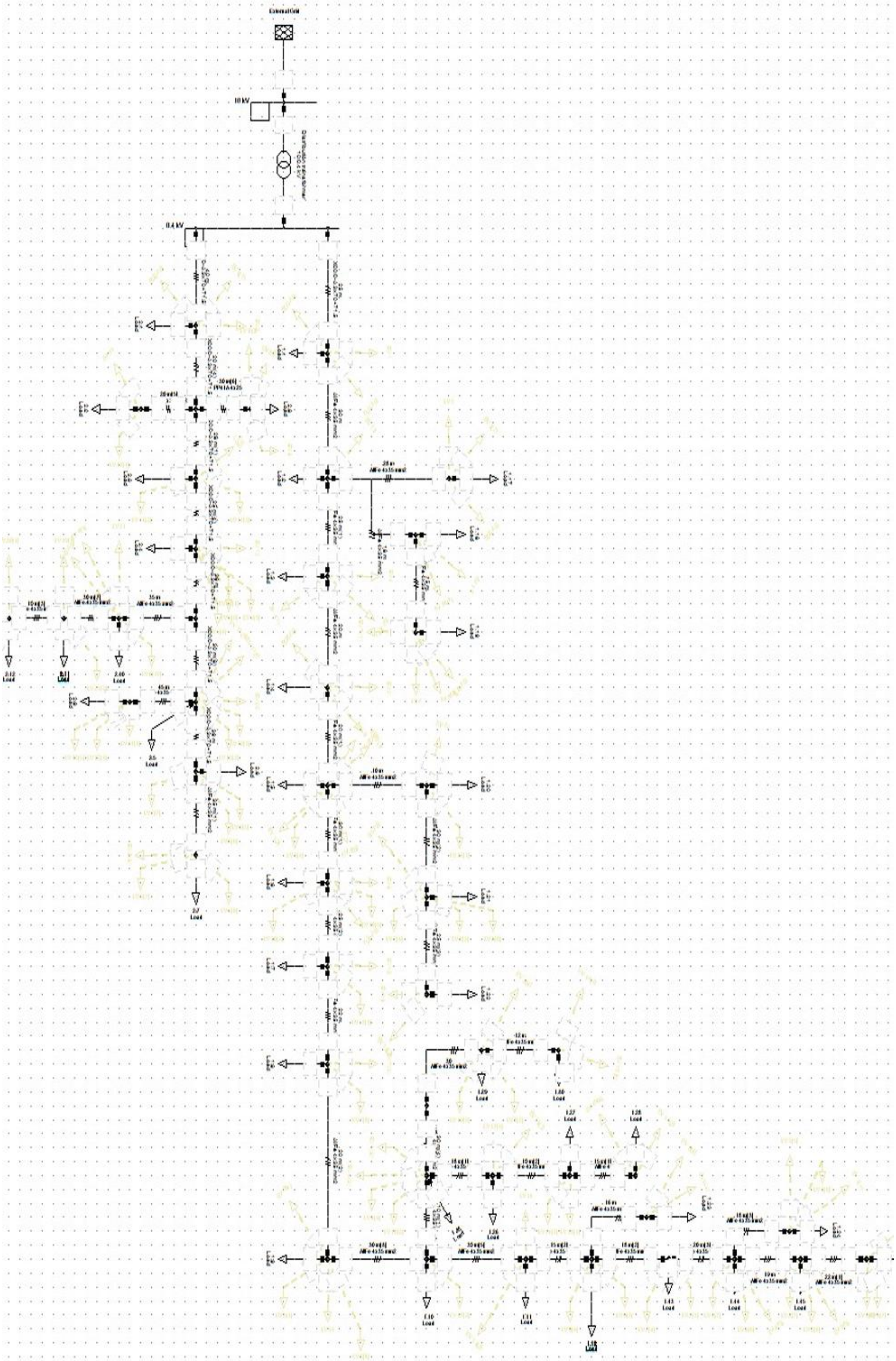
It was found that the length of the feeder, point of connection and level of EV penetration played a crucial part when it comes to voltage stability. All selected busbars from the second feeder remained within allowed limits of voltage values while only one busbar from the beginning of the first feeder was above the limiting value. This was mainly due to the length of the feeder, amount of loading and the distance from the source feeder.

For large fleets of EVs being connected and charged at the same time, voltage stability and power quality becomes of crucial importance. Distribution system operators must pay attention to the impacts of charging on power quality and stability of the distribution system, especially if vehicles are in close range, and situated farther from source.

If no modifications are to be made to increase the network's capacity, then only a limited number of vehiclescan be allowed, with reference to the point of connection. A possible solution could be integration of small distributed generators or implementation of renewables, dispersed along the network to decrease voltage variations and increase power quality, especially near the end of the feeders, where critical nodes are.

Future work might include analyzing and modeling the impact of connection of photovoltaics or small wind generators in terms of distributed generation, which are expected to improve the voltage levels and overall variations.

APPENDIX 1



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