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B&H Electrical Engineering, Volume 16, Issue 2, 2022:37-44
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2022-0016

Review scientific paper

Submitted: November 4, 2022

Accepted: December 18, 2022

ANALYSIS OF UNSYMMETRICAL CUSTOMER AND ELECTRIC VEHICLE CONNECTION ON VOLTAGE PROFILES AND VOLTAGE UNBALANCE - CASE STUDY REAL LOW VOLTAGE DISTRIBUTION NETWORK

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Abstract: In the past couple of years, the integration of electrical vehicles (EV) in the power system has been capturing the attention of many researchers, which has led to this being a frequently analysed topic in scientific papers and seminars. Some of the main parameters related to power quality that are observed, while integrating EVs, are voltage variations and voltage unbalance. The low-voltage rural network, of a small settlement located on the outskirts of Zavidovici, has been modelled for the purpose of this paper. Several cases were considered. As the first base case, an analysis was performed when there were no connected vehicles in the network, then the case with 20% penetration, 35% penetration, and 80% vehicle penetration. Practical analysis was done in DIgSILENT Power Factory software. It has been concluded that electrical vehicles cause a voltage drop in the network, while at the same time causing an increase in voltage unbalances.

Keywords: low voltage network, electrical vehicles, voltage variations, voltage unbalance, EN 50160 standard

INTRODUCTION

In the past few years, more and more people and governments are becoming aware of how much the power systems affect the environment and its pollution, which leads to greater integration of renewable energy sources that are environmentally friendly. The EU aims to have an economy with net-zero greenhouse gas emissions and to be climate-neutral by 2050. To achieve this goal, they motivate end-users to invest and switch to low-carbon technologies.

One of these solutions is the integration of electric vehicles (EVs). They are considered environmentally friendly. Therefore, a very important thing is the fact that EV charging is based on renewable sources. In that case, we will get the desired effect - the reduction of harmful emissions. A typical electric vehicle is equipped with a battery bank that stores energy. The fact that EVs can have various influences on the electricity network, both positive and negative, must be taken into consideration. It depends on the way they are used.

Voltage unbalance can be observed by changes in voltage magnitudes or angles in a three-phase system. It can appear in residential distribution networks including rural distribution systems.

The way this technology is implemented will affect the entire power grid. If consumers have the freedom to charge electric vehicles in an uncontrolled manner, this can cause an increase in the daily maximum load and this automatically affects the level of power losses and the power quality itself. There is also a possibility of overheating of the lines due to insufficient cross-section. In the case of regulated charging of electric vehicles, the impact will be positive in the way that they act as small distributed generators.

In this project, two main parameters are analysed: voltage variation and voltage unbalance. All power quality parameters are categorized according to EN 50160. Voltage variations should not exceed ±10% of the rated voltage Un. On the other hand, the voltage unbalance must be in the range of 0% to 2% of the quotient of the negative and positive voltage sequence component.

This project was done by modelling one low-voltage distribution network feeder of transformer 10/0.4 kV. In this work, 12 different scenarios are analysed with different load distributions among phases and three different levels of electric vehicle penetration (20%, 35%, and 80% for each scenario). Therefore, it will be clearly shown how the analysis of power flow looks like without electric vehicles and with electric vehicles integrated, at different levels of integration.

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Chapter 2 presents the literature review; chapter 3 shows the analysed part of the real low voltage network and chapter 4 contains of information about paper methodology. Finally, all analysis and results about voltage variations and voltage unbalance are in chapter 5 and 6. Last chapters (7, 8 and 9) are the main conclusions, references and biography.

1. LITERATURE REVIEW

The paper [1] systematically analyses a real-world low voltage network and different stages and shares of connected PVs, residential battery storages and EVs to different phases. It is shown that connected systems can significantly increase the voltage unbalance factor and potentially cause negative impact on the equipment and the power system as a whole. According to [2] uneven electric vehicles charging scenario can cause significant voltage unbalance that goes beyond its allowed limit of 2 %. In the paper [3] author presents some power quality parameters and possible negative impacts on the network. Also, there are few ways of controlling and effective solutions for better power quality. Similar analysis was finished in a paper [4] where author practically analyses and concludes on all of the possible impacts that different penetration levels of EVs in the network can have. The paper [5] shows the analysis of all effects that installation of fixed compensation to the low voltage network can have, including some important conclusion. Through papers [6] and [7] it is presented whole theory connected to power quality, parameters that are important to power quality and all other things related to the topic that are base for further analysis and conclusions. A study in [8] uses the Monte Carlo method for analysing the charging impact of EVs on a low-voltage UK Generic Distribution Network. The results they get show that distributed generation can help normalize the voltage profile even for high penetration of EVs. Through analysis in paper [9] it is presented that by controlling the charging rate, high penetration of EVs would be possible, with little or no upgrade needed, for the existing distribution network. The power quality parameters are defined with EN 50160 norm and it is the main topic of paper [10]. The study [11] presents simulation results of the integration of EVs and PHEVs in terms of power quality, and experimental results of a smart charger, which was specially developed for EV charging and that allows mitigation of the power quality degradation. According to paper [12] there is a way to predict voltage unbalance in the network in the presence of plug-in electric vehicles. Method that is used for this is analysed in noted paper and it is called Monte Carlo-based stochastic analysis. Through paper [13] it is presented a probabilistic methodology that can be used for evaluation of the power quality impact (harmonics and voltage unbalance levels) in low voltage residential networks with increased simultaneous integration of nonlinear loads and electric vehicles.

The contribution of this paper is that it analyses the impact of single-phase customer and EV connection on an example of one real LV network, and not on some test network. In accordance with the aforementioned literature, this paper analyses the impact of connecting electric vehicles to the low-voltage network and confirms the results obtained in some of those works ([4], [8] and [9]).

2. ANALYZED PART OF ONE REAL LOW-VOLTAGE DISTRIBUTION NETWORK

All analyses in the paper were done on a real low-voltage (LV) network of an example of a village in the municipality of Zavidovići. The transformer supplying the area is 10/0.4 kV with a power of 0.16MVA. This is a rural area and therefore very suitable for voltage unbalance analysis. The modelled part of the network includes 56 buses and 34 loads. The georeferenced scheme of the analysed part of the network is given in Figure 1.

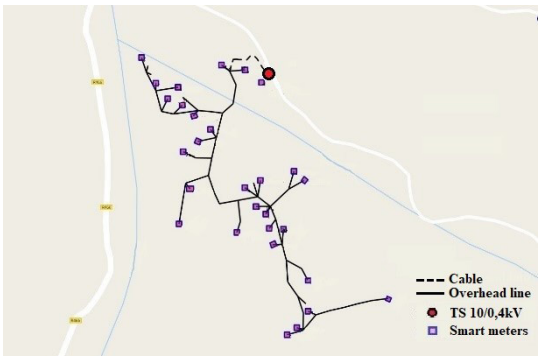

Figure 1: Georeferenced scheme of the analysed part of the network

The data used in the modelling part are readings from smart and control meters. Readings were taken for every fifteen minutes from the control meter at transformer substation 10/0.4 kV. Smart meters for household consumers enable a record of daily energy consumption for each consumer. The percentage of energy, and therefore power, for each consumer, was obtained by dividing their daily energy consumption by the total energy of the transformer. This leads to the calculation of consumer power. It is calculated by multiplying the percentage of energy for each consumer with the peak power of the transformer. The total power of the modelled loads in the analysed LV feeder is 21.54 kW. The network model from DIgSILENT Power Factory software is presented in the Figure 2.

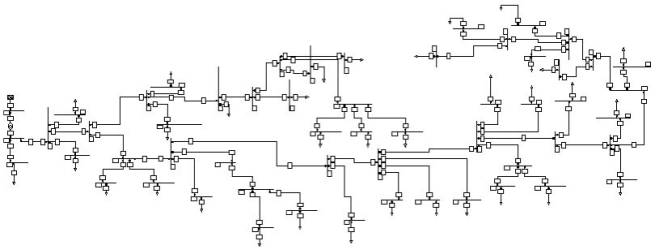

Figure 2: Model of the network from DIgSILENT Power Factory software

B&H Electrical Engineering, Volume 16, Issue 2, 2022:37-44
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2022-0016

3. METHODOLOGY

All of the analyses in the paper were obtained in DIgSILENT Power Factory software. The analysis is divided into several scenarios, among which one part of the scenario includes the analysis without electric vehicles, while in the other there is the integration of vehicles at different penetration levels. The first part consists of scenarios without electric vehicles. Division for these scenarios is based on the distribution of loads per phase and that is the following:

1. Distribution of 33% 33% 33%
2. Distribution of 40% 30% 30%
3. Distribution of 50% 25% 25%.

The second part of the analysis is with including of electric vehicles with different penetration levels. The integration of electric vehicles was made by taking into account the phase distribution of customer loads in the network. The percentages of EVs analysed (20%, 35 %, 80%) are taken from the total number of loads, and e. g. 20% of EV penetration means that 20% of customers in the network have one EV. If, for example, a power distribution is 33%-33%-33% and 20% EVs is taken into consideration, in that case the specified percentage of vehicles will be divided in such a way that the same number of vehicles is connected to each phase. The same is in the case with the 40%-30%-30% power distribution, only in that case 40% of the vehicles is connected to one of the phases, and 30% to the other two. The same working principle applies when the power distribution is 50%-25%-25%. The following table presents different penetration levels of EVs.

Table I: Penetration of EVs per scenario

Penetration of EVs per scenario		
First scenario (33% - 33% - 33%)	**Second scenario (40% - 30% - 30%)**	**Third scenario (50% - 25% - 25%)**
20% (6) EVs	20% (6) EVs	20% (6) EVs
35% EVs (12) EVs	35% EVs (12) EVs	35% EVs (12) EVs
80%EVs (28) EVs	80%EVs (28) EVs	80%EVs (28) EVs

All electric vehicles in this study were modelled as loads with a power of 2.3 kW, due to the fact that all chargers are single phase chargers. An unbalanced three-phase load flow is applied to the model, and also one of the goals was to obtain results for these voltage variations. According to EN 50160, voltage variations should not exceed ±10% of the nominal voltage and voltage unbalance should be within the range of 0% to 2%. In the used software there is an option to export results needed to calculate the unbalance factor. These data are u1, which is positive–sequence voltage and u2, which is negative-sequence voltage. In total, unbalance factor is defined according to EN50160 as a ratio between u2 and u1 (ku=u2/u1).

4. RESULTS AND DISCUSSIONS

In this part, all the cases analysed in the paper are presented, including graphs as results based on the analysis of power flows from the used software.

4.1. Scenarios without electric vehicles

As already mentioned, the first cases are cases without connecting electric vehicles to the grid. These cases form the basis for further analysis.

4.1.1. First scenario (33%- 33%- 33%)

The first scenario analysed without electric vehicles is the scenario where power is divided at 33% per phase.
Figure 3 shows the voltage drop when the power is divided by 33% per phase. It is clearly shown that the voltages of all phases have a small drop, but they are all symmetrical. Also, this voltage drop does not have a significant effect on the network because the voltages are within the allowed voltage limit of ±10% Un.

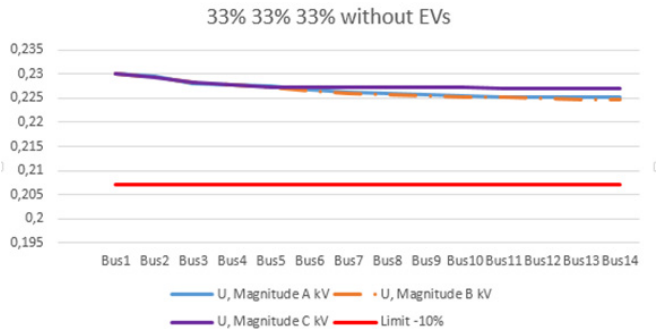

Figure 3: Voltage drop in the case with power distribution at 33% per phase

4.1.2. Second scenario (40% - 30% - 30%)

The second scenario is a scenario without electric vehicles in which the power is divided 40% -30%- 30% by phases.

In Figure 4, phase B has the largest voltage drop due to the power distribution of 40%- 30%- 30% by phase, where 40% of the total power is on phase B. Thus, phases A and C are almost symmetrical because they have the same power distribution per phase (30%). However, this distribution still does not have a significant impact on the modelled network because the voltage does not exceed the limit of ±10% Un.

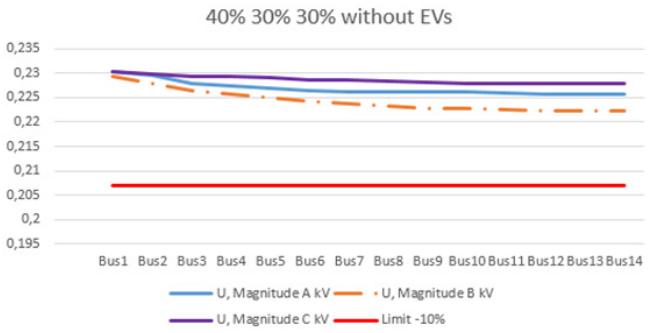

Figure 4: Voltage drop with a distribution of 40% -30%- 30% for each phase

4.1.3. Third scenario (50%- 25% -25%)

The third scenario is a scenario without electric vehicles in which the power is divided 50%- 25%- 25% by phases.

Phase B in Figure 5 has the largest voltage drop because 50% of the power is concentrated in that phase. Phases A and C are symmetrical due to the fact that they have the same power distribution per phase (25%).

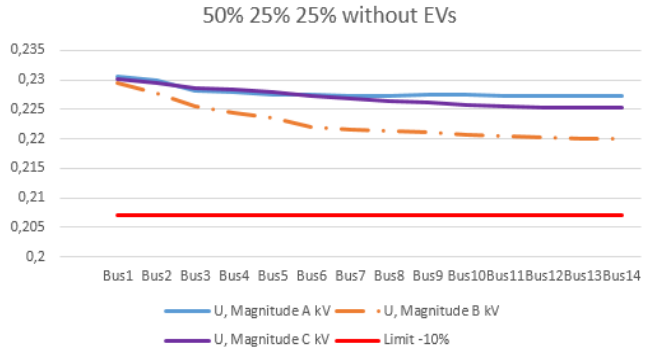

Figure 5: Voltage drop with a distribution of 50%- 25%- 25% for each phase

4.2. Scenarios with electric vehicles

In this part of the work, it will be shown how different levels of integration of electric vehicles affect the main parameters of the quality of electricity in the low-voltage network.

4.2.1. Scenario 33%- 33%- 33% with 20% EV

In this scenario, 6 electric vehicles are included in the network. According to Figure 6, it is clear that phase B is the most loaded and therefore this phase has the highest voltage drop (216 V). The network consists of 16 three-phase and 18 single-phase consumers. However, all charging is single phase. The final distribution is: 2 vehicles on each phase (Table II).

Table II: Distribution of electric vehicles by phase for the case of 20% integration

Number of electric vehicles per phases		
Phase A	Phase B	Phase C
2	2	2

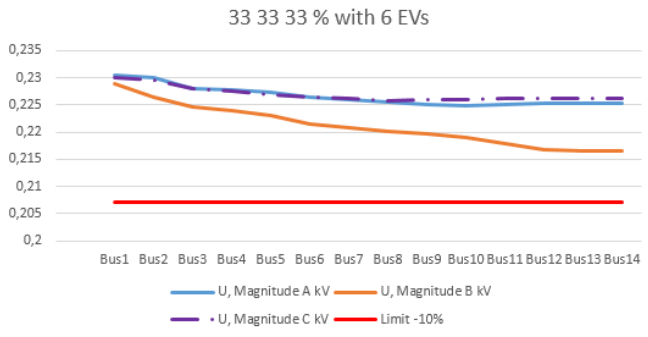

Figure 6: Voltage drop with 33% power distribution per phase with 20% EV integration

4.2.2. Scenario 33%- 33% -33% with 35% EV

According to this scenario where 12 EVs are connected to the grid, it is presented in Figure 7 that the voltage drop is more visible. These 12 vehicles are placed in such a way that 4 vehicles are on each phase (Table III). In this case, even though the integration of the vehicle is now 35%, it still does not exceed the lower voltage limit and therefore does not have too much of a negative impact on unbalance and voltage variations. The largest voltage drop is in phase A and it drops to the value of 216 V.

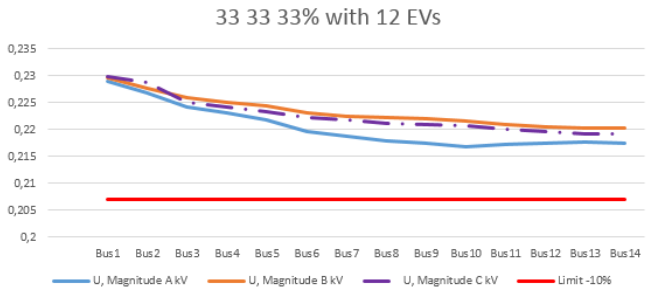

Figure 7: Voltage drop with 33% power distribution per phase with 35% EV integration

Table III: Distribution of electric vehicles by stages for the case of 20% integration

Number of electric vehicles per phases		
Phase A	Phase B	Phase C
4	4	4

4.2.3. Scenario 33%- 33% -33% with 80% EV

In this scenario, the number of electric vehicles in the network is very high (Table IV) and therefore, looking at Figure 8, it is clear that the largest number of EVs is connected to phase A. Phases B and C have a slightly lower voltage drop due to the smaller number of connected electric vehicles. This scenario with 80% vehicle integration exceeds the lower voltage limit and thus negatively affects the overall state of the network. The voltage on phase A is now 197 V.

B&H Electrical Engineering, Volume 16, Issue 2, 2022:37-44
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2022-0016

Table IV. Distribution of electric vehicles by phase for the case of 80% integration

Number of electric vehicles per phases		
Phase A	Phase B	Phase C
10	9	9

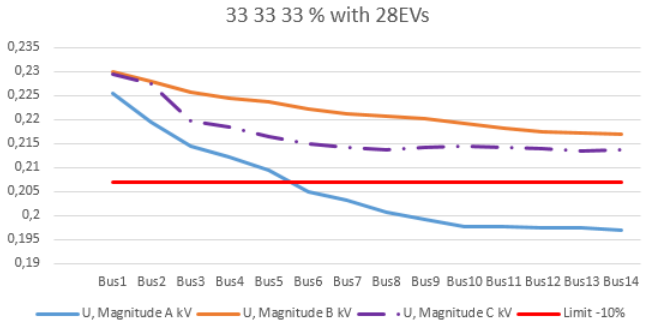

Figure 8: Voltage drop with 33% power distribution per phase with 80% EV integration

4.2.4. Scenario 40% -30%- 30% with 20% EV

In this scenario, 6 electric vehicles are included in the network. According to Figure 9 the biggest voltage drop is in the phase B (223 V). This means that the largest number of EVs is in phase B while the smallest number of vehicles is in the phase A (Table V).

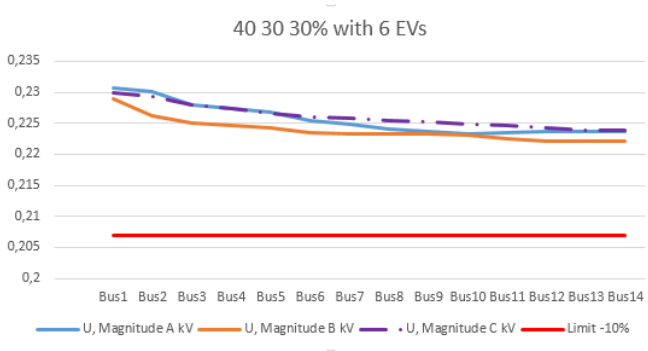

Figure 9: Voltage drop with 40% 30% 30% power distribution per phase with 20% EV integration

Table V: Distribution of electric vehicles by stages for the case of 20% integration

Number of electric vehicles per phases		
Phase A	Phase B	Phase C
1	3	2

4.2.5 Scenario 40% -30% -30% with 35% EV integration

Within this scenario it is presented the case with 35% EV integration into the network. According to the obtained Figure 10, it is visible that with the increase in the number of connected vehicles, the voltage drop also increases. The case with 35% vehicle integration has a voltage drop that does not exceed the lower limit. Also, it can be seen that the largest number of vehicles is connected to phase A (Table VI) and because of that the largest voltage drop is in the phase A where the voltage value is 214 V.

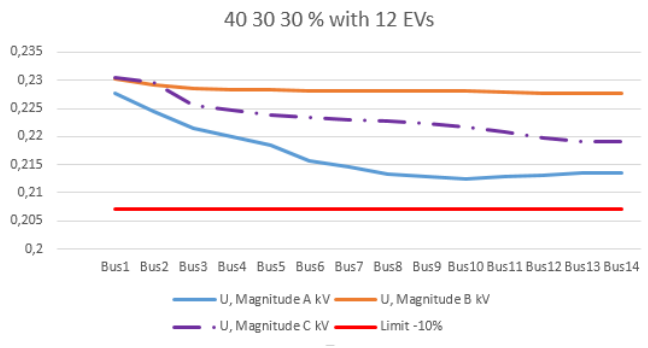

Figure 10: Voltage drop with 40% 30% 30% power distribution per phase with 35% EV integration

Table VI: Distribution of electric vehicles by phase for the case of integration of 35%

Number of electric vehicles per phases		
Phase A	Phase B	Phase C
6	3	3

4.2.6. Scenario 40% -30%- 30% with 80% EV integration

This case shows how 80% EV in the network influence on the voltage. In this scenario power distribution is 40% - 30% - 30%. There is significant voltage drop of 192 V that breaks the lower voltage limit (Figure 11). Distribution of EVs per phase is presented in the Table VII.

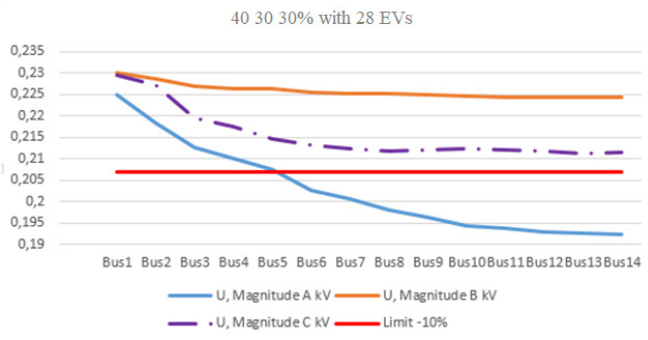

Figure 11: Voltage drop with 40% 30% 30% power distribution per phase with 80% EV integration

Table VII: Distribution of electric vehicles by phase for the case of integration 80%

Number of electric vehicles per phases		
Phase A	Phase B	Phase C
12	8	8

4.2.7. Scenario 50%-25%-25% with 20% EV integration

The sixth scenario refers to power distribution of 50% -25%-25% by phases with 20% integration of electric vehicles. The vehicles are arranged in such a way that 4 vehicles are in phase B, while phases A and C have one vehicle each connected and therefore these two phases are symmetrical (Table VIII). Voltage drop of phase A is the largest and voltage value in this phase is 220 V (Figure 12).

Table VIII: Distribution of electric vehicles by phase for the case of integration 20%

Number of electric vehicles per phases		
Phase A	Phase B	Phase C
1	4	1

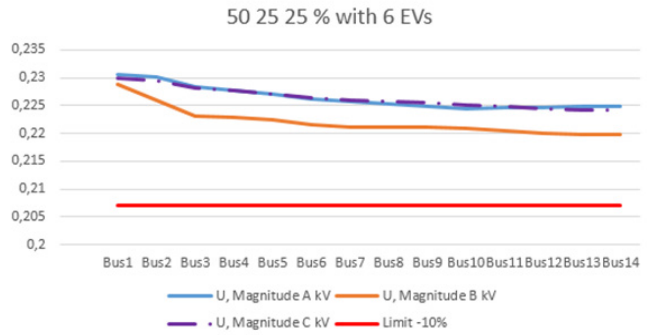

Figure 12: Voltage drops with 50% 25% 25% power distribution per phase with 20% EV integration

4.2.8 Scenario 50% 25% 25% with 35% EV integration

As in all previous scenarios, when it comes to vehicle integration of 35%, the voltage drop is quite noticeable 215 V (Figure 13). In this case, 5 vehicles are in phase A, 3 vehicles are in phase C, and 3 vehicles in phase B (Table IX).

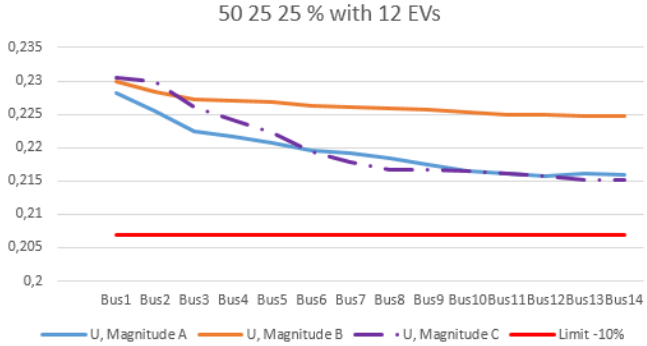

Figure 13: Voltage drop with 50% 25% 25% power distribution per phase with 35% EV integration

Table IX: Distribution of electric vehicles by phase for the case of integration 35%

Number of electric vehicles per phases		
Phase A	Phase B	Phase C
5	3	3

From the Figure 13 there can be seen voltage drop but it is still in the acceptable borders that should not have negative influence on the network condition.

4.2.9. Scenario 50%- 25%- 25% with 80% EV integration

In the case with 80% vehicle integration, the voltage crosses the lower limit and drops to a value of 189 V (Figure 14). It can be seen that phase A has the largest voltage drop, which indicates that the majority of vehicles are connected to it.

In this case vehicles are distributed as follows: 14 vehicles are in phase A, 7 vehicles are in phase C and 7 vehicles are connected to phase B (Table X).

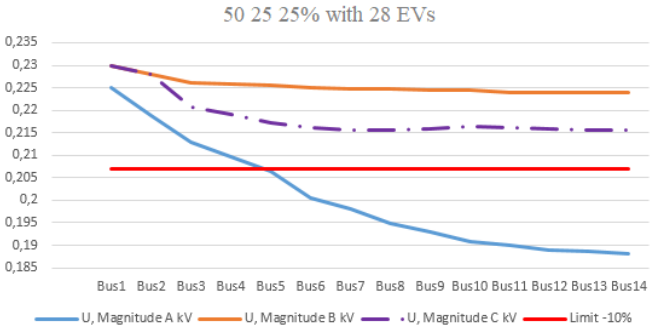

Figure 14: Voltage drop with 50% 25% 25% power distribution per phase with 80% EV integration

Table X: Distribution of electric vehicles by phase for the case of integration 80%

Number of electric vehicles per phases		
Phase A	Phase B	Phase C
14	7	7

5. VOLTAGE UNBALANCE

After analysing all the mentioned cases, and its positive and negative sequence symmetrical components of the voltage, the calculation of voltage unbalance was made, which is another parameter that is affected by the integration of electric vehicles into the network. Looking at Figure 15 - Figure 17, in each of the cases of electricity distribution, it is evident that the integration of electric vehicles leads to an increase in voltage unbalance.

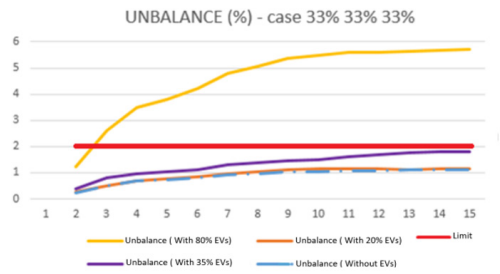

Figure 15: Voltage unbalance for the case of distribution at 33% per each phase with different levels of EV integration

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ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2022-0016

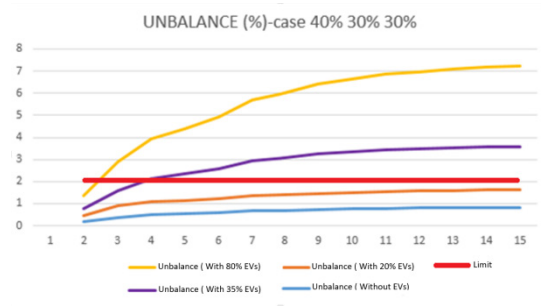

Figure 16: Voltage unbalance for the case of distribution at 40% 30% 30% per phase with different EV integration levels

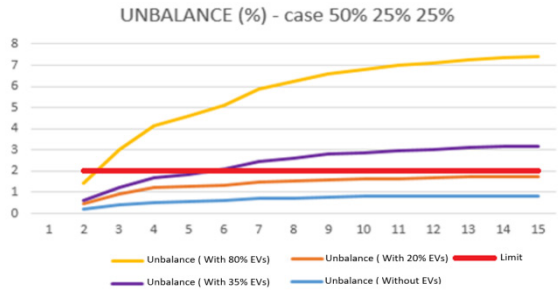

Figure 17: Voltage unbalance for the case of distribution 50% 25% 25% per phase with different levels of EV integration

It can be seen from the previous pictures that in cases where the vehicles are not connected or when the vehicle penetration is up to 20%, then the unbalance factor is in the range of 0% to 2%, which is the allowed ratio. On the other hand, when a large number of vehicles are connected to the network, the voltage unbalance increases and reaches very large deviations from the normal state of the network. In the case where the power distribution is 40%-30%-30% and 50%- 25%- 25% by phases, and when there is 35% and 80% EVs in the network, the unbalance reaches the highest values. These values exceed limit of 2% that is allowed by EN 50160 Standard.

6. CONCLUSION

The main goal of this work was to show the impact that the connection of electric vehicles can have on the network in different scenarios. Several scenarios were modelled and analysed, and after all the analysis, it was concluded that electric vehicles have a significant impact on the parameters of power quality - voltage variations and voltage unbalance. All scenarios where electric vehicles were added experienced a voltage drop. However, only the case where there are 80% of connected vehicles led to exceeding the lower voltage limit of -10% Un. When it comes to voltage unbalance, in the case of adding more vehicles, it will grow and reach the limits from standard EN 50160. In the case where there is already a certain imbalance of the customer loads present in the network before EV integration, if electric vehicles were connected to such a network, it would only lead to an additional increase in the unbalance, which would then reduce the capacity of the network.

Also, what is shown through this work is the fact that in addition to the degree of vehicle integration, which affects the state of the network, the method of connection has a great influence, that is, the fact of which phase how many vehicles will be connected. In order to reduce the voltage drop during the integration of EVs into the network, it is necessary to monitor which terminal and which phase the vehicles are connected to. Also, what can be done in order to prevent or reduce the negative impact is the phase balance optimization, which gives a solution which consumers and EV need to be re-phased, i.e. connected to another phase. This optimization represents an analysis before the actual connection and it could predict the actual state of the network. Another thing that can affect the improvement of the situation in the network when EVs are connected is the introduction of a night mode of vehicle charging when the network is much less loaded. It is also possible to improve the paper by analysing the influence of large number of EVs on overloading of the transformer. However, in this study case not all LV feeders in the LV network have been analysed and therefore the specified effect cannot be analysed in this model.

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