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# ANALYSIS OF THE IMPACT OF UNBALANCED CONNECTION OF CONSUMERS AND ELECTRIC VEHICLES ON VOLTAGE VARIATION AND VOLTAGE UNBALANCE

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**Abstract:** Voltage unbalance and voltage variations are common issues in low voltage distribution networks caused by unbalanced connection of single-phase loads and electric vehicles (EVs) among phases. Part of the real low voltage grid in Bosnia and Herzegovina, in the vicinity of the town of Tešanj, was analysed. The impact on single-phase consumer and single-phase EVs penetration was analysed. The grid was modelled using DIgSILENT PowerFactory software. Three cases of the distribution of consumers by phases were analysed. Each of the three cases is expanded with four scenarios depending on the penetration of EV into the grid. Results showed that none of the twelve scenarios remained within the permissible limits of -10% voltage variation limit of EN 50160 for phase A. Seven of the twelve scenarios exceeded voltage unbalance limits +2% according to EN 50160.

**Keywords:** electric vehicle, voltage unbalance, consumer, voltage, phase

## INTRODUCTION

The transformation of power systems from passive, conventional ones with one-way flow of energy into a dynamic system based on distributed production and two-way flow of energy has caused great interest. The implementation of electric vehicles (EVs) also affects the power grid. If customers were allowed to charge their vehicles when they wanted, mostly in the afternoon after work, there would be a large impact of electric vehicles due to uncontrolled charging. This would have a negative impact on the daily peak load. Additionally, due to single-phase charging of EVs, unbalance in the grid can be harmful and unregulated charging of EVs would increase energy losses, overload equipment, and degrade power quality. Power quality is an important aspect of power system operation because it directly affects efficiency, reliability, and safety. The quality of electricity is defined as follows: “Electricity characteristics at a certain power system location that are equivalent to a set of technical reference parameters” according to standard 61000-4-30 [3]. EN 50160 classifies power quality characteristics as either a continuous phenomenon or a single event. The EN 50160 standard states that the following characteristics are processed continuously: grid frequency, supply voltage fluctuations, quick voltage changes, supply voltage unbalance, harmonic voltages, interharmonic voltages, and grid signal voltages. Voltage events include supply voltage interruptions, supply voltage drops and transient overvoltage [2]. In this project, two power quality parameters were analysed: variation and unbalance of the supply voltage. According to the standard EN 50160, variations in voltage shouldn’t be more than ±10% of the nominal voltage Un. According to the same standard , the values of the negative component of the symmetrical phase voltage of the supply must be between 0% and 2% of the positive component of the symmetrical phase voltage [2]. Most equipment, especially motors, can handle a voltage unbalance of less than 2%; however, if it is larger than 2%, the motor and transformer will overheat. Voltage unbalance represents a condition in a three-phase system in which the effective value of the line voltage (fundamental component) or the phase angle between the three phases is not equal. Faulty capacitor banks, single-phase equipment, and an unbalanced single-phase load in a three-phase system are the sources of the voltage unbalance [4, 5]. This study examines 12 scenarios combining different consumer and EVs distributions on a model of a real distributed power system.

This paper is organised as follows. After the Introduction, Chapter literature review gives detailed overview of used books, articles, and regulations. Chapter Analysis of a real low voltage distribution grid describes the part of the grid that was used for analysis. Chapter Methodology presents used software, description of how obtained data is used and distribution of consumers and EVs. Chapter Results and discussion presents obtained results for each of the scenarios. The results are presented in the form of tables and graphs. The last chapter presents the Conclusions.

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## 1. LITERATURE REVIEW

The primary document addressing requirements from the supplier's perspective is standard EN 50160[1], which characterises voltage parameters of electrical energy in public distribution systems. This standard gives limits for every power quality parameter.

In [2], the authors concluded that EV charging affects power quality parameters, voltage variations and voltage unbalances. In every situation, there was a voltage drop that emerged as EV penetration grew and was followed by a rise in unbalance. The findings also demonstrated that, even with the same number of cars connected to each phase, the impending voltage fluctuation is significantly influenced by the cars distance from the transformer.

According to [3] the monitoring, analysis, and enhancement of bus voltage to sustain a sinusoidal waveform at rated voltage and frequency is known as power quality. The primary factors contributing to disruptions and issues with energy quality include unforeseen circumstances, the electricity provider, consumers, and producers. Power quality events are categorized into seven groups according to IEEE standards using a number of additional terms, including transient, short-term, long-term, voltage unbalance, waveform distortion, voltage fluctuation (including flicker), and power frequency variation.

"Any power problem that results in variations in voltage, current, or frequency that affect the correct or complete operation of utility or end-user equipment" is the revised definition of power quality proposed by the authors in [4]. The authors outlined the potential issues that may arise from variations in power quality as well as the solutions for these issues.

As per reference [5], the voltage unbalance will exceed the EN 50160 standard limitations when more vehicles are added. Before EV integration, there would already be some load unbalance among customers on the grid; adding EVs would just make the unbalance worse and lower network capacity.

According to the findings in [6], an excessive number of EVs charging continuously causes an EV capacity to be reached. Variations in EV charging over the day are anticipated, and they may make it simple for prohibitions to be broken. The ideal course of action is to implement controlled charging, which should ensure that the voltage stays within EN 50160 tolerances, outside of the network peak demand time.

After analysing the LV network, the authors of [7] concluded that slow charging stations can accommodate the controlled charging of a sizable number of plug-in electric vehicles. It is important to arrange the slow charging stations equally among the phases in order to prevent an increase in voltage unbalance. Due to their large effect, public rapid charging stations shouldn't be linked to the endpoints of the LV supply. Separate transformer stations or feeds are two potential possibilities.

Due to enhanced and flattened load profiles, the energy distribution system can work well—even better than it would without plug-in EVs—by controlling the charging of these vehicles. The electricity grid is significantly impacted by distributed generation in the form of small photovoltaic (PV) installations. According to the study authors the usage of EVs and PV plants on the grid can benefit these networks, because it lowers the peak demand on the electrical distribution networks [8].

The data reported by the authors in [9] demonstrate how tariff charging keeps the voltage unbalance factor within generally accepted bounds. In comparison to more conventional approaches, the suggested method for fortifying the EV connection network is more affordable and can help to suppress voltage violations to some extent. It is based on the increased voltage level on specific line segments with the insertion of suitable transformers. reinforcements.

Single-phase chargers have been a major factor in the development of unbalanced EV loads, according to [10]. The network component parts lose more energy as a result. Unbalanced voltages cannot be solved by an even distribution of EVs across all phases as EVs can be charged at random.

The coordinated control approach ensures correct functioning in a typical distribution network, as verified by the simulation findings in [11]. In order to reduce network reinforcement, the suggested dynamic power balancing system is built as an addition to the current distribution network.

Mismatched plug-in EV charging has a detrimental effect on system demand, voltage unbalance factor, and distribution network voltage profiles, according to the authors of [12]. The voltage unbalance factor and voltage fluctuations are reduced by coordinated online genetic algorithm optimization.

According to [13], end users should be urged to three-phase their LC technology in order to prevent voltage unbalance issues. Greater power injection into the grid is made possible by the three-phase connection of LC technology, which lowers the value of the voltage unbalance factor and the frequency of occurrence of the voltage unbalance factor that exceeds the limit.

## 2. ANALYSIS OF A REAL LOW VOLTAGE DISTRIBUTION GRID

A part of the real rural low voltage distribution network, in the area surrounding Tešanj, was examined. It was

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selected as a representative example of a household-dominated LV grid to examine the effects of consumer and electric vehicle distribution on grid voltage conditions. A 160 kVA installed capacity 10/0.4 kV distribution transformer supplies the region because of the length of the main line and the distribution of distant loads. Thirteen of the forty customers in the feeder are active, while the remaining nine are either inactive or not active at all. It will be crucial for the study to know that, of the 31 active customers, 5 are three-phase and the remaining 26 are single-phase. Additionally, a PV power plant with an installed capacity of 23 kVA, linked in three phases to the 0.4 kV grid, is one production capacity in the grid under consideration.

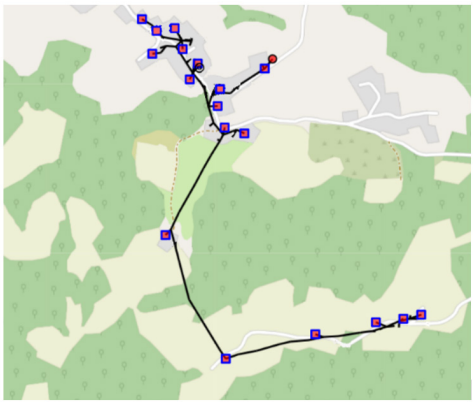

Figure 1: Georeferenced scheme of the modelled grid

Figure 1 shows the entire considered grid. The red circle represents transformer substation 10/0.4 kV, while the blue-pink squares represent consumers. The grid branch is divided into two parts after transformer substation. The first upper branch is with more densely distributed consumers. There is a PV power plant on that part, which is represented by a black circle. The second branch, which is significantly longer than the first, has a smaller number of consumers, and it is characteristic that at the very end of the feeder there are consumers who direct the unbalance of the entire grid. Since the distance of these consumers from substation is large, any minor change in the consumption of these consumers will significantly affect the quality of electricity of the entire grid.

In this paper, busbars on the main line to which consumers are connected directly were specially considered. There are 15 such buses. The bus voltages from the main line are displayed on the voltage fluctuations and unbalances graphs. The data from the control meter was processed using the provided data for the actual grid that was taken into consideration. From the control meter fifteen-minute data, the day with the greatest peak load of the year was selected. That rule led to the selection of 12.12.2021. The graph of hourly meter data for the day with the highest peak demand is displayed in Figure 2.

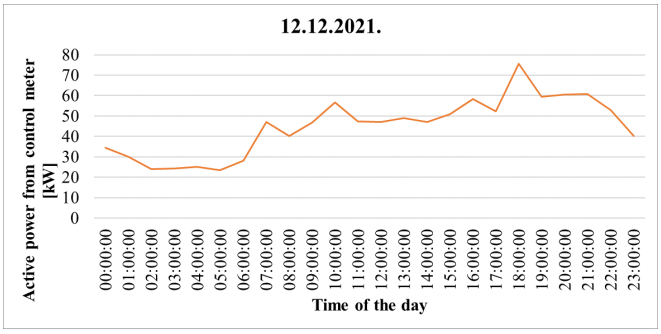


Figure 2: The day of the highest energy consumption

## 3. METHODOLOGY

DIgSILENT PowerFactory software was used for the analysis in this paper. Different load distributions per phase define the scenarios examined in this paper. In one project, the DIgSILENT Power Factory software Variations feature allowed for altering the grid topology by adding loads and examining the power flow under various conditions. Since the power of each consumer must be entered into the simulation, data from the actual energy consumption readings of the meter is used to determine the energy consumption of each consumer. Metering data includes readings from each customer smart meter as well as the control meter at the transformer substation. Smart meter readings are recorded daily, while control meter readings are recorded every 15 minutes during the year. The quantity of energy consumed during the hour with the greatest energy consumption is multiplied by the proportion of each consumer consumption relative to the total consumption to determine their power. On December 12, 2021, at 18:00 h, the highest power on the control meter during EVs peak consumption is equal to 75,664 kW. The grid model has 31 active consumers, of which 26 are single-phase and 5 three-phase consumers. This model is used to simulate 12 different scenarios. This data is used to calculate the peak power for each user. The day and hour of the day with the highest consumption is chosen and modelled. As a result of calculating and comparing the daily consumption, December 12, 2021, was chosen to be studied as the day with the highest peak energy consumption under typical circumstances (without power interruption). The unbalance of consumers per phase is followed by the same unbalance in EVs distribution in each of the nine scenarios in which EVs are connected to the grid with 10%, 20%, and 50% penetration. To make the problem more realistic, the consumption of EVs was added to the already existing consumption of consumers, i.e. they were added to the same phase. Therefore, if the EVs is charged in the owner household, the consumption during EVs charging will be added to the household consumption. The analysis of this paper can be divided into two parts. The first part of the analysis included three cases where the EVs were unrelated. These cases served as the “foundation” for the second part of the analysis,

which included EV. Table I, which displays the distribution of the loads by phases of the first section of the analysis, includes those three scenarios. Three further possibilities were added in the second portion of the study, each based on the distribution of EVs by phase and the penetration rates of 10%, 20%, and 50% in the three basic instances.

A new percentage for EV penetration was added while maintaining the proportion specified in the analysis first section. Table II displays the distribution of EVs utilized in the second portion of the investigation.

Table I: Percentage of load per phase per cases

| First case | Second case | Third case |
|---|---|---|
| 33%-33%-33% | 40%-30%-30% | 50%-25%-25% |

Table II: EVs percentage according to the scenario of the second part of the analysis

| | |
|---|---|
| **First case (33%-33%-33%)** | **Without EV** |
| | 10% |
| | 20% |
| | 50% |
| **Second case (40%-30%-30%)** | **Without EV** |
| | 10% |
| | 20% |
| | 50% |
| **Third case (50%-25%-25%)** | **Without EV** |
| | 10% |
| | 20% |
| | 50% |

Since all EVs on the market require the same conventional residential single-phase charging power, all EVs are modelled in this study as 2.3 kW loads. Because it permits the choosing of the connecting phase, this load-like depiction of the vehicle seemed acceptable. In every scenario, "Unbalanced three-phase AC Load Flow" was employed, and the ensuing unbalances and voltage fluctuations were noted. The unbalance factor was utilized for additional analysis in this work and is given in the DIgSILENT PowerFactory Flexible Data section. An assessment of the acquired results with respect to the standard limits is given in the next chapter.

## 4. RESULTS

Table III shows the distribution of load power for all three cases. The percentages refer to the distribution of consumer power per phase, not the number of consumers per phase. The sum of all power of all loads is 24.165 kW and is distributed by cases and phases as shown in Table III.

Table III: Distribution of load power by case

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **First case** | 8.04 kW | 8.11 kW | 8.02 kW |
| **(33%-33%-33%)** | 33.25% | 33.55% | 33.19% |
| **Second case** | 9.93 kW | 7.20 kW | 7.04 kW |
| **(40%-30%-30%)** | 41.07% | 29.79% | 29.14% |
| **Third case** | 12.07 kW | 6.14 kW | 5.96 kW |
| **(50%-25%-25%)** | 49.95% | 25.39% | 24.66% |

### 4.1. First case (distribution of consumers by stages 33%-33%-33%)

#### 4.1.1. Consumer distribution scenario 33%-33%-33% without added EVs

The first case is defined as having an equal load distribution per phase. First, scenario without connected EVs is defined. Consumers are distributed so that each phase is loaded with approximately equal power. A certain number of consumers is distributed to each phase so that the power ratio per phase is 33%-33%-33%. The total load power of 24,165 kW is distributed according to Table III for the first case.

From Figure 3, it is seen that only the phase A voltage experiences a very large drop as it approaches the end of the main line, especially after the ninth busbar. The reason for this is that at the end of the grid is a concentrated distribution of high-power loads in phase A. The current flow through a long line leads to a large voltage drop on this phase. The total power of loads distributed by phases is the same, but the distribution of consumers and EVs per grid is different, and therefore the phase A drop is specific. Phase B and phase C voltage levels are nearly constant and are within the EN 50160 standard allowable limits. According to EN 50160, Phase A exceeded the voltage variation limit of -10%. Phase A voltage loss is notably greater than it was in the earlier cases.

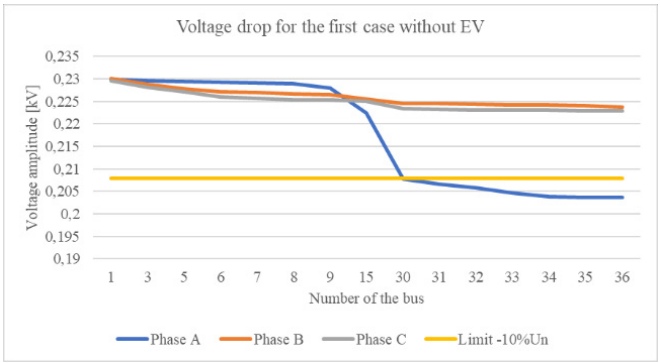


Figure 3: Voltage drop along the main line of the first case without EV

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#### 4.1.2. Consumer distribution scenario 33%-33%-33% with 10% added EVs

The 33%-33%-33% consumer distribution scenario, with 10% added EVs, included three EVs distributed along the main line. The distribution of EVs is done considering the equal distribution of the power of the first case. The total load power, including five EVs in each phase, is distributed according to Table IV.

Table IV: Distribution of power and EVs by stages in the first case with 10% EVs

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Distribution of consumer power by phases** | 10.34 kW<br>33.27% | 10.41 kW<br>33.50% | 10.32 kw<br>33.22% |
| **Distribution of EVs power by phases** | 1<br>2.3 kW | 1<br>233 kW | 1<br>2.3 kW |

In this scenario, the voltages of phases B and C are almost symmetrical with a small voltage drop that is within the permitted limits of EN 50160. Phase A violated the lower limit of voltage variation of -10% according to EN 50160, as can be seen in Figure 4. As expected, in this scenario, the voltage drop of phase A was higher than in the previous scenario. In this scenario, the voltage unbalance is within the limit of +2% according to EN 50160, as can be seen in Figure 7.

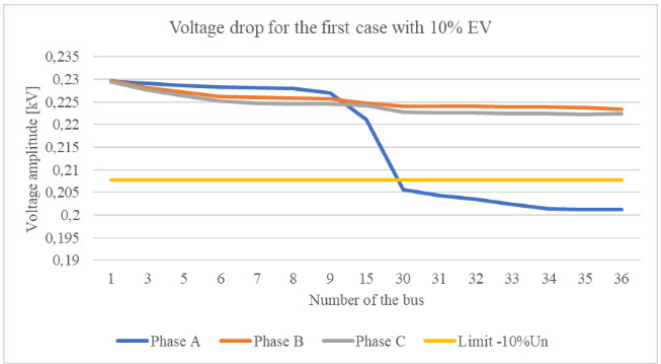


Figure 4: Voltage drop along the main line of the first case with 10% EVs

#### 4.1.3. Consumer distribution scenario 33%-33%-33% with 20% added EVs

The 33%-33%-33% consumer distribution scenario, with 20% added EVs, included 6 EVs equally distributed in phases, along the main line. The total power of the load, including two EVs in each phase, is distributed according to Table V. The distribution of EVs is made considering the equal power distribution of the first case. The voltages of phases B and C are almost symmetrical with a small voltage drop that is within the permitted limits of EN 50160.

Table V: Distribution of power and EVs by stages in the first case with 20% EVs

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Distribution of consumer power by phases** | 12.64 kW<br>33.28% | 12.71 kW<br>33.47% | 12.62 kW<br>33.24% |
| **Distribution of EVs power by phases** | 2<br>4.6 kW | 2<br>4.6 kW | 2<br>4.6 kW |

Phase A violated the lower voltage variation limit of -10% according to EN 50160, as can be seen in Figure 5. As expected, in this scenario the voltage drop of phase A was higher than in the previous scenario. In this scenario, the voltage unbalance is within the limit of +2% according to EN 50160, as can be seen in Figure 7.

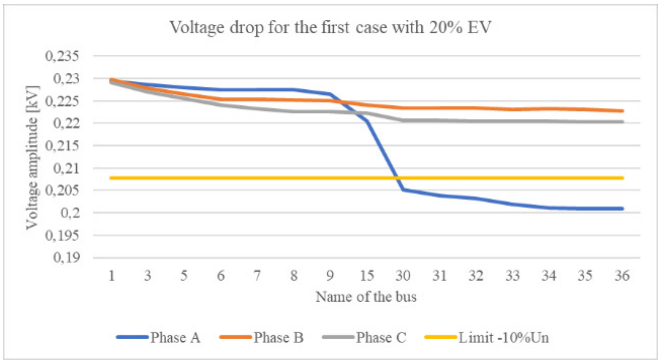


Figure 5: Voltage drop along the main line of the first case with 20% EVs

#### 4.1.4. Consumer distribution scenario 33%-33%-33% with 50% added EVs

The consumer distribution scenario 33%-33%-33%, with 50% added EVs, included 15 EVs evenly distributed in phases, along the main line. The total load power, including five EVs in each phase, is distributed according to Table VI. The distribution of EVs is done considering the equal distribution of the power of the first case.

Table VI: Distribution of power and EVs by stages in the first case with 50% EVs

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Distribution of consumer power by phases** | 19.54 kW<br>33.30% | 19.61 kW<br>33.42% | 19.52 kW<br>33.28% |
| **Distribution of EVs power by phases** | 5<br>11.5 kW | 5<br>11.5 kW | 5<br>11.5 kW |

The voltage of phases B and C are symmetrical with a small voltage drop that is within the permitted limits of EN 50160. Phase A violated the -10% voltage variation limit of EN 50160, as can be seen in Figure 6. As expected, in this scenario the voltage drops of phase A are bigger than in

the previous scenario. The voltage drop is more noticeable than in the previous scenarios. The voltage unbalance is within the limit of +2% according to EN 50160 as can be seen in Figure 7, but the curve approaches the limits.

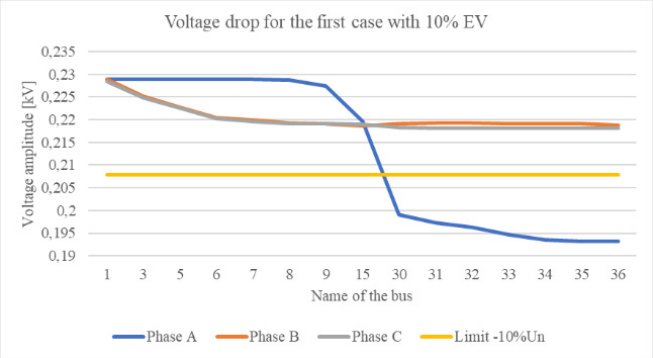


Figure 6: Voltage drop along the main line of the first case with 50% EVs

Figure 7 shows the voltage unbalance graph for each of the scenarios of the second case. The voltage unbalance is within the limit of +2% according to EN 50160 in all scenarios, except with 20% added EV.

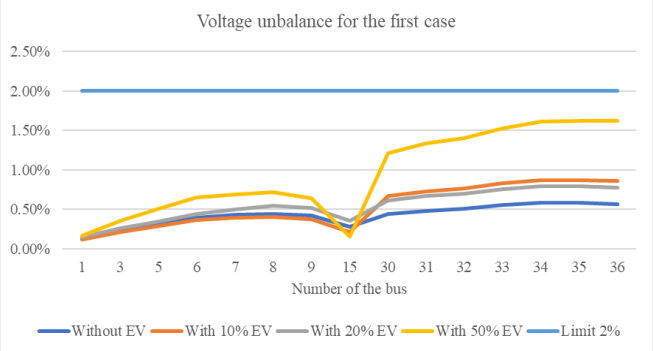


Figure 7: Voltage unbalance along the main line for the first case

## 4.2. Second case (distribution of consumers by phases 40%-30%-30%)

### 4.2.1. Consumer schedule scenario 40%-30%-30% without added EVs

The second case is defined as having a 40%-30%-30% load distribution per phase and no EVs is connected. Therefore, the percentages refer to the distribution of consumer power per phase and not to the number of consumers per phase. The total load power of 24,165 kW is distributed according to Table III for the second case.

From Figure 8, it is seen that only the phase A voltage experiences a very large drop as it approaches the end of the main line, especially after the ninth busbar. Phase B and phase C voltage levels are nearly constant and are within the EN 50160 standard allowable limits. According to EN 50160, Phase A exceeded the voltage variation limit of -10%. Phase A voltage loss is notably greater than it was in the earlier cases.

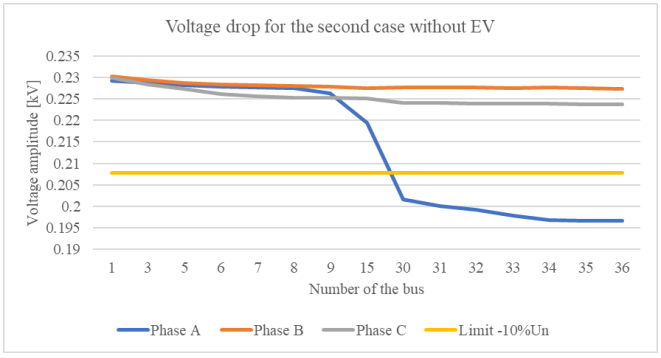


Figure 8: Voltage drop along the main line of the second case without EV

### 4.2.2. Consumer distribution scenario 40%-30%-30% with 10% added EVs

The 40%-30%-30% consumer distribution scenario with 10% added EVs included 3 EVs, equally distributed in phases along the main line. The total load power, including one EVs in each phase, is distributed according to Table VII. The EVs distribution was not performed considering the equal power distribution of the second base case, but it is the closest to that distribution.

Table VII: Distribution of power and EVs by stages in the second case with 10% EVs

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Distribution of consumer power by phases** | 12.23 kW | 9.50 kW | 9.34 kW |
| | 39.35% | 30.57% | 30.07% |
| **Distribution of EVs power by phases** | 1 | 1 | 1 |
| | 2.3 kW | 2.3 kW | 2.3 kW |

In this scenario, the voltage drop of phases B and C is more visible, but it is within the permitted limits of EN 50160. Phase A violated the lower limit of voltage variation of -10% according to EN 50160. As expected, in this scenario the drop the voltage of phase A was higher than in the previous scenario as seen in Figure 9. The voltage unbalance is outside the limit of +2% according to EN 50160, as can be seen in Figure 12.

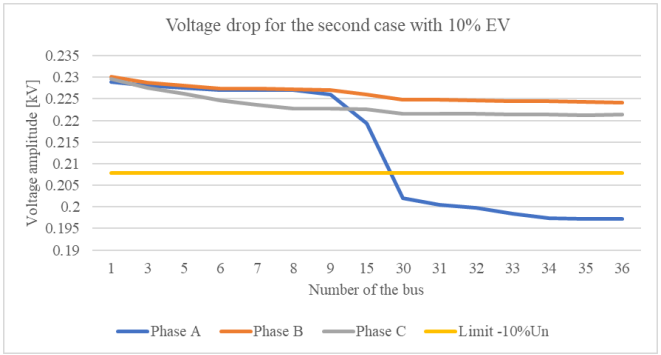


Figure 9: Voltage drop along the main line of the second case with 10% EVs

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### 4.2.3. Consumer distribution scenario 40%-30%-30% with 20% added EVs

The 40%-30%-30% consumer distribution scenario with 20% added EVs included 6 EVs, equally distributed in phases along the main line. The total load power is distributed according to Table VIII. The EVs distribution is not done considering the equal power distribution of the second case, but it is the closest to that distribution.

Table VIII: Distribution of power and EVs by stages in the second case with 20% EVs

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Distribution of consumer power by phases** | 16.83 kW | 11.80 kW | 9.34 kW |
| | 44.32% | 31.08% | 24.61% |
| **Distribution of EVs power by phases** | 2 | 2 | 2 |
| | 4.6 kW | 4.6 kW | 4.6 kW |

The voltages of phases B and C are almost symmetrical with a small voltage drop that is within the permitted limits of EN 50160. Phase A violated the lower limit of voltage variation of -10% according to EN 50160, as can be seen in Figure 10. As expected, in this scenario the voltage drop of phase A was higher than in the previous scenario. The voltage unbalance is within limit of +2% according to EN 50160, as can be seen in Figure 12. An important factor in this is the EVs' location. So, in this scenario, the position of the EVs is closer to the substation and results in less impact on the voltage conditions, which means that voltage unbalance is within the limit of +2% according to EN 50160 in all scenarios.

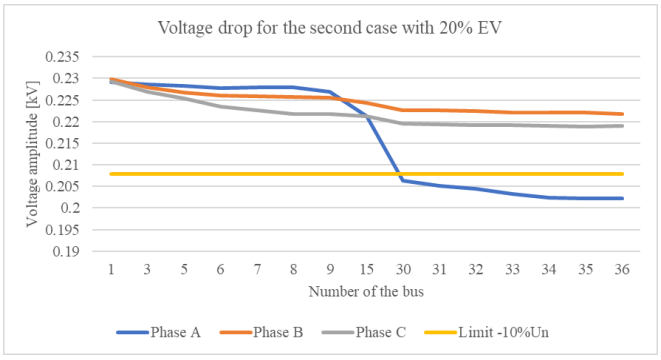


Figure 10: Voltage drop along the main line of the second case with 50% EVs

### 4.2.4. Consumer distribution scenario 40%-30%-30% with 50% added EVs

The 40%-30%-30% consumer deployment scenario with 50% added EVs included 15 EVs distributed along the main line. The total load power, including EVs, is distributed according to Table IX. The distribution of the EVs was performed considering the equal power distribution of the second base case.

Table IX: Distribution of power and EVs by stages in the second case with 50% EVs

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Distribution of consumer power by phases** | 23.73 kW | 18.70 kW | 16.24 kW |
| | 40.44% | 31.87% | 27.69% |
| **Distribution of EVs power by phases** | 6 | 5 | 4 |
| | 13.8 kW | 11.5 kW | 9.2 kW |

In Figure 11 a slightly different graph can be seen. After the ninth bus, the voltages of phases B and C are nearly symmetrical; prior to that, phase C voltage is greater than phase B voltage, but both are still within the standard EN 50160 allowable bounds. In accordance with EN standard 50160, Phase A exceeded the lowest limit of voltage fluctuation, which is -10%. As expected, in this scenario the voltage drop of phase A was higher than in the previous scenario. The voltage unbalance is outside the +2% limit of EN 50160, as can be seen in Figure 12. As the scenarios change, the voltage unbalance curve peaks at higher points.

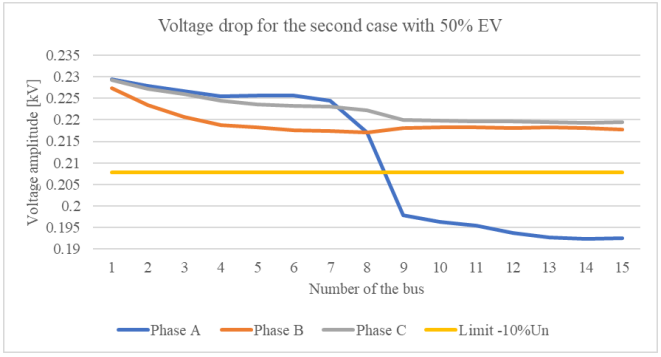


Figure 11: Voltage drop along the main line of the second case with 50% EVs

Figure 12 shows the voltage unbalance graph for each of the scenarios of the second case. The voltage unbalance is within the limit of +2% according to EN 50160 in all scenarios, except with 20% added EV.

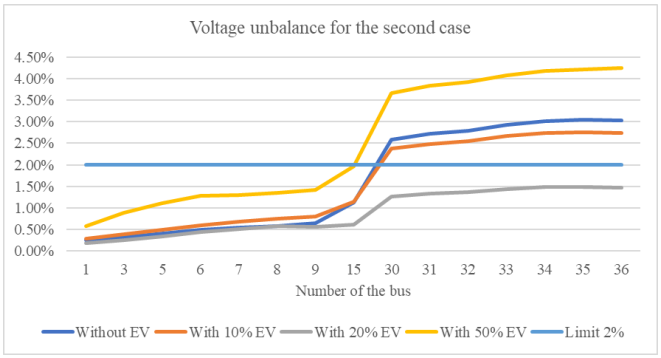


Figure 12: Voltage unbalance along the main line for the second case

### 4.3. The third case (distribution of consumers by stages 50%-25%-25%)

#### 4.3.1. Consumer distribution scenario 50%-25%-25% without added EVs

The third case is defined to have a 50%-25%-25% load distribution per phase. Therefore, the percentages refer to the distribution of consumer power per phase and not to the number of consumers per phase. The total load power of 24,165 kW is distributed according to Table III for the third case.

Figure 13 shows that the voltages of phases B and C are no longer symmetrical. They are within the permitted limits of EN 50160, but the voltage drop is more visible. Phase A violated the lower voltage variation limit of -10% according to EN 50160. As expected, in this scenario the voltage drop of phase A was higher than in the previous case but this difference is not visible in the graph. The voltage unbalance is outside the limit of +2% according to EN 50160, as can be seen in Figure 17.

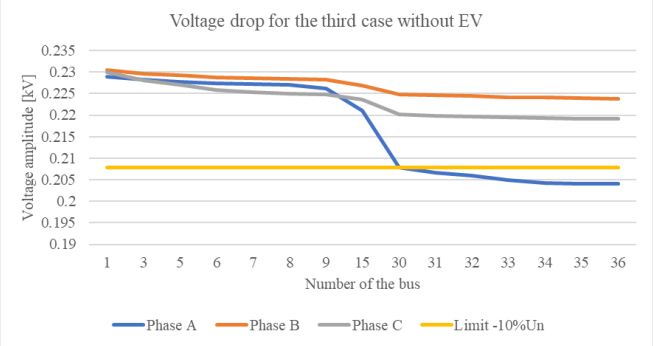


Figure 13: Voltage drop along the main line of the second case without EV

#### 4.3.2. Consumer distribution scenario 50%-25%-25% with 10% added EV

The consumer distribution scenario 50%-25%-25%, with 10% added EVs, includes 3 EVs, evenly distributed in phases, along the main line. The total power of the load, including one EV in each phase, is distributed according to Table X. The distribution of EVs is not made with respect to the equal power distribution of the third case, but it is the closest to that distribution.

Table X: Distribution of power and EVs by stages in the third case with 10% EVs

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Distribution of consumer power by phases** | 14.37 kW | 8.44 kW | 8.26 kW |
| | 46.26% | 27.16% | 26.59% |
| **Distribution of EVs power by phases** | 1 | 1 | 1 |
| | 2.3 kW | 2.3 kW | 2.3 kW |

The voltages of phases B and C are no longer symmetrical, which is visible in Figure 11. They are within the permitted limits of the EN 50160 standard, but the drop is greater and more noticeable. Phase A violated the lower voltage variation limit of -10% according to EN 50160. As expected, in this scenario the voltage drop of phase A was higher than in the previous scenario. The voltage unbalance is outside the limit of +2% according to EN 50160, as can be seen in Figure 14.

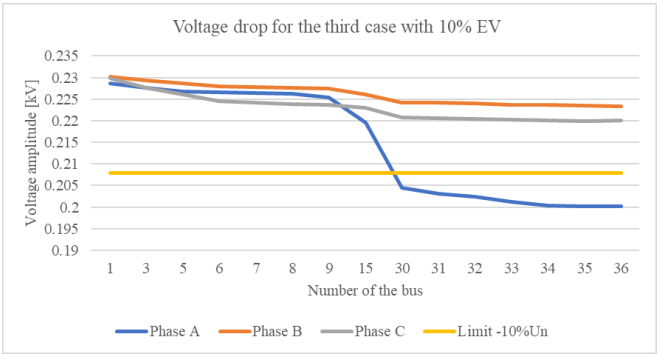


Figure 14: Voltage drop along the main line of the second case with 10% EVs

#### 4.3.3. Consumer distribution scenario 50%-25%-25% with 20% added EVs

The consumer distribution scenario 50%-25%-25%, with 20% added EVs, includes 6 EVs evenly distributed in phases, along the main line. The total load power is distributed according to Table XI. The EVs distribution is not done considering the equal power distribution of the harder case, but it is the closest to that distribution.

Table XI: Distribution of power and EVs by stages in the third case with 20% EVs

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Distribution of consumer power by phases** | 16.67 kW | 10.74 kW | 10.56 kW |
| | 43.91% | 28.28% | 27.81% |
| **Distribution of EVs power by phases** | 2 | 2 | 2 |
| | 4.6 kW | 4.6 kW | 4.6 kW |

The voltages of phases B and C drop symmetrically. They are within the permitted limits of EN 50160, but not with the same values. It can be seen in Figure 15 that phase A violated the lower limit of voltage variation of -10% according to EN 50160. As expected, in this scenario the voltage drop of phase A was higher than in the previous scenario. In this scenario, the voltage unbalance is outside the limit of +2% according to EN 50160, as can be seen in Figure 17.

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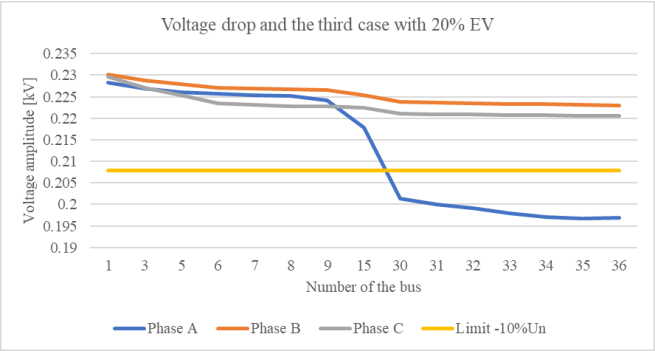


Figure 15: Voltage drop along the main line of the second case with 20% EVs

### 4.3.4. Consumer distribution scenario 50%-25%-25% with 50% added EVs

The 50%-25%-25% consumer distribution scenario with 50% added EVs involved 15 EVs deployed along the main line. The total load power, including EV, is distributed according to Table XII. The power of loads modelled without EVs is shown in Table III. The distribution of EVs was performed considering the power distribution of the third case.

Table XII: Distribution of power and EVs by stages in the third case with 50% EVs

| | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Distribution of consumer power by phases** | 28.17 kW<br>48.02% | 15.34 kW<br>26.14% | 15.16 kW<br>25.84% |
| **Distribution of EVs power by phases** | 7<br>16.1 kW | 4<br>9.2 kW | 4<br>9.2 kW |

It can be seen that this is the worst scenario of all the scenarios. Figure 16 shows the voltage drop along all phases is higher than in other scenarios. The voltages of phases B and C do not drop symmetrically but are within the permitted limits of EN 50160. Phase A violated the lower limit of voltage variation of -10% according to EN 50160. As expected, in this scenario the voltage drops

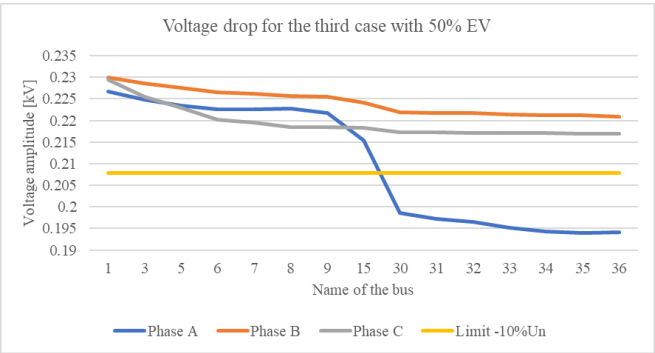


Figure 16: Voltage drop along the main line of the second case with 50% EVs

of phase A is higher than in the previous scenario. The voltage unbalance is outside the limit of +2% according to EN 50160 and represents the worst-case scenario. Almost the entire curve is out of limits, as can be seen in Figure 17.

The voltage unbalance is outside the limit of +2% according to EN 50160 in all scenarios of this case, as can be seen in Figure 17.

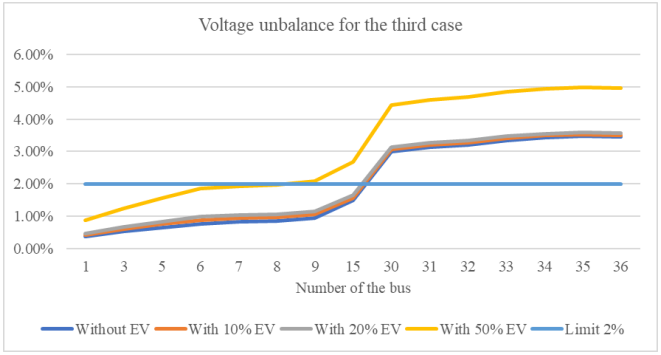


Figure 17: Voltage unbalance along the main line for the third case

## 5. DISCUSSION

The 33%-33%-33%, 40%-30%-30% and 50%-25%-25% asymmetry scenarios depict realistic asymmetries encountered in the distribution network. The 10%, 20% and 50% EV penetration scenarios depict several steps in the number of implementations of electric vehicles in Bosnia and Herzegovina.

A large number of EVs charging uncontrollably can raise concerns about the stability of the power system. Strategies to mitigate the negative impacts of asymmetric connections and EV integration should be implemented in the form of laws, regulations and incentive systems. The focus should be on limiting charging during peak daily load and encouraging off-peak charging.

EVs can be used as backup power for houses and buildings with garages and larger parking lots. In this way, the reliability of the power supply is increased.

The most expensive and worst solution is to do network reinforcement. Investing in smart technologies, which enable smart charging and demand response, is a better and more optimal solution. A prerequisite for the development of smart technologies is the installation of smart EV charging stations with the ability to communicate with control centres. Smart technologies cannot be applied to single-phase sockets in garages.

The key impact of technological innovations is reflected in the management of charging in every household, and

the prerequisite for its implementation is the installation of smart charging stations. Smart meters can help manage charging by sending signals about the price of electricity, based on which the meter and home management system will signal to disconnect the EV.

EV charging management can be used to manage the system when there is no required electricity from non-renewable energy sources. In this case, during the day, the excess energy produced from the renewable source is stored in the battery and used when needed.

Smart charging is a way of optimizing the distribution network and can be performed in the form of load power balancing, V/f regulation that reduces losses or through the implementation of a vehicle-to-grid scheme.

The reliability performance of the electric power system can be significantly improved by the integration of EVs in the battery exchange mode, which functions in such a way that users take a full battery from the station and leave an empty one for charging.

A workplace EV charging scheme through charging systems would reduce peak loads so that EVs could be charged at work. The government could provide incentives for companies and thus encourage owners to participate in the creation of a smart grid.

Companies that own public EV chargers promote lower charging prices during off-peak hours. In addition to the charging schedule, it is possible to delay charging depending on the peak load at the time the EV is connected to the grid.

Installing PV panels can enable the generation of renewable energy during the day, which can be used to charge EVs. Charging costs of EV are lower than the fuel used by internal combustion engine cars.

EVs are mostly charged in the afternoon, when the system is at its peak, and the goal is to charge EVs at night, when demand is lowest and electricity prices are lowest. In this way, drivers ensure that they have a full battery every morning, and charging stops automatically when the battery reaches its maximum capacity.

If vehicle charging is managed, these vehicles play the role of dispersed batteries in the systems. The battery can have a positive impact in terms of improving system stability and locally reducing asymmetry. The charge management would be done by phases and thus compensate for the difference in load per phase.

## 6. CONCLUSION

This paper shows that uncontrolled EVs integration can have more negative than positive effects on the power system and power quality. The purpose of this study was to investigate how different load distribution and EVs penetrations per phase affect voltage variation and unbalance. Due to the choice of a grid with a long feeder and the choice of load distribution by phases and by the length of the lines, the voltage of phase A is outside the normal limits in all scenarios. This is due to the concentrated distribution of high-power loads at the end of the line in phase A. An important finding is that the EVs connection point and the phase to which it is connected define how the EVs affects the variations and unbalance of the distribution grid. A total of twelve scenarios were modelled, of which four fundamental scenarios do not include EVs and nine scenarios that include different penetrations of EVs. None of the twelve scenarios remained within the permissible limits for the voltage drop in phase A. In all scenarios, phases B and C remained within ±10% of the nominal voltage Un.

Seven of the twelve scenarios exceeded both the voltage variation and unbalance limits. It is concluded that EVs charging affects both power quality parameters studied in this paper. All scenarios recorded a voltage drop, which increased with greater EVs penetration, accompanied by an increase in unbalance. Connecting EVs to such a grid would inevitably contribute to an increase in unbalance as it reduces the capacity of the grid, exacerbating the already existing unbalance. During the testing of all scenarios, it is noticeable that adding an EVs at the end of the grid would lead to a significant voltage drop. It would even happen that there would be an excessive loading of the phase so that the convergence of the calculation is not achieved in those scenarios. Care should be taken that if EVs are added to the same phase, they are distributed throughout the grid. These events were not expected, but since there is three-phase generation capacity in the grid, it justified the increase in voltage after a major drop.

Future work could include analysis of regulated charging and optimal scheduling of EVs in stages to ensure that power quality parameters do not change beyond permissible limits.

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