

# PHASE BALANCE OPTIMIZATION OF CUSTOMERS AND ELECTRIC VEHICLES IN A REAL LOW VOLTAGE ELECTRICITY DISTRIBUTION NETWORK

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**Abstract:** Phase unbalance is a common issue encountered in LV electricity distribution networks, caused by uneven allocation of single-phase loads among phases. This paper analyses a part of a real LV distribution network, situated in Bosnia and Herzegovina. The impact of single-phase customers and single-phase charging of electric vehicles was analysed. To reduce unbalance and improve the voltage profiles, Phase Balance Optimization in DigSILENT PowerFactory software was performed in six scenarios with different customer and electric vehicle unbalance. The goal was to find a method with the least number of changes in the customer and electric vehicle phase connection that fits within defined limits of voltage variations and voltage unbalance of a European norm for power quality (EN 50160). Results showed that all analysed scenarios were improved, with reference to voltage variation and voltage unbalance values, and were found acceptable by the limits from standard EN 50160.

**Keywords:** phase unbalance, low voltage, distribution network, electric vehicles, phase balance optimization, voltage variations, voltage unbalance

## INTRODUCTION

In low voltage (LV) electricity distribution networks, one of the most frequent power quality (PQ) issues is voltage unbalance. Voltage unbalance occurs due to unbalanced single-phase loading in a three-phase system (single phasing of equipment). Voltage unbalance is one of the power quality parameters from European norm EN 50160. The limit of allowed unbalance is 2%, expressed as ratio of negative sequence component divided by positive sequence component. Most equipment is tolerant to unbalance that is less than 2%, however if it rises above 2% it causes motor and transformer overheating. This is due to the current unbalance varying as a cube of voltage unbalance at the terminals [1]-[2].

Plug-in electric vehicles have many advantages that could help overcome the problems of power systems, with one of the problems being voltage unbalance in distribution networks. Voltage unbalance factor (VUF) can be improved or worsened, depending on the type of charging (coordinated or uncoordinated). Most plug-in electric vehicles (PEVs) are, in real applications, connected to residential or commercial networks with single-phase connection. As they charge or discharge, they impact the network in a way that it leads to voltage unbalance. The effect of PEVs charging on network voltage unbalance is, in the paper [3], investigated in the form of optimization problem. An objective function is the minimisation of

VUF, performed in different scenarios, subject to network security and PEVs constraints, using PSO algorithm. VUF is minimized by optimally selecting the PEV point of connection (phase a, b or c), state of PEVs (charging or discharging), and charging/discharging rating power. Also, the paper evaluates the impact of uncoordinated and coordinated charging of PEVs on VUF. The presented method is studied based on an unbalanced three-phase distribution network. Finally, from the results it can be seen that the coordinated charging/discharging of PEVs can significantly improve VUF value [3].

An efficient hybrid method is proposed in the work [4], which aims at mitigating voltage unbalance and improving the voltage in the higher penetration of electric vehicles (EVs) and distributed generation (DG). The proposed hybrid method is the combination of the mayfly algorithm (MA) and the radial basis function neural network (RBFNN), called the mayfly algorithm-radial basis function neural network (MA-RBFNN) method. The contributions of the proposed work is that the network unbalancing and voltage profile are successfully mitigated, with the loss of network energy, utilizing obtainable network capacity and better comfort level for EV consumers [4].

The network performances due to uncoordinated EV and DG distribution is investigated in the article [5]. The following power quality-related performances are evaluated as a multiobjective optimization problem:

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voltage imbalance, neutral current, energy loss, and bus voltage. To solve the multiobjective optimization problem to coordinate EV and DG in a distribution grid, the differential evolution optimization algorithm is employed. This article proposed a method to coordinate EV and DG distribution. The proposed method allows DSOs to jointly optimize the optimal dispatch of DGs and phase sequence to improve the network's performance. If the network requires further improvement, for a particular location, the EV charging or discharging rate is coordinated.

In work [6], an intelligent hybrid strategy for improving voltage and reducing unbalance, considering higher penetration of electric vehicles (EVs) and distributed generation (DG), is proposed in the paper. The proposed hybrid strategy is the combination of binary version of equilibrium optimization (BEO) and Chaos Net strategy and therefore it is named as BEO-CNS. The main objective of this work is: (1) presenting a multi-objective optimization issues to reduce voltage profile and network unbalance, including loss of energy network; (2) presenting an enhanced control method that secure DSOs effectively use the capacity of available network and enhance the comfort level for EV users. The proposed BEO-Chaos Net strategy is used in distribution system, it is connected with EV to optimize the dispatch of DGs and optimise phase sequence, enhancing the network's operation and solve the multi-objective optimization issues.

Re-phasing tactic is commonly used for solving phase balance issues, while network reconfiguration helps with power loss reduction. Therefore, a new method was introduced in [7], which includes an optimization using Bacterial Foraging with Spiral Dynamic (BF-SD) algorithm for re-phasing, network reconfiguration and distributed generator (DG) placement. The analysis was conducted on a IEEE 123 node test feeder. They conclude that re-phasing and reconfiguration are a much cheaper method for handling unbalance when compared to DG installation. Load re-phasing and unbalance problem in distribution networks have been investigated furthermore. In [8] a phase swapping at pole level (PSPL) method for an optimal allocation of consumers per phase is proposed.

The topology of the network and energy consumption are used as input data while the objective function was minimization of current unbalance factor. The analysis was performed on a real LV network and the results showed reduction of unbalance factor and energy losses.

Authors of [9] introduced a new method for long-term load balancing through Modified Leapfrog Organization Routine algorithm (MOLFOP).

The analysis was conducted on a sample LV distribution network. The proposed algorithm was proven to be successful in long term load balancing, reducing losses and providing with an appropriate load balancing in the analysed network.

Work done in [10] presents the load balancing based on Genetic Algorithm to decrease power losses during a time interval of one day. Study was done on a real LV distribution network of Romania. The paper also compares previously obtained results using Particle Swarm Optimization to results obtained in this paper and concludes that the Genetic Algorithm approach provides with better results. Further research would include finding the optimal position of balancing points in the network.

In the study [11] EVs are characterised as unbalanced loads with random plug-in times, durations, charging rates and locations. Hence, to utilise the integration of PEVs in both operational modes (grid-to-vehicle, vehicle-to-grid) to guarantee power loss reduction, voltage profile maintaining and load current balancing, a charging coordination algorithm is proposed. The introduced algorithm can perform an optimal calculation to determine proper phase for PEVs in distribution feeders. Also, it can decline the unbalancing by deploying a new device called phase switcher, which is in series with chargers in residential buildings. The phase switcher is connected to the smart load management centre, which uses the proposed algorithm to determine the proper phase for connection or disconnection of PEVs and finding the appropriate numbers of PEVs. To show the effectiveness of the proposed algorithm, simulation results are provided [11].

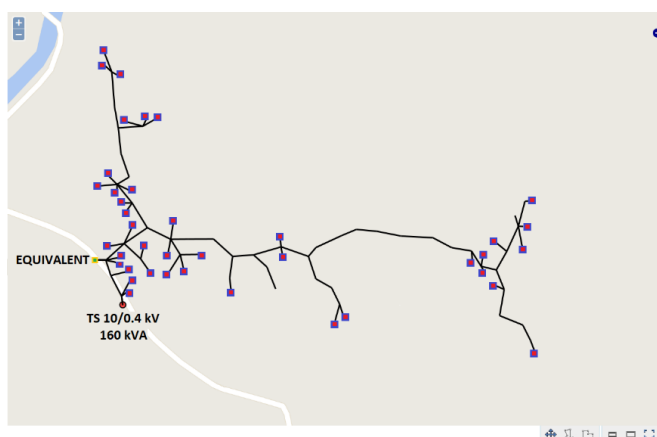


Figure 1: Topology of the analysed LV network

To dynamically reduce voltage unbalance along low voltage distribution feeders in [12], a distributed intelligent residential load transfer scheme is proposed. Residential loads are transferred, in this scheme, from one phase to another to minimize voltage unbalance along the feeder. The central controller, installed at the distribution transformer, observes the power consumption in each house and determines the house(s) to be transferred from an initially connected phase to another. The transfer is carried out by the help of a static transfer switch, with a three-phase input and a single-phase output connection, through which each house is supplied. The steady-state and dynamic performances of the proposed load transfer scheme are investigated by MATLAB analyses and PSCAD/EMTDC simulations [12].

In paper [13], single phase connection of PV installations has been analysed. In the paper [13], a novel method is proposed to mitigate voltage unbalance in LV distribution grids by optimally re-phasing grid-connected rooftop PV systems. A modified version of the discrete bacterial foraging optimization algorithm (DBFOA) is introduced. The optimization technique is used to minimize the overall voltage unbalance of the network as the objective function, subjected to various network and operating parameters. The impact of utilizing the proposed PV re-phasing technique as opposed to a fixed phase configuration are compared based on overall voltage unbalance, which was observed hourly throughout the day. The case studies show that the proposed approach can significantly mitigate the overall voltage unbalance during the daytime and can facilitate to increase the usable PV capacity of the considered network by 77%.

Work done in [14] focuses on two power quality parameters (voltage profiles and voltage unbalance) in a real LV distribution network, with single-phase customers and electric vehicle (EV) charging in several EV penetration levels. The goal was to analyse how different load-phasing and EV penetration impacts voltage variations and unbalance. Out of thirteen analysed scenarios, seven fulfilled the requirements of European standard for power quality (EN 50160) [15], while the remaining six exceeded the limits. Therefore, the need arose to find a possible solution for the remaining six scenarios and improve the results to fit within the limits defined in EN 50160.

This paper continues on the analysis done in [14], with a goal to find the best optimization method that would improve the balance among the phases for all six scenarios that violated the standard limits. Moreover, new results should meet both the EN 50160 standard limits and require the least number of changes in the network topology. All analysis was conducted using DIgSILENT PowerFactory software and Phase Balance Optimization toolbox within Distribution Network Tools.

The novelty of this work is this is the first paper to implement phase balance optimisation calculation for both customer and single-phase EV charging. This work was done on a real network with real data and not on test network.

After the introduction, section 1 describes the methodology used, section 2 presents the results while section 3 concludes the analysis.

## 1. METHODOLOGY

Since this paper continues on the analysis done in [7], the same LV distribution network and appropriate scenarios were used as in [7].

### 1.1. Analysed network

The network topology is provided in Figure 1, while the detailed description of scenarios is given in Table I.

As shown in Figure 1, the network consists of modelled residential loads and a lumped load marked as equivalent. Merging the loads into a single lumped load was required due to restriction on number of terminals in an educational license of DIgSILENT PowerFactory.

### 1.2. Analysed scenarios

This subsection lists all the scenarios analysed in [7]. The base line scenarios (33% - 33% - 33%, 40% - 30% - 30%, 50% - 25% - 25%) represent the underlying balance of loads and EVs among three phases. For all three base line scenarios, analysis for 10%, 20% and 50% penetration of EVs was done. The scenarios that violated at least one of the power quality parameters are depicted by red colour, and these six scenarios are in the focus of this paper, as shown in Table I.

Table I: Overview of analysed scenarios

| Penetration of EVs per scenario     |     |     |                                      |     |     |                                      |     |     |
|-------------------------------------|-----|-----|--------------------------------------|-----|-----|--------------------------------------|-----|-----|
| First scenario<br>(33% - 33% - 33%) |     |     | Second scenario<br>(40% - 30% - 30%) |     |     | Fourth scenario<br>(50% - 25% - 25%) |     |     |
| 10%                                 | 20% | 50% | 10%                                  | 20% | 50% | 10%                                  | 20% | 50% |
| EVs                                 | EVs | EVs | EVs                                  | EVs | EVs | EVs                                  | EVs | EVs |

### 1.3. Phase Balance Optimization

Asymmetric loads are common in distribution networks, however, they result in higher loadings and losses in lines and transformer windings, which makes them undesirable. Phase Balance Optimization within Distribution Network Tools allows a distribution of the connected phases of asymmetric elements to reduce the power unbalance in the network. This tool works on radially operated feeders, which is suitable for the network analysed in this work [9].

The optimization algorithm can be executed for two different objective functions. In both cases the minimized quantity is the power unbalance  $s$ . For branch elements it is defined as follows:

Let  $N$  be the number of phases, and let:

$$\hat{S} = \frac{1}{N} \sum_{i=1}^N S_i \quad (1)$$

be the average complex power (at one end) of a branch element, where  $S_i$ ,  $i=1, \dots, N$  are the complex powers on phases. Let

$$\bar{S} = \frac{1}{N} \sum_{i=1}^N |S_i| \quad (2)$$

be the average of the absolute values of the powers on different phases. Then the power unbalance factor  $s_b$  for the branch element  $b$  is defined as

$$s_b = \left( \frac{1}{S} \right) \max_{i=1, \dots, N} \{ |S_i - \hat{S}| \} \quad (3)$$

To decrease the voltage variation, the voltage unbalance had to be altered using the Phase Balance Optimization tool in DlgSILENT PowerFactory. This means that the voltage variations were indirectly altered through unbalance. Objective function used in the process was 'Minimize Average Power Unbalance', which takes into account the power unbalance of all  $M$  branch elements, which are part of the analysed feeder. The average power unbalance is defined as:

$$\bar{s} = \frac{1}{M} \sum_{b=1}^M s_b \quad (4)$$

The optimization method was 'Large loads and generators first'. This algorithm iterates over all loads and generators in order of their apparent power, starting with the largest load or generator. For each load or generator, it will permute the connections of the load or generator or their supplying branch elements. After calculating the objective function for all possible connections, it will choose the best connection for this load or generator.

At each iteration, the algorithm will evaluate several modifications. The threshold in the frame 'Acceptance of change' determines the minimal improvement required for such a modification. If a modification does not lead to an improvement larger than this threshold, it is not applied to the solution.

## 2. RESULTS AND DISCUSSION

This section is organized according to six analysed scenarios in this paper, that required alterations to fit within the defined limits from standard EN 50160. Each scenario has its own subsection and includes both old results obtained in [7] and new results derived from phase balance optimization.

### 2.1. First scenario (33% - 33% - 33% load distribution) with 50% of EV penetration

Despite an equal distribution of loads per phase, the large amount of EVs being connected and charged simultaneously violated a voltage variation limit of 207 V (or -10% of  $U_n$ ). Therefore, this scenario successfully qualified for Phase Balance Optimization process. Results before optimization are given in Figure 2.

The resulting voltage variations, after the phase balance optimisation calculation are provided in Figure 3. Total number of permutations required for such a modification

was 5. List of changes is provided in Table II. Within that setting the minimal improvement value chosen for the 'Acceptance of change' was 4%.

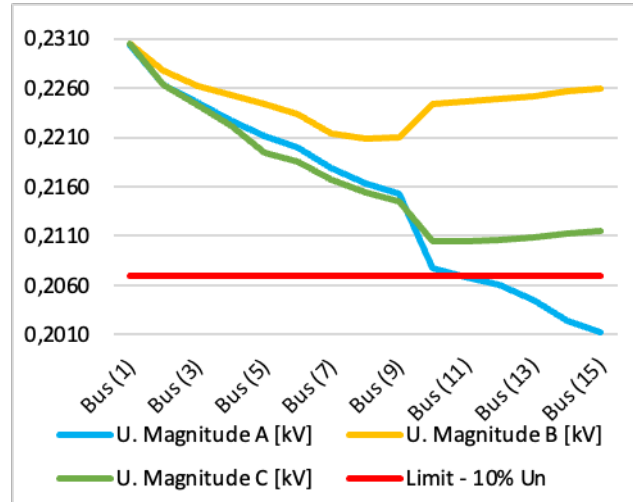


Figure 2: Voltage variations along the main feeder before optimization, 1<sup>st</sup> scenario of 33% - 33% - 33% load distribution and 50% of EV penetration

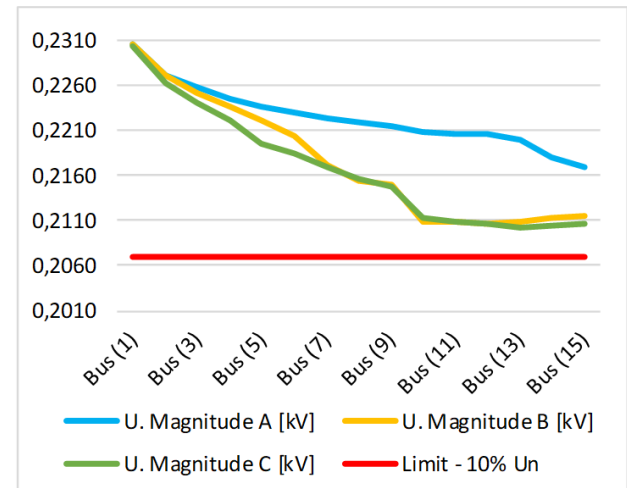


Figure 3: Voltage variations along the main feeder after optimization, 1<sup>st</sup> scenario of 33% - 33% - 33% load distribution and 50% of EV penetration

In Table II as well as in other similar tables below, if a phase number is red, it means that it is the phase to which the single-phase load is connected to. If a load and EV are combined in results, it means that they are both single-phase and are connected to the same phase and will therefore be permuted as a single load. The number in the bracket indicates whether the load is three-phase or single-phase. This should help the reader keep track of changes in the tables easily.

As can be seen from the resulting graph in Figure 3., phases A and C experienced a reduction in voltage drop while advancing towards the end of the main feeder. Phase 1 now has the lowest value of 216.953 V, which

is higher than the value it had before optimization, which was 201.284 V. The phase with the lowest value is now phase 3 with lowest recorded voltage at the very end of the feeder being 210.650 V.

Table II: Data permutation per element, 1<sup>st</sup> scenario of 33% - 33% - 33% load distribution and 50% of EV penetration

| List of changes              |                |           |
|------------------------------|----------------|-----------|
| Elements (no. of phases)     | Original phase | New phase |
| EV 10                        | 1              | 3         |
|                              | 2              | 1         |
|                              | 3              | 2         |
| EV 19                        | 1              | 2         |
|                              | 2              | 3         |
|                              | 3              | 1         |
| EV 9                         | 2              | 3         |
|                              | 3              | 2         |
| EV 18                        | 1              | 2         |
|                              | 2              | 3         |
|                              | 3              | 1         |
| EV 20                        | 2              | 3         |
|                              | 3              | 2         |
| Number of modified elements: | 5              |           |

## 2.2. Second scenario (40% - 30% - 30% load distribution) with 20% of EV penetration

The feature of all studied second scenarios was the distribution of 40%-30%-30% loads per phase. The combination of this load phase distribution with 10% of EV penetration resulted with acceptable results since no limits were violated. However, the penetration of 20% caused a violation of voltage variation limit, as shown in [7]. Violation of limit is shown in Figure 4.

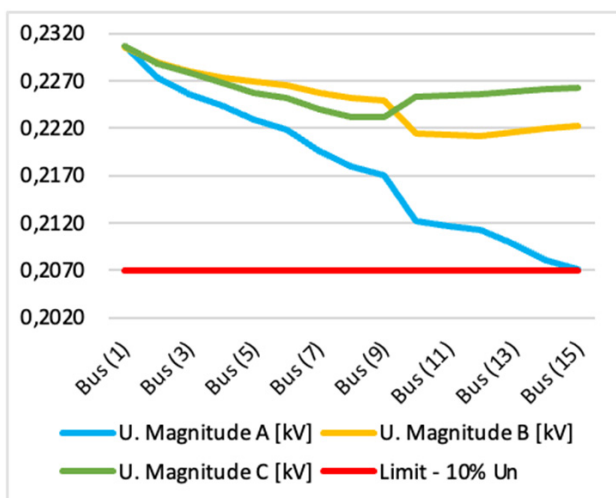


Figure 4: Voltage variations along the main feeder before optimization, 2<sup>nd</sup> scenario of 40% - 30% - 30% load distribution and 20% of EV penetration

Using the same settings as in the previous scenario and a new minimal improvement value of 5%, the results obtained are presented in Figure 5. Total number of required changes for this modification is 1. The list of changes regarding data permutation of phases of each element included in the process is shown in Table III.

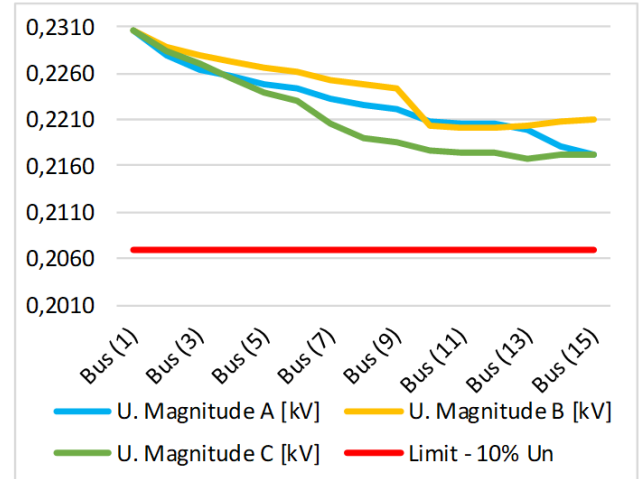


Figure 5: Voltage variations along the main feeder after optimization, 2<sup>nd</sup> scenario of 40% - 30% - 30% load distribution and 20% of EV penetration

The lowest voltage value at the very end of the feeder in the second scenario with 20% of EVs without optimization was 207.110 V. This value was increased to 215.356 V thanks to the permutations performed within the optimization.

Table III: Data permutation per element, 1<sup>st</sup> scenario of 40% - 30% - 30% load distribution and 20% of EV penetration

| List of changes              |                |           |
|------------------------------|----------------|-----------|
| Elements (no. of phases)     | Original phase | New phase |
| EV 7                         | 1              | 3         |
|                              | 2              | 1         |
|                              | 3              | 2         |
| Number of modified elements: | 1              |           |

## 2.3. Second scenario (40% - 30% - 30% load distribution) with 50% of EV penetration

As could be expected, the second scenario with 50% of EV penetration continued the violation made with a lower penetration of 20% EVs. Voltage variations per phase are given in Figure 6.

As in previous cases, objective function used was 'Minimize average power unbalance' and the method was large loads and generators first. The minimal improvement value which gave acceptable results was 0.6% and the total number of changes within this modification was 9. The resulting voltage drop across the main feeder after the optimization

is provided in Figure 7. List of changes is provided in Table IV, given in the order as provided in the DlgSILENT PowerFactory.

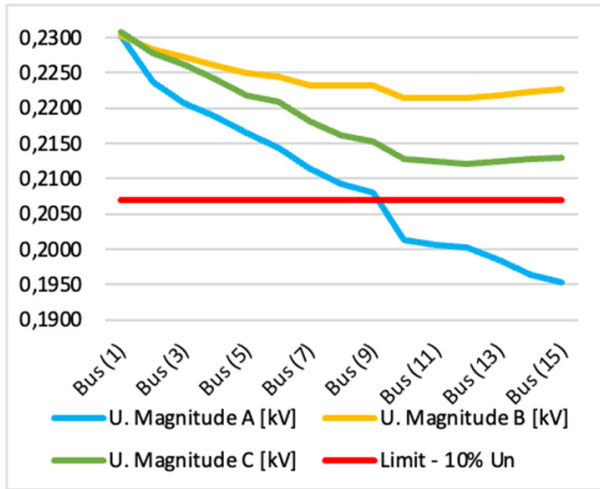


Figure 6: Voltage variations along the main feeder before optimization, 2<sup>nd</sup> scenario of 40% - 30% - 30% load distribution and 50 % of EV penetration

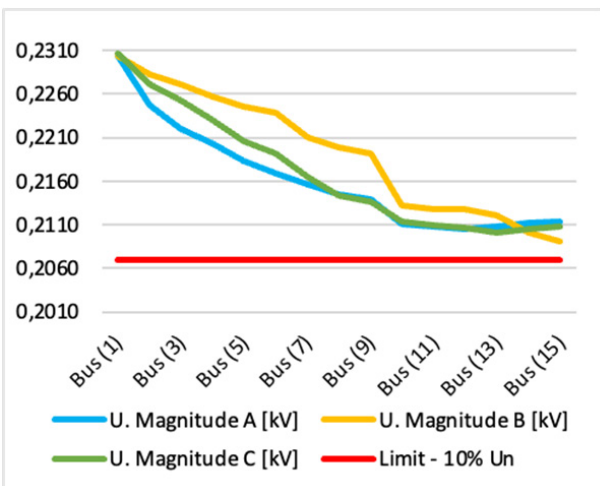


Figure 7: Voltage variations along the main feeder after optimization, 2<sup>nd</sup> scenario of 40% - 30% - 30% load distribution and 50 % of EV penetration

The lowest value of voltage variation recorded before optimization was 195.303 V. After performing Phase Balance Optimization, the voltage value was increased to 211.379 V. The phase with the lowest value of voltage is now Phase 2 with voltage of 209.081 V. This value is close to the limit, however, was the best possible result.

#### 2.4. Fourth scenario (50% - 25% - 25% load distribution) with 10% of EV penetration

All fourth scenarios shared the same load distribution of 50%-25%-25%. Phase A, being doubly loaded when compared to other two phases, has experienced the largest voltage drops in all combinations of EV penetration. The graph with voltage variations along the main feeder before optimization is provided in Figure 8.

Table IV: Data permutation per element, 2<sup>nd</sup> scenario of 40% - 30% - 30% load distribution and 50% of EV penetration

| List of changes              |                |           |
|------------------------------|----------------|-----------|
| Elements (no. of phases)     | Original phase | New phase |
| Load (4535294 (1))           | 1              | 3         |
|                              | 2              | 1         |
|                              | 3              | 2         |
| EV 7                         | 1              | 3         |
|                              | 2              | 1         |
|                              | 3              | 2         |
| Load (4536118) + EV          | 1              | 2         |
|                              | 2              | 1         |
| EV 9                         | 1              | 2         |
|                              | 2              | 3         |
|                              | 3              | 1         |
| Load (4535987) + EV          | 1              | 2         |
|                              | 2              | 3         |
|                              | 3              | 1         |
| Load (4535111) + EV          | 1              | 2         |
|                              | 2              | 3         |
|                              | 3              | 1         |
| Load (4536150) + EV          | 1              | 2         |
|                              | 2              | 3         |
|                              | 3              | 1         |
| EQUIVALENT                   | 1              | 3         |
|                              | 2              | 1         |
|                              | 3              | 2         |
| EV 20                        | 2              | 3         |
|                              | 3              | 2         |
| Number of modified elements: | 9              |           |

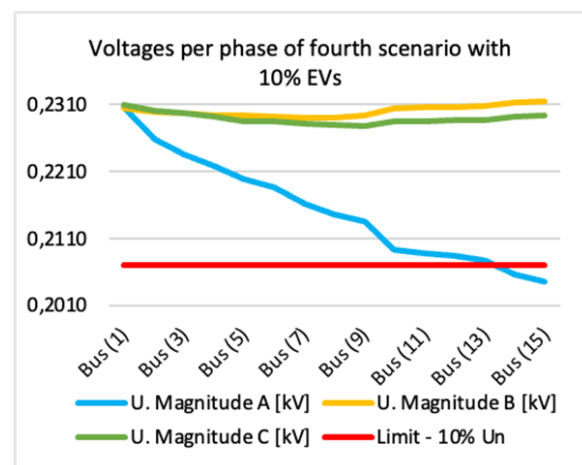


Figure 8: Voltage variations along the main feeder before optimization, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 10% of EV penetration

Within that setting the minimal improvement value chosen for the 'Acceptance of change' was 2%. Total number of changes for this modification was 3. Voltage variations obtained after the optimization is shown in Figure 9. List of changes is provided in Table V.

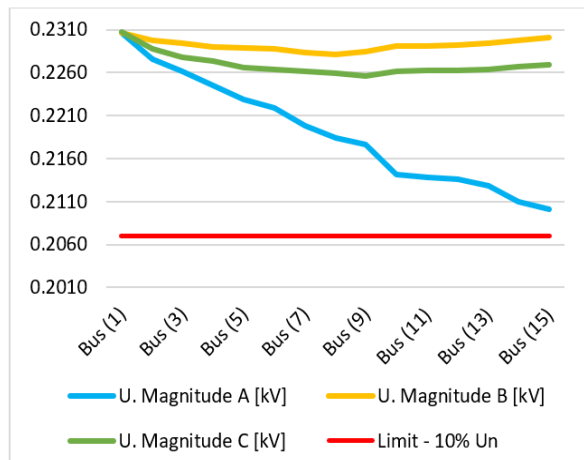


Figure 9: Voltage variations along the main feeder after optimization, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 10% of EV penetration

Table V: Data permutation per element, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 10% of EV penetration

| List of changes              |                |           |
|------------------------------|----------------|-----------|
| Elements (no. of phases)     | Original phase | New phase |
| Load (4536657 (1))           | 1              | 2         |
|                              | 2              | 3         |
|                              | 3              | 1         |
| Load (4416406 (1))           | 1              | 2         |
|                              | 2              | 3         |
|                              | 3              | 1         |
| EV 7-8 (Equivalent)          | 1              | 3         |
|                              | 2              | 1         |
|                              | 3              | 2         |
| Number of modified elements: | 3              |           |

The lowest value of voltage at the very end of the feeder before the optimization was recorded to be 204.542 V. This value was increased to 210.049 V, thanks to Phase Balance Optimization.

## 2.5. Fourth scenario (50% - 25% - 25% load distribution) with 20% of EV penetration

Voltage variation along the main feeder of the 4<sup>th</sup> scenario with 20% of EV penetration before optimization is provided in Figure 10.

The input settings of the Phase Balance Optimization are the same as in previous scenario, with minimal

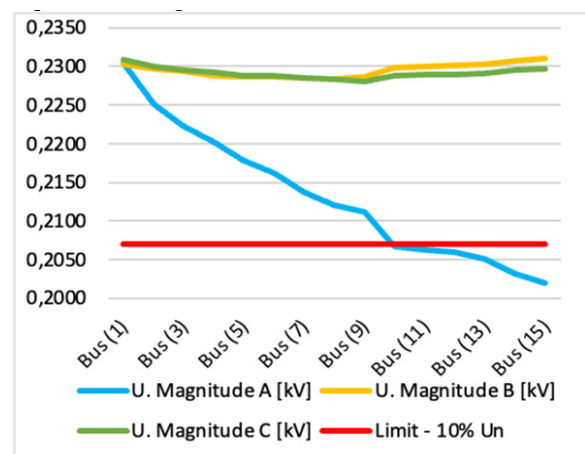


Figure 10: Voltage variations along the main feeder before optimization, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 20% of EV penetration

improvement value of 2%. For such a modification total of 3 changes are required to take place. The resulting voltage variations are provided in Figure 11. Table VI shows the list of changes made by such a modification.

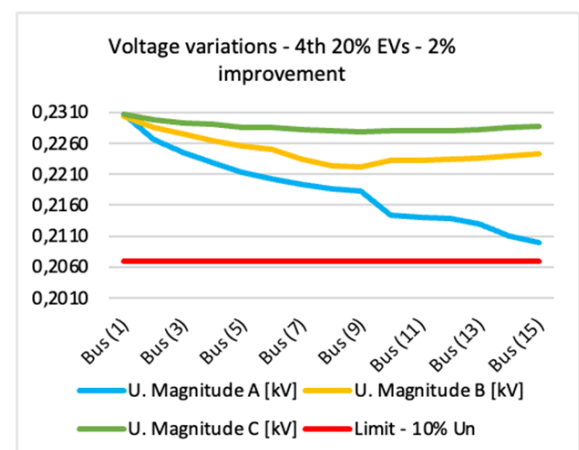


Figure 11: Voltage variations along the main feeder after optimization, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 20% of EV penetration

Table VI: Data permutation per element, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 20% of EV penetration

| List of changes              |                |           |
|------------------------------|----------------|-----------|
| Elements (no. of phases)     | Original phase | New phase |
| Load (4536657 (1))           | 1              | 3         |
|                              | 2              | 1         |
|                              | 3              | 2         |
| EV 4                         | 1              | 2         |
|                              | 2              | 3         |
|                              | 3              | 1         |
| EV 9-12 (Equivalent)         | 1              | 3         |
|                              | 2              | 1         |
|                              | 3              | 2         |
| Number of modified elements: | 3              |           |

The lowest recorded value of voltage at the very end of the feeder before optimization was found to be 201.969 V. This voltage was increased to value of 213.384 V thanks to Phase Balance Optimization, making this scenario acceptable in terms of the observed power quality parameters.

## 2.6. Fourth scenario (50% - 25% - 25% load distribution) with 50% of EV penetration

The last analysed scenario was also the worst possible combination of load distribution and EV penetration. The results obtained in [7] show that this scenario is the only one that managed to violate both voltage variation and unbalance limit. Voltage drop along the main feeder is shown in Figure 12, while the voltage unbalance is provided in Figure 13.

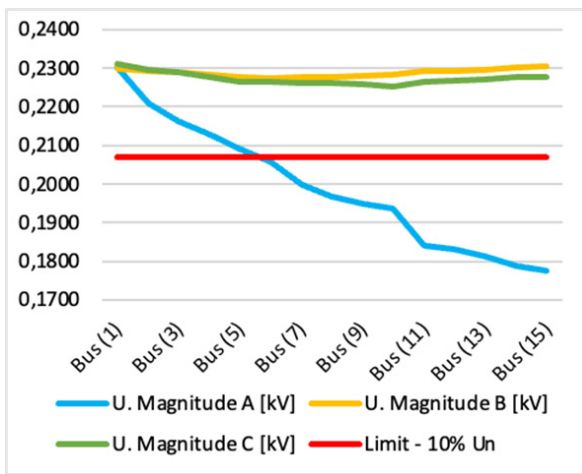


Figure 12: Voltage variations along the main feeder before optimization, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 50% of EV penetration

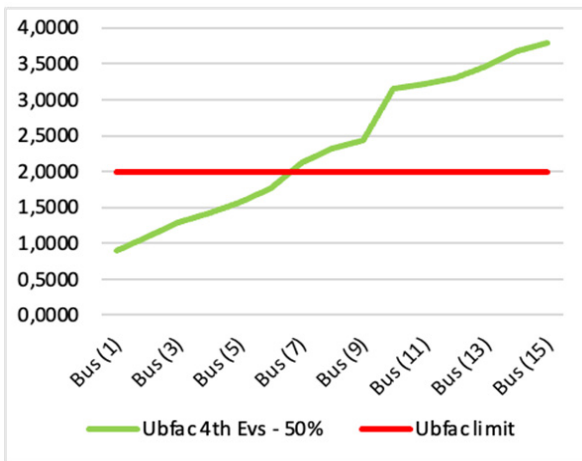


Figure 13: Unbalance along the main feeder before the optimization, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 50% of EV penetration

In this case, the goal was to find an optimal distribution of loads which will satisfy both unbalance and variations limit. The minimal improvement value which gave satisfying results was found to be 0.5%. The resulting voltage

variation and unbalance after optimization are presented in Figure 14 and Figure 15, respectively. The required number changes for this modification was 18, with the detailed information provided in Table VII in the order given as in DlgSILENT Power Factory output window.

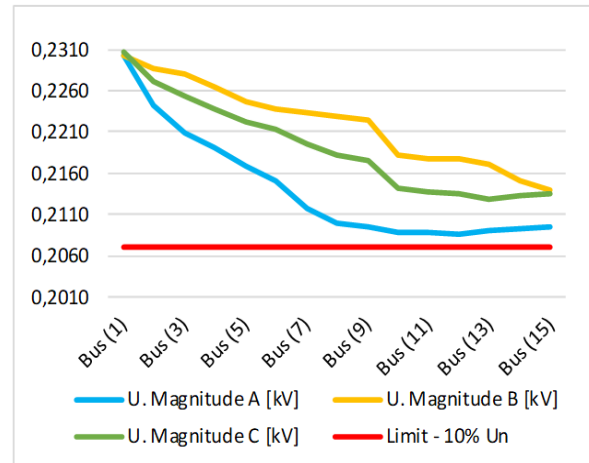


Figure 14: Voltage variations along the main feeder after optimization, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 50% of EV penetration

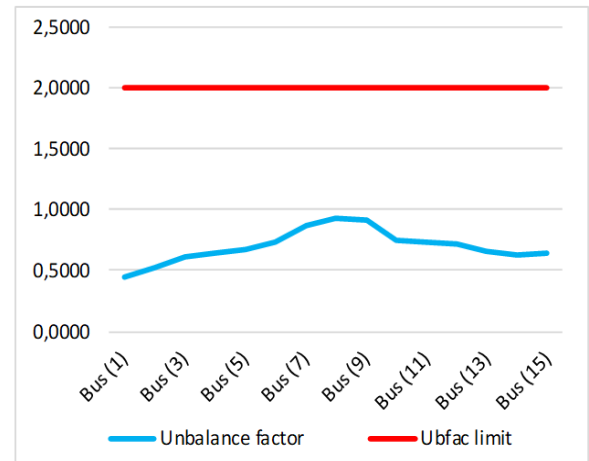


Figure 15: Unbalance along the main feeder after the optimization, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 50% of EV penetration

Table VII: Data permutation per element, 4<sup>th</sup> scenario of 50% - 25% - 25% load distribution and 50% of EV penetration

| List of changes          |                |           |
|--------------------------|----------------|-----------|
| Elements (no. of phases) | Original phase | New phase |
| EV 21                    | 2              | 3         |
|                          | 3              | 2         |
| Load (4535294 (1))       | 1              | 2         |
|                          | 2              | 3         |
|                          | 3              | 1         |
| Load (8718660 (1))       | 1              | 2         |
|                          | 2              | 3         |
|                          | 3              | 1         |

|                              |    |   |
|------------------------------|----|---|
| EV 22                        | 1  | 3 |
|                              | 2  | 1 |
|                              | 3  | 2 |
| Load (4534972) + EV          | 1  | 3 |
|                              | 2  | 1 |
|                              | 3  | 2 |
| Load (4766199 (3))           | 1  | 2 |
|                              | 2  | 3 |
|                              | 3  | 1 |
| EV 14                        | 1  | 2 |
|                              | 2  | 1 |
| Load (4535987) + EV          | 1  | 2 |
|                              | 2  | 3 |
|                              | 3  | 1 |
| Load (4535111) + EV          | 2  | 3 |
|                              | 3  | 2 |
| Load (4416406 (1))           | 1  | 2 |
|                              | 2  | 3 |
|                              | 3  | 1 |
| Load (4536150 (1))           | 1  | 2 |
|                              | 2  | 3 |
|                              | 3  | 1 |
| Load (4536371) + EV          | 1  | 2 |
|                              | 2  | 1 |
| EV 5                         | 2  | 3 |
|                              | 3  | 2 |
| Load (4535472 (3))           | 1  | 2 |
|                              | 2  | 3 |
|                              | 3  | 1 |
| Load (4536010) + EV          | 1  | 2 |
|                              | 2  | 1 |
| EQUIVALENT                   | 1  | 3 |
|                              | 3  | 1 |
| Load (4765141 (3))           | 1  | 3 |
|                              | 3  | 1 |
| EV 19                        | 1  | 2 |
|                              | 2  | 3 |
|                              | 3  | 1 |
| Number of modified elements: | 18 |   |

The lowest value of voltage at the very end of the feeder before optimization was recorded to be 177.624 V. After optimizing the network, this value was increased to be 209.528 V. On the other hand, the highest unbalance at the very end of the feeder before optimization was recorded to be 3.79%. After optimization, this value was reduced to 0.65%.

### 3. CONCLUSIONS

Voltage variations and unbalance as power quality parameters are of extreme importance for the proper behaviour of equipment in low-voltage electricity distribution networks. Introducing a large fleet of EVs without regulated charging causes additional loading stress, since they act as usual loads when in charging mode. Connection of electric vehicles impacts both the voltage variation and voltage unbalance of the network.

In all analysed scenarios of the previous work [7], loads experienced voltage drops that increased with distance from the starting point of the transformer and with increase of EVs connected. The purpose of this project was to optimize all scenarios which violated any of the given limits, with a least number of required changes in terms of phase data permutations.

Results showed that even with the optimization, the critical scenarios are all those with 50% of EV penetration, since even after optimization the values are close to the limits, especially as the load distribution per phase gets more uneven. This means that having that many EVs charging simultaneously leads to reaching the limit of its capacity. During the day, charging of EV's is expected to have variations which could easily cause a limit violation. Best solution is to introduce regulated charging, outside of periods of network peak demand, which should guarantee that the voltage is within the limits from EN 50160. Possible solution could be integration of distributed generators which could improve the voltage profiles, especially near the end of the feeder and in remote areas, followed by regulated charging.

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