

ANALYSIS OF VOLTAGE PROFILES, UNBALANCE VOLTAGES AND PHASE BALANCE OPTIMIZATION OF SINGLE-PHASE CUSTOMER AND PHOTOVOLTAIC CONNECTION AT REAL LOW VOLTAGE FEEDER

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Abstract: Voltage unbalance is common issue encountered in low voltage distribution networks, caused by uneven allocation of single-phase customers among phases. This paper analyses part of real low voltage distribution network in Bosnia and Herzegovina. The impact of single-phase customers and single-phase connected micro photovoltaic power plants (MPPP-s) were analysed. To reduce unbalance and improve voltage profiles, Phase Balance Optimization toolbox in DigSILENT PowerFactory software was performed in six scenarios with different distribution of customers and different percentage of penetration of MPPS-s. The aim was to find method with least number of changes in customer and photovoltaic phase connection that fits within defined limits of voltage variations and voltage unbalance of European standard for power quality (EN 50160). Conclusion is that MPPP-s cause voltage increases in the network, as well as an increase in voltage unbalance, but these effects can be mitigated by proper distribution of customer loads and MPPS-s among phases.

Keywords: low voltage network, micro photovoltaic power plant, Phase Balance Optimization, voltage variations, voltage unbalance, EN 50160 standard

INTRODUCTION

Voltage unbalance is one of the most common power quality problems in LV distribution networks. Unbalanced single-phase loading in a three-phase system causes voltage unbalance. One of the power quality parameters from the European standard EN 50160 is voltage unbalance. The percentage of permissible unbalance is 2%. The majority of equipment can withstand unbalances of up to 2%, however, if they exceed 2%, the result can be motor and transformer overheating. This is caused by the current unbalance at the terminals fluctuating as a cube of the voltage unbalance [1], [2]. The type of connecting can either improve or make the voltage unbalance factor (VUF) worse.

One of the aims is to investigate how utility-scale PV-DG impacts both steady-state and dynamic planning and operation of power distribution systems. The small distributed renewable PV systems are often not owned or operated by the utility. Distributed producing and storage units can increase service reliability by creating supply islands that reduce the impact of breakdowns on customers inside their protective zones. This generation could level the load curve, improve voltage reliability and profile, reduce feeder losses, increase transmission capacity margin, and provide environmental benefits, whose findings are covered in [3], [4].

Through [5], identifying of voltage variations on uniform and non-uniform feeder without violating upper voltage limit is presented.

In [6], the impact of the residential grid-connected photovoltaic (PV) system on the LV network was evaluated in terms of voltage profiles and effect of unbalanced PV connection and in the end efficient because of relatively short feeder length and high cable rating used in taken LV network.

During high level of integration, one of issues is that the voltage profile is expected to change and increase to impermissible level by high PV penetration. Different voltage increases mitigation techniques investigated active power curtailment, reactive power injection and a hybrid combination of these two methods [7]-[9].

By applying Forward/Backwards Sweep (FBS) and Newton-Raphson (NR) methods, improvement of voltage profiles and assessment of voltage unbalance of the three-phase unbalanced distribution network on three phase unbalanced 8-bus system is done in [10], with three different PV penetration levels (30%, 50% and 80%).

In [11], [12], it was shown that installation of a distribution static compensator (DSTATCOM) at 2/3 of the beginning of the feeder can reduce voltage unbalance effectively.

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A case study of a real distribution power system of housing estate is done in [13]. Voltage unbalance and energy losses were simulated by using system characteristic and load data from GIS database of Provincial Electricity Authority (PEA) with the DlgSILENT Power Factory software. The number of installable single-phase rooftop PV systems varies directly with load density and the number of installed single-phase rooftop PV systems can be increased if the installation locations are closer to the transformer.

The novelty of this paper is that the most of the presented references are focused on the situation with high penetration of micro-PV power plants, in which the vast majority had disturbances with the power quality, therefore, this paper focuses on a more realistic, smaller penetration of micro-PV power plants in the LV distribution network of Bosnia and Herzegovina (B&H), taking into consideration the rare presence of PVs in the power system of B&H, which will enable obtaining of a more realistic permissible limit of PV penetration in the power system, considering its characteristics of an underloaded power system of B&H.

After the introduction with literature review, Chapter 1 gives an overview and the concept of modelling of analysed LV feeder and mathematical model of the optimization which is used for, while Chapter 2 presents summary of obtained results for different scenarios with comments and discussion. In the last, Chapter 3, there is conclusion regarding analysed problematics.

1. RESEARCH OF ONE REAL LOW VOLTAGE DISTRIBUTION NETWORK

1.1. Methodology

The real part of the rural LV distribution voltage transformer station (TS), in the vicinity of Tešanj, was analysed. It was chosen to check how the arrangement of consumers and micro-PV power plants affect the voltage parameters of the power quality in the network. Due to the length of the main feeder line of 584 meters and the distribution of remote customers, the area is supplied by a 10/0.4 kV distribution transformer with an installed capacity of 160 kVA. The analysed LV feeder consists of 26 consumers, of which all 26 are active and registered. From those 26 active consumers, 7 are three-phase, while the other 19 are single-phase, which will be important for the further analysis. Figure 1 shows the entire considered network. The blue-pink squares represent consumers, with three locations and two consumers on each location denoted, which in total gives 26 customers. It can be seen that consumers are most densely distributed in the middle of the network. The greater the distance of consumers from the substation is, the more significant is the effect to the changes of power quality in this distribution network caused by changes in the consumption of these consumers.

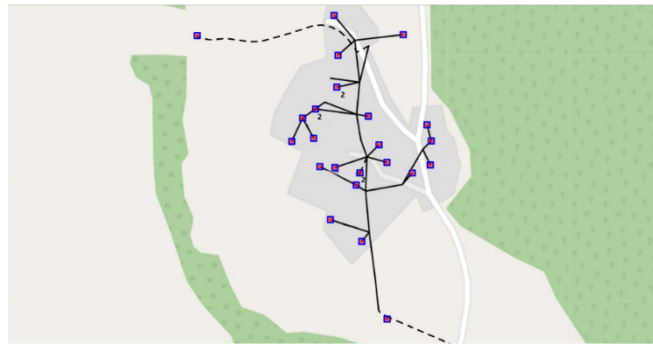


Figure 1: Georeferenced representation of modelled network

Only the busbars on the main feeder to which consumers are connected directly were considered. There are 17 such busbars. The graphs of voltage variations and voltage unbalances represent the busbar voltages across the main feeder line. From the submitted literature from Public Electric Utility Elektroprivreda of Bosnia and Herzegovina d.d., for the network that was considered, the data from the control meter was processed. From the fifteen-minute readings from the control meter at the substation (TS) during the summer months (June, July, August) in the year because those months have most sunny days, the day with the lowest consumption during high micro-PV power plants' production should be determined by filtering all values of consumption in the three mentioned summer's months around the middle of the day. The reactive energy readings from the control meter at the substation (TS) were ignored throughout the whole analysis because they were equal to 0 MVar and readings of the active power from the control meters were only present. Based on mentioned facts, the day 02ND July 2021, at 12:30 P.M. was chosen. the lowest consumption of the day from the control meter during high production of micro-PV power plants is equal to 2.512 kW, which is a multiplier of the active power read from the control meter (0.0628 kW) and the measurement constant, which is equal to 40. The minimum modelled load is 2.512 kW. It is distributed in the model among three consumers, two of 1 kW (one is in the beginning and the another one is in the middle of the network) and the third one of 0.512 kW is in the end of the network. Other customers are equal to 0 kW. The customer has a micro-PV power plant and it produces electricity during the day, there is no one at home, so the consumption is 0 kW at that moment of the day. Through all scenarios, before applying the optimization, the phase „b“ is the most loaded. Therefore, it is necessary to optimize and improve violated voltages and voltage unbalances, i.e., the results of which are not within the EN 50160 standard. Figure 2 shows a graph of hourly meter values for the mentioned day with the lowest consumption during high production of micro-PV power plants, which is around the middle of the day.

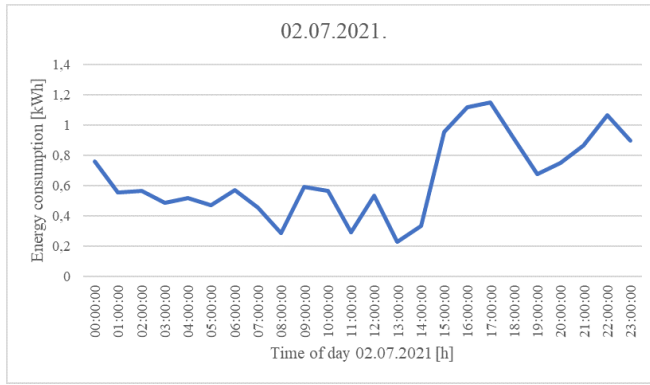


Figure 2: Day with the lowest consumption during high production of micro-PV power plants

1.2. Phase Balance Optimization

Although unsymmetric customers are commonly seen in distribution networks, their increased loading and losses on lines and transformer windings make them undesirable. The Phase Balance Optimization (PBO) feature, located in the Distribution Network Tools toolbox of DIgSILENT PowerFactory, facilitates the reconfiguration of connected phases for unsymmetrical elements to diminish power unbalance within the network. This tool is applicable to radially operated feeders.

The optimization algorithm provides the option to execute for two distinct objective functions: "Minimize average power unbalance" (utilized for all scenarios) and "Minimize power unbalance at feeding point." In both cases, the primary focus is on minimizing power unbalance (s). For branch elements, this is defined as follows:

Let N represent the number of phases, and consider:

$$\bar{S} = \frac{1}{N} \sum_{i=0}^N S_i \quad (1)$$

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

$$\bar{S} = \frac{1}{N} \sum_{i=0}^N |S_i| \quad (2)$$

denote the mean of the absolute values of powers on various phases. Subsequently, the power unbalance factor (sb) for the branch element b is defined as follows:

$$S_b = \left(\frac{1}{S} \right) \max \{ |S_i - \bar{S}| \} \quad (3)$$

To mitigate voltage variation, adjustments were made to the voltage unbalance utilizing the Phase Balance Optimization tool within DIgSILENT PowerFactory. Consequently, voltage variations were indirectly modified by addressing unbalance. The optimization process employed an objective function named 'Minimize Average

Power Unbalance,' which considers the power unbalance across all M branch elements within the analysed feeder. The average power unbalance is specifically defined as:

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

To achieve the minimization of power unbalance, 3 different optimization methods are available to select and execute:

1. Large loads and generators first (This algorithm sequentially processes all loads and generators based on their apparent power, commencing with the most substantial load or generator. For each load or generator, it systematically rearranges the connections of the load or generator and its supplying branch elements. Following the calculation of the objective function for all potential connections, the algorithm selects the optimal connection for the given load or generator.)
2. Simulated annealing (This is a stochastic optimization method, which reconnects the grid randomly, and during a cool down of the 'system' it will reach good solutions. During the execution of the algorithm, so called temperature T_n is tracked, which cools down the longer the algorithm lasts. At each iteration n of the algorithm, first a new proposal for reconnections is generated.)
3. Genetic algorithm (This is also stochastic optimization, with a search-based optimization technique based on the principles of biological evolutions though Genetics and Natural Selection. It is commonly used to find optimal or near-optimal solutions and values of the problems from the search space, which otherwise would have taken a significant amount to solve.)

During the analysis of the six mentioned scenarios, the method was used whose results of voltage variations were the most acceptable, that are, within the limits of the standard EN 50160 and with the smallest gaps between voltage variations.

2. RESULTS AND DISCUSSION

There is total 9 scenarios and in 6 of them, there came to exceeding of limits of voltage profiles. Other 3 scenarios are within the standard EN 50160; therefore, this section is organized according to 6 analysed scenarios in this paper, which required alterations to fit within the defined limits from standard EN 50160. Each scenario has its own subsection and includes results before optimization and after optimization, with new results obtained from Phase Balance Optimization. In Table I an overview of analysed scenarios is shown, where 6 scenarios with the violated limit of voltage profiles and voltages unbalances are analysed and denoted by red colour.

Analysing the impact of penetration of single-phase micro-PV power plants on the voltage and its unbalance, the critical case is when the load is the least. This is done in a way as to determine the moment of minimum consumption, i.e., the minimum 15-minute recorded power value, when the production from micro-PV power plants is the highest (they work at maximum power), i.e., minimum consumption in the period 11 A.M. to 1 P.M. in winter time, or from 12 P.M. to 2 P.M. in summer time. The values for one of the specified periods are filtered out and thus the required moment is obtained. Furthermore, this leads to maximum voltages and it is a critical case to be analysed. The total power in the network for the obtained moment is 2.512 kW and this power (about a third) is distributed on the feeder of the default network as a percentage based on the measured power on the smart meter and it is entered into the network's model for 3 customers (the rest of them are equal to 0 kW). The scenarios were modelled when the distribution of single-phase micro-PV power plants by phase in the network are: 33%-33%-33%, 40%-30%-30% and 50%-25%-25%, respectively. The distributions 33%-33%-33 %, 40%-30%-30% and 50%-25%-25% represent the distributions of single-phase micro-PV power plants by phases "a", "b" and "c", that is, how many of them are there per phase in the given scenario. The percentages 10%, 20% and 50% represent the percentages of micro-PV power plants, that is, how many customers have them in the network for the given scenario. By completing the phasing and penetration percentage of the micro-PV power plants which are determined, installed capacities of micro-PV power plants are determined as 80% of the connected power of each customer who has a power plant in the given scenario, which is the standard power value of a single prosumer.

Table I: Overview of analysed scenarios

	1 st scenario (33%-33%-33%)	2 nd scenario (40%-30%-30%)	3 rd scenario (50%-25%-25%)
Number of PVs per scenario	3 PVs (10%) 6 PVs (20%) 15 PVs (50%)	3 PVs (10%) 6 PVs (20%) 15 PVs (50%)	3 PVs (10%) 6 PVs (20%) 15 PVs (50%)

2.1. First scenario (33%-33%-33% customer distribution) with 50% penetration of micro photovoltaic power plants

In Table II, distribution of micro-PV power plants per phase at 33%-33%-33% customer distribution and 50% penetration of micro-PV power plants is shown:

Table II: Distribution of micro photovoltaic power plants per phase for the first scenario

	Phase "a"	Phase "b"	Phase "c"
Number of PVs per phase	5	5	5
Installed capacity of PV power plants	26.8 kW	26.8 kW	27.44 kW
Absolute value of loads per phase	33.5 kW	33.5 kW	34.3 kW

2.1.1. Before Phase Balance Optimization

The large amount of micro-PV power plants causes disturbances in the power quality of electricity and being connected violated a voltage variation limit of 255 V (or +10% of U_n), while the layout of consumers is symmetrical and favourable. Therefore, this scenario has to be improved by Phase Balance Optimization applied. Results before optimization are given in Figure 3 (up). Voltage variations per phase "b" are denoted by blue dash dot line in order to show which phase is the most loaded. It is phase "b" and for each scenario, before applying optimization, the phase "b" is denoted by blue dash dot line and highest value of voltage variations is in this phase in the end of the feeder, i.e. at terminal T17 and it is equal to 271.12 V. Voltage variations per phase "c" are out of upper voltage limit of standard EN 50160 and the highest

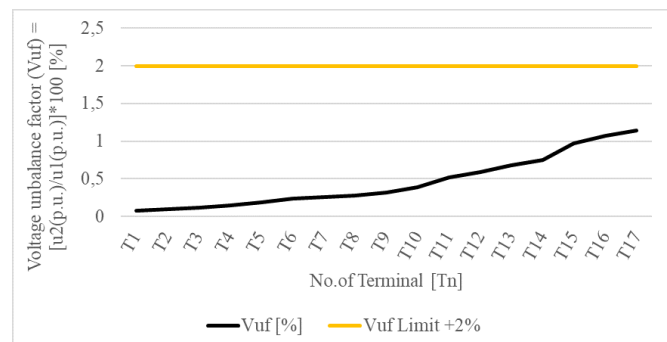
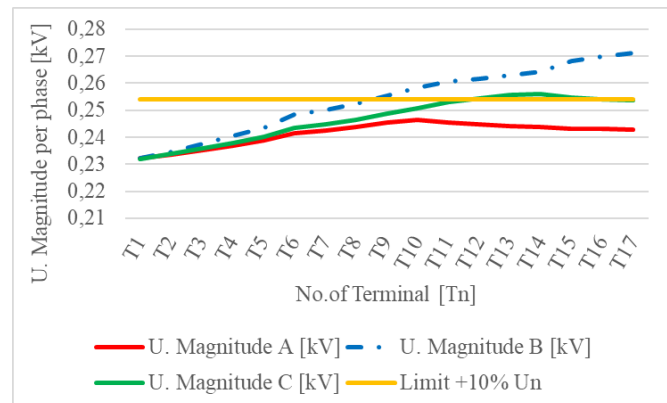


Figure 3: Voltage variations (up) and voltage unbalance (down) along the main feeder before optimization for the first scenario

value is 256.02 V at terminal T14, while voltage variations per phase „a“ are within of the limit of the standard EN 50160 and highest value is 246.51 V at terminal T10.

Voltage unbalance before applying Phase Balance Optimization is shown in Figure 3 (down). The voltage unbalance before applying optimization is within voltage unbalance limit of standard EN 50160. The highest value of voltage unbalance is in the end of the feeder and it is 1.13 % in the end of the feeder, i.e., at terminal T17.

2.1.2. After Phase Balance Optimization

Optimization method applied in this scenario was Simulated annealing. That is type of stochastic optimization, with aim to maximize or minimize objective functions when the stochastic problems are taken into consideration.

The resulting voltage variations, after the Phase Balance Optimization calculation are provided in Figure 4 (up). As can be seen, all three phases experienced an increase in voltage while advancing towards the end of the main feeder. On all three feeders, there are busbars with increased voltages out of the standard EN 50160. The highest value of voltage variations is in phase "a" and it is equal to 258.06 V at terminal T15 and it is out of the limit of the standard EN 50160. This value is higher than the value it had before optimization, which was 246.51 V. The highest value of voltage variations per phase "c" is 255.89 V at terminal

T14, while the highest value of voltage variations per phase „b“ decreased to 257.35 V in the end of the feeder, i.e. at terminal T17 thanks to the permutations performed within the optimization, which is lower than voltage variations per phase "b" before applying Phase Balance Optimization, where it was equal to 271.12 V. Also, voltage variations per phases "a" and "c" decreased from the same reason as voltage variations per phase "b".

Voltage unbalance after applying Phase Balance Optimization is shown in Figure 4 (down). It is noticeable that the voltage unbalance after applying optimization has significantly been improved in comparison to the scenario before applying optimization. The highest value of voltage unbalance is in the end of the feeder and it is 0.25 % in the end of the feeder, i.e., at terminal T17.

Table III presents the alterations in phase connections, with a total of 5 permutations necessary for this modification. In this table, and others to follow, a phase number highlighted in red signifies the connection point for both the single-phase customer and micro-PV power plants. The number within parentheses indicates whether the customer has a three-phase or single-phase connection. This color-coded system is designed to facilitate the reader's easy tracking of changes in the tables.

Table III: Data permutation per element for the first scenario

Elements (no. of phases)	Original phase	New phase
Customer 5172632 (1-ph) at Terminal 17	1	3
	2	1
	3	2
PV7 (at Terminal 22)	1	3
PV9 (at Terminal 24)	3	2
PV8 (at Terminal 30)	2	1
PV1 (at Terminal 40)	2	1

2.2. Second scenario (40%-30%-30% customer distribution) with 20% penetration of micro photovoltaic power plants

In Table IV, distribution of micro-PV power plants per phase at 40%-30%-30% customer distribution and 20% penetration of micro-PV power plants is shown:

Table IV: Distribution of micro photovoltaic power plants per phase for the second scenario

	Phase "a"	Phase "b"	Phase "c"
Number of PVs per phase	2	3	1
Installed capacity of PV power plants	10.72 kW	16.08 kW	5.36 kW
Absolute value of loads per phase	13.4 kW	20.1 kW	6.7 kW

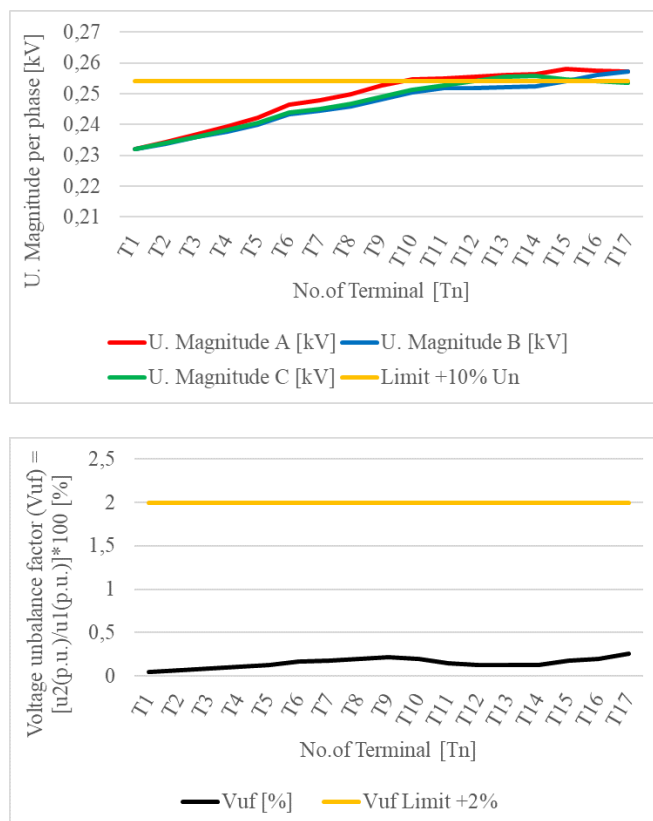


Figure 4: Voltage variations (up) and voltage unbalance (down) along the main feeder after optimization for the first scenario

2.2.1. Before Phase Balance Optimization

This scenario again has to be improved by Phase Balance Optimization applied. Results before optimization are given in Figure 5 (up). The highest value of voltage variations is in phase "b" and it is equal to 262.56 V at terminal T17. Voltage variations per phase "a" and "c" are within upper voltage limit of standard EN 50160 and their highest values are 244.01 V at terminal T13 and 231.25 V at terminal T1, respectively.

Voltage unbalance before applying Phase Balance Optimization is shown in Figure 5 (down). The voltage unbalance before applying optimization is within upper voltage limit of standard EN 50160, but it is very close to the voltage unbalance limit and optimization would be desirable. The highest value of voltage unbalance is in the end of the feeder and it is 1.80 % in the end of the feeder.

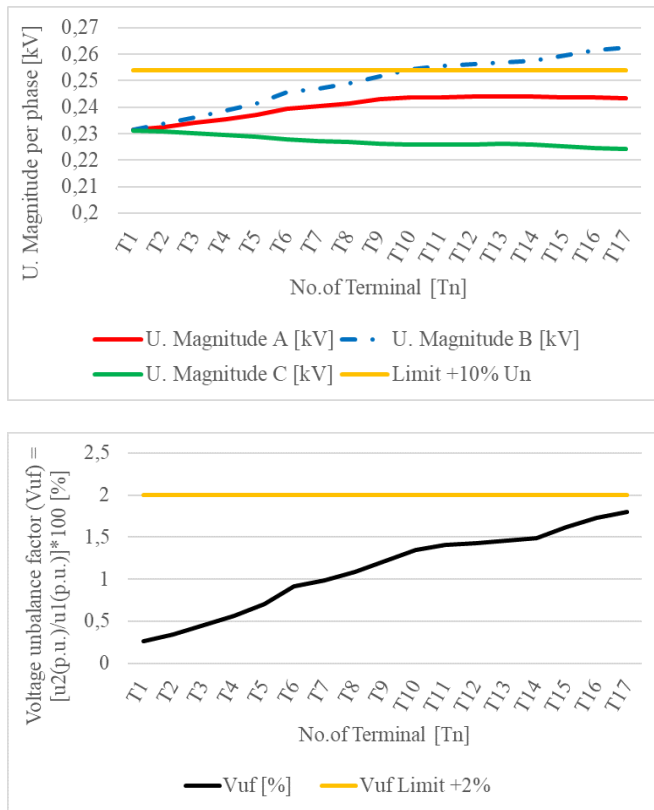


Figure 5: Voltage variations (up) and voltage unbalance (down) along the main feeder before optimization for the second scenario

2.2.2. After Phase Balance Optimization

Optimization method applied in this scenario was Genetic algorithm. The resulting voltage variations, after the Phase Balance Optimization calculation are provided in Figure 6 (up). All voltage variations are within the upper voltage limit of standard EN 50160. The highest value of voltage variations is in phase „a“

246.18 V at terminal T13, which is higher than the value it had before optimization, which was 244.01 V, but it did not have a negative impact for the network, since they remained within limit of standard EN 50160. The same situation is with voltage variations per phase "c". After applying optimization, highest value of voltage variations per phase "c" is 244.50 V at terminal T17, which is again higher than the value it had before optimization, which was 231.25 V. Voltage variations per phase "b" have successfully been improved thanks to the permutations performed within the optimization and there came to the decrease in voltage increase. After optimization, the highest value is 243.46141 V at terminal T13, which is less than the highest value before optimization, which was 262.56 V.

Voltage unbalance after applying Phase Balance Optimization is shown in Figure 6 (down). It is noticeable that the voltage unbalance after applying optimization has significantly been improved in comparison to the scenario before applying optimization, which was 1.80 %. The highest value of voltage unbalance is 0.43 % at terminal T10.

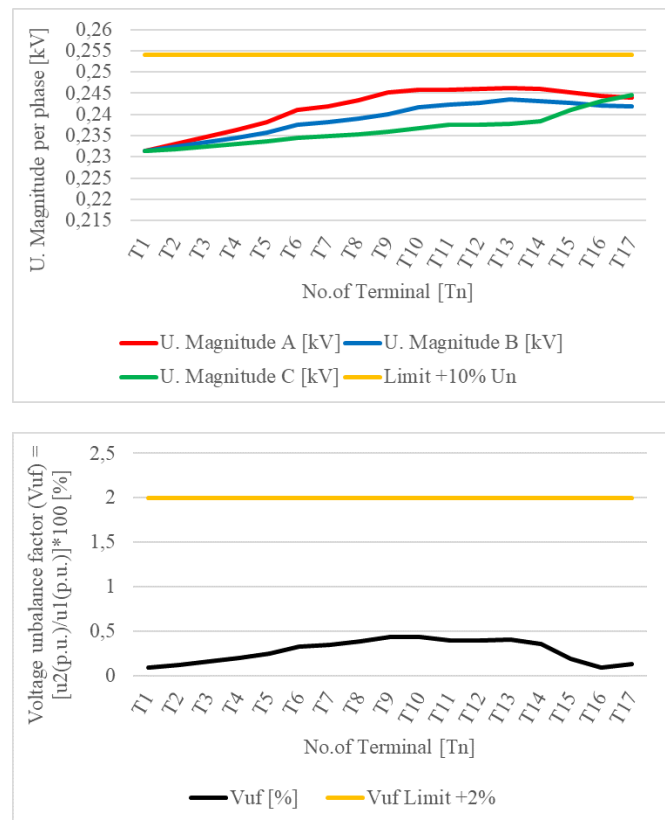


Figure 6: Voltage variations (up) and voltage unbalance (down) along the main feeder after optimization for the second scenario

The total number of changes needed for this modification is 9. Table V displays the list of changes related to the permutation of phase data for each element involved in the process.

Table V: Data permutation per element for the second scenario

Elements (no. of phases)	Original phase	New phase
PV7 (at Terminal 17)	2	3
PV (at Terminal 18)	2	1
PV1 (at Terminal 19)	1	2
	1	2
Customer 5113008 (1-ph) at Terminal 20	2	3
	3	1
PV3 (at Terminal 21)		
	2	3
Customer 5172578 (1-ph) at Terminal 27	1	2
	2	1
PV6 (at Terminal 27)	1	2
PV4 (at Terminal 31)	2	1
PV2 (at Terminal 32)	3	2

2.3. Third scenario (40%-30%-30% customer distribution) with 50% penetration of micro photovoltaic power plants

In Table VI, distribution of micro-PV power plants per phase at 40%-30%-30% customer distribution and 50% penetration of micro-PV power plants is shown:

Table VI: Distribution of micro photovoltaic power plants per phase for the third scenario

	Phase "a"	Phase "b"	Phase "c"
Number of PVs per phase	5	6	4
Installed capacity of PV power plants	26.8 kW	32.16 kW	22.08 kW
Absolute value of loads per phase	33.5 kW	40.2 kW	27.6 kW

2.3.1. Before Phase Balance Optimization

As could be expected, the third scenario with 50% penetration of micro-PV power plants also led to violating of voltages. Voltage variations per phase are illustrated in Figure 7 (above). Once more, the extensive integration of micro-PV power plants, influenced by customer distribution, resulted in a breach of the voltage variation limit of 255 V (or +10% of U_n). This scenario necessitates improvement through the application of Phase Balance Optimization. The highest value of voltage variations is in phase "b"

and it is equal to 282.55 V at terminal T17. Voltage variations per phase "a" and "c" are within upper voltage limit of standard EN 50160 their highest values are 247.84 V at terminal T10 and 245.04 V at terminal T14, respectively. It is important to notice that peak of voltage variations per phase "a" is very close to the upper voltage limit and should be careful with voltage variations per this phase.

Voltage unbalance before applying Phase Balance Optimization is shown in Figure 7 (down). The voltage unbalance before applying optimization is barely within voltage unbalance limit of standard EN 50160. The highest value of voltage unbalance is in the end of the feeder and it is 1.95 % in the end of the feeder, i.e., at terminal T17.

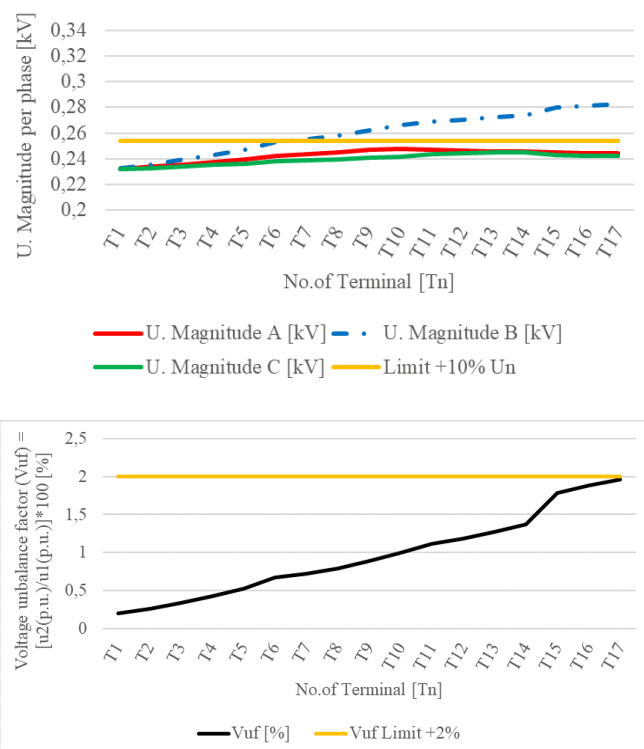


Figure 7: Voltage variations (up) and voltage unbalance (down) along the main feeder before optimization for the third scenario

2.3.2. After Phase Balance Optimization

Optimization method applied in this scenario was Simulated annealing. The voltage variations obtained after conducting the Phase Balance Optimization calculation are depicted in Figure 8 (above). It is evident that all three phases encountered an increase in voltage as they progressed toward the end of the main feeder.

All voltage variations are out of upper voltage limit standard EN 50160. Voltage variations have highest value in phase "b" and it is 258.83 V at terminal T15, which is less than the value it had before optimization,

which was 282.55 V, thanks to the permutations performed within the optimization. The highest value of voltage variations per phase "a" and "c" after optimization is 257.18 V at terminal T17 and 255.63 V at terminal T15, respectively. Those voltage variations per phase are different than voltage variations per phase before optimization and are increased, which led to violating in the network. Voltage variations per phase "a" and "c" before optimization were equal to 247.84 V and 245.04 V, respectively. The reason for this is 50% penetration of micro-PV power plants and the network's inability to handle the mentioned percentage of micro-PV power plants, what is common for all scenarios with this percentage of them.

Voltage unbalance before applying Phase Balance Optimization is shown in Figure 8 (down). The voltage unbalance after applying optimization has been significantly improved and it is within voltage unbalance limit of standard EN 50160. The highest value of voltage unbalance is 0.26 % at terminal T11.

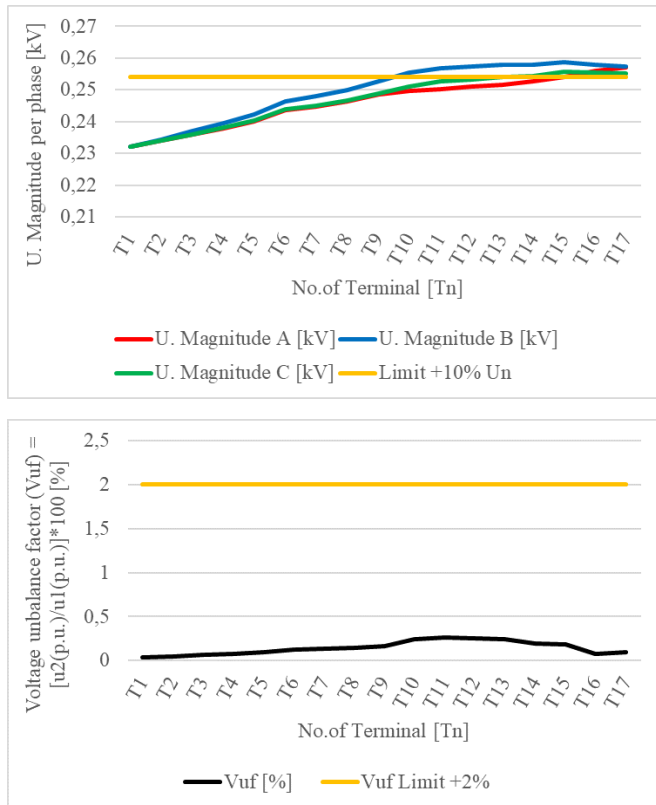


Figure 8: Voltage variations (up) and voltage unbalance (down) along the main feeder after optimization for the third scenario

The modifications are detailed in Table VII. The total number of permutations necessary for this alteration was 10.

Table VII: Data permutation per element for the third scenario

Elements (no. of phases)	Original phase	New phase
PV13 (at Terminal 17)	2	1
PV (at Terminal 18)	2	3
Customer 5113008 (1-ph) at Terminal 20	1	2
	2	1
PV7 (at Terminal 22)	1	2
PV12 (at Terminal 23)	1	2
	1	2
Customer 5172578 (1-ph) at Terminal 27	2	3
	3	1
PV10 (at Terminal 27)	1	2
PV4 (at Terminal 31)	2	1
PV14 (at Terminal 34)	3	1
PV1 (at Terminal 40)	2	3

2.4. Fourth scenario (50%-25%-25% customer distribution) with 10% penetration of micro photovoltaic power plants

In Table VIII, distribution of micro-PV power plants per phase at 50%-25%-25% customer distribution and 10% penetration of micro-PV power plants is shown:

Table VIII: Distribution of micro photovoltaic power plants per phase for the fourth scenario

	Phase "a"	Phase "b"	Phase "c"
Number of PVs per phase	1	2	-
Installed capacity of PV power plants	5.36 kW	10.72 kW	0 kW
Absolute value of loads per phase	6.7 kW	13.4 kW	0 kW

2.4.1. Before Phase Balance Optimization

Voltage variations per phase along the main feeder before optimization are provided in Figure 9 (up). This scenario has to be improved also by using Phase Balance Optimization. The highest value of voltage variations is in phase „b" and it is equal to 257.92 V at terminal T17. Voltage variations per phase "a" and "c" are within upper voltage limit of standard EN 50160 their highest values are 240.78 V at terminal T13 and 230.95 V at terminal T1, respectively, with the fact that the voltage variations per phase "a" being closer to the limit in comparison to the voltage variations per phase "c".

Voltage unbalance before applying Phase Balance Optimization is shown in Figure 9 (down). The voltage unbalance before applying optimization is within voltage unbalance limit of standard EN 50160 but the scenario is still a critical because the highest value of voltage unbalance in the end of the feeder, i.e., at terminal T17, touches the limit. That highest value of voltage unbalance is in the end of the feeder is equal to 1.95 %.

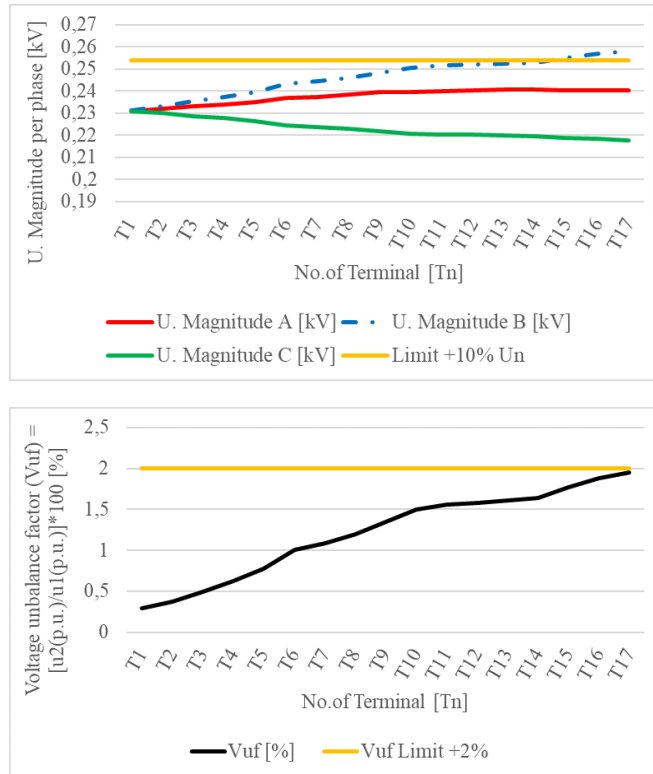


Figure 9: Voltage variations (up) and voltage unbalance (down) along the main feeder before optimization for the fourth scenario

2.4.2. After Phase Balance Optimization

Optimization method applied in this scenario was Genetic algorithm. Voltage variations per phase obtained after the optimization are shown in Figure 10 (up). All of them are within upper voltage limit standard EN 50160. Highest value of voltage variations before the optimization was recorded to be 257.9282 V and it was in phase "b". Highest value of voltage variations is decreased and it is 246.353 V at terminal T17, thanks to Phase Balance Optimization.

Phase "a" has the highest value of 233.55 V at terminal T13, which is less than the value it had before optimization, which was 240.78 V. Also, phase "c" has the highest value of 240.53 V at terminal T11, which is now higher than the value it had before optimization, which was 230.95 V, but it did not lead to violation of limits.

Voltage unbalance after applying Phase Balance Optimization is shown in Figure 10 (down). It is noticeable

that the voltage unbalance after applying optimization has significantly been improved in comparison to the scenario before applying optimization, which was 1.95 %. The highest value of voltage unbalance is in the end of the feeder, i.e., at terminal T17 and it is 0.65 %.

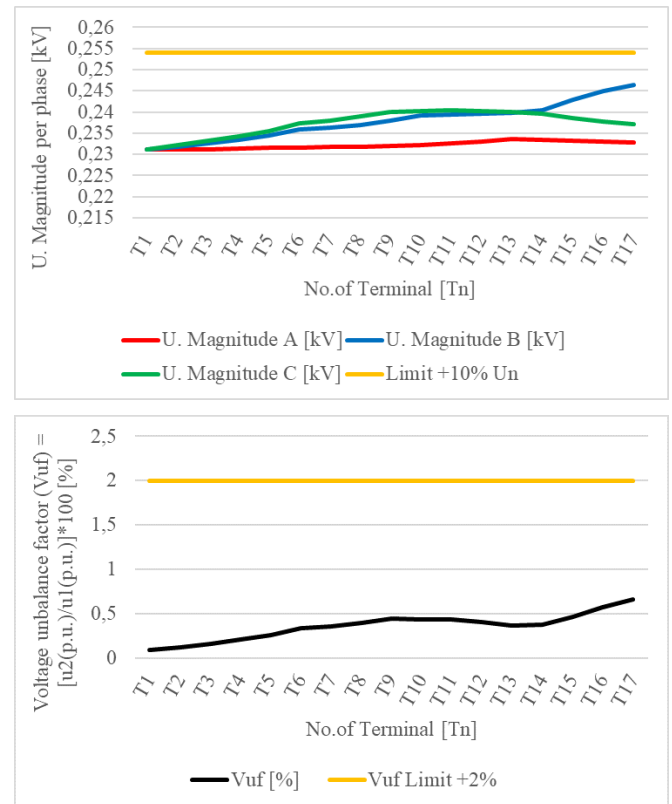


Figure 10: Voltage variations (up) and voltage unbalance (down) along the main feeder after optimization for the fourth scenario

The modification required a total of 5 changes. The specific alterations are outlined in Table IX.

Table IX: Data permutation per element for the fourth scenario

Elements (no. of phases)	Original phase	New phase
Customer 5172632 (1-ph) at Terminal 17	2	3
	3	2
	1	2
Customer 5113008 (1-ph) at Terminal 20	2	3
	3	1
PV5 (at Terminal 20)	1	3
PV3 (at Terminal 21)	2	3
Customer 5172578 (1-ph) at Terminal 27	1	2
	2	3
	3	1

2.5. Fifth scenario (50%-25%-25% customer distribution) with 20% penetration of micro photovoltaic power plants

In Table X, distribution of micro-PV power plants per phase at 50%-25%-25% customer distribution and 20% penetration of micro-PV power plants is shown:

Table X: Distribution of micro photovoltaic power plants per phase for the fifth scenario

	Phase "a"	Phase "b"	Phase "c"
Number of PVs per phase	1	4	1
Installed capacity of PV power plants	5.36 kW	21.44 kW	5.36 kW
Absolute value of loads per phase	6.7 kW	26.8 kW	6.7 kW

2.5.1. Before Phase Balance Optimization

Voltage fluctuations per phase along the primary feeder in the fifth scenario, with a 20% penetration of micro-PV power plants prior to optimization, are depicted in Figure 11 (up).

The highest recorded value of voltage variations before optimization was found in phase "b" and it is

275.18 V at terminal T17. Voltage variations per phase "a" and "c" are within upper voltage limit of standard EN 50160 their highest values are 235.15 V at terminal T9 and 231.29 V at terminal T1, respectively, where the voltage variations per phase "a" are slightly being closer to the limit in comparison to the voltage variations per phase "c".

Voltage unbalance before applying Phase Balance Optimization is shown in Figure 11 (down). The voltage unbalance before applying optimization is out of voltage unbalance limit of standard EN 50160. The highest value of voltage unbalance is at terminal T17 equal to 2.68 %.

2.5.2. After Phase Balance Optimization

Optimization method applied in this scenario was Genetic algorithm. Voltage variations per phase obtained after the optimization are shown in Figure 12 (up). All of them are within upper voltage limit standard EN 50160. Highest value of voltage variations after optimization was recorded to be 247.63 V at terminal T13 and it is in phase "a", which increased in comparison with value before optimization, which was 235.15 V, but, there is not negative impact on the network.

Phase "b" has the highest value of 245.37 V at terminal T15, which is less than the value it had before

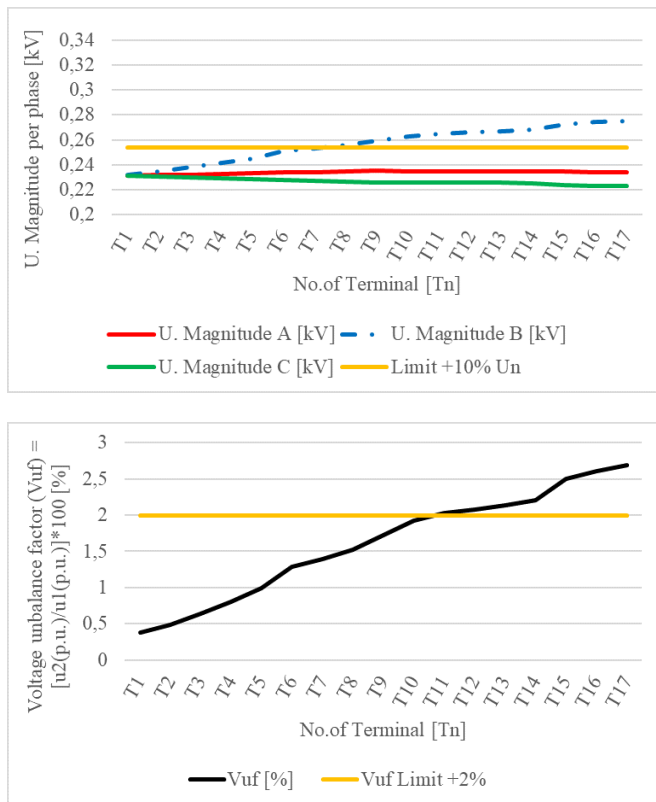


Figure 11: Voltage variations (up) and voltage unbalance (down) along the main feeder before optimization for the fifth scenario

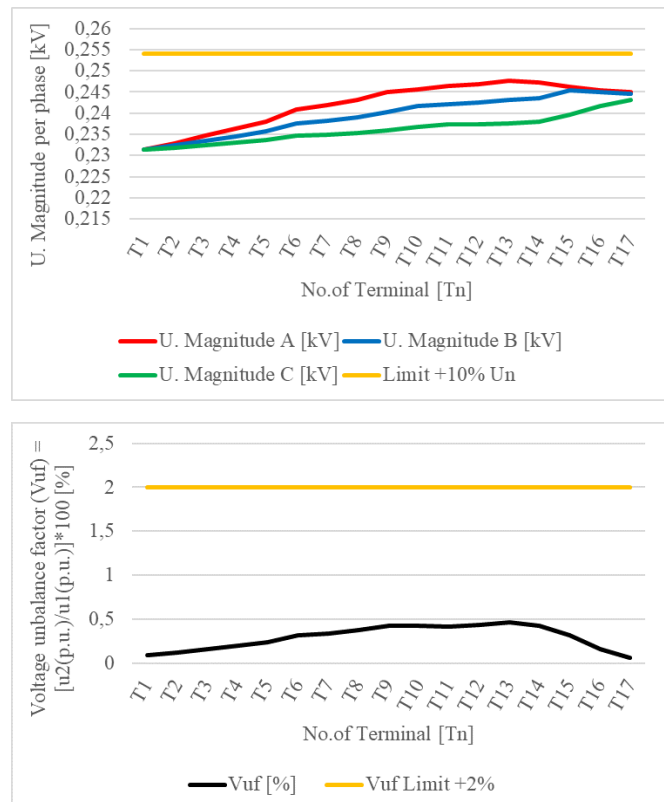


Figure 12: Voltage variations (up) and voltage unbalance (down) along the main feeder after optimization for the fifth scenario

optimization, which was 275.18 V. Also, phase „c“ has the highest value of 243.17 V at terminal T17, which is now higher than the value it had before optimization, which was 231.29 V, but it did not lead to a violating and there is no negative impact on the network.

Voltage unbalance after applying Phase Balance Optimization is shown in Figure 22 (down). It is noticeable that the voltage unbalance after applying optimization has significantly been improved in comparison to the scenario before applying optimization, which was 2.68 %. The highest value of voltage unbalance is 0.46 % at terminal T13.

To implement this modification, a total of 6 changes are necessary. The changes made through this modification are detailed in Table XI.

Table XI: Data permutation per element for the fifth scenario

Elements (no. of phases)	Original phase	New phase
PV7 (at Terminal 17)	2	3
Customer 5113008 (1-ph) at Terminal 20	1	2
	2	1
PV3 (at Terminal 21)	2	3
	1	2
Customer 5172578 (1-ph) at Terminal 27	2	3
	3	1
PV4 (at Terminal 31)	2	1
PV2 (at Terminal 32)	3	2

2.6. Sixth scenario (50%-25%-25% customer distribution) with 50% penetration of micro photovoltaic power plants

In Table XII, distribution of micro-PV power plants per phase at 50%-25%-25% customer distribution and 50% penetration of micro-PV power plants is shown:

Table XII: Distribution of micro photovoltaic power plants per phase for the sixth scenario

	Phase "a"	Phase "b"	Phase "c"
Number of PVs per phase	4	7	4
Installed capacity of PV power plants	21.44 kW	37.52 kW	22.08 kW
Absolute value of loads per phase	26.8 kW	46.9 kW	27.6 kW

2.6.1. Before Phase Balance Optimization

Voltage variations per phase along the main feeder of the sixth scenario with 50% penetration of micro-PV power plants before optimization are shown in Figure 13 (up). The highest recorded value of voltage before optimization was found in phase "b" and it is 284.53 V at terminal T17. Voltage variations per phase "a" and "c" are within upper voltage limit of standard EN 50160 and their highest values are 240.22 V at terminal T10 and 246.76 V at terminal T14, respectively, where the voltage variations per phase "c" are being closer to the limit in comparison to the voltage variations per phase "a".

Voltage unbalance before applying Phase Balance Optimization is shown in Figure 13 (down). The voltage unbalance before applying optimization is within voltage unbalance limit of standard EN 50160. The highest value of voltage unbalance is in the end of the feeder and it is 2.20 %.

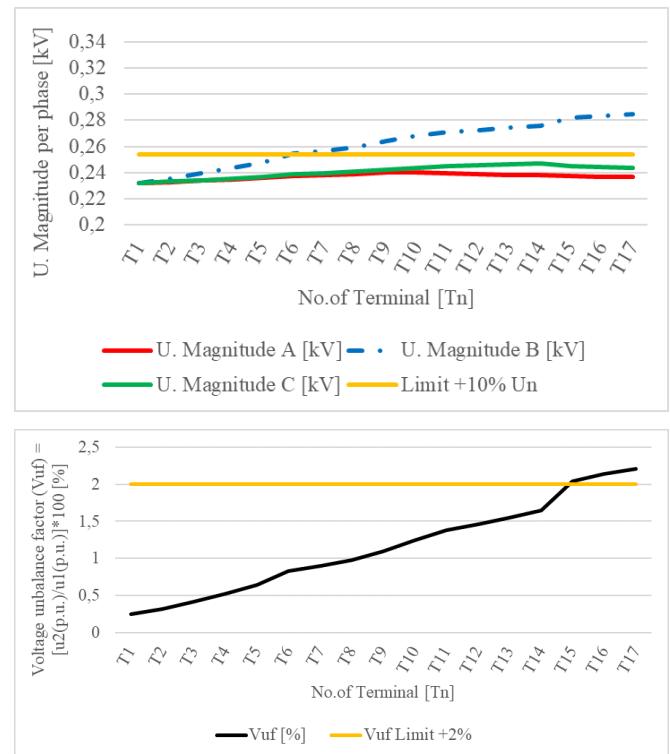


Figure 13: Voltage variations (up) and voltage unbalance (down) along the main feeder before optimization for the sixth scenario

2.6.2. After Phase Balance Optimization

The optimization technique employed in this context was the Genetic algorithm. The resulting voltage variations, post the Phase Balance Optimization computation, are depicted in Figure 14 (above). Notably, all voltage variations exceed the upper voltage limit stipulated in standard EN 50160. Among the phases, phase "c" exhibits the highest value of 258.05 V at terminal T17, surpassing its pre-optimization value of 246.76 V.

In contrast, phase "b" registers the highest value of 255.80 V at terminal T15, which is lower than its pre-optimization value of 284.53 V. This favourable outcome is attributed to the Phase Balance Optimization, rendering voltage variations within acceptable limits based on observed power quality parameters.

Similarly, phase "a" records the highest value of 254.07 V at terminal T15, an increase from its pre-optimization value of 240.22 V, bringing it close to the upper voltage limit.

Voltage unbalance after applying Phase Balance Optimization is shown in Figure 14 (down). It is noticeable that the voltage unbalance after applying optimization has significantly been improved in comparison to the scenario before applying optimization, which was 2.20 %. The highest value of voltage unbalance is 0.20 % at terminal T17.

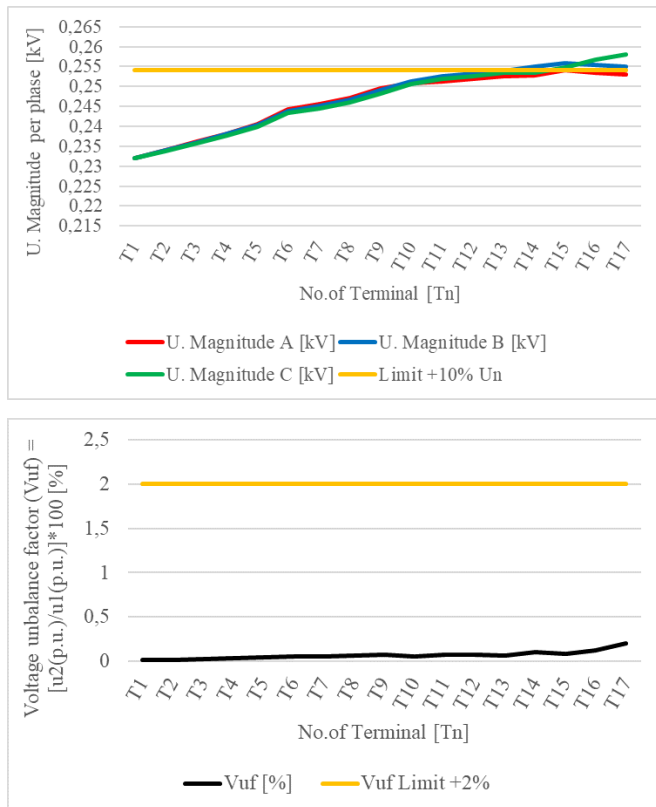


Figure 14: Voltage variations (up) and voltage unbalance (down) along the main feeder after optimization for the sixth scenario

For this modification, a total of 12 changes were necessary, and detailed information is presented in Table XIII in the same order as it appears in the output window of DigSILENT PowerFactory.

Table XIII: Data permutation per element for the sixth scenario

Elements (no. of phases)	Original phase	New phase
PV16		
(at Terminal 17)	2	3
	1	3
Customer 5113008		
(1-ph) at Terminal 20	2	1
	3	2
PV3 (at Terminal 21)	2	3
PV7 (at Terminal 22)	1	3
PV9 (at Terminal 24)	3	2
PV10 (at Terminal 27)	1	3
PV11 (at Terminal 28)	3	1
PV8 (at Terminal 30)	2	1
PV4 (at Terminal 31)	2	3
PV2 (at Terminal 32)	3	2
PV14 (at Terminal 34)	3	2
PV15 (at Terminal 39)	2	1

3. CONCLUSION

Total of 10 scenarios were modelled in this paper, of which first basic scenario is without connected micro-PV power plants, while other 9 scenarios are with them connected. Out of those 9 scenarios, voltage variations and voltage unbalance in 3 of them are within standard EN 50160 while other 6 scenarios have violated voltage variations and voltage unbalance. Exceeding of one or both of permissible limits of standard EN 50160 happened and it has to be improved. For the first, the third and the sixth scenario with 50% of connected micro-PV power plants, they led to exceeding the upper voltage limit of +10% of the nominal voltage (U_n) even with Phase Balance Optimization applied. Voltage variations and voltage unbalance of second, fourth and fifth scenario have successfully been improved after applying Phase Balance Optimization. The reason for this occurrence is that the network cannot handle 50% of penetration of micro-PV power plants in the network. An important fact is that the its connection point and the phase to which it is connected define how the micro-PV power plant affects the voltage variations and voltage unbalance in the distribution network. For the voltage unbalance, in the case of adding more micro-PV power plants, the same impact as for voltage variations is valid.

Following a comprehensive analysis, it was determined that PV integration significantly influences power quality parameters, specifically voltage variations and

unbalance. Across all examined scenarios, customers experienced voltage increases, escalating with the distance from the transformer's starting point and further intensifying with higher PV penetration. This surge in voltage was accompanied by an increase in unbalance.

To mitigate the adverse effects of voltage violations, the implementation of Phase Balance Optimization was crucial. This optimization provides a solution wherein consumers and micro-PV power plants are re-phased or connected to another phase with the minimal required changes in terms of phase data permutations and their corresponding terminals. This optimization serves as a pre-emptive analysis before actual connection, offering insights into the anticipated state of the network.

All three optimization methods (Large loads and generators first, Simulated annealing and Genetic algorithm) were calculated for all 6 scenarios, but the optimization with the most permissible results and smallest gaps between the graphs of the voltage variations per phase is chosen. Also, it is important to take into consideration that the graphs of the voltage profiles per phase do not touch the upper voltage limit (+10%) of the standard EN 50160 and are far from the upper voltage limit.

Furthermore, this research highlights that, beyond the extent of PV integration impacting the network's condition, the choice of optimization methods for connection (such as prioritizing large loads and generators, utilizing simulated annealing, and employing the genetic algorithm) plays a significant role. This involves determining on which phase and how many micro-PV power plants will be connected.

To mitigate voltage increases during the integration of micro-PV power plants into the network, careful consideration is necessary regarding the specific terminal and phase to which the micro-PV power plants are connected. Anticipated variations in connected micro-PV power plants on residential structures throughout the day pose a potential risk of breaching limits. However, it is important to note that not all low-voltage (LV) feeders within the LV network were analysed in this study case, preventing a comprehensive assessment of the specified effect in this network model.

An alternative solution could involve employing a different optimization approach focused on integrating distributed generators, which has the potential to enhance voltage profiles in the network, particularly in proximity to the feeder's end and in remote areas.

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