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# INFLUENCE OF VOLTAGE UNBALANCE ON THE SOLUTION OF ONE PLANNING MODEL OF LOW-VOLTAGE DISTRIBUTION NETWORKS

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**Abstract:** Considering that the need for electricity is constantly increasing, a crucial problem is the lack of new power facilities. Likewise, due to the large expansion of existing consumption, one of the primary tasks is the reconstruction of existing facilities. Due to their complexity, such problems cannot be solved unplanned, but the development of adequate system solutions must be planned. The biggest problem in finding such solutions is matching both companies and consumers needs. The best way to do this is to develop mathematical models that can meet the already mentioned needs. The development of such models is not a simple task, considering that the final solution is influenced by a number of factors, many of which have a random nature. Therefore, the use of stochastic optimization methods is imposed as a realistic basis for the development of such models, as it is the case in the model presented in this paper. Considering that voltage unbalance is one of the mentioned influential factors, this paper will give the answer to the question whether it has a significant impact on the final solution of the developed model.

**Keywords:** LV networks, planning model, optimization, stochastic methods, voltage unbalance

## INTRODUCTION

Development of power system must meet a number of different goals. First of all, the power system must be economically efficient, must ensure a reliable supply for ultimate customers and should not have negative impacts on the environment. Beside these general goals, there are a number of additional goals and criteria. At the same time, various random factors affect the operation of the system. Therefore, a large number of possible alternatives (variants) are often obtained. From the whole group of possible solutions, the planner tries to find the best or, depending on the accepted conditions, the optimal alternative. In essence, it is a complex problem associated with multiple goals, uncertainties, and multiple variables. Considering that this is a complex problem, the planner is, in essence, faced with multicriteria optimization task [1]. Low-voltage distribution networks have lower voltage level in comparison to transmission and medium-voltage networks, reduced operational safety, lack of two-way power supply, low customers' loads, a lot of overhead lines with longer lengths of low-voltage feeders. Most common problems that occur in these networks are related to the power quality and losses. In market conditions companies are obliged to provide quality power supply to ultimate customers, but at the same time they have to take care about their own interests. Ultimate goal of planning is to find the optimal network configuration. When it comes to low-voltage distribution networks, planning essentially consists of determining the size and location of the transformer station, the types of conductors to be used, and the spatial configuration of the network [2]. The best solutions can be obtained by creating various mathematical models that describe the current state of the system using various optimization methods. The best solution depends on a number of different factors such as current construction of the network, spatial configuration, the number of powered customers, the perspective of future development, the projected load, etc. One of these factors is possible voltage unbalance that can occur in the network. Therefore, it is important to give the answer to the question whether voltage unbalance has an impact to the solution of model or not, or what is its role in the overall planning process. The contribution of this paper could be reflected in the presentation of some kind of methodology given in last chapter, that can be used to detect the impact of voltage unbalance on the obtained model solutions. The paper gives a brief overview of such model and future considerations of this impact on some on other developed planning models.

## 1. THEORETICAL REMARKS OF OPTIMIZATION METHODS

In practice, there are different algorithms for development of such models. Most of offered algorithms that should solve the issue are based on use particle swarm optimization, genetic algorithms, dynamic optimization, stochastic approaches, etc. [3]-[6]. Most of these algorithms are designed to satisfy the needs of distribution companies. However, with the introduction of market conditions in the power sector, the situation is changing significantly.

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Now customers have the opportunity to choose their own power supplier and their requirements come to the fore, and these are primarily quality power supply with, if possible, the lowest possible price. So, if distribution company wants to keep the customers, it must firstly satisfy customers' requirements and only after that can take into account its own interests. This paper treats a model that, in some way, satisfies both, the needs of distribution companies and customers, and is based on the use of modern hierarchical and stochastic algorithms.

### 1.1. Fuzzy clustering algorithm

Fuzzy clustering is process of placing objects into one or more groups. In the literature can be found a lot of fuzzy clustering algorithms. The basic division is into hard clustering and soft clustering. Hard clustering implies the division of objects into strictly separate groups, while soft clustering implies the possible belonging of the object to several groups [7]. Objects are placed in groups based on their similarity. There are different measures to assess similarity such as distance, connectivity or intensity, and the most commonly used distance between two objects. The simplest way is to draw a straight line between the objects (Euclidean distance or straight-line distance). The distance between two objects is calculated as [8]:

$$d_{Euclidian}(1,2)=\sqrt{(x_1-x_2)^2+(y_1-y_2)^2} \quad (1)$$

where $x_1$, $x_2$, $y_1$, $y_2$ are spatial coordinates of the object.

All distances between objects are forming matrix of distances. Nondiagonal elements are distances between pairs of objects and diagonal elements are 0 (object distance from itself). Since the distance between objects 1 and 2 is identical as distance between objects 2 and 1 matrix is symmetric. This matrix is shown in Table I.

Table I: Euclidean matrix of distances

| Objects | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 0 | $d_{1,2}$ | $d_{1,3}$ | $d_{1,4}$ | $d_{1,5}$ |
| 2 | $d_{2,1}$ | 0 | $d_{2,3}$ | $d_{2,4}$ | $d_{2,5}$ |
| 3 | $d_{3,1}$ | $d_{3,2}$ | 0 | $d_{3,4}$ | $d_{3,5}$ |
| 4 | $d_{4,1}$ | $d_{4,2}$ | $d_{4,3}$ | 0 | $d_{4,5}$ |
| 5 | $d_{5,1}$ | $d_{5,2}$ | $d_{5,3}$ | $d_{5,4}$ | 0 |

### 1.2. Analytic hierarchy process (AHP)

Analytic Hierarchy Process (AHP) was developed by Thomas L. Saaty. Therefore, it is also known as Saatys' method. The idea is to establish a goal first, and then to establish criteria that, and have influence to the decision [9], [10]. Criteria can be classified into one or more levels (first, second, ...), so hierarchy of criteria is obtained, whereby the criteria from first level have the highest influence on the decision (Figure 1).

The basic procedure by which the AHP method is implemented can be presented in several steps [11]:

1. Structuring the problem and selecting the criteria;
2. Establishing the criteria priorities (evaluation) by comparing pairs (weighing);
3. Comparing pairs of alternatives for each criterion (scoring);
4. Obtaining an overview of relative scoring for each alternative.

To make a comparison, a scale of numbers that shows mutual importance between criteria is needed. Each decision can be represented by a number on the scale. One common scale is shown in Table II [12].

Table II: Example of Saaty's scale of relative importance

| Intensity of importance | Definition of importance | Explanation |
|---|---|---|
| 1 | Equal | Two activities contribute equally to the objective |
| 2 | Weak or slight | |
| 3 | Moderate | Experience and judgement slightly favour one activity over another |
| 4 | Moderate plus | |
| 5 | Strong | Experience and judgement strongly favour one activity over another |
| 6 | Strong plus | |
| 7 | Very strong | An activity is favoured very strongly over another |
| 8 | Very, very strong | |
| 9 | Extreme | An activity is favoured extremely over another |

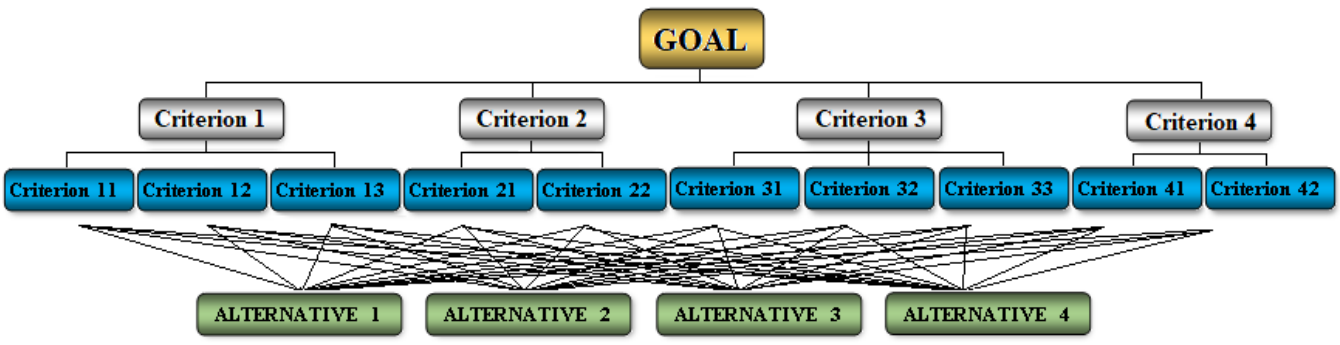



Figure 1: Decomposition of the problem

### 1.3. Simulated annealing algorithm

It represents the analogy between annealing of metals and problems of combinatorial optimization. It is independently presented by S. Kirkpatrik and V. Cherny. Obtained results do not depend on the initial configuration. When heating material to maximum temperature (annealing temperature), at which the the internal structure of the material becomes stochastically organized. Slow cooling causes that internal configuration of units takes less energy state. At each temperature $T$ material reaches thermal equilibrium, which can be characterized by the probability of possessing of energy E according to the Boltzmanns' distribution [13], [14]:

$$P(E)=\frac{1}{Z(T)}\cdot e^{\left(-\frac{E}{k_B\cdot T}\right)} \quad (2)$$

where are:

$Z(T)$ – normalization factor
$k_B$ – Boltzmann's constant

Some analogies between physical and simulated annealing process are given in Table III [15].

Table III: Analogies between simulated and physical annealing

| OPTIMIZATION PROBLEM | PHYSICAL SYSTEM |
|---|---|
| Initial solution $x$ | Current state of the material |
| Objective function $f(x)$ | Energy of the current state |
| Control parameter $T$ | Temperature |
| Optimal solution $x_{opt}$ | Basic state |
| Simulated annealing | Gradually cooling |

The algorithm begins at very high temperature. As the temperature decreases, the algorithm rarely accepts solutions that lead to increasing of objective function. This means that the search begins globally, but as the temperature decreases, at very low temperature, the search becomes local.

## 2. MODEL SETTING AND SOLUTION

Planning model of distribution networks should offer the optimal configuration of distribution network. Flowchart of such model, which can be used for planning and construction of distribution networks, is shown in Figure 2 [1], [16].

Proposed planning model of low-voltage distribution networks should ultimately offer the optimal configuration of the low-voltage distribution network, which gives the lowest values of voltage drops on low-voltage feeders, i.e. within the given limits, as well as minimal power losses of the entire distribution network. These are two basic conditions that must be satisfied when it comes to customers' demands for quality power supply (voltage

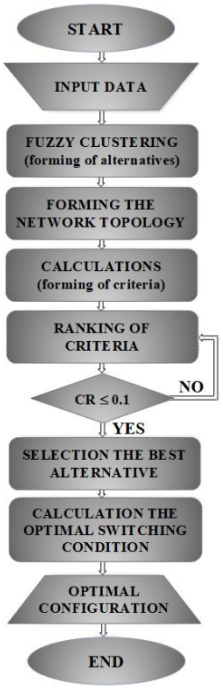



Figure 2: Flowchart of proposed planning model of low-voltage distribution networks

drops) on one side, and distribution companies (power losses) on other side. The main task of the model is to select the best alternative of all constructed (variants with different number of low-voltage feeders), and to determine the optimal switching condition of the network. According to the flowchart by applying the model, the best solution is obtained by applying the following steps:

- Providing input data, namely:
  1. Spatial coordinates of objects (measuring points) - from georeferenced maps;
  2. Individual customers' loads - they are needed for power flow calculations (they can be obtained by using peak loads method, by assessment using coincidence factor, by using load curves ...);
  3. Network parameters data - characteristics of standard transformers, standard R and X of conductors.
- Forming of alternatives - these are networks with two, three, four and more low-voltage feeders. For that purpose serves fuzzy clustering algorithm and in the model it is used for:
  1. determining the location of transformer station (in spatial centre of consumption),
  2. determining the number of low-voltage feeders (by spatial grouping of customers).
- Forming the network topology – low-voltage networks are plotted on georeferenced maps (AutoCAD) which gives the topological appearance of all alternatives;

- Calculations (forming the criteria) - criteria are established to evaluate the formed alternatives. Two most important criteria are:
  1. voltage drops at ultimate customers – interest of customers,
  2. power losses in low-voltage lines - interest of distribution company.

The values of these criteria are obtained by power flow calculation that can be performed using any software package designed for this (Matpower, PowerCAD, etc.). Other criteria may be:
- investment costs,
- maintenance costs,
- reliability and security of delivery,
- power lines load, etc.

- Ranking the criteria - it is necessary to harmonize all criteria and do the ranking of all offered solutions. A suitable tool is the AHP method (Excel), which evaluates each solution with given criteria. It is implemented in two steps:
  1. Forming a certain number of variants - they are formed in the second step of the procedure when alternatives with five, six, seven or more low-voltage feeders are obtained, from which it is necessary to choose the best one;
  2. Forming and ranking the criteria – they are formed in the fourth step of the procedure on the basis of which the ranking of alternatives is performed. All criteria do not have an equal impact on making the final decision, so it is necessary to rank them, i.e. compare them with each other. Each criterion is evaluated according to the values given in Table II. An example of an initial table of comparing pairs of criteria is shown in Table IV.
  - Consistency checking - after the ranking of the criteria, it is necessary to check whether it was done correctly, since it is a matter of subjective engineering assessment. According to the AHP method, the so-called consistency checking is performed. Ranking is done correctly if worth:

$$CR > 0.1 \tag{3}$$

where $CR$ is consistency degree. Calculating of this factor is described in literature [16].
If consistency is not satisfied, it is necessary to re-rank, i.e. repeat the procedure until a satisfactory (consistent) solution is obtained.
  - Calculation the best alternative - the procedure is the same as for criteria ranking, except that it is done for each criterion separately. In this way, an estimated mark of how much which criterion affects each alternative separately is obtained. Adding of these marks gives the priority mark of each alternative. The alternative with highest mark is considered as the best, as it is presented in the example of equation 4:

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} 0,22965 \\ 0,24758 \\ 0,25210 \\ 0,27067 \end{bmatrix} \tag{4}$$

where $S_1$, $S_2$, $S_3$ and $S_4$ are solutions (alternatives/variants) of the proposed model. Calculation of these values is also presented in literature [16].
In this way, the best spatial topological solution of the low-voltage distribution network is obtained.
  - Calculation the optimal switching condition - the best spatial topological solution does not mean that it is optimal because it depends on subjective engineering assessment. Therefore, for the best spatial variant optimal switching condition is determined. Simulated annealing algorithm is suitable for this calculation. Of course, this does not mean that other algorithms such as Genetic Algorithm or Particle Swarm Optimization cannot be suitable for this purpose.
  - Optimal configuration - applying simulated annealing algorithm finally gives the optimal radial configuration of the low-voltage distribution network. Algorithm used in this paper is implemented in Matlab. When it comes to control parameters selected initial annealing temperature was $T = 1000$ and end temperature was $T = 0.000001$. Chosen cooling factor was 0.95. The total duration of the simulations was 7.4 minutes. Since power losses are related to optimal network configuration, a diagram of movement of power losses during simulation process is given in Figure 3.

Table IV. Example of an initial table of comparison criteria by pairs

| Criterion | Voltage drop | Power losses | Power lines load | Investment costs |
|---|---|---|---|---|
| Voltage drop | 1 | 2 | 6 | 7 |
| Power losses | 1/2 | 1 | 5 | 6 |
| Power lines load | 1/6 | 1/5 | 1 | 2 |
| Investment costs | 1/7 | 1/6 | 1/2 | 1 |

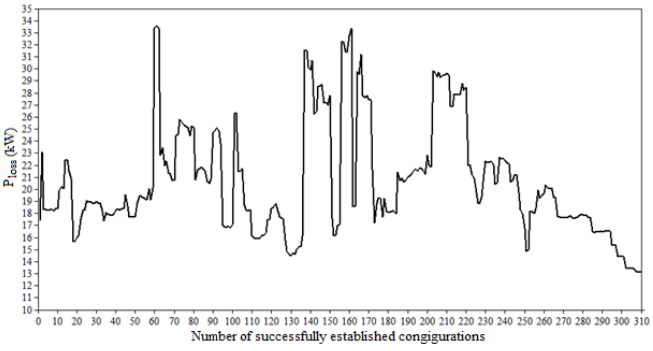
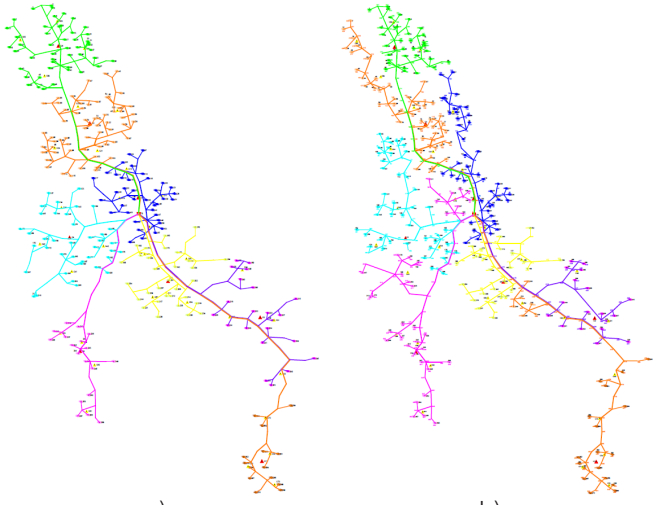



Figure 3. Movement of power losses during simulation process

Constraints such as network topology, voltage drops and transformer loading are also set in simulated annealing algorithm and are not incorporated during simulation process. The best indicator for this is the fact that total of 405 simulations were performed and 310 possible configurations were successfully established. The remaining 95 simulations were treated as impossible solutions and were not taken into consideration.

Thus, consistent application of the proposed planning model provides a spatial (Figure 4a), and ultimately optimal solution. An example of such solutions, i.e. their comparative presentation is shown in Figure 4.



a) b)

Figure 4. Comparative presentation of the best spatial a) and optimal b) solution

It is necessary to emphasize that the proposed model is used for planning of distribution network but in last step it actually turns into a reconfiguration problem due to the use of simulated annealing algorithm (obtaining optimal solution from best spatial – Figure 4).

In this model, four criterion for determining the best solution are used:

1. Voltage drop at ultimate customers;
2. Power losses in LV feeders;
3. Average load of power lines;
4. Investment costs.

The results for each alternative and optimal solution are given in Table V.

Minimal amount of power losses was $P_{loss}$ = 13.09 kW, and the maximum voltage drop at the end of low-voltage feeders was $\Delta U$ = -7.5%. It is obvious that the best results gives optimal solution what is the ultimate goal of using this model.

Table V. Obtained results for each solution

| Solution | Voltage drop [%] | Power losses [kW] | Average load of power lines [%] | Investment costs [€] |
|---|---|---|---|---|
| 5 LV feeders | -11.7 | 20.92 | 57.80 | 207,395 |
| 6 LV feeders | -11.0 | 18.71 | 47.90 | 238,631 |
| 7 LV feeders | -10.8 | 18.68 | 41.05 | 263,265 |
| 8 LV feeders (best spatial) | -10.1 | 17.38 | 35.80 | 268,912 |
| Optimal | -7.5 | 13.09 | - | - |

## 3. VERIFICATION OF THE INFLUENCE OF VOLTAGE UN BALANCE ON THE OBTAINED SOLUTION

### 3.1. Existing low-voltage network

Proposed planning model is applied on a practical example of a real low-voltage distribution network. 270 electricity customers, mostly from the household category, were supplied through this low-voltage distribution network. The network is powered from 10(20)/0.4 kV transformer station, rated power 400 kVA, through 5 low-voltage feeders. Standardized data on low-voltage power lines and transformer station are also given, while power lines lengths were determined from a georeferenced map. Spatial view of the existing low-voltage network is shown in Figure 5.

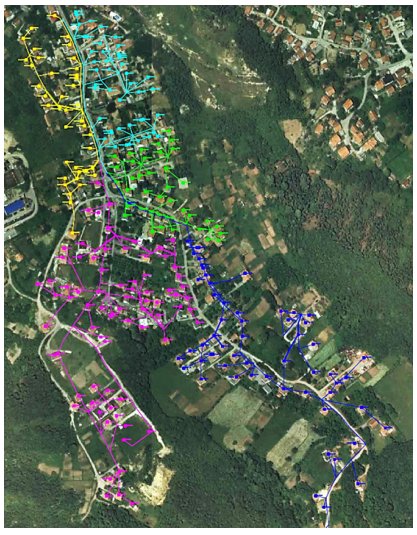


Figure 5: Spatial view of existing low-voltage distribution network

After obtaining the best spatial solution, the task is to check whether such a solution can be influenced by voltage unbalance that can occur in the network. The procedure for obtaining of such solution is presented in the literature [16].

### 3.2. Checking the effect of voltage unbalance

The notion of voltage unbalance implies an uneven load distribution across the phases of a low-voltage network. It is usually a consequence of the customers themselves: an unbalanced distribution of consumables by phases in the customers' installation, as well as an uneven consistence factor of consumables connected to different phases [17]. However, the most pronounced voltage unbalance is due to the uneven connection of single-phase customers by phases, so that at some point all three phases in the network are not equally loaded, and as a result there is voltage unbalance. The voltage unbalance of the supply voltage is estimated by the method of symmetrical components. Namely, in the conditions of voltage unbalance, except direct voltage component $U_d$, there is at least one of two components: inverse $U_i$ and / or zero $U_0$. Voltage unbalance is defined by the European standard EN50160. The base voltage component is measured in a 10-minute time interval for 50 Hz systems or a 12-minute time interval for 60 Hz systems. According to European standard EN 50160, under normal operating conditions, 95% of the 10-minute mean values of the rms value of the inverse or zero voltage component must not, within each weekly interval, exceed 2% of the corresponding direct component. In exceptional cases, unbalances of up to 3% may be allowed [18], [19], [20]. According to this standard, the following worth:

$$u_1(\%) = \frac{U_i}{U_d} \cdot 100\% \tag{5}$$

$$u_0(\%) = \frac{U_0}{U_d} \cdot 100\% \tag{6}$$

As there were a large number of 15-minute voltage readings for the existing network over a period of one year, the calculation of voltage unbalance according to IEC Standard 61000-4-30, which was previously in use, was applied. According to this Standard, for a three-phase system, observing only the basic harmonics of line voltages, worth [19]:

$$u_1(\%) = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \cdot 100\% \tag{7}$$

whereas is

$$\beta = \frac{U_{12}^4 + U_{23}^4 + U_{31}^4}{\left(U_{12}^2 + U_{23}^2 + U_{31}^2\right)^2} \tag{8}$$

where 1, 2, 3 are the phase designations, and $U_{12}$, $U_{23}$, and $U_{31}$ are the basic harmonics of the line voltages.

Therefore, according to the given equations, the percentage values of voltage unbalance, ie the inverse voltage component, were calculated. Based on these values, the maximum and minimum value of voltage unbalance and the value of standard deviation were determined. In the case of the considered network, these values are:

$u_{max}$ = 0,284488
$u_{min}$ = 0
$\sigma$ = 0,039591

Furthermore, it was necessary to determine according to which distribution the calculated values of unbalance were distributed. According to the obtained results, an approximate coincidence of the actual distribution with the normal Gaussian distribution can be observed, as it is shown in Figure 6.

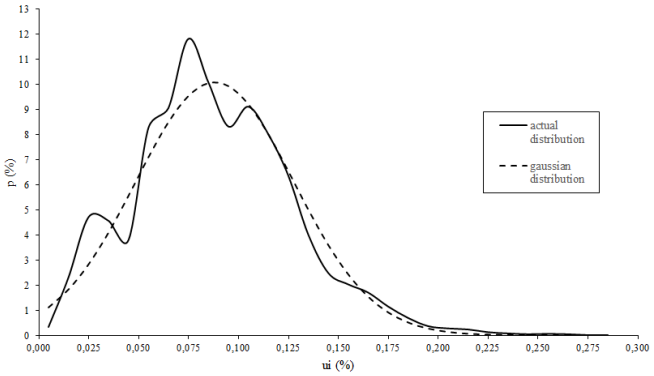



Figure 6: Distribution of calculated values of voltage unbalance

Based on the calculated results and the results visible in Figure 5, it is obtained:
$u_{average}$ = 0.088199
$u_{most\ probably}$ = 0.075

In order to confirm the validity of these calculated values obtained on the basis of the old Standard, voltage unbalance was measured at the transformer station with the Mavowatt 50 instrument in two seven-day time intervals, in 10-minute cycles, according to the European standard EN50160. The results of the obtained measurements are shown in Figures 7 and Figure 8.

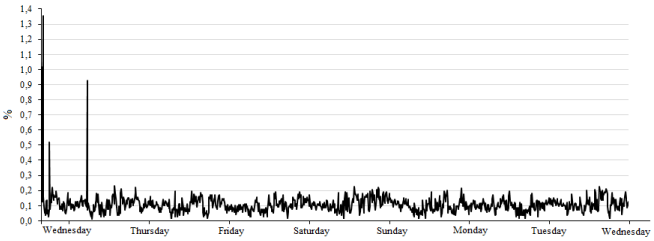



Figure 7: Percentage amount of voltage unbalance in the first seven-day time interval

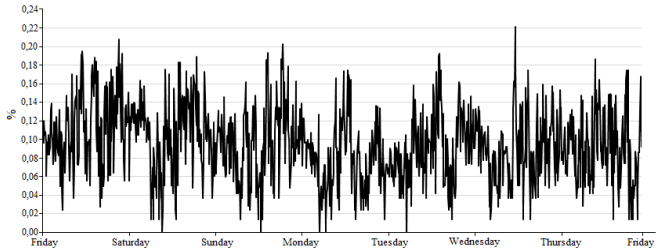



Figure 8: Percentage amount of voltage unbalance in the second seven-day time interval

It can be concluded that the measurement results are similar to the calculated values. The average value of the measured voltage unbalance in the first interval is $u_{average}$ = 0.10799, and in the second interval $u_{average}$ = 0.09472. Thus, the calculated value does not deviate significantly. In addition, all measured values of voltage unbalance are 100% within the limits prescribed by the norm, i.e. < 2%. It can be said that the calculated maximum value of voltage unbalance is $u_{max}$ = 0.284488 << 2%, which implies the conclusion that voltage unbalance does not significantly affect to the results. In order to confirm this, the load readings of the transformer station on the days when the characteristic values of voltage unbalance appear were selected, and based on them, the load calculation of all customers was performed. The obtained results are given in Table VI.

Table VI: Spatial solutions at characteristic values of voltage unbalance

| Maximum voltage unbalance | Minimum voltage unbalance |
|---|---|
| $\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} 0,23047 \\ 0,24705 \\ 0,25164 \\ 0,27084 \end{bmatrix}$ | $\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} 0,22981 \\ 0,24757 \\ 0,25196 \\ 0,27067 \end{bmatrix}$ |
| **Average voltage unbalance** | **Most probable voltage unbalance** |
| $\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} 0,22945 \\ 0,24794 \\ 0,25225 \\ 0,27036 \end{bmatrix}$ | $\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} 0,23056 \\ 0,24743 \\ 0,25215 \\ 0,26986 \end{bmatrix}$ |

In this calculation, the days with the occurrence of the maximum, minimum, average and most probable values of voltage unbalance were selected, and with energy consumed by customers in a period of one year in all cases. After calculating the customers' load in these selected days and implementing the procedure shown in the planning model, it can be concluded that in all cases the best spatial solution is an alternative with eight low-voltage feeders, that is, that voltage unbalance does not affect the final solution.

## 4. CONCLUSION

Modern planning models should be based on the use of modern algorithms and software solutions. There is no unique and generally accepted model. In the paper is presented a model based on a combination of modern hierarchical and stochastic algorithms, namely the fuzzy clustering algorithm, the analytical hierarchical process, and the simulated annealing algorithm. Such distribution network planning models include several interrelated analyses. The basic requirement, which must always be satisfied, is the operation of the network in accordance with technical regulations. The application of the presented model provides a number of spatial solutions, and the ultimate goal is obtaining the optimal network configuration. The analysis of the results shows that even the possible voltage unbalance that may occur in the network does not have a significant impact on the final solution. Namely, in the paper are presented the results of calculations for different values of voltage unbalance that occurred during a period of one year. It can be seen that the values of voltage unbalance are far below the limits prescribed by the norm, which is confirmed by measurements at certain seven-day intervals. Obviously, such low values of voltage unbalance cannot affect the final results. The best way to ignore the need to analyse the impact of voltage unbalance is to observe the load values of low-voltage feeders and transformers by phases, when calculating the customers' load, and to take their sum as an hourly load. In this way, the effect of voltage unbalance would be included in the value of the maximum load. Then, it could be only discussed about the influence of voltage unbalance due to the occurrence of voltage on the neutral conductor, but since these are extremely small values, this impact could be neglected. The limitation of this paper is that it does not give explanation if such methodology can be implemented on high-voltage networks where higher values of unbalance can occur. Also, it remains unknown whether this methodology of detection of voltage unbalance can be applied to other developed planning models. All of these questions can be answered in future research.

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