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Application of Classifier System and Co-Evolutionary Algorithm in Optimization of Medium-Voltage Distribution Networks Post-Fault Configuration

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Introduction

During the operation of power electric distribution network there are disturbances occurring in its elements. The power failures and delivery limitations depend on the network operation system configuration, and the way and time of recovery depend on system configuration, distribution equipment and network automatics [1– 3].

The analysed problem of choosing the substitute configuration of the distribution system can be described as a multiobjective programming problem. This article describes the development of this type of calculation methods, simultaneously containing their own innovative solution proposals concerning the application of a classification system working with the co-evolutionary algorithm.

In works [4–10] are presented methods concerning the use revolution algorithms drawn up to resolve multi-criteria problems in optimising electric power networks. Heuristic search algorithms - their use is hindered in the event of calculations for large numbers of current network nodes in the analysed network. In such instances assumptions may be applied limiting the extent of solutions, which reduces the calculation process, but in consequence causes the search for sub-optimal solutions.

Genetic and evolutionary algorithms - the benefit of application of evolutionary algorithms is the possibility of their use in large numbers of decisively variable decisions and also complex descriptions of function purpose and limiting conditions.

Cooperation of the co-evolutionary algorithm with the classification system (drawn up by the author of the work) enables significant reduction of the classification time (reduces the iterative calculation process on average by 40 %), which is significant from the practical point of view in the application of this method in current systems of distribution network operation management. The application of a classification system to the analysed task also enables improvement of the effectiveness of the performance process of designating the scenario of the substitute network configurations. Improvement of the efficiency of the network configuration designation process is obtained using the sought information (with use of the announcement creation process), in the collections of classifiers to create sub-populations of solutions for the co-evolutionary algorithm, which would be used to search for the collection of Pareto-optimal solutions. The process of creating a collection of classifiers describing the substitute network configuration was performed by the author supported by the theoretical genetic basics of self-teaching system. Classifiers may be created (for analysed network structure) for the most probable break down situations, which arise from regarding the stage of choice of the simulated break down situations reliability characteristics and the usage durations of network elements.

A method using the classifier system

The classifier system is a system that learns the syntactic simple rules in order to co-ordinate its actions in any environment and includes the three basic components [11]:

- Rule and message system;
- Evaluating system;
- Evolutionary algorithm.

In the classifier system the information from the outer environment is processed into the messages of a given format. The messages are further placed on the message list, where they can activate the classifiers. The classifier is an attribution rule of the following syntax:

<classifier> : : = <condition> : <message>.

In the elaborated method (based on the classifier system idea) known procedures, performing message processing or classifier evaluation have been used.

Certain modifications resulting from the specificity of the considered problem, have been introduced:

- The message about the fault is described in the form: a list with numbers of not supplied nodes, and a list with numbers of fault elements:

<message>:: =(numbers of not supplied nodes)+ (numbers of fault elements);

- In the classifier notation following syntax has been taken into account in the notation actually used:

<classifier>::=<post-fault configuration>:< numbers of not supplied nodes + numbers of fault elements>.

With regard to the specific character of the analysed task (concerning breakdown of elements in the network structure) the author has drawn up a modified announcement processing procedure (describing network break down situations). In the suggested method the announcement processing process and the evaluation of classifiers is divided into two stages described below.

Stage 1 consists of the search in the collections of classifiers for such, for which the conditions are compatible with the announcement describing the existing network breakdown. Comparison of the announcement (containing information about damaged network elements and of network nodes deprived of current supply) with the conditions of classifiers enables the search and activation of classifiers containing coded information about network configurations, in which there are no damaged elements. Conformity of the announcement with the conditions of the classifiers in the first stage of the suggested method is defined on the basis of comparison of the numbers of network nodes without power supply recorded in the announcement (describing the existing breakdown), with the numbers of network nodes recorded in the first part of the classifiers (which corresponded to the concealed zeros on the appropriate positions of communication code tracts and classifier). After searching for classifiers conforming to the announcement the evaluation takes place of the so-called offer of these classifiers. The classifier distinguished by the highest offer was next used as a following announcement.

Stage 2 concerns the search for classifiers whose conditions will be according to the announcement of the classifiers designated in stage 1. The conformity of the announcement with the conditions of the classifiers in this stage was defined on the basis of the differences between the power supply routes of the chosen line sections (from the list of network nodes deprived of power supply) with the configuration recorded in the announcement and classifiers. With regard for these specific nature of the analysed task the author suggested a two-part description of the announcement. The first part of the announcement is recorded as a length of zero-ones relating to the number of elements equal to the number of network line sections of the analysed network. Value *1* on the defined position corresponding to the number of the network length, indicates length with power supply, and *0* indicates network node without power supply as a result of breakdown. The second part of the announcement contains information about the damaged elements and also information about the configuration of network elements. For the description of this part of the announcement the author introduced the following marking notation:

- *0* - means damaged element;
- *1* - means actually used element;
- # - means element remaining in reserve.

Below is showing an example of the process of creating announcements for the breakdown status of the electric power network system (composed of a small number of elements), the structure of which is reflected in graphic form on Fig. 1.

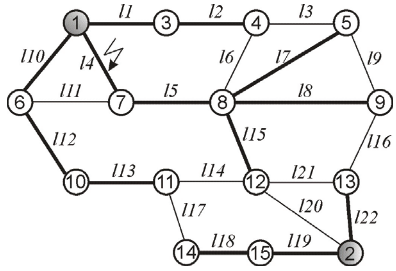

Fig. 1. Graph of the analysed distribution network

For the network graph from drawing 1, the case is examined of a breakdown on line *l4*. The announcement describing the considered breakdown status was described as follows:

(*message 1*): 111101000110111 | 11#0#####1#11####11##1.

The sought for classifiers in the first stage:

(*classifier 1*): 111101100110111 | 11110###11#1111##11##1,

(*classifier 2*): 111101111111111 | 11111#01#1111#1##11##1.

After the performance of the first stage, the classifier characterised with the best assessment is used as the following announcement enabling continuation of the process of searching the collection of classifiers. For example if the best offer would be submitted by classifier number 1 it would be used as an announcement number:

(*message 2*): 111101100110111 | 11110###11#1111##11##1.

The sought for classifiers in the second stage:

(*classifier 3*): 110011111111111 | 01#111##11#11#11#11##1,

(*classifier 4*): 111111111111011 | 11#11#11#1#111###11#10.

The performance of the process of creation of announcements enables search in the collection of classifiers for information, the use of which assists the process implemented by the co-evolutionary algorithm.

Evaluating system in the elaborated method

In the initial part of calculations a message on the fault occurring in the network is being read. Procedures verifying the matching between the classifiers and the generated message are performed subsequently and then the classifiers are assessed. The strength *S* of the classifier, which has shown the best bid in the so-called auction process, is increased by the reward given by the system. Simultaneously its strength is decreased by the value of the bid given by the classifier.

The bid of the best classifier increases the strength of other active classifiers proportionally to their bids. Moreover, the strength of all the active classifiers is decreased by a certain, determined value. The effective bid value has been calculated in a following way [11]:

$$S_i(t+1) = S_i(t) - c_{bid} \cdot S_i(t) - c_{tax} \cdot S_i(t) + r(t), \quad (1)$$

$$B_i = c_{bid} \cdot (e_{bid1} + e_{bid2} \cdot Sp_i) \cdot S_i, \quad (2)$$

$$EB_i = c_{bid} \cdot (e_{bid1} + e_{bid2} \cdot Sp_i) \cdot S_i + e_{br}, \quad (3)$$

where B_i – bid value of the *i–th* classifier, EB_i – effective bid value of the *i–th* classifier, Sp_i – specificity of the *i–th* classifier, S_i – strength of the *i–th* classifier, c_{bid} – investment coefficient ($c_{bid}=0,1$), e_{bid1}, e_{bid2} – coefficients of the classifier linear specificity function ($e_{bid1}=0,65$, $e_{bid2}=0,35$), e_{br} – random value generated with the use of a normal distribution generator, c_{tax} – turnover tax coefficient $c_{tax}=001$, r – coefficient of reward paid for the best classifier $r=2$.

The rule and message procedures perform the process of classifiers checking and evaluation, in aspect of using the information contained in them for solving the problematic situations. This allows for appointing of the group of classifiers containing the useful information on the searched post-fault network configuration.

Co-evolutionary algorithm in the elaborated method

To modifications of the evolutionary algorithm enabling solutions of multi-criteria tasks are counted among others the application of the co-evolutionary approach. Application of the co-evolutionary algorithm to the analysed task creates *m* population; in each of them the adaptation function is defined on the basis of another component quality indicator vector. After successive performance (population supplementation with new elements), and through renewed reproduction, these populations are connected, and then were again divided so that each population elements may attain an unlimited population. The sought-after solution is the Pareto- optimal collection of solutions.

To encode the individuals representing various network configuration variants in a form of a sparse graph, the bequest of chromosomes in the form of a vector of inversion has been assumed. Each component of the vector of inversion, corresponding to the number of the graph node, is equal to the number of the supplying node.

A linear scaling method of population individuals' fitness function has been also used in the algorithm. Two specialised reconfiguration operators have been used in the algorithm to create new solutions [12]. The mutation operator enables to introduce the random changes into the network configuration. In order to obtain proper solutions following limiting constraints resulting from technical requirements for proper operation of the distribution network have been taken into account:

- Not exceeding of the maximum transmission currents of the line sections

$$0 \le P_j \le c_j \quad j = 1,2,...,n, \quad (4)$$

where P_j – active power passing through the branch *j* of the network, c_j – arc capacitance equal to its flow capacity;

- Not exceeding of the allowable voltage drops in the network nodes supply routes

$$\Delta U_n \le \Delta U_i \le \Delta U_l \quad i = 1,2,...,k, \quad (5)$$

where ΔU_i - calculated voltage drop in the supply circuit of the *i-th* network node, ΔU_n, ΔU_l - allowable supply voltage drop of the network node.

On the base of the source data [5, 6, 7, 8, 9, 10] and own research following values of significant parameters of the calculation system have been assumed in the calculation procedures: number of classifiers $n=200$, crowding factor for classifier population $c_s=3$, crossover probability $p_k=0,95$, mutation probability $p_m=0,15$.

Assumed optimization criteria

Following criteria have been assumed substantial for the optimisation problem of post-fault network configuration (of membership functions $u_1(X)$, $u_2(X)$, $u_3(X)$, $u_4(X)$, $u_5(X)$ its detailed description is contained in [12]):

- Minimisation of the number of switching activities leading to obtaining a substitute network configuration;
- Minimisation of the number of switching activities leading to obtaining a substitute network configuration

$$\underset{j}{Min}\ u_1(X_j) = |n_j - n_0| \quad \text{where } j = 1, 2, \ldots, m, \quad (6)$$

where X_j – vector containing information on the *j-th* variant of the distribution network configuration, m – number of solution variants, n_j – number of switching activities, n_0 – number of switching activities in the basic configuration;

- Minimisation of the undelivered power value

$$\underset{j}{Min}\ u_2(X_j) = \sum_{i=1}^{lw} P_{sr,i} \cdot q_i \cdot T_{p,i}, \quad (7)$$

where $P_{sr,i}$ – average active load of the *i-th* user node of the network, l_w – number of nodes, q_i – unreliability factor of the supply circuit of the *i-th* user node, $T_{p,i}$ – operation time;

- Minimisation of the voltage deviation in the network nodes

$$\underset{j}{Min}\, u_3(X_j) = \max_i \left(\frac{U_i}{U_N} \cdot 100 \right), \quad (8)$$

where U_N – distribution network nominal voltage, U_i – voltage value in the *i-th* user node of the network;

- Minimisation of the power load degree coefficient of the found group of the most loaded network elements

$$\underset{j}{Min}\ u_4(X_j) = \max_k \frac{\sum_{i=1}^{n} P_{\max,i}}{n}, \quad (9)$$

where m – number of sections being loaded in the given variant of network configuration;

- Minimisation of the technical losses in the distribution systems

$$\underset{j}{Min}\, u_5(X_j) = \sum_{j=1}^{m} \frac{P_j^2 + Q_j^2}{U_N^2} \cdot R_j, \quad (10)$$

where k – the number of power supply route network nodes of the reception network, n – the number of the most heavily loaded network elements.

The assumed membership functions used for the main variables description have been defined as follows:

$$u_i(X) = \begin{cases} 1, & \text{if} \quad f_i(X) \le f_i^{min}, \\ \left(\dfrac{f_i^{max} - f_i(X)}{f_i^{max} - f_i^{min}} \right), & \text{if} \quad f_i^{min} < f_i(X) \le f_i^{max}, \\ 0, & \text{if} \quad f_i^{max} < f_i(X). \end{cases} \quad (11)$$

Case studies

In this part of the study the problem of calculation connected with the medium voltage urban electric power distribution network malfunction state is considered, the simplified electrical diagrams of the analysed network are presented in Fig. 2 and 3. The considered network malfunction state, which caused disconnection from normal operation of a section of bus-bars of the main station supplying number 6, the location of malfunction occurrence is marked on Fig. 2. The consequence of this malfunction is lack of power supply for a significant proportion of the network nodes. The current of each branch is evaluated by deriving the distribution power flow equations for a radial configuration network [12].

The sought after solution is the designated substitute network configuration enabling restoration power supplies for the greatest number of consumer network nodes possible.

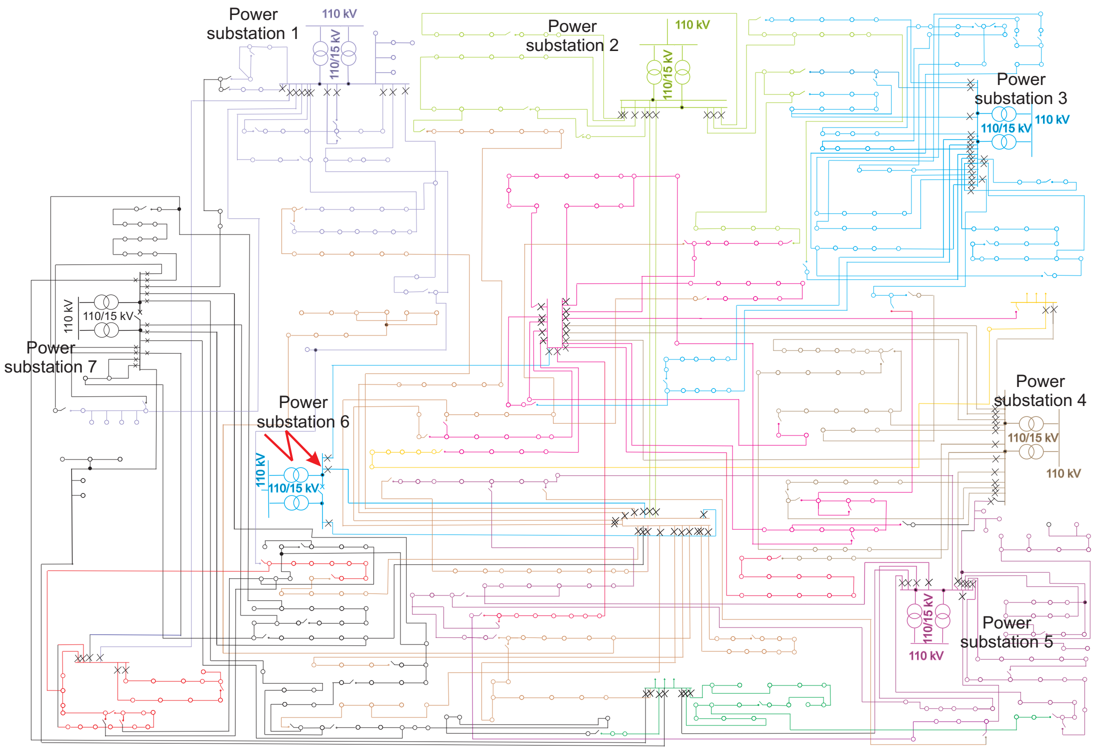

Fig. 2. Diagram of the analysed distribution network

The examined assignment is a multi-criteria optimisation task, for its solution the author proposed use of a co-evolutionary algorithm working together with the classification system. The sought after solution of the analysed multi-criteria optimisation problem is the collection of Pareto-optimal solutions. In order to seek the distribution network substitute configurations enabling the most rational use of the existing network infrastructure the author considered the collection of five criteria. Presented below is the announcement record describing the existing malfunction. For the below considered breakdown situation in the analysed network, which is composed of 556 network nodes the author accepted the abbreviated description of announcements and also classifiers. The abbreviated description however contains instead of the zero-one tract (part of the first announcement) the numbers of line sections deprived of power, whereas as part of the second announcement the numbers of damaged elements are given. In the elaborated calculation model a so-called vector of inversion has been used for the network configuration description.

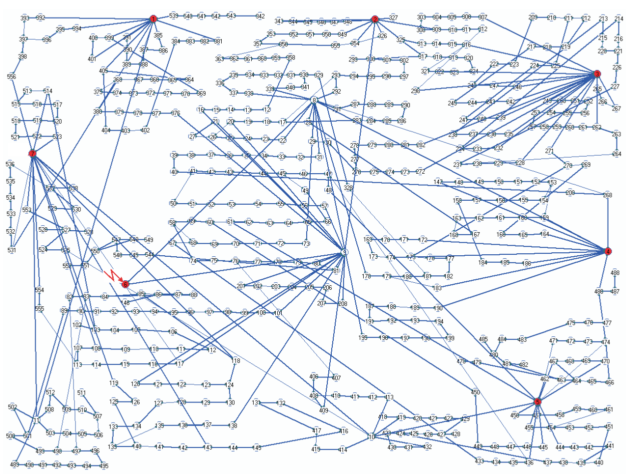

Fig. 3. Graph of the analysed medium voltage network

Accepting such an abbreviated method of description for breakdowns existing in the analysed network, the announcement describing the breakdown is defined as follows:

- Numbers of not supplied nodes: *8,22,28,29,31,73,178,195,291,292,338,339,23,167,32,72,179,196,287,2. ... 549,550,203,368,359,51,548,551,360,50,552,361,362,363*;
- Numbers of fault elements: *a section of bus-bars of the main station supplying number 6.*

In order to present the classifiers very transparently the author introduced (similarly as for the announcements) a simple means of describing the condition and action of the classifier:

- Condition: (a list with numbers of not supplied nodes) + (a list with numbers of fault elements);
- Message: (post-fault configuration).

The significant assumption proposed in the article of the method is the use of the population containing classifiers and the population containing substitute network configuration solution variants for the considered distribution network malfunction state.

The first of the populations named constitutes a collection of classifiers (which serve as centres gathering information useful in the future for the formulation of post-malfunction substitute network configurations), which may be supplemented by newly obtained classifiers (which contain substitute network configuration scenarios for probable network malfunction states) that are recorded in the collection of classifiers with the use of the so-called press model in order to maintain the constant number of the classifiers collection. The second population is composed of five subpopulations of which each is connected with another optimisation criterion. In the first stage of the calculations performed with the proposed method are the announcement creation processes and the evaluation of classifiers (performed according to the genetic principles of self-teaching systems), consisting of the search in the collection of classifiers for information assisting the process of designating the solution to the analysed task.

During this part of the calculation classifiers are sought, the conditions of which are compatible with the announcement describing the existing state of electric power distribution network malfunction. For the consideration of the designated network malfunction state (during the announcement creation process) in the first stage of the classifiers registered in Table 1.

Table 1. Active classifiers after first process evaluating

No	Condition: (numbers of non-supplied nodes) and (numbers of fault elements)	Answer of system (recorded in the vectors of inversion)	S_i	Bid	SA_i
1.	(8,22,28,29,31,73,178,195,291,292,338,339,23,167,32,72,179,196,287,293,337,340,24,168,33,71,180,197,288,294,336,341,25,34,70,181,198,289,295,335,330,26,69,182,199,290,296,334,329,331,68,177,194,286,297,333,328,176,193,285,332,192,284,191,187,188) and (line 6_8)	x,x,x,x,x,x,x,4,6,5,1,13,14,15,16,9,18,19,20,9,9,8,22,23,24,25,21,8,8,276,8,31,32,33,36,37,38,39,40,200,42,43,44,45,… ,550,551,7,7,554,7	$S_1 = 10$	$B_1 =$ 0,813 $EB_1 =$ 0,802	S_1=10+ 0,622
2.	**(9,16,20,21,57,80,81,101,117,120,138,201,208,376,409,15,19,27,56,79,544,100,116,121,136,202,207,377,408,14,18,55,78,545,99,115,122,135,137,206,378,406,13,17,54,77,546,98,114,205,379,407,12,283,53,76,547,97,204,380,358,52,549,550,203,368,359,51,548,551,360,50,552,361,362,363) and (line 6_9)**	**x,x,x,x,x,x,x,6,2,5,7,13,14,15,16,9,293,17,18,19,9,8,22,23,24,20,26,8,8,276,8,31,32,33,36,37,38,39,40,200,42,43,44,… ,550,551,7,7,554,7**	$S_2 = 10$	$B_2 =$ **0,823** $EB_2 =$ **0,831**	S_2=10+ 2
3.	(178, 179, 180, 181, 182, 177, 178) and (line 8_22)	x,x,x,x,x,x,x,6,2,5,7,13,14,15,16,9,293,17,18,19,9,8,22,23,24,20,26,8,8,276,8,31,32,33,36,37, … 50,551,7,7,554,7	$S_3 = 10$	$B_3 =$ 0,423 $EB_3 =$ 0,501	S_3=10+ 0,211

Note: S_i – strength of the *i-th* classifier, Current value SA_i strength of the *i-th* classifier

The classifiers, which fulfil this condition are described in the literature as active classifiers, values of the so-called offer are calculated for them according to the procedures of the evaluation algorithm which is described in point 2. The evaluation takes place on the basis of the suitability of the information contained in particular classifiers. In the column relating to network configurations noted in the inversion vector only the initial and final elements of this vector are noted. In the last column of table number 1 contains the calculation results of the offer for particular classifiers. According to the idea of classifying systems through the process of announcement creation, then follows the evaluation of the revealed classifiers, which consists of the calculation of the so-called offer of the classifiers being the measure of their suitability to resolve the analysed task. The offer for classifier number 1 calculated according to dependencies 2 and 3 amounted appropriately to $B_1 = 0{,}813$ and $EB_1 = 0{,}802$. Whereas the offer for classifier number *2* amounted correspondingly to $B_2 = 0{,}823$ and $EB_2 = 0{,}831$ and the offer for classifier number 3: $B_3 = 0{,}423$ and $EB_3 = 0{,}501$. This process is continued to the moment of lack of subsequent classifiers for which the conditions shall be compatible with the last designated announcement. This algorithm is based simultaneously on 5 subpopulations, from which each evaluation was the basis for another adaptation function. The sought-after solution in this case is a collection of solutions in the form of alternative configurations of the analysed network. The choice of the final solution variant depends upon the decision maker decider, who in this instance may be the operator managing the operation of the electric power Medium Voltage distribution network. On the graph in figure 4 the course of the change of values of best solutions is shown in chosen subpopulation 4 in the event that an evolutionary algorithm began calculation with randomly generated initial subpopulations. The results of calculations are presented in graphic form in Fig. 5.

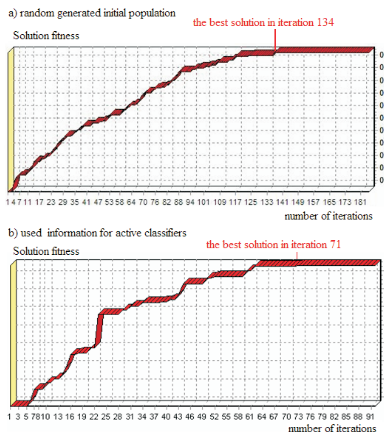

Fig. 4. Example of best solutions fitness waveform in subpopulation number 4

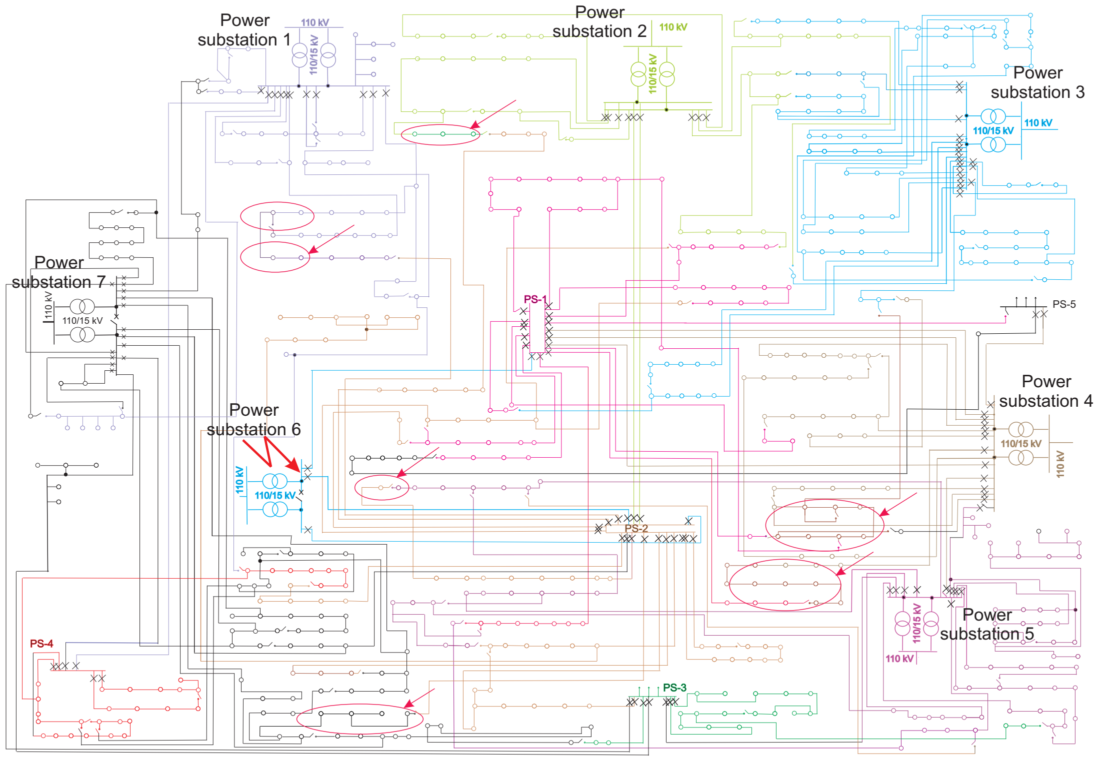

Fig. 5. Diagram of the analysed distribution network with network configurations

The Fig. 5 presents the chosen (appropriate to the best solution of subpopulation numbers 4) designated substitute configuration of the analysed network. Cooperation of the co-evolutionary algorithm with the classification system enables significant reduction of time of obtainment of solutions (reduces the iterative calculation process on average by 40 %), which is significant from the practical point of view in the application of this method in current systems of distribution network operation management. For the best obtained network configurations for criterion 4: $u_4(x) = 0{,}721$, additionally: $u_1(x) = 0{,}519$, $u_2(x) = 0{,}952$, $u_3(x) = 0{,}739$, $u_5(x) = 0{,}692$. The final decision of selection of solution variant (among the sought after collection of solutions with particular subpopulations) may be taken by the operator managing work of the electric power distribution network.

Conclusions

The calculations performed for the mapped real system of the medium voltage municipal distribution network of 556 nodes have given satisfactory results, confirming the adequate direction of the research. On the base of the results obtained so far the authors assume that the results can be further used in creation of decisive procedures for complex power electric systems management, taking the fault operation states into special consideration. The method proposed by the author of the work is typified by the short time of designating the most rational post breakdown configurations in complex electric power Medium Voltage distribution network structures. It is the use by the classifying system working with the co-evolution algorithm that enables the effective creation of substitute scenarios for the Medium Voltage electric power distribution network. The method drawn up may be used in current systems managing the work of distribution networks to assist network operators in taking decisions concerning connection actions in supervised electric power systems.

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The methodology of restoring power supply to consumers in case of a distribution grid failure is an important issue in literature on operation and reliability of electrical energy distribution grids. The article presents a concept of a new method which supports the operation of distribution grids operators in case of a failure using a classifier system working in tandem with a coevolutionary algorithm. The method presented in the article enables constructing scenarios for adjustments to medium voltage power distribution grids configuration (power system switchgear operation adjustments). The developed method is based on the theoretical rudiments of genetic-based machine learning systems. The method uses information on previous power distribution grid failures and enables using information from simulated grid failures. Decision variables, which take into account the reliability parameters of distribution grid elements among other things, have been described using the fuzzy set theory. The final part of the article describes sample calculations related to failures of a selected actual power distribution grid performed using the developed method. Ill. 5, bibl. 12, tabl. 1 (in English; abstracts in English and Lithuanian).

F. Sylwester. Klasifikacinės sistemos ir koevoliucinio algoritmo pritaikymas vidutinės įtampos elektros energijos tinklų poavarinėms konfigūracijoms optimizuoti // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 9(115). – P. 9–15.

Pateikta naujo metodo, skirto padėti elektros energijos skirstomųjų tinklų operatorių darbui avarijų atvejais ir pagrįsto klasifikacijos sistema, bendradarbiaujančia su koevoliuciniu algoritmu, koncepcija. Metodas leidžia nustatyti vidutinės įtampos elektros energijos skirstomųjų tinklų konfigūracijos pakeitimų (susijusių su elektroenergetinės perjungimo aparatūros darbo būsenos pakeitimais) scenarijus. Aprašomasis metodas grindžiamas genetinių besimokančiųjų sistemų teorijos pagrindais. Naudojama informacija apie anksčiau elektros energijos skirstomajame tinkle įvykusias avarijas bei leidžiama naudoti informaciją, gaunamą iš imituojamų avarinių būsenų tuose tinkluose. Remiantis neapibrėžtųjų aibių teorija buvo aprašyti pasiūlyto sprendimo kintamieji, įvertinantys, be viso kito, skirstomojo tinklo elementų patikimumo parametrus. Baigiamojoje straipsnio dalyje pateikiamas sukurtuoju metodu atliktų pavyzdinių skaičiavimų, susijusių su pasirinkto realaus elektros energijos skirstomojo tinklo avarijos būsenomis, aprašymas. Il. 5, bibl. 12, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).