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Selected evolutionary algorithms for multicriterial optimization based on the example of the programming of the energy distribution systems development

***Abstract**. This paper deals with the current problems of the multicriterial optimization algorithms on the basis of the example of the programming of the energy distribution system development. The article presents the results of the analysis of selected two evolutionary algorithms the purpose of which was to find a set of Pareto-optimum solutions. The solution sought after are the Pareto-optimum development strategies for the selected distribution network system.*

Streszczenie.** Artykuł dotyczy aktualnej problematyki algorytmów optymalizacji wielokryterialnej na przykładzie programowania rozwoju systemu dystrybucyjnego energii. Przedstawiono rezultaty analiz dla dwóch wybranych algorytmów ewolucyjnych, których celem było odszukanie zbióru Pareto-optymalnych rozwiązań. Przy czym poszukiwanym rozwiązaniem będą Pareto-optymalne strategie rozwoju dla wybranego układu sieci dystrybucyjnej. **(Wybrane algorytmy ewolucyjne do optymalizacji wielokryterialnej na przykładzie programowania rozwoju systemów dystrybucyjnych energii).

Słowa kluczowe: algorytmy ewolucyjne, optymalizacja wielokryterialna, optymalizacja strategii rozwoju.
Keywords: evolutionary algorithms, multi-criteria optimization, optimization of strategy of development.

Introduction

The problems of planning and optimization of the development of the electrical energy systems, including the energy distribution systems is a very up-to-date issue, which is proven by a large number of publications on that topic, including in particular [1, 2, 3, 4]. It is assumed that distribution networks will evolve in the direction of the intelligent networks. Moreover, certain part of the distribution networks requires modernisation. The modernization may include in particular [5, 6, 7, 8]: using of improved connection apparatuses, the strengthening of the network through new linking lines GPZs, solutions improving the levels of voltage of the network, reserve power supply systems and also wider application of telemechanics, short-circuit finders and other solutions allowing fast diagnostics of failures and effective operation of the network traffic, also in the interference situations.

Most frequently, a solution to the problem of optimization of the distribution system development strategy is a collection of hundreds of variables meaning replacement, modernization of network devices and new investments. In order to solve the problem, in particular heuristic as well as evolutionary algorithms are applied. The latter ones provide solutions which may be adopted as final ones or be the exit point for other methods. An advantage of the evolutionary algorithms is the possibility of working on a certain set of solutions and related parallelism of the calculations. These algorithms combine the principles of the evolution theory transposed to the mathematical description with directed, albeit random, exchange of information [9, 10]. Selected applications of the evolutionary algorithms for optimization of the distribution networks may be found in particular in the following publications: [11, 12, 13, and 14], in which also the effectiveness of the algorithms with other methods was compared.

In order to solve the tasks of the multicriterial optimization methods employing the Pareto techniques are applied. The methods include in particular the adaptation method of weighted sums, simulated annealing, evolutionary algorithms and hybrid algorithms [9, 15].

Application of the evolutionary calculations to the multicriterial optimization entails the problem of evasion of the equation and non-equation related limitations, which quite often appear in the real optimization problems. In order to solve the problem, in particular the penalty function method, encoders, and repair algorithms are applied. In respect of the optimization methods based on the evolutionary calculations in which all the optimization criteria are treated equally quite often a Pareto set is obtained which has very many solutions. Therefore, the problem of selection of the best solution appears. In order to simplify the procedure the number of the solutions in the Pareto set may be reduced by introduction of the non-differentiation divisions or application of the fuzzy logics.

In this article, the evolutionary algorithms for multicriterial optimization are presented as well as application of the selected evolutionary algorithms for optimization of the development strategy of an exemplary distribution network.

Evolutionary algorithms

In the solving of the multicriterial optimization problems, the methods aggregating the individual criteria to the form of the scalar function of the objective are popular. A known form of non-linear aggregation of the objective function is also the limited criteria method or the method of programming of the objective [9]. However, criteria which are opposite or incomparable with each other can be aggregated. Therefore, a set of compromise solutions is determined on the basis of the optimum concept in the meaning of Pareto. The group of evolutionary algorithms for the optimization in the Pareto meaning are designated as MOEA (Multi Object Evolutionary Algorithm). Below, the most popular MOEAs are presented which are discussed in more detail in [16, 17, 18, and 19].

In this group of algorithms, MOwGA (Multiobjective Optimization Genetic Algorithm) is very popular. In the MOwGA method, the given specimen is given his/its rank on the basis of the number of specimen which dominate him/it in the current population. NGGA (Non-Generational Genetic Algorithm) is a type of MOwGA. In this method the value of adaptation of the given specimen is determined on the basis of the sum of two components: the number of domination which determines the weighted average number of specimen which dominate specific solution and the number of the shifting of the niche determining the weighted average number of specimen which lie close to the given solution in accordance with the division function.

NSGA (Non-Dominated Sorting Genetic Algorithm) is another popular method which differs from the basic genetic algorithm in the selection method. In the first step of NSGA, all non-dominated specimen are identified in the population and are given the same high value of the artificial value of adaptation pro rata to the size of the population. Subsequently, in order to maintain the diversity, the pre-determined artificial values of adaptation of non-dominated specimen are subjected to the division function. In another step, new non-dominated solutions are identified in the remaining population which are subject to the above activities.

In the NPGA (Niched Pareto Genetic Algorithm) method, a tournament selection was applied, which is based on the concept of domination in the Pareto meaning. PAES (Pareto Achieved Evolution Strategy) is another Pareto method. PAES takes advantage of the evolutionary strategies (1+λ) or (μ+λ). The evolutionary strategy adopted is based on the local research but also uses the archival set of already found non-dominated solutions which serves the purpose of determining the rank of both the current and the future solution.

However, a Pareto (external) set applied in the SPEA (Strength Pareto Evolutionary Algorithm) method has been obtained in the former generations. In each generation, non-dominated solutions are copied to the set. Subsequently, for each component of the external set, a real number referred to as the durability is determined. The value of the number is analogous to the ranks in the MOwGA method and is equally dependent on the number of solutions which dominate the given case. The value of adaptation of the solutions in the current population depends on the degree to which they are dominated by the solutions from the external set. In order to limit the numerical amount of the external set in the SPEA method, the technique of the intervals of indistinguishability without loss of information about the course of the Pareto front is applied.

Many metrics have been proposed for assessment of the methods based on the Pareto set which allow comparing the set of non-dominated solutions with each other. Also, testing optimization problems are being designed which allow assessing the effectiveness of individual methods [9, 18]. In this article, the author limited himself to presentation of the results obtained for two selected evolutionary algorithms.

Optimization of the development strategy of the selected distribution system

The following part of this paper deals with analyses of application of selected evolutionary algorithms to solution of the problem of optimization of the development strategy of the energy distribution systems. Generally known VEGA (Vector Evaluated Genetic Algorithm) was applied for the calculations which has been implemented in the Delphi environment, as well as NSGA (Non-Dominated Sorting Genetic Algorithm) which has been embedded in the "gamultiobj" function of the Matlab software. The structure and technical data of a real electrical energy distribution network were assumed as the basis for the calculation for the problem of optimization of the development strategy of the distribution system. The structure of the electrical energy distribution network has been presented on Figure 1 below.

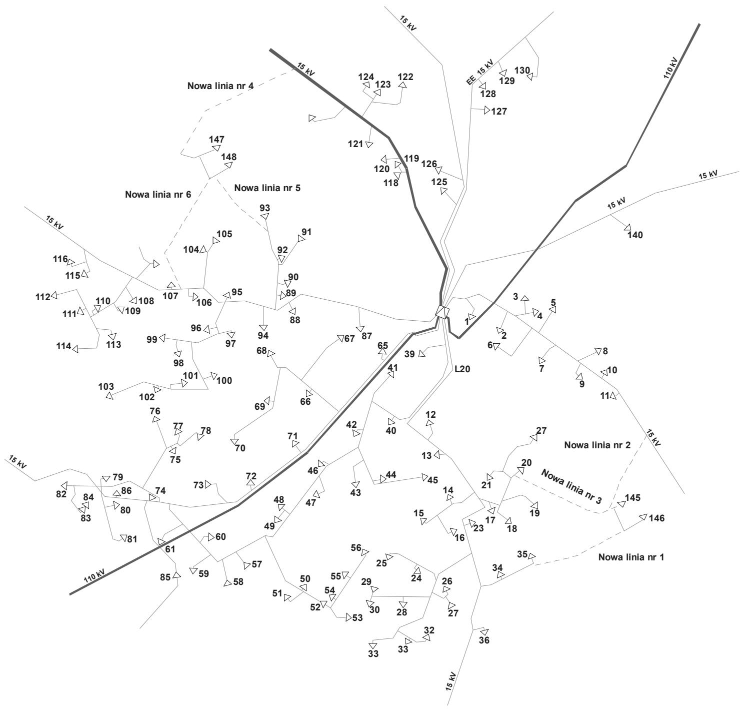

Fig.1. Drawing of analysed distributional net

Multivariation phases of modernisation and development of the network may be described in the form of a graph (the nodes of which may include subgraphs reflecting the alternative variations of changes of the network for specific stage) or a matrix describing the variation strategies of network development. In the problem discussed in this paper, a graph has been created which describes the possible network development strategies and which consists of 40 nodes, containing descriptions of the network development phases.

Additionally, in the created graph, an algorithm which finds the best paths (development strategies) has been introduced into the solution assessing function of the graph created. The purpose of the calculations was to find the best in terms of the adopted criteria set of the Pareto-optimum solution reflecting the best development strategies of the network in question.

In the proposed model the following criteria have been assumed relating to the discounted costs and expenditures:

- minimisation of the costs of technical losses ($k_k \cdot (\Delta P + ke \cdot \Delta Q)$);
- minimisation of the costs of fail safeness and interruptions (Ka);
- minimisation of the costs of voltage deviations (Ko);
- maximisation of the net present value (NPV savings resulting from modernisation of the network).

The following formulas have been applied for assessment of the solutions created by the evolutionary algorithms [4, 5, 6]:

(1) $$K_d = \sum_{t=1}^{n} K_t \cdot \frac{1}{(1+p)^t}$$

(2) $$K_t = \sum_{k=1}^{m} Ka_k + \sum_{k=1}^{m} k_k \cdot (\Delta P_k + k_e \cdot \Delta Q_k) + \sum_{k=1}^{m} Ko_k$$

(3) $$NPV = \sum_{t=0}^{t=n} \frac{(CI_t - CO_t)}{(1+p)^t}$$

where: K_d, – discounted network operation costs, n – the number of intervals in the calculation period; t – another year of operation of the network; m – the number of components of the network; k – component k, Ka – costs of failures; Ko – costs of voltage deviations; ΔP, ΔQ – losses on the active and passive power; ke - rate passive power, p – discount rate; CI_t – cash inflows generated during year t; CO_t – cash expenditures incurred in year t.

It was assumed that after the modernisation, the network will meet the technical requirements in terms of: the voltage and current Kirchhoff's laws, non-exceeding the permissible thermal and short circuit capacity of the elements of the network. In order to make calculations allowing finding the optimum development strategy of the network in question, author's own software has been partially used which was created in the Delphi environment, into which a co-evolutionary algorithm was implemented which was based on the modified concept of the VEGA algorithm.

Moreover, built-in functions of the Matlab software have been used, including in particular the "Optimization Tool" module, which provides the "gamultiobj - Multiobjective optimization using Genetic Algorithm" function which allows multicriterial optimization using the genetic algorithm. In the "gamultiobj" function, the NSGA has been used.

Modified VEGA algorithm was used for the initial part of the calculations. The VEGA has been adjusted to the analysed problem (the modification consisted in the application of the niche formation mechanism to the processed populations). The algorithm is based on the co-evolutionary approach, i.e. cooperation of several sub-populations. In the algorithm applied, the method of random selections in accordance with the remaining balances without reiterations. The crossing operator has been applied which used the generated binary vectors as the forms for creation of the solutions. Mutation operator was used for insignificant changes in the processed solutions.

Tested different methods of selection. The best results were obtained with the method of selection of random selection by residues without repetition. For the analysis method was used for linear scaling to fitness value solutions. The algorithm work parameters were selected as follows: p_c =0,95 and p_m= 0,08, with the numerical amounts of the populations up to 100 elements. The analyzes employed population exchange ratio equal to 0,4. Not used elitist strategy.

The course of the changes of the best solutions and the changes of the average adaptation in subpopulations are shown on Figure 2. Since it was assumed that the maximum and minimum values of the assessment function are known, the values presented in the graph have been normalized to the value from the range 0÷1. The results obtained by using the modified VEGA, taking the form of a set of Pareto-optimum solutions have been recorded in Table 1.

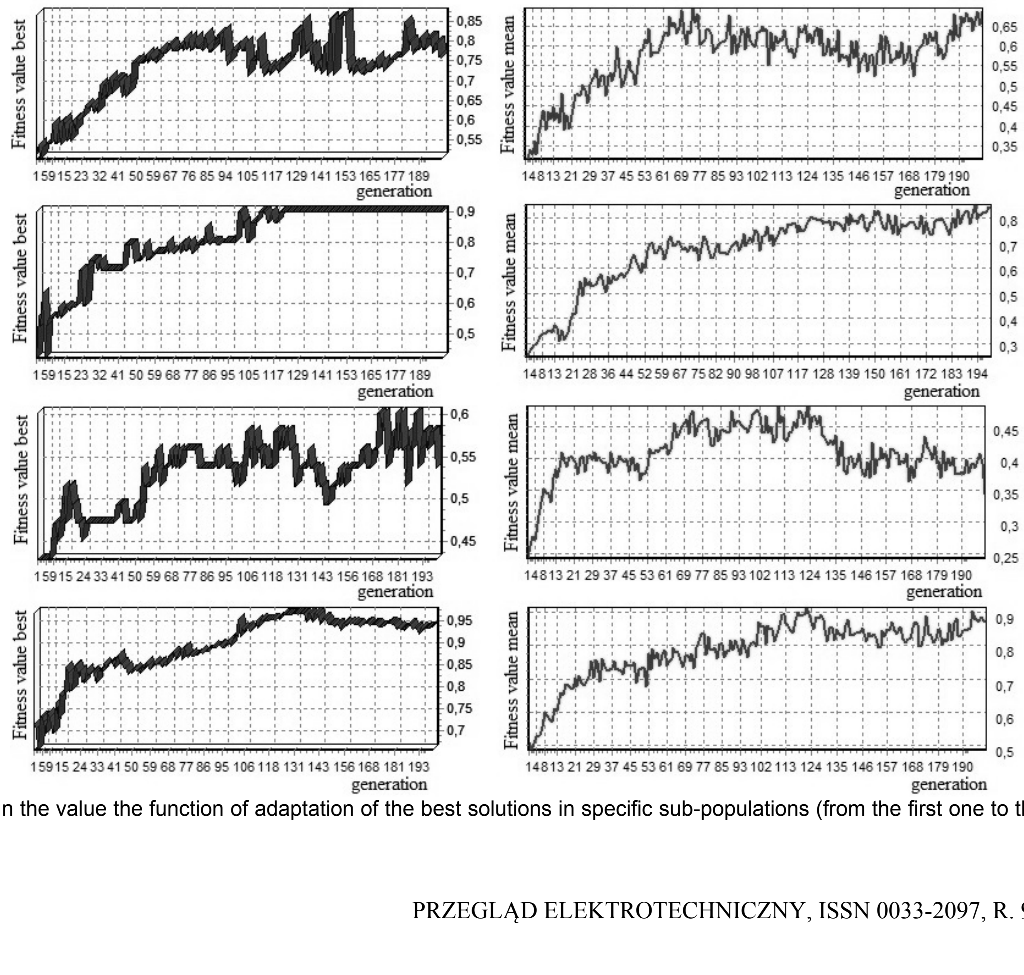

Fig.2. Changes in the value the function of adaptation of the best solutions in specific sub-populations (from the first one to the fourth one).

The results presented in Table 1 reflect the best solution variations obtained in individual subpopulations processed by the algorithm. For the sake of verification of the results obtained, solution to the problem in question has been sought using the NSGA which has been implemented into the “gamultiobj” – “Multiobjective optimization using Genetic Algorithm” function of the Matlab software.

Table 1. Set of Solutions for algorithm VEGA (for 4 criteria)

nu.	results for sub population 1	results for sub population 2	results for sub population 3	results for sub population 4
1	131 328	145 354	126 439	110 680
2	134 594	142 924	128 581	133 560
3	131 455	147 343	125 154	119 170
4	170 266	163 072	149 709	80 000

The Matlab software also provides a graphical interface providing the user with high opportunities to configure an evolutionary algorithm in conformity to the discussed problem. An appropriate representation of the solutions to the problem may be selected, and the following have been selected for the research in question: real-numerical vectors describing changes in the network, selection method: “Stochastic uniform”; the crossing and mutation operators: “Scattered” and “Uniform”; scaling method: “Rank”, as well as algorithm work parameters, i.e.: p_c = 0,98, p_m = 0,08, and the numerical amounts of the population: 400 ÷ 500.

The calculation halting criteria were adopted in the form of a set iteration number after which no improvement of the objective function occurred. Below, results of the calculations are presented which have been obtained using the “gamultiobj” function which allows setting of the set of Pareto-optimum solutions with a pre-set number of components of the set (Table 2).

Table 2. Set of Solutions for algorithm NSGA (for 4 criteria).

nu.	results for sub population 1	results for sub population 2	results for sub population 3	results for sub population 4
1	131 492	145 004	125 627	131 240
2	143 721	143 158	135 405	80 030
3	136 256	156 211	131 273	86 270
4	137 907	143 158	130 790	90 510
5	138 032	143 158	131 068	80 450
6	131 555	144 354	125 545	122 020
7	138 752	143 158	132 076	82 830
8	137 612	148 211	130 343	80 110
9	134 575	152 924	129 486	81 380
10	138 192	142 734	130 980	85 500

Figure 3 presents the solution in the graphical form on which subsequent phases of the modernisation and development of the network have been presented marked symbolically which were comprised in the variation selected from the found set of the best development strategies of the distribution network.

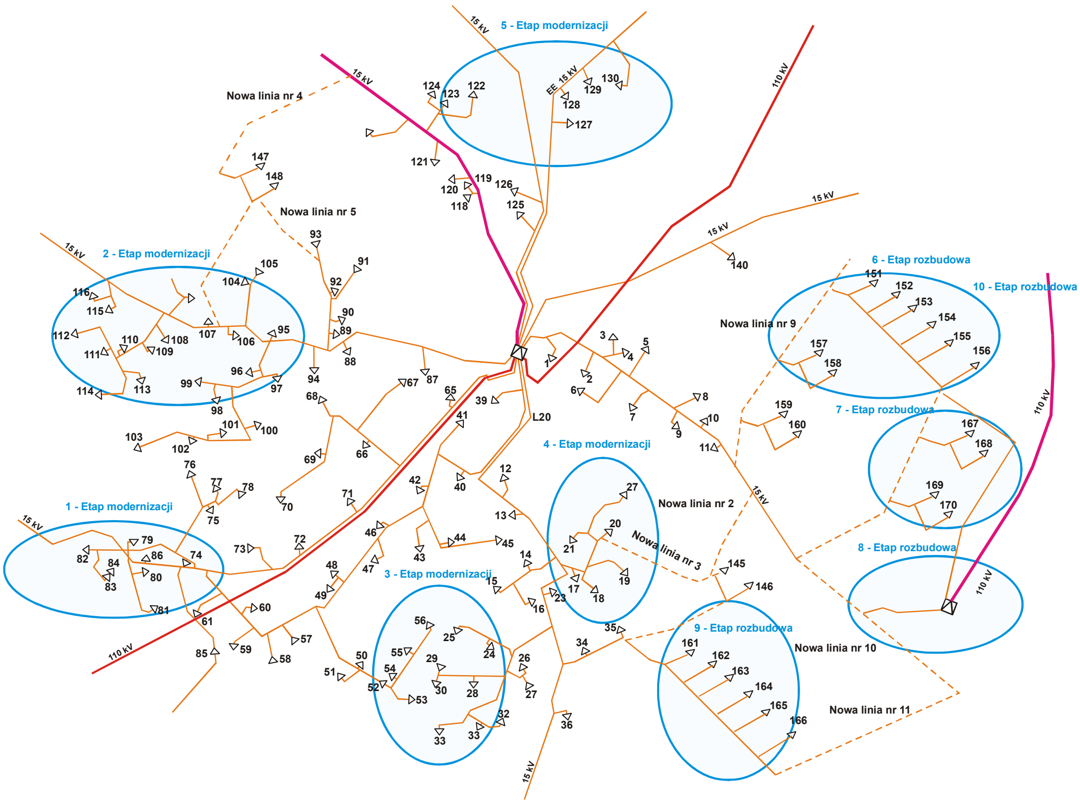

Fig.3. Distribution network with the marked development phases which were contained in the best development strategy of the network which was found

When analysing the results obtained using the evolutionary algorithms VEGA and NSGA, it may be stated that the first of them finds solutions from the Pareto system which are very good in terms of individual criteria (related to individual sub-populations), which however are poorer in terms of the remaining criteria. On the other hand, NSGA deals with the finding of the pre-set number of solutions of the Pareto set, which may be specified as the best compromise solutions. It may be understood that in the course of the search it performs, NSGA equally takes all the criteria into account. There is no significant advantage of specific “main” criteria (for specific sub-population) like it happens with VEGA.

In order to give picture of the effects of the “gamultiobj” function, the description of the task was modified describing it as a problem with two criteria. In the first one, discounted network operation costs were accumulated and the other was related to the calculation of the net present value.

Figures 4 and 5 present graphs presenting the Pareto front obtained for the problem in question which describes the set of the solutions obtained for different phases of the calculation process. On the basis of the results presented in the literature it may also be noted that similar results like those obtained using the NSGA can be obtained using the SPEA (Strength Pareto Evolutionary Algorithm) in which external Pareto set is used which has been obtained in previous generations. In each generation, new non-dominated solutions are copied to the set. It also results in the obtaining of the set of solutions upon determination of which the criteria taken into account have similar influence on the course of the process of seeking the final set of solutions.

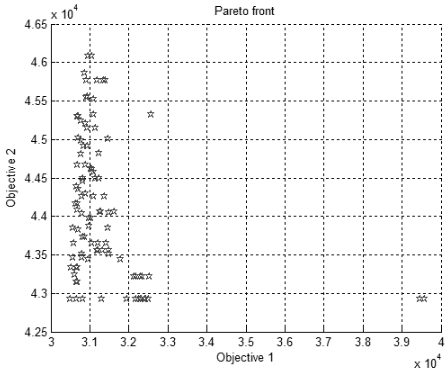

Fig.4. The calculations for function "gamultiobj" for 70 iteration

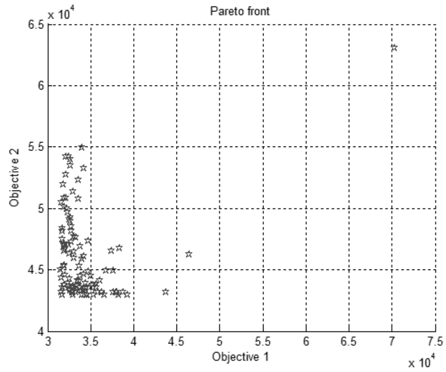

Fig.5. The calculations for function "gamultiobj" for 100 iteration

Conclusions

In this paper, selected aspects of application of the evolutionary algorithms to multicriterial optimization were presented on the basis of the example of optimization of development of the energy distribution system. The paper presents the possibilities and the effectiveness of the selected evolutionary algorithms. The obtained results have been presented and compare in the form of tables and the graphs. On the basis of the present state of knowledge and author's own research it may be stated that the evolutionary algorithms may be applied for the solving of the tasks of multicriterial optimization which is also confirmed by many publications and empirical results. The analyses performed allow stating that the evolutionary algorithms may provide an effective method of seeking optimum or suboptimum strategies of development of the energy distribution systems. The Matlab software, in particular the "gamultiobj" function with the implemented NSGA provides a very useful method for the user to solve complex problems of multicriterial optimization. The readily available graphic interface which provides access to a number of procedures and operators applied in the evolutionary calculations allows testing and effective adaptation of the evolutionary algorithms to solve the complex problems, in particular the problems of multicriterial optimization.

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