FORUMUL REGIONAL AL ENERGIEI – FOREN 2008
Neptun, 15-19 iunie 2008

Reference no: S3-16-en

THE RECONFIGURATION OF ELECTRIC NETWORKS USING PARETO OPTIMALITY AND EVOLUTION STRATEGIES

Bogdan Tomoiagă, National Power Grid Company “Transelectrica” – Transport Branch Cluj
Mircea Chindriş, Technical University of Cluj-Napoca
Ciprian Bud, National Power Grid Company “Transelectrica” – Transport Branch Cluj

Abstract

The reconfiguration of an electrical network consists in modifying the existing configuration by exchanging the functioning links between its elements in order to improve different performances. The reconfiguration problem is one of *multi-criteria optimisation*, where the solution is chosen after the evaluation of a group of indexes, named *partial criteria*, which represent multiple purposes.

In the paper, authors propose to formulate the reconfiguration problem as *Pareto optimality*. On the other hand, to search the optimal solution authors propose *an original algorithm* based on *evolution strategies*. The proposed algorithm has been implemented in the visual environment programming language *C++ Builder* that, due to its graphic interface, ensures an extreme lightness in the use. This software product was implemented for several *IEEE* test electric distribution networks where optimal configurations were obtained in a very short time.

Introduction

In general, electrical distribution networks (EDN) are operating in radial configurations. The reconfiguration of an electrical network consists in modifying the existing configuration by exchanging the functioning links between its elements in order to improve different performances [1]. The reconfiguration problem is one of *multi-criteria optimisation*, where the solution is chosen after the evaluation of a group of indexes, named *partial criteria* (in this case active power losses, continuity in power supply, etc.), which represent multiple purposes.

Many solutions for onset the multi-criteria optimisation problems can be found in the literature; among them, we remind *optimisation with weights* (where a weight characterize the importance of a criterion) and *the main criteria method*, frequently useful in the distribution networks (EDN) reconfiguration problems: the main criterion is chosen, also indicating acceptable values for the other criteria, and the problem is solved in these conditions [2]. To eliminate the subjectivity of the above method, authors propose to formulate the reconfiguration problem as *Pareto optimality*. On the other hand, to search the optimal solution (configuration of electric network) we propose *an original algorithm* based on *evolution strategies* (considering the main genetic operators as *crossover, mutation* etc.).

The problem of reconfiguration is expressed in an original form (Pareto optimality) allowing considering more criteria in an objective manner in the optimisation process. On the other hand, an original solution to solve the problem (using evolution strategies) in a non-prohibitive time is also presented. The proposed algorithm has been implemented in the visual environment programming language *C++ Builder* that, due to its graphic interface, ensures an extreme lightness in the use. This software product was implemented for several electric distribution networks where optimal configurations were obtained in a very short time.

1. Criteria for reconfiguration [3]

1.1. Active power losses

For symmetric-sinusoidal regime, we can calculate active power losses (Joule-Lenz) [4] considering the relationship:

$$\Delta P = \sum_{(i,j)\in E} 3 \cdot R_{(i,j)} \cdot I^2_{(i,j)} \cdot \alpha_{(i,j)} \quad (1)$$

where:

ΔP – the value of active power losses;
(i, j) – extremities of an electric line;
E – the set of network lines (branches);
$I_{(i,j)}$ – the electric current through line *(i, j)*;
$R_{(i,j)}$ – electric resistance of a line *(i, j)*;
$\alpha_{(i,j)}$ – binary variable; its value *1* or *0* represent the status of a electric line: in operation or out of operation.

In a same manner, it is possible to formulate relationships for *un-sinusoidal* or/and *unsymmetrical* cases.

1.2. Continuity in power supply

It is a very important criterion, because the number of interruptions has some important economical consequences, and is powerfully influenced by the functioning schema adopted.

Hereby, particular importances are sustained interruptions (longer than 3 minutes); international legislation proposes a specific index *SAIFI* (system average interruption frequency), calculated as follows [5]:

$$SAIFI = \frac{\sum_{s=1}^{n} N_s}{N_t} \quad (2)$$

where:

N_s – total number of customer interruptions in interruption s;
N_t – total number of customers served;
n – total number of interruptions.

The minimisation of this index, assumed in Romanian legislation, may represent an important reconfiguration criterion.

1.3. Others criteria

A. Radial configuration of adopted functioning scheme [4]

$$\sum_{(i,j)\in U} \alpha_{(i,j)} = n - p \quad (3)$$

where:

n is the number of electric network node;
p is the number of connected components;

B. Assurance of power supplies for all customers; the attached graph will be connected;
C. It must be possible to impose and/or interdict the availability of an electric line [4];
D. Admitted number of manoeuvres [6];
E. Branch loads limits [4]:

$$I_{(i,j)} \le I_{\max,(i,j)}; \forall (i,j) \in E \quad (4)$$

F. Voltage drops limits [4]:

$$U_j^{\min} \le U_j; \forall j \in X \quad (6)$$

where X is the network nodes set.

2. Multi-criteria optimisation using genetic algorithms

The presented criteria (chapter 1) can be grouped in two different categories:

- criteria that must be minimized/maximised (*objective functions*);
- criteria that must be framed in some limits (*restrictions*).

Multi-criteria optimisation represent the model of some problems where the solution is chosen after the evaluation of a group of indexes, named *partial criteria* (in this case active power losses, continuity in power supply, etc.), which represent multiple purposes [2].

The selection of a point from the set of acceptable variants (which, in the case of reconfiguration, signify the cover trees set of the network attached graph) can be realised based of some additional information, which impose the weights of partial criteria. Knowing this information, we can formulate a *rule* to choose the optimal variant, named *selector*, which represent a mono-criterion optimisation problem.

To create the synthesis function it is necessary to convert all partial criteria in the same measurement units. A very used one is to convert in costs (complicate operation). On the other hand, in most cases, partial criteria are contradictory.

Therefore, the major difficulty in these kinds of problems consists in the incompatibility of different solutions.

Thus, we can use *Pareto optimality* concept where is defined a dominate relation among solutions. In Pareto optimisation, central concept is named *un-dominated solution*, described as follows:

- there exists no other solution that is superior at least in case of one objective function value;
- it is equal or superior with respect to other objective functions values.

The set of Pareto solutions form Pareto-frontier associated to a problem. To solve theses kind of problems, evolution strategies has a high potential.

Srinivas and *Deb* [8] have given a genetic algorithm for Pareto optimisation using *ecological niche* method.

Algorithm establishes un-dominated solutions from a population *P(t)*; for this population it is recalculate its fitness using ecological niche method. (figure 1).

P1. From population P(t) are established the chromosomes which are un-dominated solutions. This population is notated with P^1*;*
P2. It is generated a high value and it is attached to each member of population P^1*;*
P3. It is recalculated the fitness for each chromosome from P^1 *applying the ecological niche method. We choose* v_1 *as smallest fitness for chromosomes from* P^1*;*
P4. Subpopulation P^1 *is temporary outside from total population P(t); the resulting population is* $P^*(t)$*;*
P5. It is calculated un-dominate solutions from $P^*(t)$ *which are introduced in population* P^2*;*
P6. It is established v an appropriate value but smaller than* v_1*;*
P7. We consider than each chromosome from P^2 *has fitness equal with v*;*
P8. We recalculation of fitness of chromosomes from P^2 *using ecological niche method;*
P9. From remaining population $P^*(t)$ *we exclude population* P^2*.*
Process described in steps P5. – P8. is repeated until we obtain all un-dominate solutions;
P10. We apply selection operator to chromosomes from P(t);
P11. We apply crossover, mutation and inversion operators.

Fig. 1. Genetic algorithm for Pareto optimisation

3. Results

Based on the algorithm presented in figure 1, authors have created an original algorithm dedicated for EDN reconfiguration (*SIGRECO/AGPareto*, with a population contained *10* chromosomes), which consider:

- objective functions, criteria presented in *1.1* and *1.2.*;
- restrictions, criteria presented in *1.3*.

The proposed algorithm has been implemented in the visual environment programming language *C++ Builder* that, due to its graphic interface, ensures an extreme lightness in the use. In this software have been implemented two common used reconfiguration algorithms:

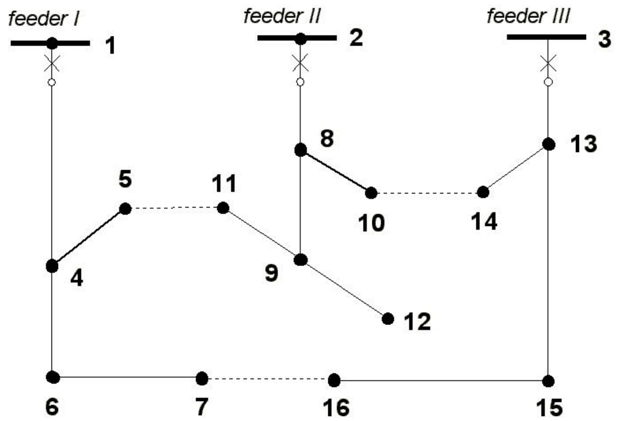
- *Optimum*, which generate all configurations and chose the best solution;
- *Branch-exchange*, which implement the same heuristic.

To test the correctitude and the convergence speed of the proposed algorithm, we studied, first, some single-objective (active power losses) *IEEE* test networks, where optimal configurations were obtained in a very short time (table 1).

3.1. Test network with 16 buses [9]

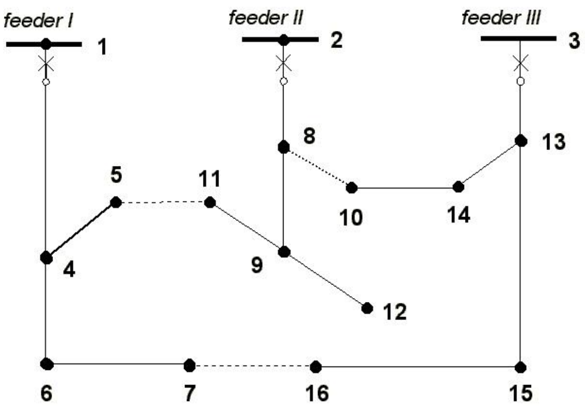
It is a simple network with three feeders and three loops. Performing *branch-exchange* method we obtain a better solution (figure 3) than in base case (figure 2).

Optimal solution (figure 4), obtained performing the two methods, *Optimum and SIGRECO/AGPareto* have been obtained in a very short time (smaller than 1 second).



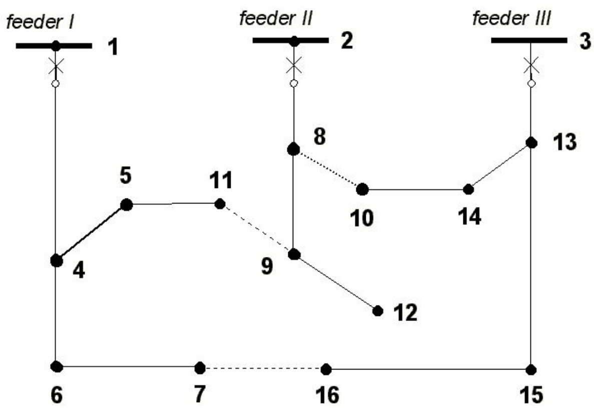
Active power losses: 0.00511 p.u.

Fig. 2. Test 16 bus network – base case



Active power losses: 0.004834 p.u.

Fig. 3. Test 16 bus network – configuration obtained applying branch-exchange method

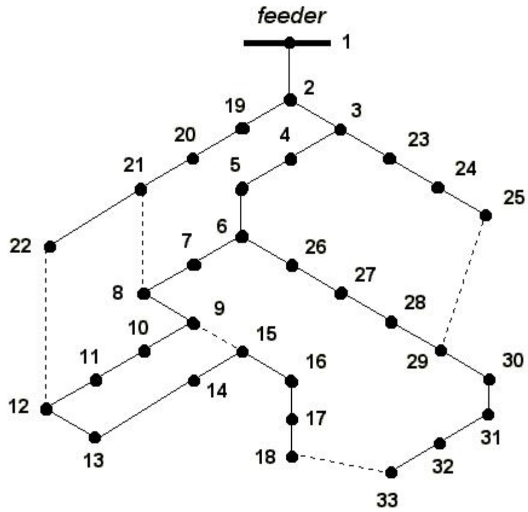


Active power losses: 0.004658 p.u.

Fig. 4. Test 16 bus network – optimal configuration

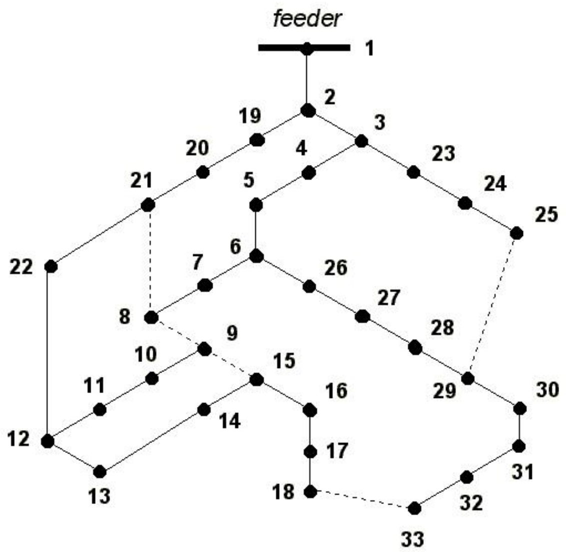
3.2. Test network with 33 buses [10]

Contains one feeder and 5 loops (figure 5). In this case, *branch-exchange* method, although is fast, not obtain the optimum solution (figure 6). It is important to remark the difference between calculus times of *SIGRECO/AGPareto* algorithm (approx. 50 seconds) and *Optimum* method (approx. 27 minutes). For this case, genetic algorithm obtains optimal solution in six generations (figure 7).



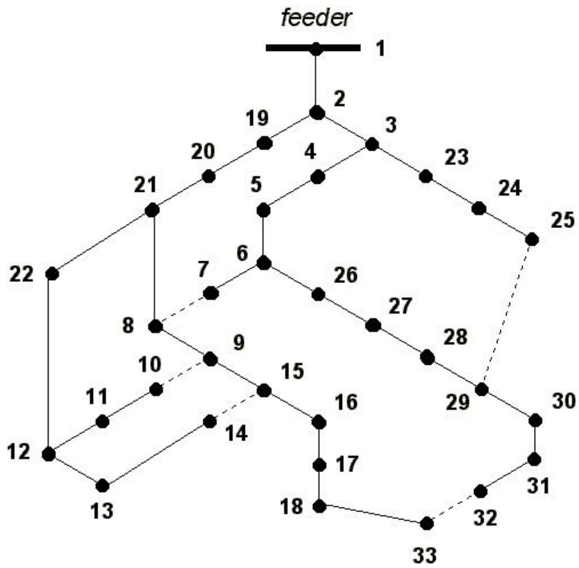
Active power losses: 202.6771 kW

Fig. 5. Test 33 bus network – base case



Active power losses: 153.4933250 kW

Fig. 6. Test 33 bus network – configuration obtained applying branch-exchange method



Active power losses: 139.551351 kW

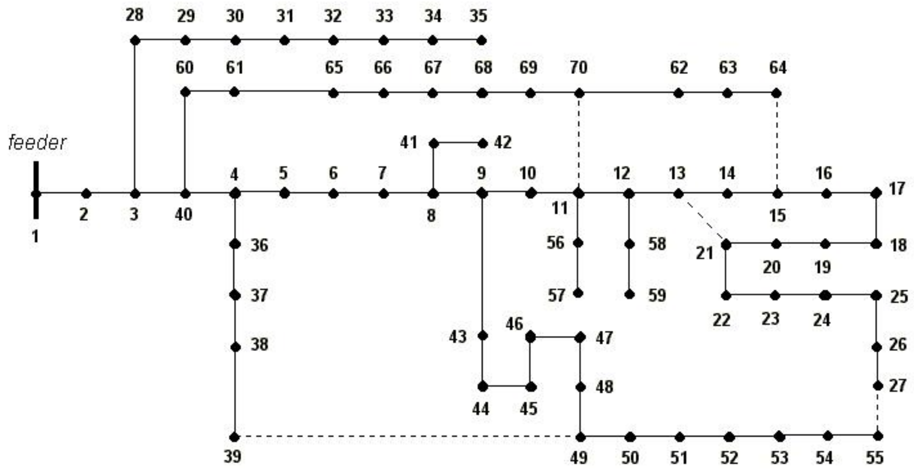
Fig. 7. Test 33 bus network – optimal configuration

Table 1. Results of different reconfiguration methods

Nodes	Method	Tie lines	Active power losses	CPU time	No. generations	Reference
16	*Base case*	*14, 15, 16*	0.00511 p.u.			[9]
	Optimum	*7, 8, 16*	0.004658 p.u.	*841ms*		
	Branch-exchange	*7, 14, 16*	0.004834 p.u.	*70ms*		
	SIGRECO/AGPareto	*7, 8, 16*	0.004658 p.u.	*511ms*	1	
33	*Base case*	*33, 34, 35, 36, 37*	202.6771000 kW			[10]
	Optimum	*7, 9, 14, 32, 37*	139.5513510 kW	*27m:47s:980ms*		
	Branch-exchange	*8, 33, 34, 36, 37*	153.4933250 kW	*490ms*		
	SIGRECO/AGPareto	*7, 9, 14, 32, 37*	139.5513510 kW	*51s:464ms*	6	
70	*Base case*	*70, 71, 72, 73, 74*	20.8736000 kW			[11]
	Optimum	*15, 59, 62, 70, 71*	9.4285400 kW	*6h:02m:15s:715ms*		
	Branch-exchange	*56, 69, 70, 71, 73*	12.6006700 kW	*620ms*		
	SIGRECO/AGPareto	*15, 59, 62, 70, 71*	9.4285400 kW	*19s:388ms*	3	

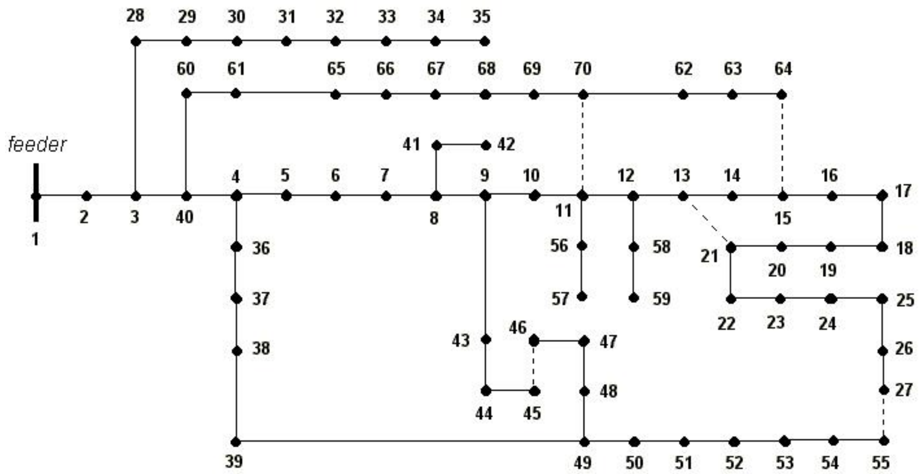
3.3. Test network with 70 buses [11]

For this network is presented initial configuration (figure 8), solution obtained running *branch-exchange* method (figure 9) and optimal solution (figure 10). It is important to remark prohibitive times (approx. 6 hours) that are necessary for running of *Optimum* algorithm – table 1.



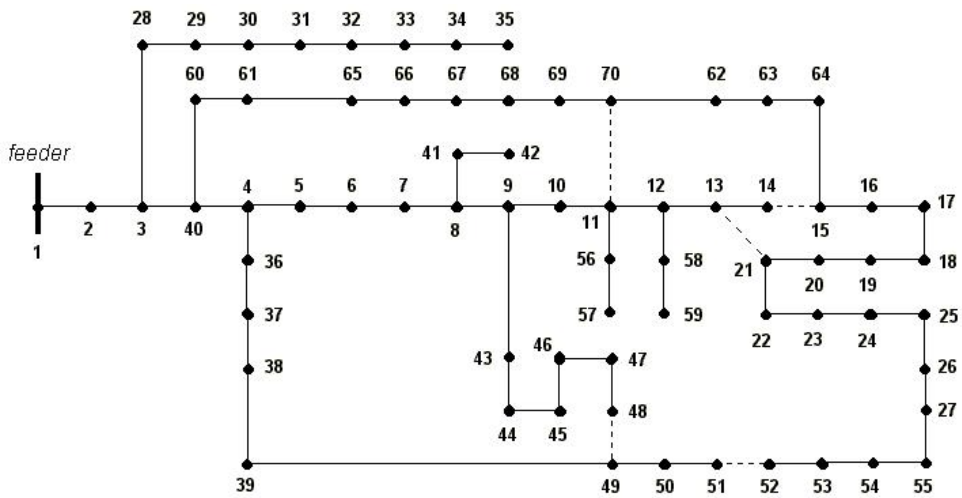
Active power losses: 20.8736000 kW

Fig. 8. Test 70 bus network – base case



Active power losses: 12.6006700 kW

Fig. 9. Test 70 bus network – configuration obtained applying branch-exchange method



Active power losses: 9.4285400 kW

Fig. 10. Test 70 bus network – optimal configuration

It is important to specify the fact that for these tests we used a PC equipped with Pentium 4 – 1.4 GHz processor. Analysing data from table 1, we ca conclude:

- applying of absolute method, in order to obtain optimal configuration (*Optimum* algorithm), imposes prohibitive execution times; a combinatorial explosive phenomenon appear if increase the network dimension. However, this method can be use where normal summer/winter operating schemes are established;
- *branch-exchange* method is very speedy (with running times smaller than one second) and obtains some solutions better than in the case of initial configuration but not optimal;
- the proposed algorithm have obtained the optimal solutions in small times (seconds); a reduce number of generations are necessary for convergence. However, in the case of 70 buses network, in reference [12] is presented a genetic algorithm which obtains optimal solution in 10 seconds, but the authors not specify the type of processor used and the standard error considered to perform power flow calculus (in our implementation it is about *0.00001 p.u.*); anyway that algorithm solve only mono-objective reconfiguration problems.

Table 2. Failure rates of branches

Branch	i	j	λ [year^{-1}]
1	1	4	0.6525
2	4	5	0.696
3	4	6	0.783
4	6	7	0.348
5	2	8	0.957
6	8	9	0.696
7	8	10	0.957
8	9	11	0.957
9	9	12	0.696
10	3	13	0.957
11	13	14	0.783
12	13	15	0.696
13	15	16	0.348
14	5	11	0.348
15	10	14	0.348
16	7	16	0.783

Considering 16 buses network from reference [9] and take into account failure rates of branches presented in table 2, we obtain functioning schemes optimising two criteria: active power losses and *SAIFI* (table 3). We can observe that, in the analyzed case, Pareto-frontier is reduced to a single solution (optimal in the case of proposed algorithm).

Table 3. Results of Pareto reconfiguration with two objectives

Nodes	Method	Tie lines	Active power losses	*SAIFI*	CPU time	No. generations	Reference
16	*Branch-exchange*	*7, 14, 16*	**0.004834p.u.**	**0.2345**	*60ms*		[9]
	SIGRECO/AGPareto	*7, 8, 16*	**0.004658p.u.**	**0.2241**	*781ms*	1	

4. Conclusions

Optimal operation of an electric distribution network is an actuality problem. One of important research way consists in the determination of optimal operation scheme, named *reconfiguration*. The potential solutions generating methods used in the present necessitate prohibitive execution times or obtain non-optimal solution (in the case of most common heuristics). One of promising direction consists in to use of evolution strategies, methods specify of artificial intelligence (in particular, genetic algorithms), which admit optimal solutions in smaller times. These kinds of methods, with the equilibrium between the *exploration* of the potential solutions space and the *exploitation* of obtained information, offer a robust frame to solve of reconfiguration problem in the case of large real networks.

Take into account the multi-objective nature of reconfiguration problem, the introducing of *Pareto optimality* concept assure an objective and robustness onset. Hereby, we can eliminate weak points of usual methods: *(i)* errors caused of objectives conversion in a same measurements unit and *(ii)* we can eliminate the subjectivities caused through introducing of weights for different criteria.

The paper presents an original paradigm to solve the reconfiguration problems and the corresponding algorithm (with its implementation in original dedicated software). The comparative tests with networks from literature have demonstrated the correctitude and the promptitude of the proposed algorithm.

References

[1] Eremia, M., et alii**,** *Electric Power Systems (vol. I) – Electric Networks*, Editura Academiei Române, Bucureşti, 2006;
[2] Sagaidac, M., Ungureanu, V., *Cercetări operaționale*, Editura CEP USM, Chişinău, 2004;
[3] Chindriş, M., Tomoiagã, B., *Reconfigurarea retelelor de distributie a energiei electrice de medie si joasã tensiune (II)*, în: Buletin Informativ, nr. 1, Cluj-Napoca, 2006, pag. 10-19;
[4] Dumbravă, V., Miclescu, T., Bazacliu, G., *Determinarea schemei debuclate de funcționare pentru rețelele electrice urbane de distribuție*, în: Energetica, nr. 4, seria B, Bucureşti, iulie - august 1995, pag. 194-201;
[5] *** IEEE *Trial Use Guide for Electric Power Distribution Reliability Indices*, IEEE Std 1366-2000;
[6] Dumbravă, V., Miclescu, T., Bazacliu, G., *Tehnici noi de reconfigurare a schemelor de exploatare pentru rețele urbane de distribuție*, în: Energetica, nr. 8-9, Bucureşti, august-septembrie 1999, pag. 357-363;
[7] Dumitrescu, D., *Algoritmi genetici şi strategii evolutive – aplicații în inteligența artificială şi în domenii conexe*, Editura Albastră, Cluj-Napoca, 2006;
[8] Srinivas, N., Deb, K., *Multiobjective function optimization using nondominated sorting genetic algorithms*, in: Evolutionary Computing, no. 2, 1995, pp. 221-248;
[9] Civanlar, S., et alii, *Distribution Feeder Reconfiguration for loss reduction*, in: IEEE Transactions on Power Delivery. Vol. 3, no. 3, July 1988, pag. 1217-1223;
[10] Baran, M., Wu, F.F., *Network Reconfiguration in Distribution Systems for Loss Reduction and Load Balancing*, in: IEEE Transactions on Power Delivery. Vol. 4, no. 2, April 1989, pag. 1401-1407;
[11] Chiang, H.-D., Jean-Jumeau, R., *Optimal Network Reconfigurations in Distribution Systems: Part 2: Solution Algorithms and Numerical Results*, in: IEEE Transactions on Power Delivery. Vol. 5, no. 3, July 1990, pag. 1568-1574;
[12] Guimaraes, M.A.N., Castro, C., Romero, R., *Reconfiguration of distribution systems by a modified genetic algorithm*, in: IEEE PowerTech'07, Lausanne, Switzerland, July 1-5, 2007.