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THE OPTIMIZATION OF DISTRIBUTION SMART GRIDS THROUGH RECONFIGURATION AND REACTIVE POWER CONTROL

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Abstract. The reconfiguration of an electric distribution system consists of exchanging the functioning links between its elements in order to improve different performances. A lot of methods and algorithms, based on diverse heuristic or evolutionary computation techniques, have been developed to solve this problem. The paper presents an original approach to solve the reconfiguration problems concerning the intelligent distribution systems combined with the reactive power control. The comparative tests performed on some well known IEEE test systems have demonstrated the correctness and the promptness of the proposed algorithm.

Key words: smart grids; power distribution systems; reconfiguration; genetic algorithms.

1. Introduction

Modern electric networks are situated, at present, in a new stage of development where will be fundamentally different from classical ones, which implies new challenges and approaches.

A direction that tends to substantially change the power distribution systems behavior is the wide appearance of distributed generation based on renewable resources (small hydro power plants, photovoltaic cells, wind turbines, etc.). Thus, the development of these sources, with low powers but

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high levels of penetration and dispersion, is encouraged worldwide. The existence of distributed generation has major implications for the power distribution systems, transforming them from passive to active systems.

Another important implication is the emergence and implementation of digital multi-functional relays. We are in front of a phenomenon of replacing conventional protective relays with multi-functional relays, featuring a wide variety of embedded functions: (i) protection and automation functions: instantaneous and time delayed overcurrent protection, autoreclosing, etc.; (ii) non protection functions: fault locator, event and fault recorder, disturbance recorder etc.; (iii) measurement functions: currents, powers, etc.; (iv) command and control, etc. Basically, by using these relays and placing them in communication systems, we assist at the development of advanced command, control, protection and automation (and data acquisition) complex systems.

Power distribution systems operation in an open electricity market requires measuring transformers and/or transducers and intelligent measuring devices with special classes of accuracy. By introducing intelligent measuring devices in communications systems, smart metering systems are obtained.

Another direction, but one of the most important, is related to power quality problems: continuity in power supply, voltage deviation, etc. As a result, monitoring power quality systems have to be implemented.

Taking into account these considerations, by carrying out of command, control, protection, automation, metering and power quality monitoring complex systems, the prerequisites for a power distribution network to become intelligent ("smart grid") are created. The most important problem is how to use such infrastructures in order to minimize active power losses, maximize consumer's supply safety, etc. *The central idea is that a "smart grid" must be an optimized system*.

The most important technical measures which can improve the performances in operation of a distribution system are the followings:

a) reconfiguration of the system, exchanging the functioning links between its elements;

b) variation (and control) of the voltage by using on-load taps changers at power transformers;

c) variation (and control) of the reactive power flow through the network;

d) changing of the operating scheme of the parallel connected power transformers.

Generally, electrical distribution systems are operated in radial configurations; as a result, the utility must find the optimal configuration by searching from a vast set of possible solutions (the set of trees of the graph attached to the network). The problem of the optimal reconfiguration of an electric distribution system, in terms of its definition, is a historical single objective problem with constraints. Since 1975, when Merlin and Back have introduced the concept of distribution system reconfiguration for power loss reduction, till nowadays a lot of researchers have proposed diverse methods and algorithms to solve the reconfiguration problem defined in this manner. A very used one is the main criteria method where the problem is defined in the following conditions: a main criterion is chosen, simultaneously indicating acceptable values for the other criteria. Usually, active power losses are adopted as main criterion (Merlin & Back, 1975; Morton & Mareels, 2000; Civanlar *et al.*, 1988; Baran & Wu, 1989; Chiang & Jean-Lumeau, 1990; Shirmohammadi & Hong, 1989; Lin & Chin, 1998; Ramos *et al.*, 2001; Carpaneto & Chicco, 2006; Yang & Guo, 2008; Nara *et al.*, 1992; Guimaraes *et al.*, 2007; Enăcheanu *et al.*, 2008; Carreno *et al.*, 2008; Queiroz & Lyra, 2006). On the other hand, some authors have solved this problem by converting of the multi-objective problem to a single objective one that assumes a weighted sum of the selected objective functions (Roytelman *et al.*, 1995; Fukuyama *et al.*, 2003; Huang, 2002).

Regardless of the formulation, the searching of the solution is also a very complex problem because of its combinatorial nature. In order to avoid the evaluation of the entire space of the solutions and to minimize the computation burden, a lot of algorithms have been developed. The most of authors have used diverse variants of different heuristics or meta-heuristics approaches: branch exchange (Civanlar *et al.*, 1988; Baran & Wu, 1989), branch and bound (Merlin & Back, 1975; Shirmohammadi & Hong, 1989), simulated annealing (Chiang & Jean-Lumeau, 1990) and others (Lin & Chin, 1998; Ramos *et al.*, 2001; Carpaneto & Chicco, 2006; Yang & Guo, 2008; Nara *et al.*, 1992). On the other hand, some authors have developed methods based on genetic algorithms (Guimaraes *et al.*, 2007; Enăcheanu *et al.*, 2008; Carreno *et al.*, 2008; Queiroz & Lyra, 2006; Huang, 2002).

Authors propose an original genetic algorithm, aiming the optimization through reconfiguration combined to reactive power variation of distribution smart grids taking into account various criteria in a flexible and robust mode. The novelty of the method (and vision) consists of: (i) criteria for optimization are evaluated on active power distribution systems (with distributed generation); (ii) original genetic algorithm to solve the problem in a non-prohibitive execution time (proper for dynamic behavior of smart grids). The proposed algorithm has been implemented in the programming language C++ and was tested with several IEEE test distribution systems where optimal configurations were obtained in short times. The issue raised is in accordance with European Comission (2009).

2. The Optimization Problem

The problem has the following form:

a) *objective function*

$$\min[\Delta P] \tag{1}$$

b) *constraints (restrictions)*

$$\sum_{ij \in E} \alpha_{ij} = n - p, \tag{2}$$

$$I_{ij} \le I_{\max,ij}; \forall ij \in E, \tag{3}$$

$$U_j^{\min} \le U_j \le U_j^{\max}; \forall j \in X, \tag{4}$$

where: ΔP is the active power losses; E – set of system lines (branches); I_{ij} – electric current through the branch ij; α_{ij} – binary variable, representing the status of a tie line (0 – open, 1 - closed); U_j – voltage on node j; X – system nodes set; n – the number of nodes in the electric system; p – the number of connected components.

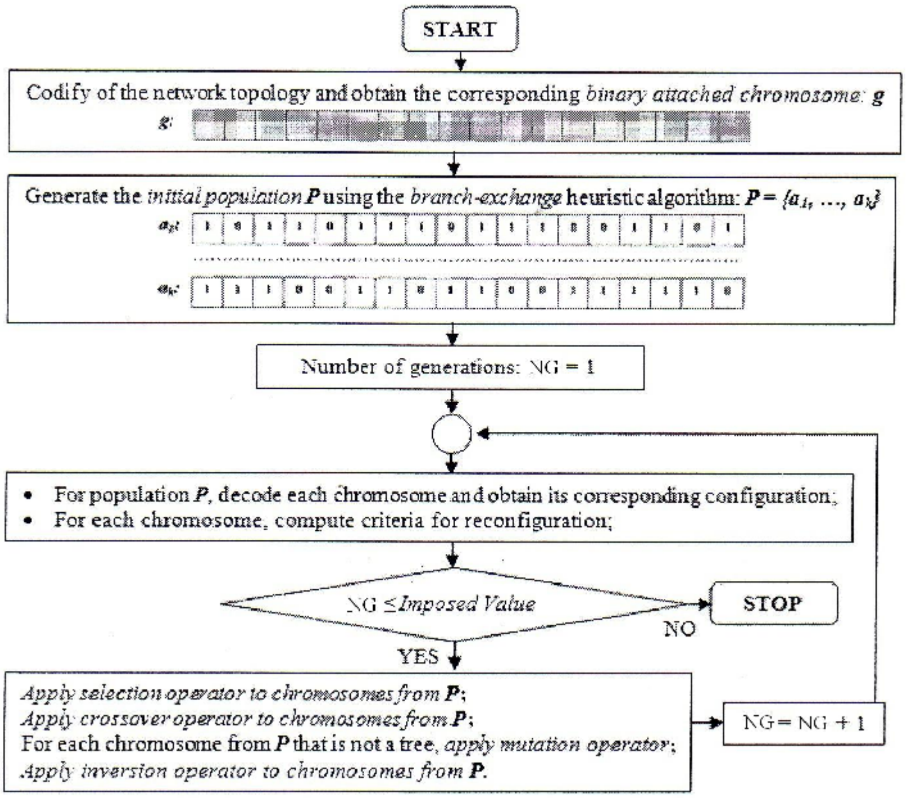
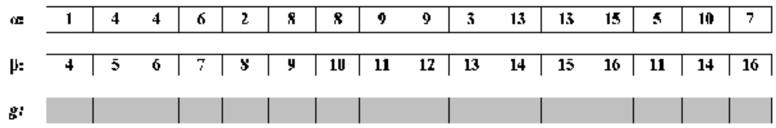


Fig. 1 – Logic diagram of the optimization algorithm.

The logic diagram of the proposed optimization algorithm is given in Fig. 1.

2.1. Genetic Coding and Decoding of Electrical Network Topology

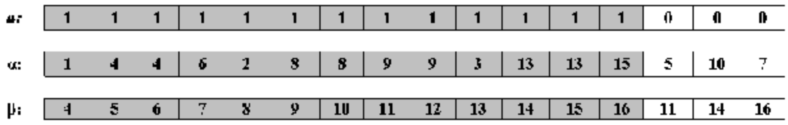
a) *Genetic Coding*. In most of the cases, the matrices of nodes adjacency or nodes–branches incidence are used to represent the graph associated to an electrical supply network. However the representation using the branches lists was preferred because a power system node is only linked with a small part of the other nodes (it results a rare graph, *i.e.* the associated matrix contains many zero elements). Consequently, the graph associated to the electric network can be described by a matrix with two lines and *m* columns (*m* is the number of the branches), each column indicating the two ends of a branch; this matrix does not contain zero elements (Biggs *et al.*, 1976). Therefore, using the representation *via* the branches lists, a binary codification of the problem (binary chromosome with fixed length) can be obtained. Binary values of the chromosome will indicate the status of any electric line: 0 – open, 1 - closed. Fig. 2 exemplifies the graph (which indicates the network topology) attached to a system represented by branches lists (α and β), and the binary attached chromosome, *g* (system coding).



α:	1	4	4	6	2	8	8	9	9	3	13	13	15	5	10	7
β:	4	5	6	7	8	9	10	11	12	13	14	15	16	11	14	16
g:																

Fig. 2 – Branches lists of system attached graph (α and β) and the attached chromosome (g).

b) *Genetic Decoding:* Considering this codification, operation scheme of the system will be obtained by making the preservation of the corresponding branches which value equals 1 (in operation). For instance, by decoding the chromosome a, the radial operation scheme will be obtained (with corresponding α and β lists) (Fig. 3).



a:	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
α:	1	4	4	6	2	8	8	9	9	3	13	13	15	5	10	7
β:	4	5	6	7	8	9	10	11	12	13	14	15	16	11	14	16

Fig. 3 – Lists of branches (α and β) obtained by decoding the chromosome a.

Using this codification, we have a population that consists of a set of chromosomes of type *a*. By decoding each chromosome, a particular operation scheme will be obtained and its performances can be tested (taking into account different criteria).

2.2. Genetic Operators

a) *Selection*. The goal of the selection operator is to assure more chances to replicate for the best chromosomes of a population. The selection is performed taking into account the fitness of chromosomes. The most used selection methods for mono-objective problems are Monte Carlo and tournament. In this implementation we choose the tournament method.

b) *Crossover*. The selection of the number and position of cut points for crossover operator depends on the system topology. If these points are selected in an inadequate mode we will obtain “bad” chromosomes: (i) un-connected systems with isolated nodes or (ii) connected systems with loops. To reduce the number of these cases we propose that the number of cut points must equal the cyclomatic number (of fundamental circuits/loops) corresponding to attached graph, $l = m - n + p$ (where: m – number of branches, n – number of nodes/ vertices, p – number of connected components).

c) *Mutation*. We cannot pass from a radial scheme to another radial configuration by simply altering the value of a chosen gene. Hereby, we use this operator only in the case when, performing crossover operator, non-radial configurations are obtained. One of the two conditions in order to have a tree or a forest is to have $n - p$ closed branches (in operation), as in relation (2). Thus, if there are more or less than $n - p$ genes equal with 1 in a chromosome, the mutation operator replaces randomly the excess/insufficiency of genes equal with 1 (in order to have $n - p$ genes equal with 1).

d) *Inversion (permutation)*. It is the most important operator used after performing crossover and mutation. The second condition in order to have a tree or a forest is to have a connected graph (for a tree) or a graph with connected components (for a forest). Thus, this operator makes some branch-exchanges, repairing existing “bad” chromosomes (which are not connected but which have $n - p$ genes equal with 1) and increases the diversity of a population.

3. Application

The proposed algorithm has been implemented in the programming language C++. In the developed program, other two well-known reconfiguration algorithms have been also implemented: (i) optimum (“brute force”): generates all possible configurations (Morton & Mareels, 2000); (ii) branch-exchange: implements the heuristic having the same name to generate candidate solutions (in order to reduce the computation burden) (Baran & Wu, 1989).

In order to test the correctness and the convergence speed of the proposed algorithm, the authors have studied, first of all, one well known single-objective (active power losses) IEEE test system, where the optimal configurations were obtained in a very short time (Table 1). The system parameters can be found in the work published by Baran & Wu (1989). Considering this test system we have introduced two DG units on nodes 12 and

24 with following parameters: P_g = 800 kW and Q_g = ±400 kVAr. In this case we obtained another optimal configuration presented in Table 2 (for Q_g = 400 kVAr both of the two DG units).

Table 1
Results of Different Reconfiguration Methods

Method	Opened branches	Active power losses, [kW]	CPU time	Population/ Generations
Base case	8-21, 9-15, 12-22, 18-33, 25-29	202.68		
Optimum	7-8, 9-10, 14-15, 32-33, 25-29	139.55	27 m:47 s:980 ms	
Branch-exchange	8-9, 8-21, 9-15, 18-33, 25-29	153.49	490 ms	
Proposed algorithm	7-8, 9-10, 14-15, 32-33, 25-29	139.55	51 s:464 ms	10/7

Table 2
Results for Reconfiguration with DG Units

Method	Opened branches	Active power Losses, [kW]	CPU time	Population/ Generations
Proposed algorithm	7-8, 8-9, 14-15, 26-27, 12-22	57.08	21s:375 ms	10/4

4. Conclusions

The reconfiguration of an electric distribution system consists of exchanging the functioning links between its elements in order to improve different performances. A lot of methods and algorithms, based on diverse heuristic or evolutionary computation techniques, have been developed to solve this problem. The paper presents an original approach to solve the reconfiguration problems combined with the reactive power control (with its implementation in original dedicated program). The comparative tests performed on some well known IEEE test systems have demonstrated the correctness and the promptness of the proposed algorithm.

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OPTIMIZAREA REȚELELOR INTELIGENTE DE DISTRIBUȚIE PRIN RECONFIGURARE ŞI CONTROLUL CIRCULAȚIEI PUTERILOR REACTIVE

(Rezumat)

Reconfigurarea unei rețele electrice de distribuție constă în schimbarea legăturilor funcționale dintre elementele ei pentru îmbunătățirea indicatorilor de performanță. Deși pentru rezolvarea acestei probleme au fost dezvoltate o serie de metode bazate pe diverse tehnici euristice sau evolutive de căutare, problema rămâne de actualitate şi prezintă noi valențe în contextual „smart grids“. Se prezintă o abordare originală pentru rezolvarea problemelor privind reconfigurarea combinată cu controlul puterilor reactive. Testele comparative cu rețele IEEE au demonstrat corectitudinea şi rapiditatea metodei propuse.