Reconfiguration of Distribution Networks with Dispersed Generation by Pareto Optimality and Evolution Strategies

B. Tomoiaga, M. Chindris

***Abstract*--In an open electricity market environment, dispersed generation is predicted to play an important position. A high level of penetration and dispersion with distributed generators of an electric network imposes some additional problems; among them, of significant importance is the reconfiguration. The problem of reconfiguration has become more difficult because the customers ask more and more quality in power supply and reliability. The paper presents an original algorithm, aiming to find out the optimal open-looped points of electrical distribution networks with dispersed generation in order to obtain optimal radial configurations using Pareto optimality and evolution strategies.**

***Index Terms*--Distribution networks, reconfiguration, dispersed generation, Pareto optimality, evolution strategies .**

I. Nomenclature

DG – dispersed generation/generator;
EDN – electric distribution network;
GA – genetic algorithm;
SAIFI – system average interruption frequency index;
ΔP – active power losses;
λ – failure rate.

II. Introduction

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. In general, electrical distribution networks are operating in radial configurations. The reconfiguration problem is one of *multi-criteria optimization*, where the solution is chosen after the evaluation of a group of indexes, named *partial criteria* (in this case active power losses, reliability, etc.), which represent multiple purposes.

Many solutions for onset the multi-criteria optimization problems can be found in the literature; among them, a very used one is *the main criteria method* (frequently used in the distribution networks reconfiguration problems): the main criterion is chosen, concomitantly indicating acceptable values for the other criteria, and the problem is solved in these conditions. To eliminate the subjectivity of the above method, this paper proposes to formulate the reconfiguration problem as *Pareto optimality*. On the other hand, in order to search the optimal solution (configuration of electric network) authors propose *an original algorithm* based on *evolution strategies* (considering the main genetic operators as *crossover*, *mutation* etc.).

The paper presents an original algorithm, aiming to find out the optimal open-looped points of electrical distribution networks with dispersed generation with the purpose of obtaining optimal radial configurations. The problem of reconfiguration is expressed in an original form (Pareto optimality) allowing considering all criteria in an objective approach in the optimization 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.

III. Reconfiguration of Distribution Network as Multi-criteria Problem

The reconfiguration issue represents a *multi-criteria optimization problem*, where the solution is chosen after the evaluation of a group of indexes, named *partial criteria*, which represent multiple purposes.

A. *Criteria for Reconfiguration*

Some criteria are taken into account to operate a network.

1) Active Power Losses: For balanced and sinusoidal regime, the active power losses (Joule-Lenz) can be calculated considering the following relationship:

$$\Delta P = \sum_{ij \in E} 3 \cdot R_{ij} \cdot I_{ij}^2 \cdot \alpha_{ij} \tag{1}$$

where: ΔP – active power losses;
E – set of network lines (branches);
I_{ij} – electric current through branch *ij*;
R_{ij} – electric resistance of branch *ij*;
α_{ij} – binary variable, represents the status of a tie line (*0* – open, *1* - closed).

To evaluate this criterion, it is necessary to perform *power flow* calculus. In radial electric networks with dispersed generation we can use a specific method, named *backward/forward sweep*, considering besides different kinds of node loads (constant powers, constant currents,

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constant admittances or a combination of the above), two types of distributed generators [1]:

- generators which provide *constant powers* (*PQ nodes*);
- generators that provide *constant active powers* and *constant modules of voltages* (*PU nodes*).

In a same manner, it is possible to formulate relationships for harmonic polluted or/and unbalanced cases.

2) Reliability of electric network: The essential attributes of interruptions in the power supply of the consumers are *the frequency* and *the duration*. While *the durations* are predominantly influenced by the electrical network structure and the existent automations, *the frequency* is mainly influenced by the adopted working scheme; *they can be minimized by the suitable choice of the loop opening points*.

For any fault that will lead to the interruption of power supply from the main distribution network, the existing distributed generators will be switching off because of a variety of reasons. We will mention only two of them:

- an operation of a power island purely with dispersed generators is considered unacceptable;
- it is important to create conditions for auto-reclose of main circuit breaker, if this equipment is used in the distribution network.

The network reliability can be considered from two points of view:

- *that of a particular consumer*; knowing failure rates of the equivalent element of the attached reliability block diagram (where restoring of supply is performed after the fault repair and/or the fault isolation) we can estimate different indices as well as the number of interruptions (possible restriction in the configuration problem – some consumers can impose maximal limits in contracts);
- *that of the entire supply network*; in this case, we propose to consider *SAIFI* (*system average interruption frequency index*), defined as [2] *Total number of customer interruptions (longer than 3 minutes) / Total number of customers served*.

Knowing the failure rates for each supplied node, we can estimate *SAIFI* using the relationship:

$$SAIFI \approx \frac{\sum_{i=1}^{n} \lambda_{ti} \cdot N_i}{N} \cdot T \qquad (2)$$

where: N – total number of customers served;
N_i – total number of supplied customers from node i;
T – the reference period [*year*];
n – the number of load nodes of the system;
N_i – total number of supplied customers from node i;
λ_{ti} – total failure rate of the equivalent element, to the attached reliability block diagram, of node i [$year^{-1}$].

Total failure rate for a node i can be calculated as: $\lambda_{ti} = \lambda_i + k \cdot \lambda_i'$, where λ_i is the failure rate when restoring of supply is performed after the fault repair, λ_i' is the failure rate when restoring of supply is performed after the fault isolation, $k \in [0,1]$ is a coefficient that estimates the weight of restoring after 3 min. (sustained interruption restored after fault isolation). In a first approximation, it can consider $k = 1$.

It must be also specified that the contingencies are considered simple and the EDN components are independent from the reliability point of view.

3) Other criteria: These criteria are, usually, considered as restrictions and they arise from operation and technological considerations.

a) Radial configuration of the network:

$$\sum_{ij \in E} \alpha_{ij} = n - p \qquad (3)$$

where n is the number of electric network nodes and p is the number of connected components.

b) Safeguard of power supplies for all customers: The attached graph of electric network should be connected;

c) It must be possible to impose and/or interdict the availability of an electric line:

d) Maximum number of admitted maneuvers:

e) Branch loads limits through lines:

$$I_{ij} \le I_{\max ij}; \forall ij \in E \qquad (4)$$

f) Voltage drops limits:

$$U_j^{\min} \le U_j \le U_j^{\max}; \forall j \in X \qquad (5)$$

where X is the network nodes set.

B. Pareto Optimality Problem Formulation

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

- criteria that must be minimized/maximized (*objective functions*);
- criteria that must be included within some bounds (*restrictions*).

Therefore, the reconfiguration issue represents one of *multi-criteria optimization problems*. In addition, these criteria are incompatible from the point of view of measurement units and often they are conflicting criteria.

Many solutions for onset the multi-criteria optimization problems can be found in the literature; among them, very used are:

- *the main criteria method* (frequently applied in the EDN reconfiguration problems): the main criterion is chosen, concomitantly indicating acceptable values for the other criteria, and they try to solve the problem;
- *the conversion of multi-objective problem to a single objective one*: making a sum (weighted or not) of objective functions. To create this synthesis function it is necessary to convert all partial criteria in the same measurement units; a very used method is to convert them in costs (usually, a complicate and often inaccurate operation).

The major difficulty in these kinds of problems consists in the incompatibility of different solutions. It is of interest to exist a model, which permits to take into account, in a same time, more objective functions and restrictions.

Thus, we can use *Pareto optimality*, concept that defines a *dominate relation* among solutions. In Pareto optimization, central concept is named *un-dominated solution*, if it satisfies the following two conditions:

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

The set of Pareto solutions form *Pareto-front* associated to a problem. To solve theses kinds of problems, evolution strategies have proven to be of potential.

IV. MULTI-CRITERIA RECONFIGURATION USING EVOLUTION STRATEGIES

In literature there are a lot of proposed methods to solve the reconfiguration problems. The most of them are based on different heuristic or meta-heuristic (branch exchange, branch and bound, simulated annealing, tabu search, etc.) approaches.

On the other hand, some authors have developed attractive methods based on evolution strategy, in particular on genetic algorithms; some significant results are presented in [3].

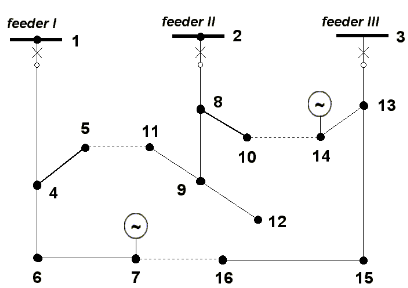

Fig. 1. Three-feeder distribution network with two dispersed generators

However, an important drawback of these methods is the fact that they solve the reconfiguration problems as single objective problems.

The method proposed in this paper solves these problems as multi-criteria problems using evolution strategies.

Taking into account the fact that the graphs attached to electric networks are *rare graphs* (for instance, the network presented in figure 1 [4]), the representation using the branches lists was preferred because 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 presents a graph attached to an electric network represented by *branches lists* (α and β) and the *binary attached chromosome g* (network 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 network attached graph (α and β) and the attached chromosome (*g*)

Considering this codification, operation scheme of the network will be obtained by making the preservation of the corresponding branches witch value equals *1* (in operation). For example, by decoding the chromosome *a*, the radial operation scheme will be obtained (figure 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 obtained through decoding chromosome *a*

Using this codification, a population consists in 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).

A. Genetic Operators

Below different genetic operators used to solve the problem of reconfiguration are presented.

1) Selection: The goal of 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; it chooses the chromosomes with the best fitness. Most used selection methods for mono-objective problems are *Monte Carlo* and *tournament*. For multi-modal function optimization we can use the *ecological niche* method. To detect more optimum points (ecological niches), a genetic algorithm (GA) must have a supplementary mechanism that encourages apparition of some sub-populations corresponding to different optimum points. For this goal, a *partitioning function*, defined between two chromosomes must be defined. We propose the relationship:

$$s\left(d\left(x_i,x_j\right)\right) = \frac{2}{1+e^{d\left(x_i,x_j\right)}} \qquad (6)$$

where: s – partitioning function;

$d(x_i, x_j)$ – distance between two chromosome x_i and x_j; in binary codification; this can be the *Hamming distance* (the number of different positions between chromosomes).

A partitioning function must satisfy the following conditions: *(i)* it must be an increasing function, *(ii)* $s(0) = 1$ and *(iii)* $\lim_{d\to\infty} s(d) = 0$ [5].

Considering the *partitioning function*, we can calculate the *partitioning fitness function* for a chromosome (as criterion for selection):

$$f^*(x_i) = \frac{f(x_i)}{\sum_{j=1}^{n} s\left(d\left(x_i,x_j\right)\right)} \qquad (7)$$

where: f^* is the partitioning fitness function;

f – fitness function;

n – number of chromosomes from an ecological niche.

2) Crossover: The selection of the number and positions of cut points for crossover operator depends on the network topology. If these points are selected in an inadequate mode we will obtain "bad" chromosomes: *(i)* un-connected networks with isolated nodes or *(ii)* connected networks with loops.

TABLE I
RESULTS OF DIFFERENT RECONFIGURATION METHODS

System	Method	Tie lines	Active power losses	CPU time	Generations	Reference
16	*Base case*	*5-11, 7-16, 10-14*	*0.00511p.u.*			[4]
	Optimum	*7-16, 8-10, 9-11*	*0.004658p.u.*	*841ms*		
	Branch-exchange	*5-11, 7-16, 8-10*	*0.004834p.u.*	*70ms*		
	SIGRECO/Pareto	*7-16, 8-10, 9-11*	*0.004658p.u.*	*511ms*	2	
33	*Base case*	*8-21, 9-15, 12-22, 18-33, 25-29*	*202.6771000kW*			[7]
	Optimum	*7-8, 9-10, 14-15, 32-33, 25-29*	*139.5513510kW*	*27m:47s:980ms*		
	Branch-exchange	*8-9, 8-21, 9-15, 18-33, 25-29*	*153.4933250kW*	*490ms*		
	SIGRECO/Pareto	*7-8, 9-10, 14-15, 32-33, 25-29*	*139.5513510kW*	*51s:464ms*	7	
70	*Base case*	*11-70, 13-21, 15-64, 39-49, 27-55*	*20.8736000kW*			[8]
	Optimum	*14-15, 48-49, 51-52, 11-70, 13-21*	*9.4285400kW*	*6h:02m:15s:715ms*		
	Branch-exchange	*45-46, 11-70, 13-21, 15-64, 27-55*	*12.6006700kW*	*620ms*		
	SIGRECO/Pareto	*14-15, 48-49, 51-52, 11-70, 13-21*	*9.4285400kW*	*19s:388ms*	4	

TABLE II
RESULTS OF PARETO RECONFIGURATION WITH TWO OBJECTIVES

System	Method	Tie lines	Active power losses	SAIFI	CPU time	Generations	Reference
16	*Branch-exchange*	*5-11, 7-16, 8-10*	*0.004378p.u.*	*0.2345*	*110ms*		[4]
	SIGRECO/Pareto	*7-16, 8-10, 9-11*	*0.004183p.u.*	*0.2241*	*610ms*	2	

To avoid these situations, we propose that the number of cut points must equal the *cyclomatic number* (of fundamental circuits) corresponding to attached graph: $l = m - n + p$ (where: m – number of branches, n – number of nodes, p – number of connected components).

3) Mutation: By simply altering the value of a chosen gene, from a radial scheme we cannot obtain another radial configuration.

Hereby, we use this operator only in the case when, performing crossover operator, it results non-radial configurations.

4) Inversion (permutation): It is the most important operator used after performing crossover and mutation (if it is necessary).

This operator makes some branch-exchanges, repairing existing "bad" chromosomes, and increases the diversity of a population.

B. Pareto Optimization Using Genetic Algorithms

Srinivas and *Deb* [6] have given a genetic algorithm for Pareto optimization using the *ecological niche* method. The proposed algorithm is described below:

S1. From population P(t) the chromosomes representing un-dominated solutions are established. This population is detonated by P^1*;*
S2. A high value of fitness is generated and it is attached to each member of population P^1*;*
S3. The fitness for each chromosome from P^1 *is recalculated applying the ecological niche method. We choose* v_1 *as smallest fitness for chromosomes from* P^1*;*
S4. Subpopulation P^1 *is temporary excluded from total population P(t); the resulted population is* $P^*(t)$*;*
S5. The un-dominate solutions from $P^*(t)$ *are calculated and then introduced in population* P^2*;*
S6. An appropriate value but smaller than v_1, v^*, *is established;*
S7. We consider that each chromosome from P^2 *has fitness equal with* v^**;*
S8. The fitness of chromosomes from P^2 *is recalculated using the ecological niche method;*
S9. The population P^2 *is excluded from the remaining population* $P^*(t)$*.*
Process described in steps S5. – S8. is repeated until all un-dominate solutions sub-sets are obtained;
S10. Apply selection operator to chromosomes from P(t);
S11. Apply crossover, mutation and inversion operators.

This algorithm establishes un-dominated solutions from a population *P(t)*; for this population, its fitness is recalculated using the ecological niche method. Based on this algorithm, authors have developed an original algorithm dedicated for EDN reconfiguration (*SIGRECO/Pareto*, with a population containing ten chromosomes), which considers:

- *objective function*: *min*[Δ*P*, *SAIFI*];
- *restrictions:* criteria presented in chapter III.A.3.

The initial population is generated using the *branch-exchange* heuristic algorithm; a potential solution is considered only if all restrictions are satisfied.

V. OBTAINED RESULTS

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, two common used reconfiguration algorithms have been also implemented:

- *Optimum,* which generates all possible configurations and chooses the best solution;
- *Branch-exchange,* which implements the same heuristic.

In order to test the correctness and the convergence speed of the proposed algorithm, we have studied, first of all, some single-objective (active power losses) *IEEE* test networks, where the optimal configurations were obtained in a very short time (table I). The networks parameters can be found in [4], [7] and [8].

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

- The execution of the absolute method, in order to obtain optimal configuration (*Optimum* algorithm), imposes prohibitive execution times; a combinatorial explosive phenomenon appears if the network dimension are increase. However, this method can be used when normal summer/winter operating schemes are established;
- *Branch-exchange* method is very speedy (with running times smaller than one second) and obtains some feasible solutions (better than in base case) but not optimal;
- the proposed algorithm have obtained the optimal solutions in reduced times (seconds); a small number of generations are necessary for convergence. However, in the case of the 70 buses network, in [3] is presented a genetic algorithm which obtains optimal solution in 10 seconds, but the authors do not specify what type of processor is used and the standard error considered to perform power flow calculus (in our implementation this is about *0.00001 p.u.*); all the same, that algorithm solve only single-objective reconfiguration problems.

Considering 16 buses network from [4], we introduced two DG units: G7 and G14 (figure 1). These DGs are considered constant PU units, with following parameters:

- G7: $P_{g7}=2$ MW, $Q_{g7MAX}=\pm0.5$MVAr, $U_{g7}=1$p.u;
- G14: $P_{g14}=1.5$ MW, $Q_{g14MAX}=\pm0.3$MVAr, $U_{g14}=1$p.u.

TABLE III
FAILURE RATES OF NETWORK BRANCHES FROM FIGURE 1

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

Performing reconfiguration, as Pareto problem, we obtain functioning schemes optimizing two criteria: active power losses and *SAIFI* (table II). Shown in table III are the failure rates of branches considered in reconfiguration calculus.

We can observe that, in the analyzed case (table II), Pareto-front is reduced to a single solution (the optimal one in the case of *SIGRECO/Pareto* proposed algorithm).

VI. CONCLUSIONS

The paper addresses the problem of electric distribution network reconfiguration in an open electricity market environment. In this context, dispersed generation is predicted to perform an important position as the customers ask more and more quality in power supply and reliability.

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

The existent reconfiguration methods used nowadays, either demand for prohibitive execution times or obtain non-optimal solutions (in the case of most common heuristics). One of most promising direction consists in to use of evolution strategies, representing specific methods of artificial intelligence (in particular, genetic algorithms), which provide optimal solutions in reduced 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 in order to solve reconfiguration problems in the case of large real networks.

The paper presents an original paradigm to solve the reconfiguration problems (Pareto optimality) and the corresponding algorithm (with its implementation in original dedicated software). The comparative tests performed on IEEE networks have demonstrated the correctness and the promptness of the proposed algorithm. Reconfiguration of electric networks operated in unbalanced and/or harmonic polluted environment (produced or not by DG units) will be developed in future works.

VII. REFERENCES

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VIII. Biographies

Bogdan Tomoiaga (b. 1975) graduated the Technical University of Cluj-Napoca, Electrical Engineering Faculty, in 1999. He also graduated two PU schools in Power Systems from the Technical University of Cluj-Napoca (2000) and Computer Science from the "Babes-Bolyai" University of Cluj-Napoca (2003). At present, he is a PhD student at the Technical University of Cluj-Napoca, Romania.

Mircea Chindris (b. 1947) graduated from the Technical University of Cluj-Napoca, Electrical Engineering Faculty, in 1970 and obtained his PhD degree from Technical University of Cluj-Napoca, in 1986. He performed more research stages in Turkey, Spain, Greece, Germany and Switzerland. Presently, he is with Technical University of Cluj-Napoca, Romania, as full professor at the Power Systems Dept.