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Evolving non-dominated solutions in multiobjective service restoration for automated distribution networks

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Abstract

The problem here dealt with is that of Service Restoration (SR) in automated distribution networks. In such networks, configuration and compensation level as well as loads insertion status can be remotely controlled. The considered SR problem should be handled using Multiobjective Optimization, MO, techniques since its solution requires a compromise between different criteria. In the adopted formulation, these criteria are the supply of the highest number of loads and the minimum power losses. The Authors propose a new MO approach, the Non-dominated Sorting Fuzzy Evolution Strategy, NS_FES, which uses part of the Non-dominated Sorting Genetic Algorithm, NSGA, proposed by K. Deb. The ability of NSGA to divide a population of solutions in classes of dominance allows a fruitful application of another efficient MO strategy already proposed and tested by the Authors (FES, Fuzzy Evolution Strategy). In this way, diversity and high quality of solutions is possible. After a brief description of the SR problem and a review of the approaches recently proposed in literature, the NS_FES solution strategy is presented in detail. Finally, test results using the three approaches (NSGA, FES, NS_FES) are carried out and compared.

Keywords: Service restoration; Multiobjective optimisation; Distribution automation

1. Introduction

The distribution network referred to in this paper has tie-switches (allowing the network reconfiguration), capacitor banks switches (allowing the compensation level control), low priority loads switches (allowing the possible disconnection of loads if the power supply is not enough). For this system, the SR problem aims at the identification of the above mentioned tie-switches layout allowing the connection of the greatest number of loads in the network without transformers overload. The loads priority problem could be handled within the proposed formulation by introducing different weights to different priority loads (e.g. hospitals, industry, commercial, residential). More details are given in the following section.

The main task of the SR can be attained transferring loads from the area directly involved in the fault to close areas where power margin is still available, through a reconfiguration, so as not to violate technical constraints.

The research in the field of distribution systems automation in the last years is focused on the opportunity of defining fast SR strategies. These must be of easy implementation and they also must give out good quality solutions in acceptable calculation times. The simulation of the behaviour of an electrical system in different working conditions allows a cheap evaluation of the efficiency of the different SR strategies. Now it is common practice to find pre-scheduled SR procedures.

The SR problem is a combinatorial optimisation problem; in the more realistic formulation here adopted, it is also a multiobjective problem. The procedure here developed allows the solution of the SR problem in short calculation times, without any simplifying hypotheses.

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In [6] a large review of articles published between 1987 and 1994 on the topic is reported. In [6] the general SR problem formulation is described widely and in detail.

Generally, the SR objectives consist of the minimisation of the number of unsupplied customers and of the execution time of the operations leading to the obtained optimal configuration. In this application the considered objectives are the losses minimisation and the number of unsupplied customers reduction. The optimisation SR problem is combinatorial on a large scale. The most of the articles on the topic use AI and Heuristic strategies for the SR problem solution. More recent publications on the subject, [2–5], confirm what yet presented in [1]. In [2] an approach based on the use of an Artificial Neural Network, ANN, together with a Pattern Recognition method is presented. In [3], the SR problem is solved through a step-by-step strategy, taking into account the Load pick-Up problem during the high customer demand times. In [4] a Genetic Algorithm is used, considering as most important the HV/MV transformers overloading problem. In [5] two algorithms for the SR problem are described using Fuzzy Logic and Heuristic rules. Them both aim at minimising the number of switching operations to get the final solution. In [6], the Authors have set up a hybrid GA for the SR problem in a MO formulation, but the solution strategy is not MO itself.

In [7], the Authors have presented an approach based on an Evolution Strategy with a Dynamic Fuzzy Logic definition of the different competing objectives. In what follows this approach will be indicated with the acronym FES (Fuzzy Evolution Strategy). This solving approach is robust and efficient, but the obtained results confirm that it does not allow a wide exploration of the search space. In this paper, the algorithm NS_FES is proposed. The potential of the NSGA is fully exploited for the creation of non dominated solutions; these have then been processed using FES already presented in [7], so as to obtain differentiated and high quality solutions. The three methods FES, NSGA and NS_FES are compared in terms of performance (quality of solutions and calculation times) in the Section 6.

2. The service restoration problem

Permanent faults in power distribution systems can take place in more or less peripheral areas, based on the original function of the faulted element; the consequences of such event can also be quite serious. Generally the out-of-service of one of the HV/MV substations can be considered a serious fault. In such case a large part of the supply power will not be available and a large number of loads could remain unsupplied. If such a fault occur the SR problem can be formulated as follows.

Minimise the number of unsupplied loads, keeping into account the possible overloads at HV/MV substations and the following technical constraints:

1. the network must keep radial topology;
2. load at HV/MV substations must not exceed a predefined limit;
3. load buses voltage must not differ too much from the rated value and the branch currents must not exceed the maximal values related to the lines sections.

Constraints (2) and (3) can be relaxed to a certain extent, especially taking into account the duration of the out-of service.

In the proposed formulation, together with the main objective of minimising the number of unsupplied customers, is also considered that of reducing power losses.

The latter allows the participation of capacitor banks into the SR process; they indeed are reactive power sources for the loads; in this way, more real power is available at HV/MV transformers. The losses minimisation is the criterion leading the adjustment of compensation when the primary objective is that of supplying the largest number of loads.

Moreover, as secondary objective, the losses reduction produces an increase of the power margins at the HV/MV substations producing the connection of a larger number of loads.

In this formulation and more in general, when it is required to consider more than one objective and the relevant constraints in a single expression, the quality of each solution can be deduced by the composition of more terms that may have quite different weight and range of variation.

The power margin in terms of apparent power at the j-th substation, can be evaluated with the following expression, M_j (δ^{L}, δ^{S}, δ^{C}):

$$A_{nj} - \sum_{i=1}^{nj} [(\delta^i_{\mathrm{L}} P_{il} + \Delta P^i(\delta_{\mathrm{L}},\delta_{\mathrm{S}},\delta_{\mathrm{C}}))^2 + (\delta^i_{\mathrm{L}} Q_{\mathrm{il}} + \Delta Q^i(\delta_{\mathrm{L}},\delta_{\mathrm{S}},\delta_{\mathrm{C}}) - \delta^i_{\mathrm{C}} Q^i_{\mathrm{c}})^2]^{1/2} \quad J = 1, .\mathrm{Nss}. \tag{1}$$

Where A_{nj} is the power that can be supplied by the j-th HV/MV transformer at the j-th substation (comprising the admissible overload). P_{il} and Q_{il} are the real and reactive load powers at the ending bus of the i-th branch. The summation, extended to the number of branches, nj, supplied by the j-th substation, represents all the power flowing through the j-th transformer. ΔP_i and ΔQ_I, respectively represent power losses and reactive power variations due to the lines inductive character; finally Q_{ic} represents the rated power of the capacitor at the ending bus of the i-th branch. Nss is the total number of working HV/MV substations.

Eq. (1), the binary variables δ_{L}, δ_{S}, δ_{C} are the control parameters of the strategy, they, respectively, represent the loads, tie-switches and capacitor banks status.

The primary objective is, therefore, that to minimise the global power margin given by:

$$Mt = \Sigma Mj \quad (2)$$

The second objective, the power losses, can be expressed as follows:

$$\Delta Pt = \sum_{i=1}^{nr} \frac{R_i}{V_i^2}[P_i^2(\delta^i_{\mathrm{L}}, \delta^i_{\mathrm{S}}, \delta^i_{i\mathrm{C}}) + (Q_i^2(\delta^i_{\mathrm{L}i}, \delta^i_{\mathrm{S}}, \delta^i_{\mathrm{C}}) - \delta^i_{\mathrm{C}}Q^i_{\mathrm{C}})^2] \quad (3)$$

where, P_i e Q_i are active and reactive power flows in the i-th branch, R_i is the resistance of the i-th branch, V_i is the voltage at the ending bus of the i-th branch and the summation is extended to the total number of branches in the network, nr.

The constraints concern the regularity of the voltage profile and the current ampacity of branches. Moreover, for each substation the following condition must be fulfilled: $Mj \geq 0$.

As it can be noted, in the adopted formulation, the loads have been considered all with the same priority. Since they can all be disconnected, the Authors have considered them as 'low priority' loads. Anyway, the loads priority can still be handled in the proposed formulation by giving appropriate weights to the loads and by modifying objective (2). Here, for example a coefficient such as the inverse of the weighed sum of the disconnected loads can be introduced. The efficiency of the proposed approach shouldn't be affected.

2.1. Implementation details

The three approaches, NSGA, FES, NS_FES, that are compared in the following Section 6 process a set of solutions of the SR problem. In this way, the binary string representing a single solution can be idealistically divided into three strings pertaining to the three different control variables sets.

In order to define a search strategy assessing feasible solutions, it is necessary to look upon the following statements concerning the studied system:

1. the radial topology is maintained for any tie-switches layout;
2. the number of open switches must equal the number of independent loops;

The solutions set corresponding to radial networks, is much smaller than the total set of binary strings attainable from a string of length equal to the total number of tie-switches in the network, n_sez (total number of strings: $2^{\mathrm{n\_sez}}$). As a consequence it is sensible considering a search space of feasible solutions meeting the topological constraint of radiality, applying then, along the search process, diversification operators producing radial solutions ('branch-exchange' type [8]).

The starting population is generated through a search algorithm allowing the creation of whatever tree from a starting graph [9]; the set of connected loads is randomly chosen, always verifying that the substations are not overloaded over the predefined limit ($Mj > 0$). Similarly, the connected capacitors banks set is randomly generated since there's no special constraint over it.

3. Non-dominated sorting genetic algorithm, NSGA

The NSGA algorithm, Non-Dominated Sorting Genetic Algorithm, was introduced by Srinivasan and Deb [10]. NSGA implements the idea of a selection method based on classes of dominance of all the solutions. To each of the sets of the best non-dominated solutions has then been applied a MO algorithm already proposed and tested by the Authors, for the same SR problem [7]. This algorithm will be described in detail in the following Section 4.

3.1. Background

The concept of non-dominance [11] is one of the basic concepts of MO.

For a problem having more than one objective function to maximise (say, f_k, $k = 1, \ldots, M$ and $M > 1$) any two solutions x_1 and x_2 can have one or two possibilities: one dominates the other or none dominates the other. A solution x_1 is said to dominate the other solution x_2, if both the following conditions are true:

1. The solution x_1 is no worse than x_2 in all objectives, $f_k(x_1) \geq f_k(x_2)$, for all $k = 1, \ldots, M$.
2. The solution x_1 is strictly better than x_2 in at least one objective, or $f^*_k(x_1) > f^*_k(x_2)$ for at least one $k^* \in \{1, \ldots, M\}$.

If any of the above conditions is violated, the solution x_1 does not dominate solution x_2. If x_1 dominates the solution x_2, it is also customary to write x_2 *is* dominated by x_1, or x_1 is not dominated by x_2, or, simply, among two solutions, x_1 is the non-dominated solution.

It is also important to observe that the concept of optimality in MO is related to a set of solutions, instead than a single one. It is, therefore, possible to define Pareto local and global optimality for sets of solutions.

P is a local optimal Pareto set, if for every member x in P, there exist no solution y in a small neighbourhood, which dominates every member in the set P.

P is a global Pareto-optimal set, if there exist no solution in the search space, which dominates every member in the set P.

From the above discussion, it is possible to point out that there are primarily two goals that a multi-criterion optimisation algorithm must achieve:

1. Guide the search towards the global Pareto-optimal region;
2. Maintain population diversity in the Pareto-optimal front.

There are many MO solution algorithms allowing the attainment of these results, but the NSGA algorithm has proved to be quite feasible for the considered implementation, since it divides the population in fronts of non-dominated solutions. In this way the search can be addressed towards interesting areas of the search space, where the global Pareto-optimal region may resides.

3.2. The algorithm NSGA

NSGA varies from the SGA (Simple Genetic Algorithm) [12] only in the way the selection operator is used. The crossover and mutation operators remain as usual. Before selection is performed, the population is first ranked on the basis of an individual's non-domination level, which is found by the procedure described in the next section and then the fitness is assigned to each population member.

3.2.1. Fitness assignment

Consider a set of N population members, each having M ($M>1$) objective function values. The following procedure can be used to find the non-dominated set of solutions:

step 0: $i := 1$;

step 1: for all $j := 1, \ldots, N$ and $j <> i$ compare solutions x_i and x_j for domination using the two conditions (a and b) for all M objectives, namely, in a maximisation problem, if $f_k(x_i) \geq f_k(x_j)$, for all $k = 1, \ldots, M$ and if for at least one $k^* \in \{1, \ldots, M\}$, it turns that $f_k^*(x_i) > f_k^*(x_j)$;

step 2: if for any j the two conditions above are satisfied, x_j is dominated by x_i, mark x_j as 'dominated';

step 3: if all solutions (when $i = N$ is reached) in the set are considered go to step 4, else increment i by one and go to step 1.

step 4: all solutions that are not marked 'dominated' are non-dominated' solutions.

All these non-dominated solutions are assumed to constitute the first non-dominated front in the population and assigned a large dummy fitness value (say N). All these solutions, in this way, have an equal reproductive potential.

In order to maintain population diversity, these non-dominated solutions are then shared with their dummy fitness value. In what follows a brief description of one of the commonly used sharing techniques is given.

These non-dominated individuals are ignored temporarily to process in the same way the rest of the population members. They are assigned a dummy fitness value, which is a little smaller than the worst shared fitness value observed in solutions of the first non-dominated front.

3.2.2. Sharing procedure

Given a set of nk solutions in the k-th non-dominated front each having a dummy fitness value f_k, the sharing procedure is performed in the following way for each solution $i = 1, \ldots, n_k$.

Step 1. Compute a normalised Euclidean distance measure with another solution j in the k-th non-dominated front, as follows:

$$d_{ij} = \sqrt{\sum_{p=1}^{P} \left(\frac{x_p^i - x_p^j}{x_p^u - x_p^l} \right)^2} \tag{4}$$

where P is the number of variables in the problem. The parameters x_p^u and x_p^l are the upper and lower bounds of parameter x_p

Step 2. Distance d_{ij} is compared with a pre-specified parameter σ_{share} and the following sharing function value is computed:

$$Sh(d_{ij})\ 1 - \left(\frac{d_{ij}}{\sigma_{\text{share}}} \right)^2, \quad \text{if} \quad d_{ij} < \sigma_{\text{share}}$$

$$Sh(d_{ij}) = 0, \quad \text{otherwise.} \tag{5}$$

Step 3. $j = j + 1$. If $j \leq n_k$, go to step 1 and calculate $\text{Sh}(d_{ij})$. If $j > n_k$, calculate the niche count for the i-th solution as follows:

$$m_i = \sum_{j=1}^{nk} Sh(d_{ij}) \tag{6}$$

Step 4. Degrade the dummy fitness f_k of the i-th solution in the k-th non-domination front to calculate the shared fitness, f'_i, as follows:

$$f'_i = f_k / m_i. \tag{7}$$

The procedure is repeated for all $i = 1, .., n_k$, and the corresponding f'_i is found. Thereafter, the smallest value f_{mink} of all f'_i in the k-th non-dominated front is found for further processing. The dummy fitness of the next non-dominated front is assigned to be: $f_{k+1} = f_{\text{mink}} - \varepsilon_k$, where ε_k is a small positive number.

The value of σ_{share} is defined using empirical laws that can be found in literature, such as the one that follows [11]:

$$\sigma_{\text{share}} \approx \frac{0.5}{\sqrt[P]{q}}$$

where q is the desired number of distinct Pareto-optimal solutions and P is the number of variables in the problem.

Moreover, the distance d_{ij} in Eqs. (3)–(5) is an Euclidean distance, but in the treated problem is a Hamming distance, since the SR problem is combinatorial.

4. Fuzzy evolution strategies, FES

The ES are optimisation strategies based on the mechanics of natural genetics and allowing species growth [13].

They are founded on three basic principles:
1. the recombination;
2. the natural selection;
3. diversity by variation.

Unlike other natural algorithms, the Evolution strategies use as fundamental operator the Mutation operator, whose application frequency depends on certain strategical parameters, assuming different values during the search process. The recombination has a secondary relevance, and may disappear.

The mutation operator is an important diversification operator allowing small perturbations on the current solution. Moreover, the ES have some other option compared with other traditional natural algorithms, like a free number of parents involved in reproduction. Standard selection can be carried out by means of either the (λ, μ) scheme and the $(\lambda+\mu)$ scheme, where the symbol μ denotes the number of parents appearing at a time in a population of imaginary individuals, and λ the number of created offspring within one synchronised generation. In the first type with $\lambda > \mu \geq 1$ the μ parents are selected from the λ offspring only. In the second type, the λ offspring and their λ parents are united and the μ fittest individuals are selected from this set of $\lambda+\mu$ solutions.

In this application, the FL principles have been used for the objects treatment in the MO optimisation [14,15], so as to weigh them in a comparable way, independently from their actual values.

For each solution then the two objectives are calculated (Eqs. (2) and (3)). At each iteration, the actual values of the two objectives are evaluated. Therefore, a Normalised Gaussian membership function is ascribed to each of the two objectives, and the correspondent numerical value is given to each objective derived from the two membership functions (mf_1, mf_2),[16].

In this way, for a given configuration, defined by a binary parameters vector, **δ**, and characterised by the values of the single objectives fi(**δ**) and the related values of membership functions mfi(fi(**δ**)), the proposed procedure generates a unique value for the global objective function value, O, defined as it follows:

$$O(\delta) = 1 - \Pi \mathrm{mfi}(\mathrm{fi}(\delta)) \quad i = 1, 2 \text{ and } n \text{ objects} \qquad (8)$$

In this application n objects equals two. In this way, the optimisation problem becomes the search for the vector **δ**, giving the minimum value of $(O(\boldsymbol{\delta}))$.The location of the MF dynamically self-adapts and periodically is newly positioned so as to keep into account the growth of quality of the solution sets as the search process proceeds. The population is, therefore, ordered with respect to the values obtained from Eq. (8) and the best μ parents, which will be subjected to the reproduction cycle. The principle ruling the reproduction cycle is that to obtain solutions belonging to the 'Pareto Front'. In this way, the diversification operators are applied in a way that aims at losses reduction and then at Power margin reduction through the connection, if possible, of more customers.

The following have been on purpose defined:
1. the so-called 'branch-exchange', ruled by a heuristic criterion aiming at losses reduction and voltage profile regularisation;
2. a loads exchange operator, also driven by a losses reduction criterion (allowing, for example, an easier loads disconnection if they are located at terminal branches, compared with those located close to the root);
3. finally, loads insertion, so as to cover the power availability in each area.

The termination criterion is connected to the flattening of the search process of one solution.

5. The proposed algorithm, NS_FES

The proposed algorithm derives from the combination of the two algorithms above presented. It has two loops, an external loop, based on NSGA, and an internal loop, based on FES. In this way the sub-populations belonging to the first non-dominated front are then processed using a Fuzzy Evolution Strategy, in order to improve their quality. It is important to observe that the combination of the two algorithms allows focusing the attention on that part of the Pareto front, which is most interesting. In many engineering problems, indeed it is desirable to consider only one part of the Pareto front, in this case it is the part having higher losses and lower Power Margin.

The procedure proceeds through the following steps:
1. creation of the first generation, fitness assignment to each solution on the basis of non-dominance criterions;
2. selection of the first non-domination front;
3. application of the FES algorithm for a predefined number of iterations to the selected front;
4. insertion in the old population of the set of processed solutions, each solution is considered once again on the basis of non-dominance and again sub-divided in classes.
5. Termination condition verification and return to step 3).

6. Application

The studied system is a power distribution network with 20 kV of rated voltage.

It has 109 branches, almost all of them can be sectionalised in one point, 81 load nodes and 18 capacitor banks, the system is similar to that studied in [6,7].

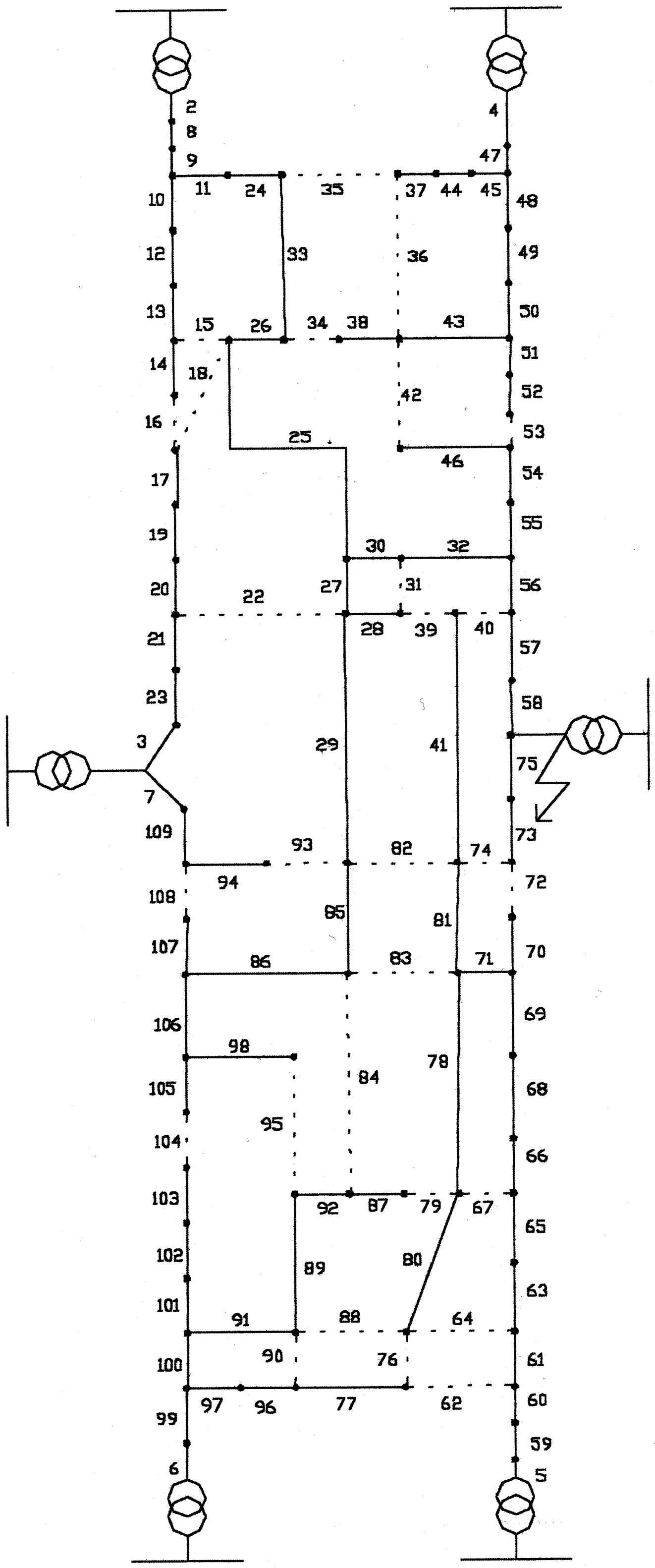

Fig. 1. Test system in the starting configuration.

The distribution system is supplied by six HV/MV substations. The service restoration concerns the permanent out of service of one of the HV/MV transformers.

The used load model is with constant power. The necessary power flow calculations have been executed using a Gauss–Seidel method [17], which is valid for distribution networks and allows the consideration of loads dependency from voltage. The method is based on an iterative algorithm with some special measures to increase the convergence speed; the bus voltages are considered as state variables. It executes the following steps: (1) put the voltages at all the nodes at the rated value; (2) calculate the load currents and the capacitive currents at all the nodes; (3) on the basis of the network topology, calculate the branch currents; (4) starting from the branch connected to the supply node, calculate the voltage at the EB below each branch; (5) compare the voltages at the nodes with those calculated or fixed before; if the error is greater than a predetermined margin go to step 2, otherwise stop.

In Fig. 1 the test system in the starting configuration is represented. All branches can be sectionalised in one point. Dots indicate MV/LV load points. In Table 1 the network and loads data are reported. In the table *Ri* and *Xi* [Ohm] are resistance and reactance of a generic branch, Pil and Qil are the loads at the relevant ending bus, respectively, in kW and kVAR, and Qic is the rated power of the capacitor bank installed at the ending bus in kVAR.

In Fig. 1 the substation where the fault has occurred is also shown. The configuration optimised with respect to objectives (2) and (3) with the lowest power margin obtained using the NS-FES algorithm is the one having the following switches in open position: 14, 17, 26, 27, 28, 29, 30, 31, 35, 38, 40, 45, 46, 58, 64, 69, 71, 77, 80, 81, 83, 85, 87, 88, 96, 98, 106, 107. The unsupplied loads are in the following nodes: 23, 40, 54, 80. The capacitor banks that are connected are located at the following nodes: 20, 8, 36, 19, 29, 48, 60, 75, 59. The relevant total power losses value is: 516.01 kW, the maximum voltage drop is 2%. In this configuration, there is no overloading of the supply transformers.

In Fig. 2 non-dominated fronts at iteration 1 and 250 are represented. As it can be noted, the insertion of an internal loop with an efficient MO algorithm guides the search towards interesting areas of the search space. In Fig. 3 the results obtained applying the three algorithms are reported. The different solutions are characterised by the values of the two objectives: the power margin at the HV/MV transformers and the power losses value. For a comparative study of the obtained solutions, on the basis of their position in the diagram of Fig. 3, it can be observed that solutions are as much better as closer they are to the origin of axes. It is clear that, from the analysis of diagram in Fig. 3, solutions

Table 1
In the table *Ri* and *Xi* [Ohm] are resistance and reactance of a generic branch, *Pi* and *Qi* are the loads at the relevant ending bus of the *i*-th branch, respectively in kW and kVAR, and Qic is the rated power of the capacitor bank installed at the ending bus in kVAR.

Branch number	Sb_i	Eb_i	R_I	X_i	P_{i1}	Q_{i1}	Q_{ic}
2	1	2	0.1588	0.0161	429	210	0
3	1	14	0.3176	0.0.322	357	159	0
4	1	30	0.2868	0.029	553	278	0
5	1	42	0.1588	0.0161	429	210	0
6	1	70	0.2868	0.029	553	278	0
7	1	81	0.3188	0.0323	585	279	0
8	2	3	0.2358	0.0239	455	228	0
9	3	4	0.1849	0.0187	307	145	0
10	4	5	0.314	0.0318	500	236	0
11	4	15	0.2311	0.0234	378	181	0
12	5	6	0.218	0.0221	581	289	150
13	6	7	0.3045	0.0308	234	107	0
14	7	8	0.3437	0.0348	415	217	150
15	7	16	0.3271	0.0331	354	163	0
16	8	9	0.1896	0.0192	384	173	150
17	9	10	0.1884	0.0191	599	321	0
18	9	16	0.1288	0.013	354	163	0
19	10	11	0.32	0.0324	320	169	0
20	11	12	0.2406	0.0244	509	231	0
21	12	13	0.1635	0.0166	261	123	0
22	12	17	0.3318	0.0336	407	199	0
23	13	14	0.1386	0.014	357	159	0
24	15	21	0.2216	0.0224	484	238	0
25	16	18	0.1955	0.0198	368	174	0
26	16	20	0.25	0.0253	445	203	300
27	17	18	0.1801	0.0182	360	174	0
28	17	24	0.1422	0.0144	0	0	0
29	17	64	0.1288	0.013	209	96	0
30	18	19	0.3105	0.0314	550	271	300
31	19	24	0.2844	0.0288	0	0	0
32	19	39	0.218	0.0221	261	111	0
33	20	21	0.218	0.0221	484	238	0
34	20	23	0.186	0.0188	463	244	300
35	21	22	0.2631	0.0266	343	165	0
36	22	26	0.1505	0.0152	275	129	0
37	22	27	0.282	0.00286	222	343	0
38	23	26	0.1422	0.0144	275	129	0
39	24	25	0.1446	0.0146	0	0	0
40	25	40	0.2524	0.0256	327	174	0
41	25	57	0.218	0.0221	0	0	0
42	26	29	0.1288	0.013	370	195	150
43	26	34	0.218	0.0221	209	103	0
44	27	28	0.2275	0.023	205	90	0
45	28	31	0.2927	0.0296	215	104	0
46	29	37	0.2406	0.0244	423	188	0
47	30	31	0.3294	0.0334	215	104	0
48	31	32	0.218	0.0221	321	152	0
49	32	33	0.1849	0.0187	206	97	0
50	33	34	0.192	0.0194	209	103	0
51	34	35	0.2595	0.0263	512	232	150
52	35	36	0.128	0.013	423	174	150
53	36	37	0.2406	0.0244	377	188	0
54	37	38	0.2548	0.0258	302	149	0
55	38	39	0.1458	0.0148	261	111	0
56	39	40	0.3096	0.0311	327	174	0
57	40	41	0.2477	0.0251	0	0	0
58	41	54	0	0	357	159	0
59	42	43	0.2358	0.0239	455	228	0
60	43	44	0.1849	0.0187	307	145	0
61	44	45	0.314	0.0318	500	236	0
62	44	55	0.2311	0.0234	378	181	0

Table 1 (*Continued*)

Branch number	Sb_i	Eb_i	R_I	X_i	P_{il}	Q_{il}	Q_{ic}
63	45	46	0.218	0.0221	581	289	150
64	45	61	0.2311	0.0234	484	238	0
65	46	47	0.3045	0.0308	234	107	0
66	47	48	0.3437	0.0348	415	217	150
67	47	56	0.3271	0.0331	354	163	0
68	48	49	0.1896	0.0192	384	173	150
69	49	50	0.1884	0.0191	599	321	0
70	50	51	0.32	0.0324	0	0	150
71	50	58	0.1635	0.0166	360	174	0
72	51	52	0.2406	0.0244	509	231	0
73	52	53	0.1635	0.0166	0	0	0
74	52	57	0.3318	0.0336	0	0	0
75	53	54	0.1386	0.014	357	159	0
76	55	61	0.2216	0.0224	484	238	0
77	55	67	0.3318	0.0336	222	343	0
78	56	58	0.1955	0.0198	368	174	0
79	56	60	0.25	0.0253	445	203	300
80	56	61	0.1386	0.014	484	238	0
81	57	58	0.1801	0.0182	360	174	0
82	57	64	0.1801	0.0182	209	96	0
83	58	59	0.3105	0.0314	550	271	300
84	59	63	0.2477	0.0251	463	244	300
85	59	64	0.2844	0.0288	209	96	0
86	59	78	0.1801	0.0182	0	0	0
87	60	63	0.186	0.0188	463	244	300
88	61	62	0.2631	0.0266	343	165	0
89	62	66	0.1505	0.0152	275	129	0
90	62	67	0.282	0.0286	222	343	0
91	62	72	0.2524	0.0256	321	152	0
92	63	66	0.1422	0.0144	275	129	0
93	64	65	0.1446	0.0146	531	245	0
94	65	80	0.2524	0.0256	327	174	0
95	66	69	0.1288	0.013	370	195	150
96	67	68	0.2275	0.023	205	90	0
97	68	71	0.2927	0.0296	215	104	0
98	69	77	0.2406	0.0244	423	188	0
99	70	71	0.3294	0.0334	215	104	0
100	71	72	0.218	0.0221	312	152	0
101	72	73	0.1849	0.0187	206	97	0
102	73	74	0.192	0.0194	209	103	0
103	74	75	0.2595	0.0263	512	232	150
104	75	76	0.128	0.013	377	174	150
105	76	77	0.2406	0.0244	423	188	0
106	77	78	0.2548	0.0258	0	0	0
107	78	79	0.1458	0.0148	261	111	0
108	79	80	0.3096	0.0311	327	174	0
109	80	81	0.2477	0.0251	585	279	0

found with the algorithm here proposed are of better quality than those found with the others.

Also from the diagram of Fig. 3 it can be observed that the algorithm NSGA finds varied but not high quality solutions. For these solutions, the high power margins and the low losses level correspond to operating conditions in which a low number of loads is supplied even if through efficient network configurations. Comparing then the solutions obtained with the two algorithms FES and NS_FES, it can be noted that the FES algorithm does not give out high quality solutions, since for comparable power margins, the losses level are higher. This means an operating condition in which the power that is available at the substations gets lost instead of being used for loads supply.

Another advantage of the developed algorithm is that the convergence towards high quality solutions occurs with a lower number of objective function calls, which in the considered case is the procedure for the network solution.

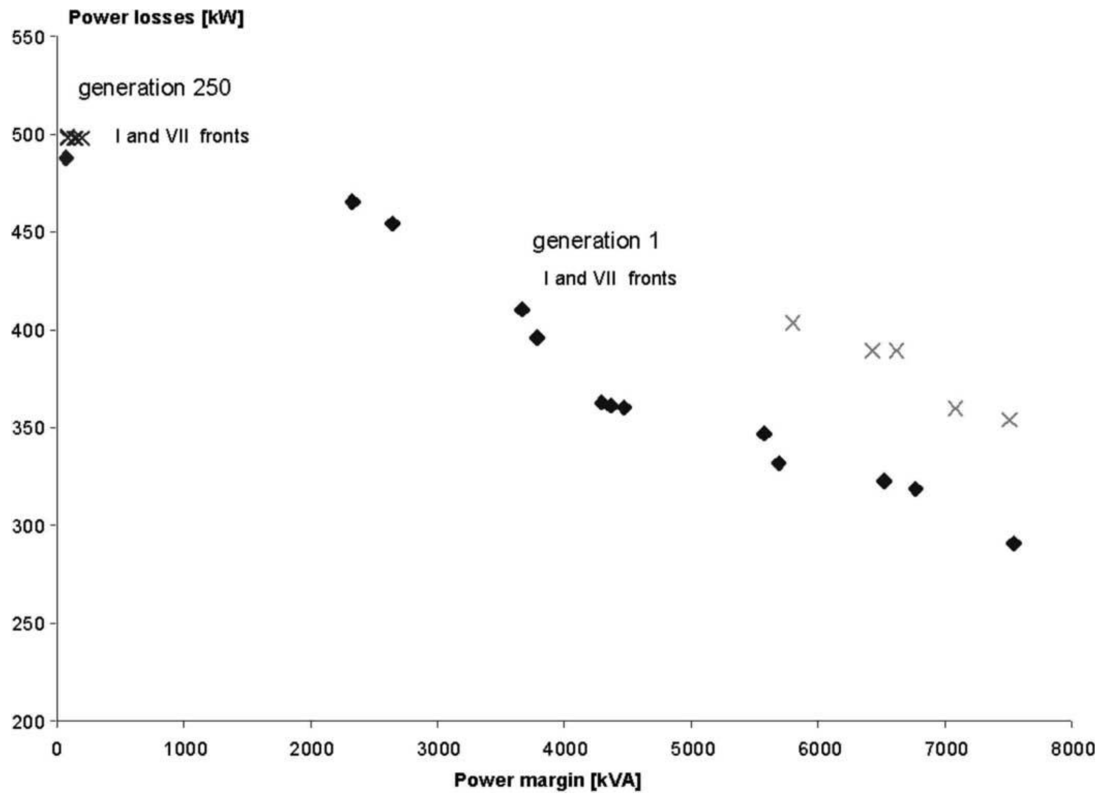

Fig. 2. Evolution of the I and VII fronts on non-dominated solution in NS_FES.

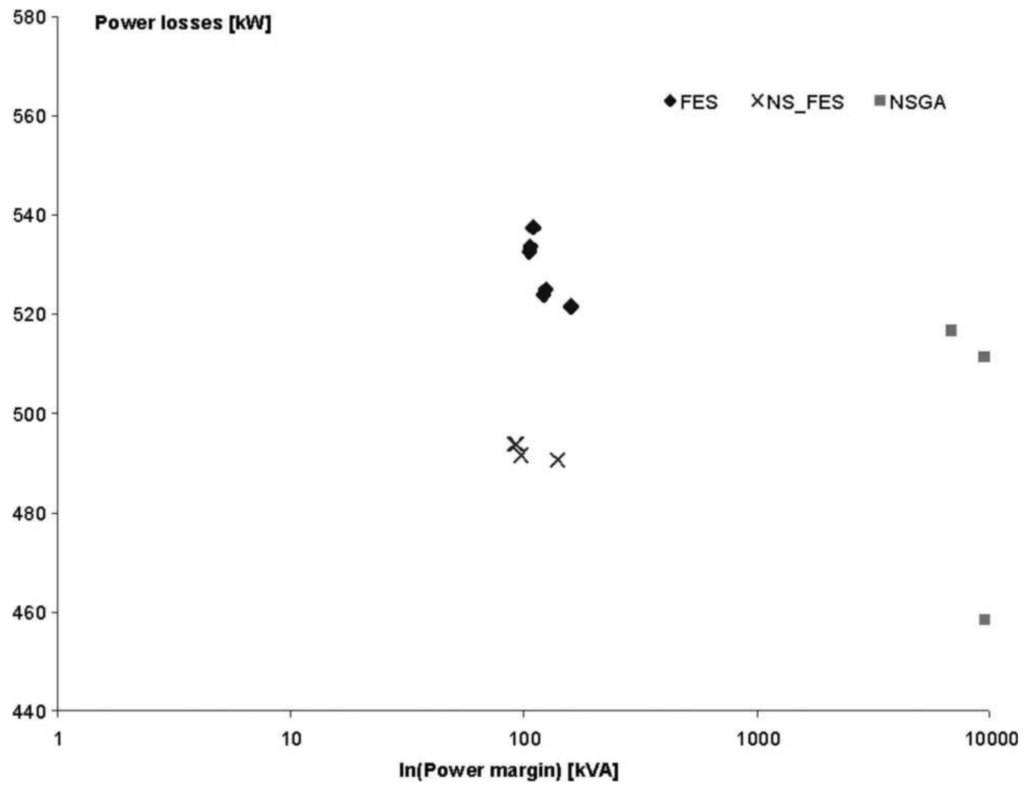

Fig. 3. Results obtained using the three algorithms: best solutions in the last generation with FES; first front of non-dominated solutions with NS_FES; first front of non-dominated solutions with NSGA.

7. Conclusions

The SR problem is one of the most interesting and important problems in automated distribution systems optimal operation. Attaining high performance in distribution systems operation is today a priority for managers in the new deregulated energy market. The tools offered by information technology on the other hand allow an efficient solution of operation problems both in difficult operating conditions and in normal status. In this paper, a sensible formulation of the SR problem is used. It gives out solution layouts characterised by a quite rational use of the power available at the substations since the minimum amount is wasted in power losses allowing the service restoration for a large number of loads.

For the solution of the SR problem, a new optimisation algorithm NS_FES is here proposed. It has proved to be quite efficient in such applications. These features are based on the fact that the algorithm implements the convergence between two requirements to be fulfilled in MO: diversification of solutions and quality of solutions. The algorithm can be applied to other problems than SR and with any other optimisation technique into the internal loop, provided it is able to give out high quality solutions.

8. List of symbols

M_{j}	power margin at the j-th HV/MV transformer;
A_{nj}	power that can be supplied by the j-th HV/MV transformer;
$\boldsymbol{\delta}^{\mathrm{L}}$	binary array containing the connection status of the loads in the network;
$\boldsymbol{\delta}^{\mathrm{S}}$	binary array containing the connection status of the tie-switches in the network;
$\boldsymbol{\delta}^{\mathrm{C}}$	binary array containing the connection status of all the capacitor banks in the network;
nj	number of branches supplied by the j-th substation;
ΔP_i	power losses at the i-th branch;
ΔQ_i	reactive power variation at the i-th branch;
Q_{ic}	rated power of the capacitor at the ending bus of the i-th branch;
R_i, X_i	resistance and reactance of the i-th branch;
Sb_i, Eb_i	Sending bus and Ending bus of the i-th branch;
$P_{i\mathrm{l}}$, $Q_{i\mathrm{l}}$	real and reactive load powers at the ending bus of the i-th branch.;
Nss	number of HV/MV working substations;
M_{t}	total power margin;
P_i, Q_i	real and reactive power flows through the i-th branch;
Nr	total number of branches;
n_sez	number of tie-switches in the network;
f_j	j-th objective function;
d_{ij}	Euclidean distance between the i-th and the j-th solution;
Sh	sharing function;
σ_{share}	sharing parameter;
λ, μ	number of offspring, number of parents;
$\mathrm{M}f_I$	i-th membership function;
$O(\boldsymbol{\delta})$	global objective function value in FES.

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