Electrical Power and Energy Systems 22 (2000) 103–110

ELECTRICAL POWER & ENERGY SYSTEMS

www.elsevier.com/locate/ijepes

Multiobjective service restoration in distribution networks using an evolutionary approach and fuzzy sets

A. Augugliaro*, L. Dusonchet, E. Riva Sanseverino

Dipartimento di Ingegneria Elettrica, Università di Palermo, Viale delle Scienze, Parco d'Orleans, 90128 Palermo, Italy

Received 10 February 1998; received in revised form 28 May 1998; accepted 1 May 1999

Abstract

In this article, the service restoration (SR) problem in electrical distribution networks is dealt with using an evolutionary strategy (ES) with a fuzzy definition of the conflicting objectives. The normal operation status allows the remote control of tie-switches, of capacitor banks and load connection. When a permanent fault occurs, the same remote control actions can be performed with the aim of restoring the service in the concerned areas. The status of these remotely controllable elements is the boolean optimisation variables for the SR problem. Besides this, here the SR problem is dealt with in a multiple objectives (MO) formulation. Indeed, the power losses' term is considered as a further objective to be minimised, together with the primary objective of maximising the number of supplied loads. Generally, the MO formulation of an optimisation problem requires a unique expression for the global objective function. In this particular case, the used ES approach necessarily requires the definition of a 'global performance' index, which is derived on the basis of the fuzzy sets theory, outperforming the weighed sum formulation of the same problem. After a brief discussion on the SR problem and a short review of the state-of-art on the topic, the proposed ES and the fuzzy MO formulation of the SR problem is presented in detail. Results obtained using this procedure applied to a test system are presented and discussed. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Service restoration; Multiobjective optimisation; Evolution strategies

1. Introduction

Some of the primary objectives of electrical utilities are 'customer satisfaction' and 'service reliability'. They indeed strongly characterise the 'service quality'. The 'customer satisfaction' can be achieved if customers are supplied as continuously as possible. Research in the field of service restoration (SR) of automated electrical systems is now focused on the elaboration of fast and easy-to-implement SR strategies. They should be able to find 'good' solutions in an acceptable calculation time.

Loads disconnections are usually related to the occurrence of a permanent fault in the network. Indeed, a permanent fault can be eliminated by the isolation of the faulty element and this causes the disconnection of all the loads below it. The fault is quite serious if the concerned area is large, namely, when the fault occurs close to or inside the HV/MV substation. If this is the case, and one of the HV/MV transformers is out of service, the SR problem is that of finding the optimal radial configuration to supply the largest number of customers. Therefore, it requires to identify the best new loading condition for the still operating HV/MV transformers and the best network configuration.

When a fault occurs at one of the peripheral lines, in radial configuration, the SR problem is that of identifying the best path to supply the few affected loads. In this case, it is possible to perform a simple reconfiguration, trying to minimise the number of switching operations (the solution is generally quite close to the previous configuration).

In this article, the SR problem for an outage at one of the HV/MV substations is dealt with. The aim of this article is that of proposing an approach for the identification of the network configuration and of the reactive power compensation level allowing the maximum number of customers to be energised. It is clear that this new configuration should meet functional and operating hard constraints.

The economical benefit derived from the opportunity of carrying out a fast SR strategy minimising the number of unsupplied customers also depends on the different customers' priorities. In the SR problem's formulation proposed here the hypothesis is that the available power after the fault occurrence is enough to supply high priority loads. The remaining loads have the same priority level and can be de-energised. The SR problem is a combinatorial optimisation problem, and in this formulation it is also an MO

* Corresponding author. Tel.: + 39-91-6566241; fax: + 39-91-488452.
E-mail address: augugliaro@diepa.unipa.it (A. Augugliaro)

0142-0615/00/$ - see front matter
PII: S0142-0615(99)00040-X

problem. Besides this, it is an NP complete problem. That is a problem for which it is not possible to find a globally optimal solution in a reasonable calculation time. In Ref. [1], an extensive review of articles published between 1987 and 1994 on the topic is reported. In Ref. [1] the general the SR problem formulation is described widely in detail. Generally, the SR objectives consist of the minimisation of the number of unsupplied customers and of the minimisation of the execution time of the switching operations leading to the final optimal or suboptimal configuration. Most of the articles on the topic use AI and heuristic strategies. More recent publications on the subject [2–5] confirm what was presented in Ref. [1]. In Ref. [2], the authors use an approach based on the use of an artificial neural network (ANN), together with a pattern recognition method. In Ref. [3], the SR problem is solved through a step-by-step strategy, taking into account the cold load pick-up problem. In Ref. [4], a genetic algorithm (GA) is used considering the HV/MV transformers overloading problem as being the most important. In Ref. [5], two algorithms for the SR problem are described using fuzzy logic and heuristic rules. Both aim at minimising the number of switching operations to get the final solution.

Finally, in Ref. [6], a hybrid GA is used for an MO formulation of the same restorative problem, but the solution strategy is not MO itself.

In this article, the solution strategy is improved using an evolutionary approach with a fuzzy definition of the different competing objectives appearing in the global objective function. This approach appears to be robust and efficient. The obtained results were compared with those obtained by the authors in Ref. [6], and this comparison is reported in the application section.

2. The SR problem

In distribution systems, permanent faults can occur in more or less peripheral areas, and their effects can, respectively, be less or more serious. Generally, a fault concerning one or more HV/MV substations is considered to be quite serious. In this eventuality, a large part of the supplying power lacks, and a large number of customers can be interested. If such a serious fault occurs, the SR problem can be formulated as follows:

> Minimise the number of unsupplied customers while meeting the following constraints:

1. the network must have a radial topology;
2. no overloading of HV/MV transformers is allowed;
3. voltage at load buses must not differ much from the rated value, and current entities in the network lines must not exceed the maximal values ruled by the sizes of the sections.

Actually, condition (3) may be considered as soft constraints, compared to the normal operation because of the presumed outage short duration.

In the proposed formulation, together with the primary objective of minimising the number of unsupplied loads, the objective of reducing the entity of power losses is considered.

The consideration of the former objective rules the capacitor banks layout making it important in the SR strategy. The compensation system is indeed a reactive power generation system for loads; in this way, HV/MV transformers can be relieved of this task, covering the active power demand more easily. The criterion of loss reduction is mainly used to activate compensation within a strategy that primarily aims at supplying as many loads as possible. Loss reduction also grows power margins at HV/MV substations and sets free power for customers' demands.

In this kind of formulation and more generally when it is required to face MO problems and the relevant constraints in a single 'fitness' expression, the quality of each single solution can be deduced from the composition of more terms. These may have a different order of magnitude and range of variation and therefore different importance in the same expression.

The power margin at each substation, M_j, namely, the apparent power available at the jth substation can be evaluated through the following expression:

$$M_j(\delta_L, \delta_S, \delta_C) = A_{nj} - [\sum_{i=1}^{nj} (\delta_L^i P_{\text{loads}}^i + \Delta P^i(\delta_L, \delta_S, \delta_C))^2 + (\delta_L^i Q_{\text{loads}}^i + \Delta Q^i(\delta_L, \delta_S, \delta_C) - \delta_C^i Q_c^i)^2]^{1/2} \quad j = 1, .N_{ss}, \tag{1}$$

where A_{nj} is the power that can be supplied by the HV/MV transformer located at the jth substation (inclusive of the admissible overload). The summation extended to the number of branches, nj, supplied by the jth substation, represents the whole apparent power entity flowing through the jth transformer. In this expression, P_{loads} and Q_{loads}, respectively, are the active and reactive power, supplying the loads at the ending bus of the ith branch ('branch' denotes the physical connection between two adjacent nodes; 'node' indicates the section at which one or more loads or lines are connected). ΔP^i and ΔQ^i, respectively, represent real and reactive power losses in the ith branch; finally, $Q^i c$ represents the rated power of the capacitor banks at the ith branch ending bus. N_{ss} is the total number of operating HV/MV substations.

In Eq. (1), the binary variables δ_L, δ_S, δ_C are the control parameters of the strategy; they represent the loads, tie-switches and capacitor banks status, respectively.

The first objective is to minimise the global power margin given by:

$$Mt = \sum M_j \qquad j = 1, .N_{ss}. \tag{2}$$

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

$$\Delta Pt = \sum_{i=1}^{nr} \frac{R_i}{V_i^2} [P_i^2(\delta_L^i, \delta_S^i, \delta_C^i) + (Q_i^2(\delta_L^i, \delta_S^i, \delta_C^i) - \delta_C^i Q_C^i)^2], \tag{3}$$

where, P_i, Q_i are active and reactive power flows in the ith branch and the summation is extended to the total number of branches in the network, nr.

It must be noted that the two objects are conflicting in terms of the main aim of the SR; it is possible that one or the other objectives is well fulfilled, but the main aim is unfulfilled. Indeed, on the basis of the consideration of each of the objectives, it can be observed that:

- the global supplied power entity increase produces power margin decrease and power losses increase;
- the reduction of the supplied load's entity provokes a power margin increase and power loss decrease;
- the capacitor banks insertion produces power loss decrease and power margin increase;
- the network's configurations with a high power loss value have a low power margin.

The above-described situation related to the particular formulation of the problem makes the use a single objective quite difficult to evaluate the quality of a single solution.

This difficulty has been overcome, but with high computational times, by the authors in Ref. [6], wherein the proposed strategy was weighting more one or the other objective (load supply, power losses), depending on the power entity available at the working HV/MV substations.

The constraints concern the regularity of the voltage profile and the current ampacity of branches. Moreover, for each substation, the power margin must be greater than zero, $Mj \geq 0$.

3. Evolutionary strategies

The evolutionary strategies (ESs) are optimisation strategies and similar to GA, they are based on the mechanics of natural genetics, which allow species growth [7].

They are founded on three basic principles:

1. recombination;
2. natural selection;
3. diversity by variation.

Unlike other natural algorithms, 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 minor relevance and may disappear.

The mutation operator is an important diversification operator allowing small perturbations on the current solution. Moreover, the ES has some other option compared to 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 or 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 scheme, with $\lambda > \mu \geq 1$, the μ parents are selected from the λ offspring only. In the second scheme, the λ offspring and their μ parents are joined, and the μ fittest individuals are selected from this set of $\lambda + \mu$ solutions.

In this application, the binary control variables are subjected to special operators so as to generate feasible solutions. In this way, each randomly created solution may be considered as a possible search path. For this reason, a set of widely different solutions is required in the starting generation.

4. Fuzzy sets in decision making [8,9]

In real situations as in the treatment of two conflicting objects in a multiobjective optimisation problem, it is often required to consider the partial fulfilment of each of the objects. In this way, the use of a membership function (MF) allows the association to each actual value y of an objective, a normalised value MF (y), expressing the degree of satisfaction of the considered objective. The truthfulness of the statement: "power margins at substations must be as low as possible", can be represented by a fuzzy set whose membership function can be represented as a bell-shaped normal distribution function, having the mean in the zero value of the abscissa and the variance depending on the actual average value of a predefined number of power margin evaluations.

In the same way, the statement "power losses must be as low as possible" can be considered.

The authors have tried different membership function shapes for the considered objectives; the bell-shaped MF produced the best results.

In what follows, each MF will be essentially characterised by two values:

- $z_{90\%}$, which is the 90th percentile (for a given set of solutions, for which both objectives have been evaluated, is the mean value of each set of values);
- the mean value, which is set to zero, for both objectives.

Once the single fuzzified values for the two objectives are obtained, there are several ways to combine them, so as to obtain a general indicator for the current solution. Among the most simple and easy ways of combining the two objectives values we have considered are their minimum (intersection) and their product. In the present application, the last one has been considered as it outperformed the first in terms of time of convergence. In Refs. [10,11], the combination of the two objects was done by means of the

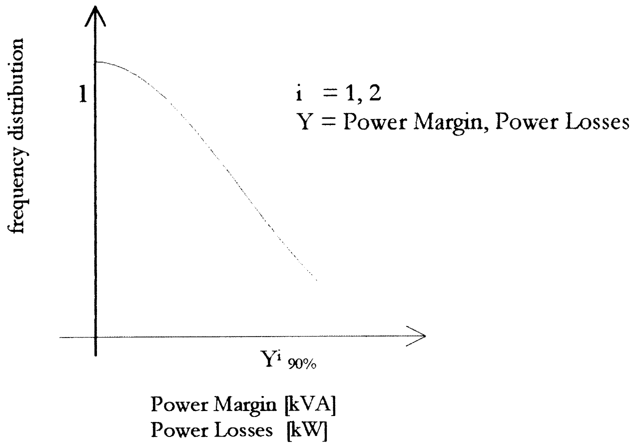

Fig. 1. The MF self-adapts to the average quality of the current generation, shifting itself along the abscissa axis. $Y_{90\%}$ indeed, corresponds to the average value of each actual objective in the current generation.

intersection operator, but any other implementation for the combination of the objects can be tried out.

5. The solution algorithm

The SR problem is an intrinsically combinatorial problem. For this reason, in the literature, the most common solution approaches are heuristic approaches and generally speaking are of 'zero degree'.

In the proposed ES solution, the reproduction cycle only includes mutation operators and does not use recombination (crossover) at all.

Each solution is coded into a binary string containing information relevant to the tie-switches, the capacitor banks and the loads' connection status. In this way, the binary string representing a single solution can be 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 note the following statements concerning the studied system:

1. radial topology is not maintained for any tie-switches layout;
2. the number of open switches must equal the number of independent loops;
3. the compensation level and the load layout do not matter.

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^{n_sez}). As a consequence, it is an advantage to consider a search space of feasible solutions meeting the topological constraint of radiality and then to apply diversification operators producing radial solutions ('branch-exchange' type [12]).

The starting population is generated through a search algorithm allowing the creation of any tree from an initial graph [13]; 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 capacitor banks set is randomly generated as there is no special constraint over it.

At each iteration and for each solution, the actual values of the two objectives are evaluated, (Eqs. (2) and (3)). Therefore, a normalised Gaussian MF, Fig. 1, is ascribed to each of the two objectives, and the correspondent numerical value is given to each objective derived from the two membership functions (f_1, f_2), [11]. In this way, with the actual value of each objective is associated a normalised value, expressing the degree of satisfaction of the statement concerning the minimisation of the considered objectives. This procedure allows the separate definition of each objective, each related to an independent scale. In the proposed application, the distributions are only characterised by the mean value, which corresponds to the desired value and the variance depending from the average value of the actual objectives over one generation. In this way, for a given configuration, defined by a binary parameters vector, δ, and characterised by the values of the single objectives, $Yi(\delta)$ ($i = 1, 2 \ldots$n_objects), and the related values of MF, $fi(Yi(\delta))$ ($i = 1, 2 \ldots$n_objects), the proposed procedure generates a unique value for the global objective function value, O, defined as it follows:

$$O(\delta) = 1 - \Pi fi(Yi(\delta)) \qquad i = 1, 2 \ldots \text{n\_objects}. \tag{4}$$

.

In this application, n_objects equals to 2.

In this way, the optimisation problem becomes the search for the vector δ, giving the minimum value of ($O(\delta)$). 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. (4), and the best μ parents are selected and then subjected to the reproduction cycle.

The principle ruling the reproduction cycle is to try to obtain solutions belonging to the 'Pareto Front' [14]. The solutions belonging to the Pareto front are solutions for which an improvement of one objective is only possible with a deterioration of the other one.

In multiobjective optimisation, the notion of optimality is not at all obvious. It may be therefore difficult to correctly define diversification operators without getting trapped in local minima. The concept of Pareto Front optimality mainly resides in respect of integrity of each of our separate criteria. On the basis of this separation between the considered objects, the implemented diversification operator tries to generate solutions that may be globally optimal, obtained by means of moves, optimising first one and then the other objective.

In this way, diversification operators are applied in a

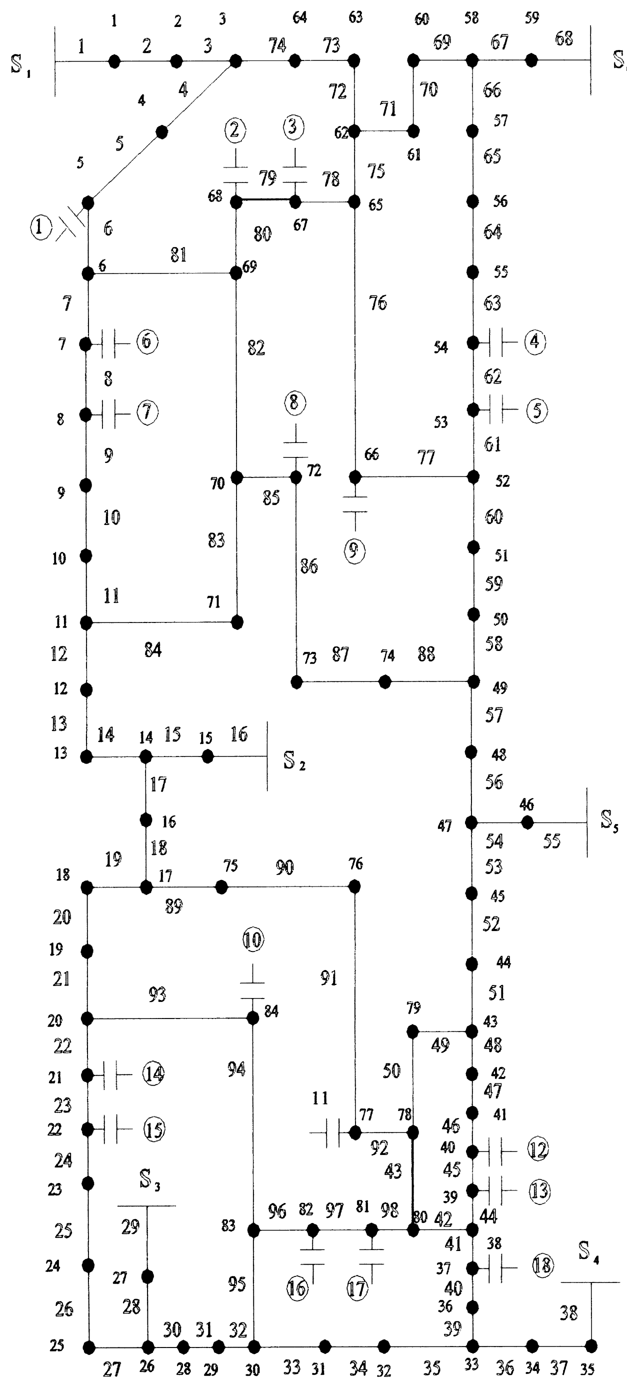

Fig. 2. Test system.

way that aims at loss reduction and then at power margin reduction through connection, if possible, of more customers.

The following operators were implemented on purpose:

1. the ‘branch-exchange’ operator, ruled by a heuristic criterion aiming at losses reduction and voltage profile flattening;
2. the ‘loads exchange’ operator, also driven by a loss reduction criterion (allowing, for example, an easier loads disconnection if they are located at terminal branches, compared to those located close to the root);
3. finally, the ‘load insertion’ operator, to cover the power availability for each area.

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

6. Application

The studied system (Fig. 2) is a meshed distribution network operating at 20 kV; the network has 98 branches, all of them provided with tie-switches, 81 load buses and 24 switchable capacitor banks; the test system is the same as used in the application developed by the authors in Ref. [6].

The distribution network is supplied by six HV/MV substations. The loads, all at the same priority level, are represented with a constant current model. A permanent fault at the transformer in the substation S_5 is considered.

The ES parameters were tuned in the following way:

- parents population: $\mu = 16$;
- offspring population: $\lambda = 22$;
- selection type: $(\lambda + \mu)$;
- maximum number of iterations = 150.

The operators allowing a driven diversification of each solution described in the last section, were applied with a frequency which is variable along the search, depending on the number of executed iterations and from the ability of the algorithm to make some other improvement on the current solution.

The final solution is reported in Table 1 and it is compared with the best solution found by the authors in Ref. [6]. It is important to note that each iteration of the procedure is faster than the corresponding one of the strategy proposed in Ref. [6]. This condition together with the reduction in the number of iterations required for the solution attainment (80 in the reported application) implies a large reduction of calculation time.

The algorithm was implemented on a personal computer provided with a Pentium 166 MHz processor, in Delphi 2.0, and it takes less than 50 s to execute 80 iterations with the above reported ES parameters.

The reported solution, has a slightly higher value of power losses, but more than 50 kVA of customers demand can be satisfied in comparison to the solution found in Ref. [6]. The proposed algorithm is robust as the starting point is randomly chosen.

In Fig. 3, the distribution of final solutions obtained, for a 50 runs sample, is reported with respect to the power losses and the power margin entity. As can be easily observed, the deviation in the values from the mean, which by itself is low (around 380 kW), is quite limited. The mean value is quite close to that obtained for the ‘best’ solution, and the

Table 1
Comparison between the optimal solution found using the strategy proposed in Ref. [6] and the one attained with the ES and FL approach herein described

	Iter	*Pt* (kW)	*Mt* (kVA)	Solution
Ref. [6]	128	342	155	Disconnected loads: 10-44-45-48-73-74-79 Open Tie-switches: 10-21-24-34-43-50-51-62-72-79-82-87-98
ES.FL	80	356	99	Disconnected loads: 19-42-44-48-73-74-79 Open Tie-switches: 10-20-32-35-43-50-56-72-76-79-82-86-97

difference is about 26 kW. The deviation of the power margin values is as well quite limited (it may not seem to be good at all, as in Fig.3, the power margin distribution of results is reported on the same graph of the power losses distribution of results); indeed most of the solution values obtained are within the range 100–300 kVA; these values represent, in per cent of the rated power at the substations (30 MVA) 0.3 and 1%, respectively. Considering (i) the supplied load entity can vary in a discrete way; (ii) it is not allowed to overload the transformers at the substations over a certain limit; and (iii) all the loads have similar entities, the course of the distribution indicates that the obtained solution differ, in terms of supplied load entity, at most for only one load.

Again in Fig. 4, a particular case in which the algorithm is able to find his own way after a bad start is shown. It is indeed clear that at the beginning it tries to disconnect loads so as to reduce power losses, and in the second phase it finds the correct way to follow and in the end, it finds a good solution even if later than usual.

A normal run of the optimisation algorithm is reported in Fig. 5.

7. Conclusions

The SR problem in automated and compensated distribution systems has been faced taking into account the presence of the capacitor banks also in the restoring phase. For this reason mainly, the objective of minimising power losses was considered together with the most important task of maximising the number of supplied loads. The MO problem has then been solved by means of an evolution strategy wherein a fuzzy coding of objectives allows their correct assessment independent of the different numerical domains of the two objectives. The ES performance was then improved by means of special operators developed on purpose. The implementation of the strategy and its extensive application on a test system put into evidence the advantages of the proposed

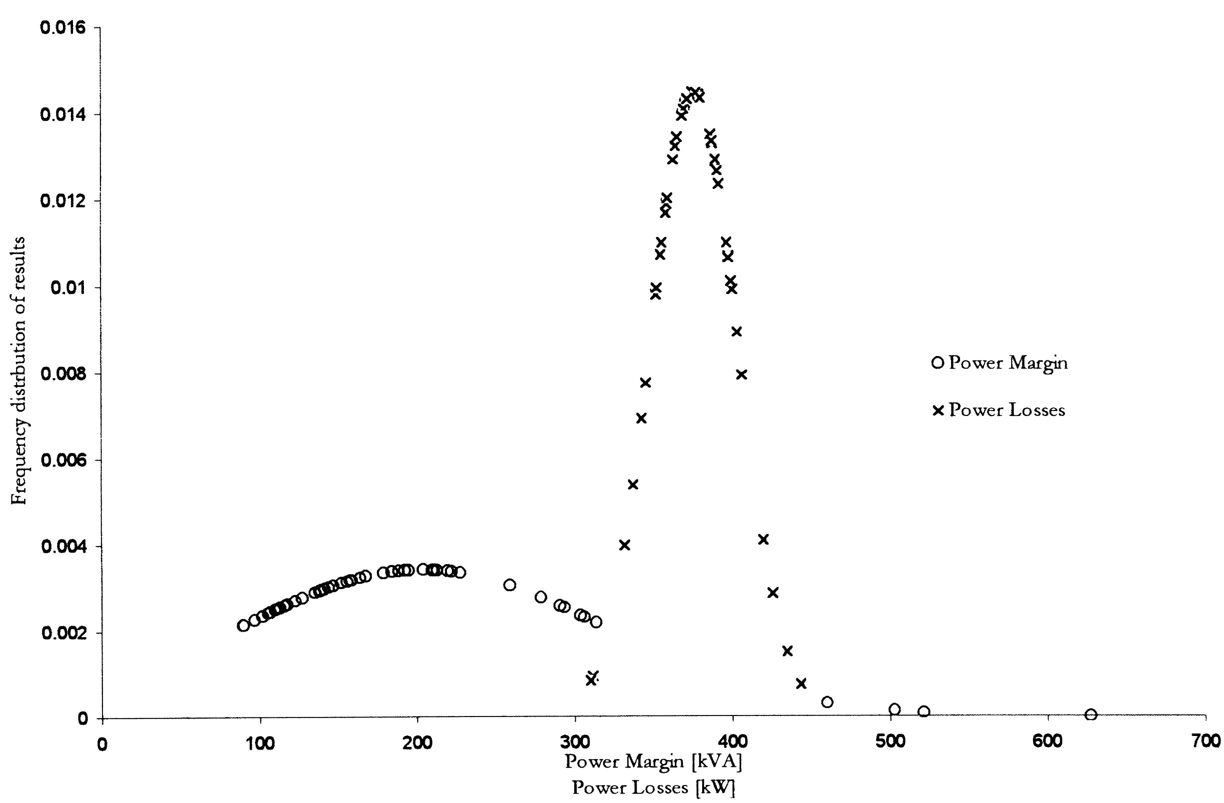

Fig. 3. On the abscissa axis the power margin (kVA) and the power losses (kW) values are reported for the best found solutions at the end of each of the 50 runs taken as a statistical sample of the efficiency of the optimisation algorithm, with sets of different starting solutions.

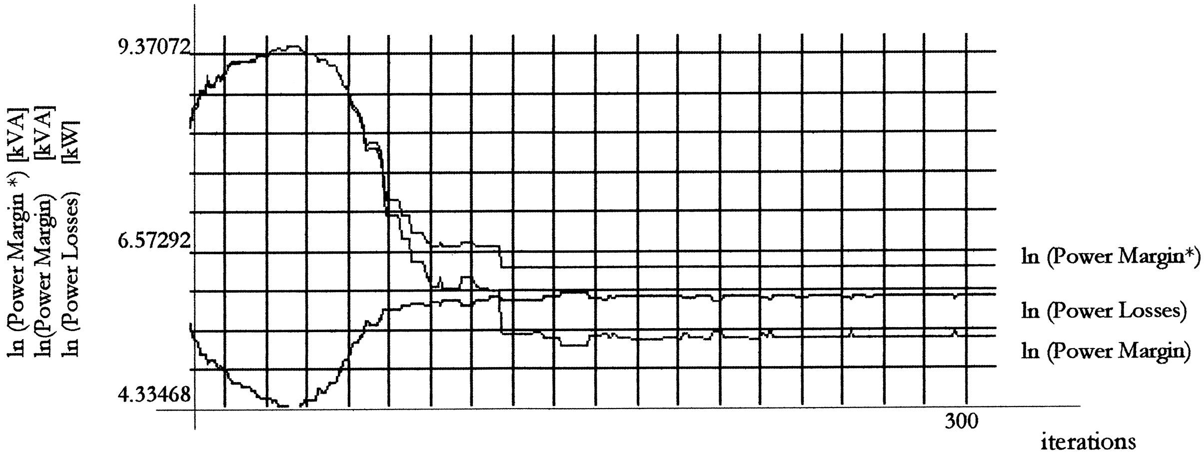

Fig. 4. Course of the power margin (kVA) and power losses (kW) values during one execution of the proposed strategy. $Mt*$ (kVA) is another type of power margin obtained as a difference between the available power at substations and the whole amount of power corresponding to the set of supplied loads (not including the real and reactive losses).

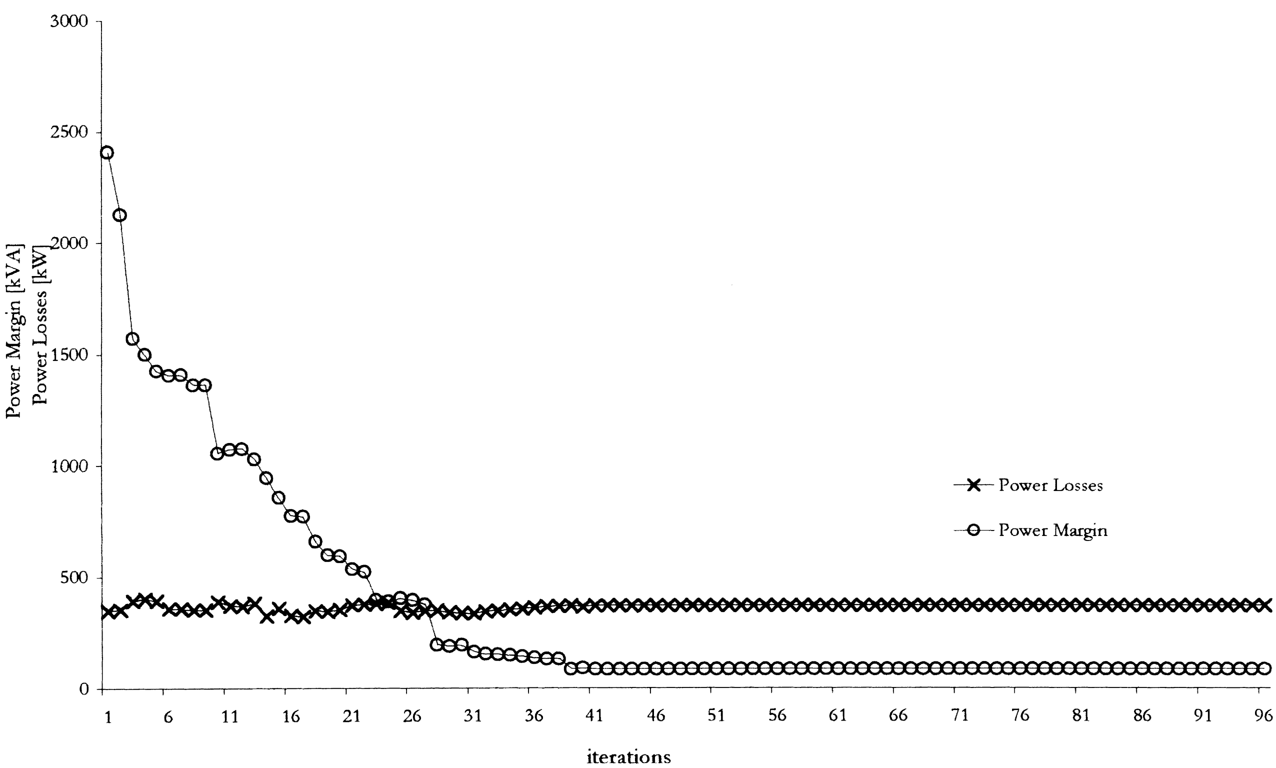

Fig. 5. Course of the power margins (kVA) and of the power losses (kW) during one run of the proposed algorithm.

strategy in this specific MO application in terms of efficiency and robustness. Finally, the algorithm offers in a short time a large number of 'good' solutions among which the operator can choose one; this could then be used as a basis for a decision support system in emergency situations.

References

[1] Curcic S, Özveren CS, Crowe L, Lo PKL. Electric power distribution network restoration: a survey of papers and a review of the restoration problem. Electric Power System Research 1996;35:73–86.

[2] Hsu YT, Huang HM. Distribution system service restoration using

artificial neural network approach and pattern recognition method. IEE Proceedings on Generation Transmission and Distribution 1995;142(3):251–6.

[3] Uçak C, Pahwa A. Optimal step-by-step restoration of distribution systems during excessive loads due to cold load pickup. Electric Power System Research 1995;32:121–8.

[4] Fukuyama Y, Chiang HD, Nan Miu K. Parallel genetic algorithm for service restoration in electric power distribution systems. International Journal of Electrical Power & Energy Systems 1996;18(2):111–9.

[5] Zhou Q, Shirmohammadi D, Liu WE. Distribution feeder reconfiguration for service restoration and load balancing. IEEE Transactions on Power Systems 1997;12(2):724–9.

[6] Augugliaro A, Dusonchet L, Riva Sanseverino E, Service restoration in compensated distribution networks using a hybrid genetic algorithm, Electric Power System Research, in preparation.

[7] Bäck T, Fogel DB, Michalewicz Z. Handbook of evolutionary computation, New York and Bristol: Oxford University Press and Institute of Physics Publishing, 1997.

[8] Zadeh LA. Fuzzy sets. Information and Control 1965;8:338–352.

[9] Frommann O. Objective Function Construction for Multipoint Optimization using Fuzzy Logic, Proceedings Eurogen 97, Trieste (Italy), 1997.

[10] Chiampi M, Fuerntratt G, Magele Ch, Ragusa C, Repetto M. Multiobjective optimization with stochastic algorithms and fuzzy definition of objective function, Proceedings of the 4th International Workshop on Optimization and Inverse problems in Electromagnetism, Brno, Czech Republic, 1996.

[11] Chiampi M, Ragusa C, Repetto M. Fuzzy multiobjective optimization in magnetics. IEEE Transaction on Magnetics 1996;32(3): 1234–7.

[12] Cinvalar S, Grainger JJ, Yin H, Lee SSH. Distribution feeder reconfiguration for loss reduction. IEEE Transaction on Power Delivery 1988;3.

[13] Walters GA, Davis KS. Evolutionary design algorithm for optimal layout of tree networks. Engineering Optimization 1995;24:261–81.

[14] Goldberg DE. Genetic algorithms in search optimization and machine learning, Reading, MA: Addison Wesley, 1989.