# Reliability and Costs Optimization for Distribution Networks Expansion Using an Evolutionary Algorithm

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***Abstract*—This paper presents a multiobjective optimization methodology, using an evolutionary algorithm, for finding out the best distribution network reliability while simultaneously minimizing the system expansion costs. A nonlinear mixed integer optimization model, achieving the optimal sizing and location of future feeders (reserve feeders and operation feeders) and substations, has been used. The proposed methodology has been tested intensively for distribution systems with dimensions that are significantly larger than the ones frequently found in the papers about this issue. Furthermore, this methodology is general since it is suitable for the multiobjective optimization of $n$ objectives simultaneously. The algorithm can determine the set of optimal nondominated solutions, allowing the planner to obtain the optimal locations and sizes of the reserve feeders that achieve the best system reliability with the lowest expansion costs. The model and the algorithm have been applied intensively to real life power systems showing its potential of applicability to large distribution networks in practice.**

***Index Terms*—Evolutionary algorithms, optimal design, power distribution systems.**

## I. INTRODUCTION

THE OPTIMAL design of an electric power distribution system has been usually approached as the minimization of a single objective (mono-objective) function which represents the economic costs of the global system expansion, considering the optimal size and/or localization of the feeders and/or substations of the distribution system in a single planning stage or in several stages (multi-stage) [1]–[8].

The multiobjective optimal design has been dealt with by few authors showing examples of application to distribution systems. In previous works [9], [10] several optimal multiobjective planning models were tested and validated intensively by computer experiments for multi-stage planning under a completely dynamic methodology [4] and a pseudodynamic one [1], [5], optimizing simultaneously various objectives (distribution system global economic costs, system reliability, voltage profile, aesthetic values associated to the distribution system, and geographic conditions of the analyzed distribution system zone). However only classic multiobjective optimization techniques were used [11], [12] to obtain a subset of satisfactory optimal nondominated solutions.

Particularly, in specialized technical papers, very few works have studied the network reliability optimization simultaneously with the minimization of the economical network expansion costs for the multiobjective optimal expansion of distribution systems. Thus, this optimal expansion has been carried out, occasionally, by a single objective (mono-objective) of a function corresponding to a linear combination of the economic costs and a reliability costs function [13], [14]. However, the economic evaluation of the reliability worth is a complex and often subjective task [15]. In this paper, the presented methodology, and the treatment of the reliability by using the concept of objective function, avoid having to evaluate such reliability economic values.

Common papers about optimal distribution design do not include practical examples of a true multiobjective optimization of real distribution networks of significant dimensions (except in [17]), achieving with detail the set of optimal multiobjective nondominated solutions [11], [12] (true simultaneous optimization of the costs and the reliability).

This paper presents a new application of a evolutionary algorithm for the multiobjective optimal design of distribution systems that allows for optimizing $n$ objectives simultaneously (based on Pareto optimality [11], [12]), as a new multiobjective planning approach. This algorithm has been used for the multiobjective optimal design of distribution systems that present significantly larger dimensions and optimization complexity than most of the networks frequently found in the specialized papers about distribution system optimal design. Also, the new algorithm uses a nonbinary alphabet, which allows for more flexibility and for easily taking into account some relevant aspects of the design such as, for example, various feeders sizes and diverse substations sizes. However the evolutionary algorithm of this paper obtains the optimal reserve feeders (feeders that are not usually operating except for failures in the distribution network in a radial operating state) that achieve the best network reliability with the lowest economical costs for single stage and multi-stage optimal designs, in this last case under the pseudodynamic methodology [1]–[5]. Furthermore, a new operator has been applied in the evolutionary algorithm, as well as the operators from a previous paper [18], what leads to achieve a curve of multiobjective nondominated solutions. Lastly, the model and the evolutionary algorithm have been applied intensively to real

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life distribution systems that shows its potential of applicability to large distribution networks in practice.

## II. Problem Formulation

A single objective (mono-objective) constrained optimization problem is the search for the optimum of a function of variables subject to several constraints [11], [12]:

$$\min z(\underline{x})$$

$$\text{subject to:} \quad g_i(\underline{x}) \leq 0 \quad i = 1, 2, \ldots, m$$
$$x_j \geq 0 \quad j = 1, 2, \ldots, p$$

where $\underline{x} = (x_1, x_2, \ldots x_p) \in R^p$, $R =$ set of real numbers.

The objective function $z(\underline{x})$ and the constraints $g_i(\underline{x})$ can be either linear or nonlinear functions of the variables $x_j$. The feasible region is:

$$\underline{X} = \{x: x \in R^p, \, g_i(x) \leq 0, x_j \geq 0 \text{ for all } i, \, j\}.$$

A multiobjective optimization problem is associated with a $n$-dimensional vector of objective functions $\underline{z}(\underline{x}) = [z_1(x), z_2(\underline{x}), \ldots z_n(\underline{x})]$ in the feasible region $\underline{X}$. Instead of seeking a single optimal solution, the subset $\underline{S}$ of "nondominated" solutions is sought [11], [12]. The main characteristic of the nondominated subset $\underline{S}$ of solutions is that for each solution outside $\underline{S}$ (but still belonging to $\underline{X}$), there is a nondominated solution for which all objective functions are unchanged or improved, and at least one which is strictly improved.

Formally, the multiobjective problem

$$\text{min-dominate } \underline{z}(\underline{x}) \text{ subject to } \underline{x} \in \underline{X}$$

has an associated set $\underline{S}$ of nondominated solutions [11], [12],

$$\underline{S} = \{\underline{x}: \underline{x} \in \underline{X}, \text{ there exists no other } \underline{x}' \in \underline{X} \text{ such that}$$
$$\underline{z}_q(\underline{x}') < \underline{z}_q(\underline{x}) \text{ for some } q \in \{1, \, 2, \ldots n\}$$
$$\text{and } z_k(\underline{x}') \leq z_k(\underline{x}) \text{ for all } k \neq q\}.$$

In this paper, the multiobjective design model is basically a nonlinear mixed-integer one for the optimal sizing and location of feeders and substations, that can be used for single stage or for multi-stage planning (under a pseudodynamic methodology [1], [5]). The vector of objective functions to be minimized is $\underline{z} = [z_1, \, z_2]$, where $z_1$ is the objective function of the global economic costs [18], and $z_2$ is a function related with the reliability of the distribution network. Then, the objective function $z_1$ is:

$$z_1 = \sum_{k\in N_S} \sum_{b\in N_b} \left[(CF_k)_b(Y_k)_b + (CV_k)_b(X_k)_b^2\right] + \sum_{(i,\,j)\in N_F} \sum_{a\in N_a} \cdot \left\{(CF_{ij})_a(Y_{ij})_a + (CV_{ij})_a \left[(X_{ij})_a^2 + (X_{ji})_a^2\right]\right\} + \sum_{(i,\,j)\in N_{FE}} (CV_{ij})_E \left[(X_{ij})_E^2 + (X_{ji})_E^2\right] + \sum_{k\in N_{SE}} (CV_k)_E (X_k)_E^2 \tag{1}$$

where

$N_{FE}$ = set of routes (between nodes) associated with existing feeders in the initial network.

$N_{FP}$ = set of proposed feeder routes (between nodes) to be built.

$N_{FR}$ = set of routes (between nodes) associated with selected routes for building feeders. The planner selects the routes of this set ($N_{FR}$) for the building of feeders. Only the feeder size is a variable.

$N_F$ = $N_{FP} \cup N_{FR}$

$N_a$ = set of proposed feeders sizes to be built.

$N_{SE}$ = set of nodes associated with existing substations in the initial network.

$N_{SP}$ = set of nodes associated with proposed locations for building substations.

$N_{SR}$ = set of nodes associated with selected locations for building substations. The designer forces to the program to select the routes of this set ($N_{FR}$) for the construction of feeders. Only the substation size is a variable.

$N_S$ = $N_{SP} \cup N_{SR}$

$N_b$ = set of proposed substation sizes to be built.

$(i, \, j)$ = route between nodes $i$ and $j$.

$(X_k)_b$ = Power flow, in kVA, supplied from node $k \in N_S$ associated with a substation size $b$.

$(X_{ij})_a$ = Power flow, in kVA, carried through route $(i, \, j) \in N_F$ associated with a feeder size $a$.

$(X_k)_E$ = Power flow, in kVA, supplied from node $k$ associated with an existing substation in the initial network.

$(X_{ij})_E$ = Power flow, in kVA, carried through route $(i, \, j)$, associated with an existing feeder in the initial network.

$(CV_{ij})_E$ = Variable cost coefficient of an existing feeder in the initial network, on route $(i, \, j)$.

$(CV_{ij})_a$ = Variable cost coefficient of a feeder to be built with size $a$, on route $(i, \, j)$.

$(CF_{ij})_a$ = Fixed cost of a feeder to be built with size $a$, on route $(i, \, j)$.

$(CV_k)_E$ = Variable cost coefficient of an existing substation in the initial network, in the node $k$.

$(CV_k)_b$ = Variable cost coefficient of a substation with size $b$, in the node $k$.

$(CF_k)_b$ = Fixed cost of a substation to be built with size $b$, in the node $k$.

$(Y_k)_b$ = 1, if substation with size $b$ associated with node $k \in (N_{SP})$ is built. Otherwise, it is equal to 0.

$(Y_{ij})_a$ = 1, if feeder with size a associated with route $(i, \, j) \in (N_{FP})$ is built. Otherwise, it is equal to 0.

An original method has been developed which allows for obtaining the function $z_2$ related to the distribution network reliability in order to carry out the optimal multiobjective design. For example, in Fig. 1, a portion of a distribution network is represented, including all the actual feeders, that is, the feeders in operation (that usually supply the power demands). It has

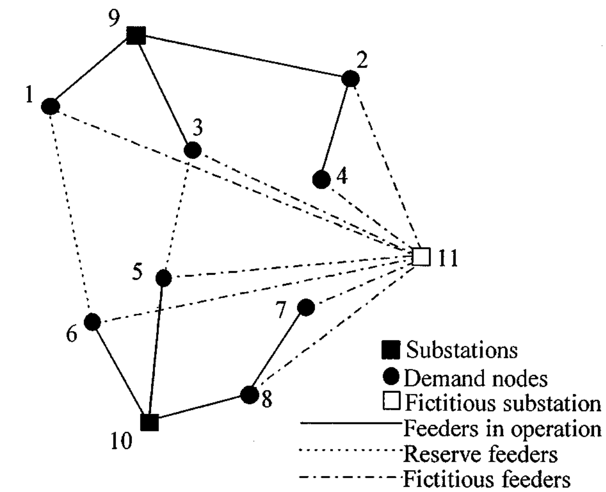


Fig. 1. Representation of fictitious feeders and the fictitious substation.

been assumed that the distribution system can be completely automated. Additional "reserve" feeders are connected to the distribution network when a feeder failure appears in the actual feeders in operation of such network. The substation that is located in the node number 11 does not really belong to the network. It is a "fictitious" substation that is connected, using the "fictitious" feeders, to the demand and transshipment nodes (network nodes) in order to calculate the $z_2$ values. Furthermore, the "fictitious" feeders are not real feeders but useful elements for evaluating the objective function $z_2$, corresponding to successive single feeder failures of the actual feeders. Thus, first order failures are approximately emulated, by applying this method, in order to carry out the multiobjective optimal design. Therefore, the electric power, that can not be supplied to the demand nodes by the actual feeders and the "reserve" ones in such failure events, is provided by the "fictitious" substation using the mentioned "fictitious" feeders. More fictitious feeders, than the "necessary" ones, exist because in this way the algorithm does not need to "examine" the distribution network for determining the minimum number of fictitious feeders in order to supply demand nodes in case of single contingency (thus, the algorithm needs lower time of CPU for calculations). The total amount of power flows carried by the "fictitious" feeders for each one of the emulated first order failures, and for all the failures, are used to obtain the $z_2$ value. This function $z_2$ is measured in kWh and, in this paper, it is named function of $EENS$ (function of "expected energy non supplied"), or $FEENS$. This described method also allows to represent several feeder failures simultaneously, without increasing the complexity of such method. The substations have not been considered in the calculation of the function $z_2$, but they can be included easily using the evolutionary algorithm described later in this paper.

The objective function $z_2$ for the optimal multiobjective design is:

$$z_2 = \sum_{(i,j)\in N_{FE}} \sum_{f\in N_f} (u_{ij})_E (X_f)_{(i,j)E} + \sum_{(i,j)\in N_F} \sum_{f\in N_f} \sum_{a\in N_a} (u_{ij})_a (X_f)_{(i,j)a} \quad (2)$$

where

- $N_f$ = set of "fictitious" routes (fictitious feeders) connecting the network nodes with the fictitious substation.
- $(X_f)_{(i,j)E}$ = power flow, in kVA, carried through the fictitious route $f \in N_f$, that is calculated for a possible failure of an existing feeder (usually in operation) on the route $(i, j) \in N_{FE}$. In this case, reserve feeders are used to supply the power demands.
- $(X_f)_{(i,j)a}$ = Power flow, in kVA, carried through the fictitious route $f \in N_f$, that is calculated for a possible failure of a future feeder (initially proposed feeder, that is built in a given solution), on the route $(i, j) \in N_F$ with a feeder size $a$, considering the reserve feeders, as above mentioned.
- $(u_{ij})_E$, $(u_{ij})_a$ are constants obtained from other suitable reliability constants in the distribution network, including several reliability related parameters such as failure rates and repair rates for distribution feeders, as well as the length of the corresponding feeders on routes $(i, j) \in N_{FE}$ or $(i, j) \in N_F$.

The simultaneous minimization of the two objective functions is subject to technical constraints [16], which are:

a) The Kirchhoff's current law constraints for all the nodes of the distribution network.
b) The capacity constraints for the feeders (and for the substations), that limit the power that can be carried by the feeders.
c) The voltage drop constraints, that limit the voltage at the distribution system nodes to the minimum allowable voltage value.

The presented multiobjective optimal design model has been applied to several real distribution networks. Also, a mono-objective model, that minimizes one single objective (costs), has been applied to such real distribution networks, also using the technical constraints mentioned previously.

## III. Optimization Technique and Multiobjective Optimization

### A. Optimization Technique (Evolutionary Algorithm)

A non binary (integer) alphabet has been used instead of the binary alphabet (frequently used in various evolutionary algorithms), which allows to implement easily the optimization model of this paper, including relevant design aspects that would have hardly been considered with a binary alphabet.

The possible solutions (individuals) obtained by the evolutionary algorithm of this paper are coded as follows: For example, a possible solution of the optimal distribution network design can be represented by a set of two strings,

$$030\,102\,111 \qquad 12,$$

where the first string represents the distribution feeders routes and the second represents the substations locations. The first string of the example of a given distribution design solution,

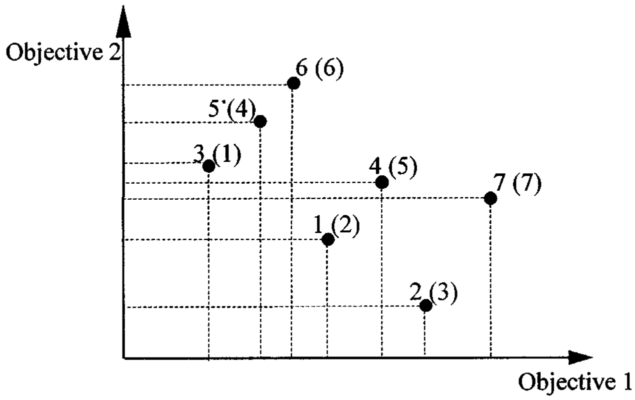


Fig. 2. Representation of solutions of a multiobjective optimization.

contains zero positions of the string indicating that the corresponding distribution routes are not used for feeders building, and its remaining positions give the used routes and the sizes of the feeders in the distribution network solution (sizes 1, 2, 3). The second string represents the substations locations where its positions give the used locations and the size of the built substations (size 1, 2). In a more general case, this string could also contain positions with values 0, representing locations not used for substations building. Furthermore, reserve feeders are represented by positions of the first string, with integer numbers greater than 100. For example, a string position with the number 103 indicates that the corresponding network route contains a reserve feeder that has been built with the feeder size number 3. The number of integer variables (that is, the number of positions of the feeders string and the number of positions of the substations string that can change during the optimization) can be calculated with the expression: $N_{FP} \cup N_{FR} \cup N_{SP} \cup N_{SR}$ where $N_{FP}$, $N_{FR}$, $N_{SP}$ *and* $N_{SR}$ have been defined in Section II.

The evolutionary algorithm works with a population of individuals (solutions), that can evolve by means of the application of several procedures of selection, reproduction, crossover and mutation [19]. Each possible solution can be evaluated (using the objective function), and a certain aptitude value is assigned to it. Thus, a higher aptitude value is associated to the solutions with a better value of the objective function (evaluation function). The aptitude determines a higher or lower probability for a given solution of surviving during the optimization. After using the habitual operators, some of the solutions will disappear and other new ones will appear, this leads to a new population and finishes a generation (iteration) of the evolutionary algorithm.

All the new operators, criteria and methods from a previous paper [18] have been used in the new algorithm of this paper for the multiobjective optimal design of distribution networks, as well as a special simplex algorithm [20], much faster than the classic one.

## B. Multiobjective Optimization

The model of this paper, can be used for the multiobjective optimal design of distribution systems considering n objectives, although it has been applied for two objective functions (economic costs and reliability). For each design solution of the distribution system, the values of the two objective functions are represented as shown in the Fig. 2, where the planner wants to minimize them simultaneously. The solutions 1, 2 and 3 are nondominated solutions [11], [12], and they are the best ones from the multiobjective optimization. If a given solution is "dominated" at least by some other, then it is named dominated solution. In this paper, the dominated solutions are classified as follows: if a solution is only dominated by another, then it is classified as solution of degree 1 (solutions 4 and 5 in Fig. 2); if it is dominated by two other solutions, then it is named solution of degree 2 (solutions 6 and 7 in Fig. 2); and so on. For example, solution number 5 is dominated solution of degree 1 because only the solution 3 has better values for the two objective functions. The nondominated solutions have the best aptitude values, the solutions of degree 2 the worst ones, and the solutions of higher degree are not considered in the optimization. A range (numbers in brackets in Fig. 2) has been assigned to the solutions of the Fig. 2. The nondominated solutions (solutions 1, 2 and 3) have been ordered from the best value to the worst value (from range 1 to range 3 respectively) only considering one of the two objective functions (for example, the objective function 1, assuming that the decision maker considers it as the most important one). The dominated solutions of degree 1 (solutions 4 and 5) and the dominated solutions of degree 2 (solutions 6 and 7) are successively ordered with the same approach as the above mentioned (that is also applied for dominated solutions of higher degree). Afterwards, the aptitude [19] of a solution "$i$" is obtained as:

$$\frac{\text{(Range of the worst solution} - \text{range of solution } i)}{\sum_j \text{(Range of the worst solution} - \text{range of solution } j)} \tag{3}$$

$$\sum_j (\text{Aptitude of solution } j) = 1. \tag{4}$$

For example, for the solution 5 of the Fig. 2:

$$\text{Aptitude of solution } 5 = (7-5)/21 = 0.095.$$

The complete multiobjective optimal design is composed of several multiobjective optimization processes, carried out successively. They stop automatically when the number of nondominated solutions becomes equal to, or greater than, the number of individuals of the population minus ten. When a process finishes, the evolutionary algorithm saves a sample of nondominated solutions (thirty solutions distributed in an uniform way along its nondominated solutions curve), and the following process starts from these nondominated solutions. During the evolution of the various multiobjective processes, the resulting curve of nondominated solutions moves, improving the two objective functions values of such solutions. The movement of the curve has been observed experimentally by measuring the displacement of a point named "center of ideals." This point is located in the middle of the linear segment between the end nondominated solutions of the curve, named "ideal solutions" (ideal solution of costs and ideal solution of reliability). When the displacement of the "center of ideals" is lower than a given small value during several successive multiobjective optimization processes, then it has been noticed that the curve of nondominated solutions practically stops and, therefore, the complete multiobjective optimal design finishes.

TABLE I
DISTRIBUTION SYSTEMS CHARACTERISTICS

| CASE | 1 | 2 | 3 |
|---|---|---|---|
| Existing nodes | 114 | 45 | 88 |
| Total number of nodes | 201 | 182 | 417 |
| Existing routes | 113 | 44 | 86 |
| Proposed routes | 113 | 163 | 387 |
| Number of variables 0-1* | 339 | 328 | 776 |

*The variables 0-1 refer to equation (1) of the mixed-integer model of section 1.

A new operator, named "filter" operator, allows for determining a maximum allowed limit of the global economic costs of the distribution system solutions. Thus, the planner establishes a percentage value ("filter" operator value) representing an increment percentage, that has to be applied to the objective function ($z_1$) cost value of the ideal solution of cost, in order to determine the mentioned economic limit. Therefore, the filter operator leads to drop expensive solutions with global economic costs larger than that limit. In this way, distribution network solutions with too many reserve feeders, and therefore unsatisfactory solutions for the planner, are discarded.

## IV. COMPUTATIONAL RESULTS

The new evolutionary algorithm has been applied intensively to the multiobjective optimal design of several real size distribution systems. A compatible PC has been used (CPU Pentium of 150 MHz and 16 Mb of RAM) with the operating system Linux 3.0 and the compiler gcc.

Table I shows relevant characteristics of three real distribution systems used for testing the evolutionary algorithm.

Most of the distribution networks data has been provided by a Spanish electric utility. Notice the high number of variables 0–1 of the three distribution networks indicating that the complexity of the optimization and the dimensions of these networks are significantly larger than most of the ones usually described in technical papers.

In this paper only the main data and results of the case 2 will be presented due to the lack of space. Fig. 3 shows the existing 10 kV feeders network (darker segments), for the case 2, and the proposed routes (remaining segments) for future underground feeder building with two proposed feeder sizes, 3×1×400Al and 3×150Al, which are also the feeder sizes of the existing feeders. The existing distribution substation size is 40 MVA, and a future substation is proposed to be built at node 182 with two proposed sizes of 8 MVA and 40 MVA. Table II gives the power demands of the distribution network nodes, that have been included correlatively from the node number 1 until the node number 180.

Table III gives relevant results from the eight multiobjective optimization processes of the complete multiobjective optimal design that have lead to the final nondominated solutions curve. This Table III provides, for each process (defined in Section III), the objective function values ("cost" in millions of pesetas, and "$FEENS$" in kWh) of the ideal solutions, the number of generations (Gen.) and the objective function values of the best topologically meshed network solution for the distribution system

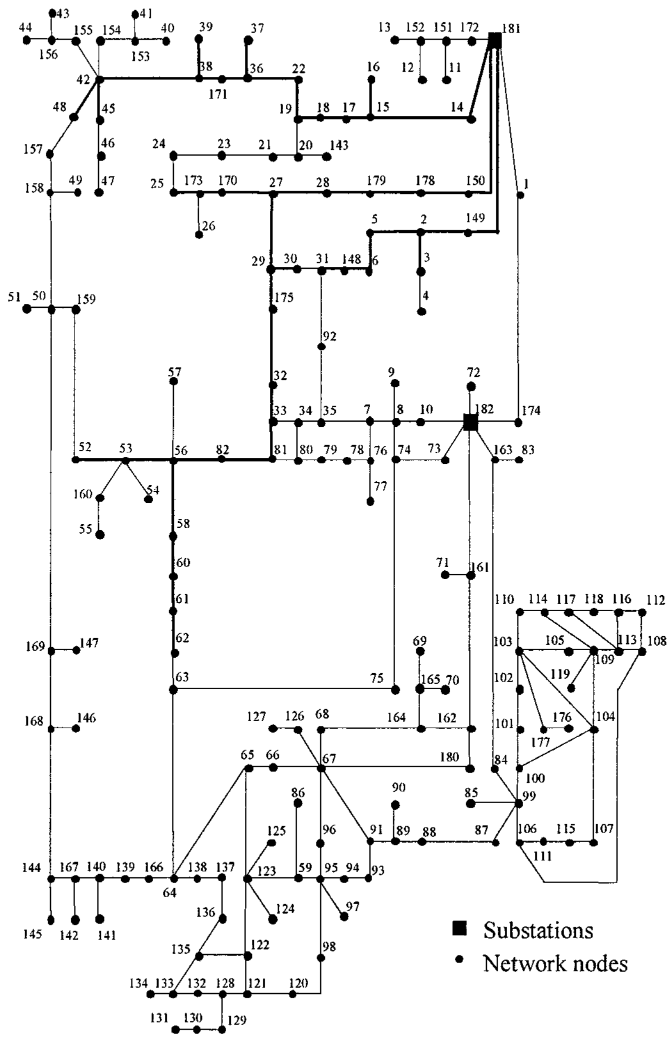


Fig. 3. Existing and future proposed distribution network for the case 2.

TABLE II
POWER DEMAND REQUIREMENTS, IN kVA, FOR THE DISTRIBUTION NETWORK NODES

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 224(1) | 35 | 448 | 140 | 7 | 112 | 15 | 140 | 197 | 0 | 0 |
| 224(2) | 176 | 224 | 6 | 34 | 125 | 4 | 119 | 168 | 0 | 0 |
| 81(3) | 140 | 140 | 29 | 67 | 140 | 0 | 224 | 10 | 0 | 0 |
| 90 | 224 | 0 | 20 | 62 | 0 | 73 | 140 | 32 | 0 | 0 |
| 128 | 45 | 32 | 140 | 140 | 38 | 0 | 27 | 15 | 0 | 0 |
| 131 | 90 | 10 | 90 | 131 | 92 | 67 | 112 | 25 | 0 | 95 |
| 353 | 140 | 5 | 0 | 140 | 66 | 105 | 90 | 50 | 0 | 95 |
| 179 | 224 | 0 | 140 | 224 | 140 | 0 | 172 | 0 | 0 | 0(178) |
| 140 | 20 | 20 | 46 | 11 | 161 | 21 | 25 | 40 | 0 | 0(179) |
| 66 | 224 | 50 | 0 | 140 | 224 | 74 | 34 | 5 | 0 | 0(180) |
| 27 | 118 | 36 | 31 | 224 | 56 | 20 | 140 | 10 | 0 | |
| 27 | 194 | 68 | 33 | 353 | 46 | 37 | 14 | 89 | 0 | |
| 5 | 193 | 90 | 90 | 91 | 224 | 23 | 62 | 0 | 0 | |
| 140 | 126 | 140 | 224 | 140 | 85 | 37 | 133 | 0 | 0 | |
| 62 | 224 | 25 | 353 | 24 | 179 | 47 | 140 | 0 | 0 | |
| 69 | 0 | 15 | 196 | 14 | 530 | 58 | 448 | 0 | 0 | |
| 0 | 224 | 20 | 140 | 79 | 75 | 48 | 90 | 0 | 0 | |

From node (1) until node (180)

from the point of view of the reliability and in a radial operating state (radial operation—best reliability). The complete multiobjective optimal design finishes when the stop criterion

TABLE III
RELEVANT RESULTS OF THE PROCESSES OF THE COMPLETE MULTIOBJECTIVE OPTIMAL DESIGN

| Process | Ideal solution of cost | | Ideal solution of reliability | | Radial operation-best reliability | | |
|---|---|---|---|---|---|---|---|
| | Cost | *FEENS* | Cost | *FEENS* | Gen. | Cost | *FEENS* |
| 1 | 1061 | 8543 | 1140 | 305 | 150 | 1113 | 372 |
| 2 | 1059 | 8611 | 1166 | 263 | 18 | 1110 | 371 |
| 3 | 1059 | 8663 | 1168 | 248 | 76 | 1133 | 288 |
| 4 | 1059 | 8669 | 1175 | 233 | 18 | 1112 | 334 |
| 5 | 1058 | 8656 | 1173 | 206 | 48 | 1123 | 297 |
| 6 | 1058 | 8656 | 1173 | 206 | 41 | 1113 | 328 |
| 7 | 1058 | 8656 | 1167 | 200 | 41 | 1108 | 333 |
| 8 | 1056 | 9020 | 1157 | 208 | 60 | 1144 | 220 |

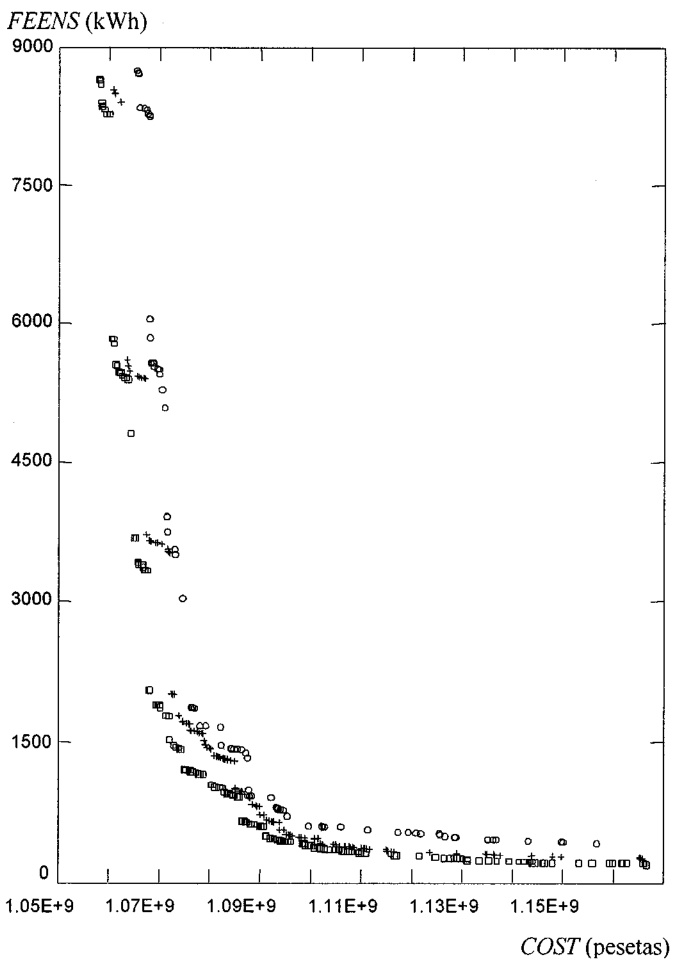


Fig. 4. Evolution of the curve of nondominated solutions.

(mentioned in the Section III of this paper) is met, showing that the movement of the curve of nondominated solutions practically stops. The used crossover rate is 0.3 and the mutation rate 0.02 in all the executed processes. The population is 150 individuals in the first four processes, and it is 200 in the lasts four. The operator filter is 15% for the first 7 processes, and 10% for the last one.

Fig. 4 shows partially the evolution of the curve of nondominated solutions during the complete multiobjective design. The horizontal axis represents the cost objective function values in pesetas and the vertical axis the $FEENS$ values in kWh. Fig. 4 contains the nondominated solutions after 100 generations (represented by the symbol ◯), the solutions at the end of the second process (symbol $+$), and the ones when concluding the complete design (symbol □) that constitute a curve of nondominated solutions. The algorithm does not obtain the complete set of nondominated solutions, since an evolutionary algorithm does not guarantee the optimal set from a strict mathematical point of view. However, according to our intensive computing testing of our algorithm, the achieved computer results indicate that the algorithm obtains a good practical curve of nondominated solutions very close to the optimal one.

Then, after analyzing the curve of the final nondominated solutions, the planner can select the definitive nondominated solution, taking into account simultaneously the most satisfactory values of the two objective functions. We believe that the set of nondominated solutions is the best set that can be offered to the planner in order to select the best satisfactory solution from such set. Furthermore, he/she might decide to use a reliability cost value and, thus, select the nondominated solution that is the "closest" one to such reliability cost condition.

As above mentioned, Fig. 3 shows the existing and future proposed distribution network for the case 2. Fig. 5 shows the final selected multiobjective nondominated solution in this paper, corresponding to the nondominated one that represents the topologically meshed distribution system in radial operating state with the best reliability achieved by the complete multiobjective optimal design. Its reserve feeders are represented by dashed segments.

On the other hand, the best mono-objective solution corresponding to the optimal global economic expansion of the distribution system has been obtained from the mono-objective optimal design model mentioned in Section II of this paper. Therefore, the topological differences between the mono-objective solution and the selected multiobjective solution can be observed. Thus, there are 61 differences, in terms of feeders sizes, between the two solutions. Therefore, notice that the simultaneous optimization of the economic cost function and the function of reliability of the power distribution system has a very significant influence in the result of the optimization, when compared with respect to the classical single optimization of the economic costs.

Similar computer results have been achieved from the multiobjective optimal design and the mono-objective one for the case 1 and case 3, when analyzing the topological differences between the obtained distribution system solutions.

Table IV gives the feeder fixed costs (F.Costs), the variable costs (V.Costs) and the objective function values of the global economic costs (O.F.Costs), in millions of pesetas, as well as the $FEENS$ values in kWh, for the three cases, corresponding to the solutions from the multiobjective optimal design model (Multiob) and from the mono-objective one (Single Objec). Table V gives the percentage of variation (%VAR) for each one of the economic costs and for the $FEENS$, where

$$\%\mathrm{VAR} = \frac{\text{Multiob value} - \text{Single Objec value}}{\text{Single Objec value}} \times 100$$

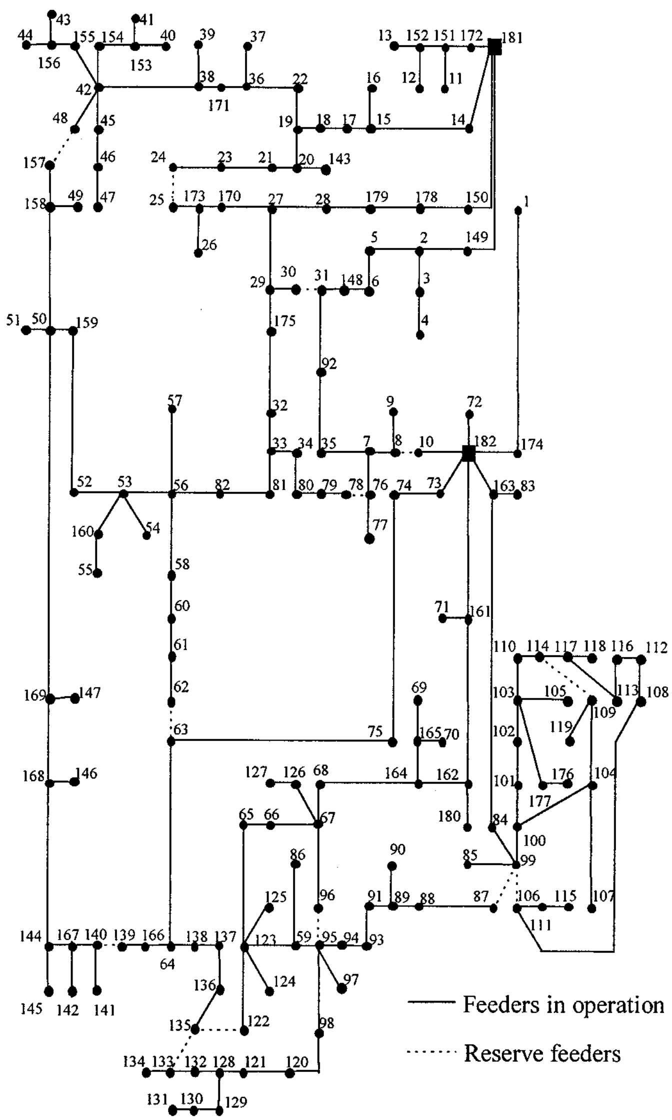


Fig. 5. Solution from the multiobjective optimal design model.

TABLE IV
COMPUTER RESULTS FROM THE OPTIMAL DISTRIBUTION SYSTEMS DESIGN MODELS

| CASES | 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|
| | Single Objec. | Multiob | Single Objec. | Multiob | Single Objec. | Multiob |
| F. Costs | 321 | 364 | 417 | 516 | 1108 | 1205 |
| V. Costs | 61.0 | 60.8 | 21.5 | 24.7 | 59.9 | 59.4 |
| O.F Costs | 1215 | 1258 | 1043 | 1144 | 2408 | 2504 |
| *FEENS* | 16760 | 1935 | 9803 | 220 | 22429 | 5073 |

Thus, for all the optimal design cases carried out, the feeder investment (built feeders in operation and built reserve feeders) is larger in the multiobjective design solution than in the single objective one, what leads to an important decrease of the values of the function of $EENS$ ($FEENS$), that is, it achieves a very significant improvement in the reliability of the optimally designed distribution networks. The objective function value of the global economic costs, for the solution from the single objective design model, is logically lower than the one from the multiobjective model, what can be explained considering that the selected multiobjective solution contains reserve feeders investments and large investments for built feeders in operation. Then, the distribution system solutions from both optimal design (multiobjective and single objective) present different distribution network topological structures, which illustrates the significant influence that the simultaneous optimization of several objectives can have in the distribution system design solutions.

TABLE V
PERCENTAGE OF VARIATION OF ECONOMIC COSTS AND OF $FEENS$

| CASES | 1 | 2 | 3 |
|---|---|---|---|
| F. Costs | 13.4% | 23.6% | 8.7% |
| V. Costs | -0.3% | 14.9% | -0.9% |
| O.F. Costs | 3.53% | 9.7% | 4.0% |
| *FEENS* | -88.4% | -97.7% | -77.4% |

The comparison of the multiobjective algorithm of this paper (evolutionary algorithm) with other existing ones (for distribution systems of significant dimensions) has not been possible since such existing algorithms are not able to consider the characteristics of our mathematical model used in this paper. In terms of computational savings, the superiority of a preliminary version of our algorithm (using a previous simple mono-objective planning model) can be found in some previous works in [16]. This superiority was more evident when the number of binary variables of the model increased.

## V. CONCLUSION

The conclusions are presented in four sections: a) Model for the multiobjective optimal design of power distribution systems. b) New developed evolutionary algorithm for the optimal design. c) Computer results. d) Future works.

a) An optimization model of nonlinear mixed-integer programming has been presented for the multiobjective optimal design of distribution networks, achieving the optimal expansion of an existing distribution system, to meet its forecasted future power demands, determining the optimal sizing and location of future feeders (reserve feeders and operation feeders) and substations, and the optimal feeder reinforcements and/or substitution of the existing feeders as well as the optimal size increase of the existing substations. This model can be used to optimize simultaneously $n$ objectives and it has been applied for the simultaneous minimization of an objective function of the true nonlinear economic costs and an objective function representing the distribution network reliability suitable for optimal design, subject to mathematical constraints that reflect the technical aspects of the design. The multiobjective optimal design model has been applied for single stage and multi-stage optimal expansion of distribution systems under the pseudodynamic methodology [1], [5].

b) A new evolutionary algorithm has been developed to implement the mentioned model, using an integer alphabet that allows us to consider relevant aspects of the optimal design easily, such as several sizes for the feeders and substations, and reserve feeders to improve optimally the distribution network reliability. A new operator, named "filter" operator, has been applied in the evolutionary algorithm, in order that the planner limits the investments in reserve feeders. This operator also contributes to improve progressively the two objective functions values of the solutions that constitute the curve of nondominated solutions during the execution of complete multiobjective design. Furthermore, the evolutionary algorithm has incorporated a new criterion for assigning aptitudes values to each one of the solutions, with large aptitude values for the nondominated solutions. Suitable safeguard criteria for the best solutions and appropriate stop criteria have also been used during the execution of the successive multiobjective optimization processes and for the multiobjective optimization design.

c) The nonlinear mixed-integer programming model and the evolutionary algorithm have been intensively tested, by computer, for the multiobjective optimal design of real distribution systems that present significantly larger dimensions and optimization complexity than the ones frequently shown for optimal design in technical papers. Also, from a practical point of view, the described new evolutionary algorithm, the model and the computer results show the importance of achieving the set of nondominated solutions, as well as its potential of applicability, in practice, for planning studies of large distribution networks. Furthermore, the planner can obtain the optimal locations and sizes of the reserve feeders that achieve the best system reliability with the lowest expansion costs.

d) At this time, we are working to include new characteristics in the algorithm, corresponding to new models for optimal operation planning (protection device locations and switching), and for optimal planning (variable future growth scenarios, risk analysis and fuzzy reliability modeling).

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