MULTIOBJECTIVE PLANNING OF POWER DISTRIBUTION SYSTEMS USING EVOLUTIONARY ALGORITHMS

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Abstract: This paper presents the applications of two Evolutionary Algorithms to solve the multiobjective design of distribution systems.

The first algorithm is based on Pareto optimality, working with a set of solutions, that can evolve by means the application of operators (selection, reproduction, crossover and mutation), obtaining the curve of nondominated solutions. Also, a new operator, named "filter", allows for the planner to discard distribution network solutions with too many reserve feeders, and therefore expensive solutions.

The second Evolutionary Algorithm is based in the Evolutionary Programming, whose basic Evolutionary engine relies on mutation rather than crossover, in solving the problem of determining the multiobjective solution, concerning economic cost and reliability. The method is easily applied in a parallel Algorithm (using various computers).

Keywords: Power distribution systems, multicriteria optimization, Evolutionary Algorithms.

1. INTRODUCTION

The optimal planning of an electric power distribution system has been frequently described by the minimization of a single objective function representing the system planning economic costs, for a single or multiple stages, including the optimal size and/or location of the feeders and/or substations of the power system [1-6].

On the other hand, Evolutionary Algorithms [8-10] have been applied to industrial optimization problems in recent years, achieving good results and showing also excellent optimization characteristics in operation and control of distribution systems.

This paper presents two Evolutionary Algorithms for the multiobjective optimal planning of distribution systems that allows for optimizing *n* objectives simultaneously, under a multiobjective planning approach. Particularly, it has been applied to the optimization of two objectives: an objective function of the distribution system economic costs, including the fixed costs and the true nonlinear variable costs, and other objective function related to the distribution network reliability.

2. PROBLEM FORMULATION

In a single objective constrained optimization problem, a function $f(\underline{v})$ of variables subject to several constraints is optimized. It can be stated as:

$$\min f(\underline{v})$$

$$\text{subject to: } r_j(\underline{v}) \le 0 \qquad j = 1, 2, ..., s$$

$$v_i \ge 0 \qquad i = 1, 2, ..., q$$

where $\underline{v} = (v_1, v_2, ... v_q) \in R^q$, R = set of real numbers.

The objective function $f(\underline{v})$ and the constraints $r_j(\underline{v})$ can be either linear or nonlinear functions of the variables v_i.

The feasible region is:

$$\underline{F} = \{ \underline{v} : \underline{v} \in R^q, r_j(\underline{v}) \le 0, v_i \ge 0 \text{ for all } j,i \}.$$

A multiobjective optimization problem is associated with a *n*-dimensional vector of objective functions $f(\underline{v})$= $[f_1(\underline{v}), f_2(\underline{v}), ...f_n(\underline{v})]$ in the feasible region $\underline{F}$.

The multiobjective problem achieves the set $\underline{N}$ of nondominated solutions,

$$\underline{N} = \{ \underline{v} : \underline{v} \in \underline{F}, \text{there exists no other } \underline{v}' \in \underline{F} \text{ such that } f_\alpha(\underline{v}') < f_\alpha(\underline{v}) \text{ for some } \alpha \in \{1, 2, ...q\} \text{ and } f_\beta(\underline{v}') \le f_\beta(\underline{v}) \text{ for all } \beta \ne q \}.$$

The multiobjective planning model of this paper is a nonlinear mixed-integer one for the optimal sizing and location of feeders and substations. The vector of objective functions to be minimized is $f = [f_1, f_2]$, being f_1 the global economic costs, and f_2 a function of the reliability of the distribution network.

3. PROPOSED EVOLUTIONARY ALGORITHMS

Two Evolutionary Algorithms are going to be described in the following paragraphs.

a) Evolutionary Algorithm based on Pareto optimality (EA-1). 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 [11]. 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 what leads to a new population and finishes a generation (iteration) of the Evolutionary Algorithm.

The complete multiobjective optimal planning 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, a sample of nondominated solutions (thirty solutions distributed in a uniform way along its nondominated solutions curve) is saved by the Evolutionary Algorithm, 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.

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 have to be applied to the objective function (f_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.

b) Evolutionary Algorithm EA-2. Evolutionary Programming is a variety of the Evolutionary Algorithms, whose basic Evolutionary engine relies on mutation rather than crossover, in solving the problem of determining the optimal topology of a radial electrical network, concerning investment and losses. It emphasizes the implicit parallelism of the method and its ease of codification and implementation. The problem of finding the optimal electrical network falls in the class of combinatorial problems, problems in which the use of meta-heuristics, namely Evolutionary Algorithms, has been popular. The fitness function was defined as being the sum of three parts: the cost of the lines, the cost of the losses, and a term associated to line overloads, included as a penalty that affects the sum of the square of the overload in each line of the network. The initial population was built with replicas of the established initial random radial network configuration. The mutation operator is applied to every single element of the population of solutions in each generation. Each element of that population being a network topology, mutation was applied in the following manner: 1. A random line is selected and removed from the network. 2. The isolated nodes are determined using a tree search Algorithm. 3. Based on the principle that the network remains radial if one of the isolated nodes is connected to a node connected to the source, the available lines that are not used and satisfy that condition are sorted out. One of these lines is randomly chosen, and added to the topology.

Each of the individuals of the populations was evaluated in the following manner: Given the network topology, each of the lines was considered to be built using the lower thermal limit cable. A DC load flow is run, and the flows are checked against the rated line limits. If the line is in overload, it is replaced with the one with more capacity. If it still is in overload, a cost (penalty) is given to the overload, and the line is marked as overloaded.

At the end of the evaluation, if the fitness of the new individual is worse (larger) than the fitness of the original individual (before mutation), this individual is accepted as the new one with a probability of 5%. This is to allow the Algorithm to pass through non-feasible parts of the solution universe. This technique has shown to lead to better results, even if it takes longer to converge than elitism. In this case, the original individual is replaced by the new one.

After the optimization, the planner can select a satisfactory solution, from the point of view of the economical costs and the reliability.

4. COMPUTATIONAL RESULTS

The two Evolutionary Algorithms (EA-1 and EA-2) have been applied to the multiobjective optimal planning of an illustrative example of a distribution system. Figure 1 shows the proposed routes for future underground feeder building with two proposed feeder sizes, 3x1x400Al and 3x150Al. The existing distribution substations sizes are 15 MVA (nodes A and B). Table 1 gives the power demands of the distribution network nodes.

TABLE 1
POWER DEMAND REQUIREMENTS, IN kVA

Node	Demand	Node	Demand	Node	Demand
1	760.7	16	1260.6	31	760.3
2	1262.9	17	770.2	32	907.9
3	760.1	18	591.8	33	1034.5
4	760.1	19	751.5	34	806.5
5	988.8	20	776.1	35	632.7
6	737.0	21	999.3	36	806.5
7	580.3	22	731.4	37	731.4
8	768.0	23	1257.4	38	965.4
9	772.6	24	958.4	39	783.7
10	994.7	25	857.7	40	1054.1
11	1000.0	26	731.4	41	608.9
12	611.7	27	731.4	A	0
13	925.9	28	1034.5	B	0
14	991.6	29	632.7		
15	1260.6	30	760.3		

a) Results obtained from the Algorithm EA-1.

Table 2 gives relevant results from the eight multiobjective optimization processes of the complete multiobjective optimal planning that have lead to the final nondominated solutions curve. This Table 2 provides, for each process (Proc.), the objective function values (“cost” in millions of pesetas, and a function of the network reliability, “FEENS” in kWh that gives a measure of the expected energy not supplied) 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 from point of view of the reliability and in a radial operating state (radial operation – best reliability). Figure 2 shows the selected solution. The complete multiobjective optimal planning finishes when a suitable criterium is meet, showing that the movement of the curve of nondominated solutions practically stops. The used crossover rate is 0.3, the mutation rate 0.05 and the population is 500 individuals in all the executed processes. The operator filter is 20% for the first 6 processes, and 10% for the last four.

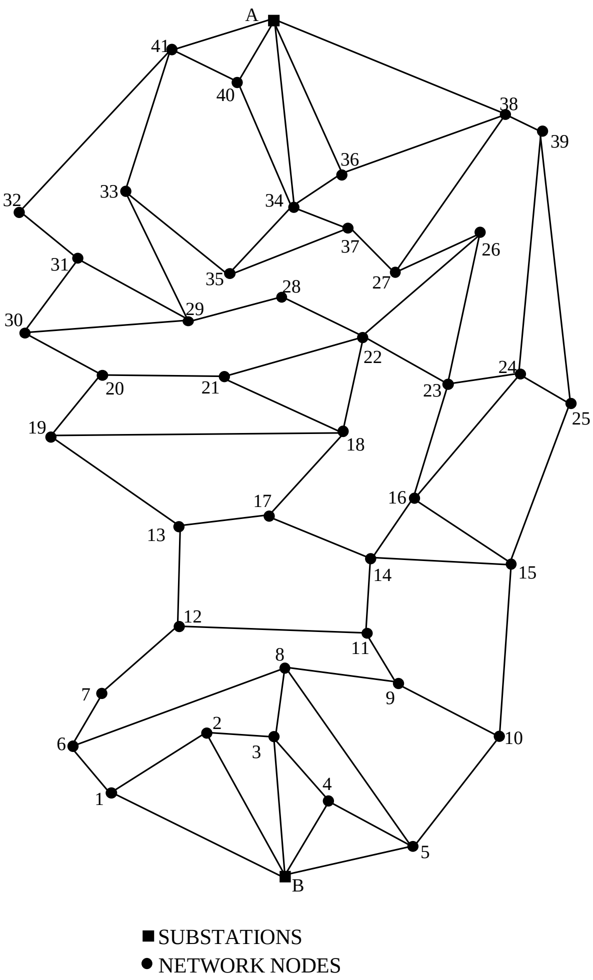

Fig. 1. Proposed distribution network.

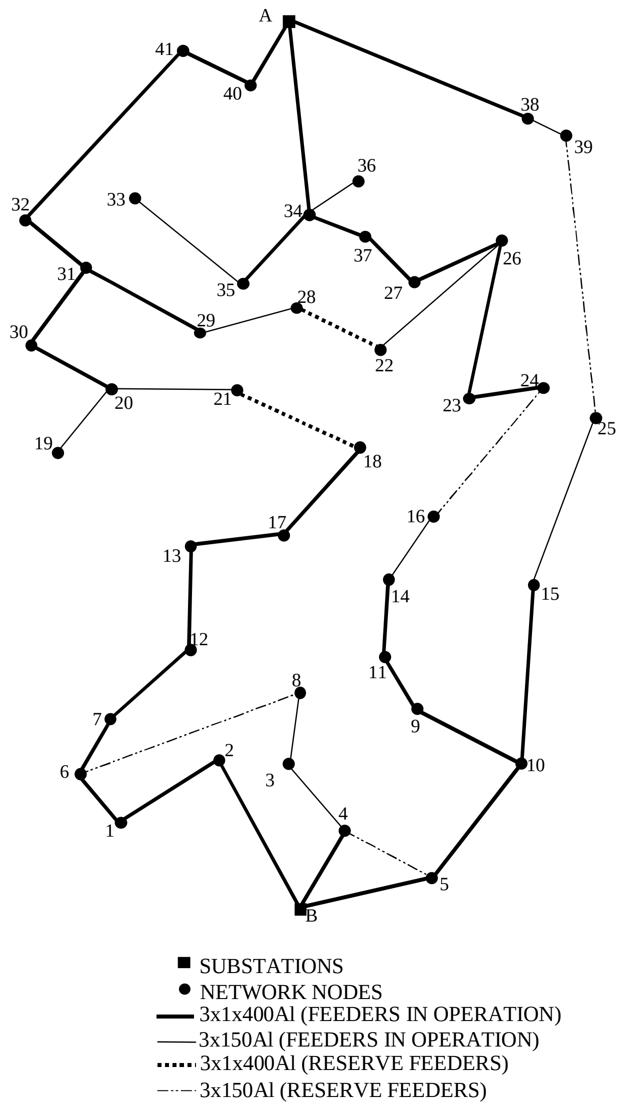

Fig. 2. Solution from EA-1.

TABLE 2
RELEVANT RESULTS OF THE PROCESSES OF THE COMPLETE MULTIOBJECTIVE OPTIMAL PLANNING WITH EA-1

	Ideal solution of cost		Ideal solution of reliability		Radial operation-best reliability		
Proc.	Cost	*FEENS*	Cost	*FEENS*	Gen.	Cost	*FEENS*
1	144.7	4114	170.2	0	973	170.2	0
2	144.6	4426	169.5	0	449	169.5	0
3	144.6	4467	168.8	0	249	173.2	0
4	144.6	4530	168.7	0	417	173.7	0
5	144.6	4530	167.3	0	256	173.5	0
6	144.6	4530	167.3	0	196	159.3	0
7	144.6	4426	159.0	250	628	159.0	250
8	144.6	4467	159.0	250	293	159.0	250
9	144.6	4530	159.0	250	506	159.0	250
10	144.6	4530	159.0	250	325	159.0	250

b) Results obtained from the Algorithm EA-2.

The population size was of 100 individuals. After about 150 generations, the Algorithm allows to obtain a set of solutions.

The two selected solutions (from EA-1 and EA-2) present the function values of the economic cost of 159 and 132 millions of pesetas respectively. About reliability (FEENS), the function values are 250 kWh (EA-1) and 585.6 kWh (EA-2).

The selected solution from EA-1 presents a cost of 20.45 % higher, but a reliability value (FEENS) of 57 % smaller, than the solution from EA-2. Table 3 shows the topological differences between the two selected solutions from the EA-1 (a) and EA-2 (b) Algorithms. Routes ("R") are represented by the initial and final nodes, and the symbols 1 and 2 represent the feeder sizes 3x150Al and 3x1x400Al respectively ("1r" and "2r" represent a reserve feeder). The symbol "-" represents a route without built feeders.

TABLE 3. TOPOLOGICAL DIFFERENCES.

R	a	b	R	a	b	R	a	b	R	a	b
1-2	2	1	9-11	2	1	18-21	2r	1	27-37	2	-
1-6	2	1	10-15	2	1	20-21	1	-	27-38	2	-
3-8	1	-	11-14	2	1	20-30	2	1	29-31	2	-
4-5	1r	2	12-13	2	1	22-28	2r	1	30-31	2	1
5-B	2	-	13-17	2	-	23-24	2	1	34-A	2	1
6-7	2	1	15-25	1	-	23-26	2	1	34-37	2	1
6-8	1r	1	16-24	1r	-	24-25	-	1	34-35	2	1
7-12	2	1	17-18	2	1	24-25	-	1	38-39	1	-
9-10	2	1	18-19	-	1	25-39	1r	1			

5. CONCLUSIONS

The two Evolutionary Algorithms, presented in this paper, have proven to be efficient tools for multiobjective planning, due to their power and flexibility, and to the fact they provide a set of good solutions instead of a single "optimal" solution. This allows the planner to have added insight on the planning process and on the problem itself. The two Evolutionary Algorithms have been applied to a multiobjective power distribution system design problem considering two objectives, economic costs and reliability of the power system, reaching the following conclusions:

a) An optimization model of nonlinear mixed-integer programming has been presented for the multiobjective optimal design of distribution networks, achieving the optimal design of a distribution system, determining the optimal sizing and location of future feeders

b) Two Evolutionary Algorithms has been developed to implement the mentioned model. The first includes a new operator, named "filter" operator allowing the planner to limit investments on reserve feeders, that has proven to be feasible and efficient. The second is based in Evolutionary Programming, being easily applied in a parallel Algorithm (using various computers).

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