DISTRIBUTION SYSTEMS EXPANSION PLANNING CONSIDERING THE EXPLOITATION OF DISTRIBUTED GENERATION BY A MULTI-OBJECTIVE GENETIC ALGORITHM

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ABSTRACT

This paper presents an algorithm dedicated to the static expansion planning of distribution systems using Genetic Algorithms (GA), where conventional expansion alternatives are considered together with the exploitation of Distributed Generation (DG). The problem is formulated as a multi-objective optimization problem, where the objective function to be minimized is composed by the annualized costs relative to the energy losses, the expected customer interruption cost (ECOST) and the investments in the system, together with the voltage drop in the network. The expansion alternatives considered are the installation of DG units based on different energy sources, the capacity enlargement of cables, the network reconfiguration and the installation of new switching devices. In the GA evolutionary process, for each feasible (radial) configuration, a non-linear power flow problem is solved and the ECOST is calculated. The fitness value of each individual is obtained by a weighted sum of its objectives function values and a penalization strategy is applied if any of the constraints are violated. A system composed of 33 nodes was used to validate the algorithm and demonstrate its applicability to large systems.

INTRODUCTION

The problem of distribution systems expansion planning consists of determining the appropriate type, local and capacity of the reinforcement to be installed in the network, taking into consideration the demand to be attended according to geographical, political and economical characteristics. Among the reinforcements to be considered, it can be cited the capacity enlargement of existing lines and substations or the installation of new ones, the installation of new switching devices or the reconfiguration of the network, etc. In general, the expansion planning solution is driven by two fundamental aspects: to attend the technical operation constraints, such as equipments limits, maximum voltage drop, radial network topology, reliability level, etc, and to minimize the economical requirements, such as system investments, operational costs, losses and lack of reliability duties.

In an open electricity market scenario, the connection of Distributed Generation (DG) units must be included within the expansion alternatives in order to attend the demand growth [1]. The expansion planning problem is modeled as a combinatorial constrained optimization problem, non-linear with mixed real and integer variables, and therefore heuristic methods can be successfully applied [2].

The problem of distribution systems expansion planning has been the object of many researchers' study during the last three decades. More recently, several papers have dealt with the consideration of multiples objectives and uncertainties through extensions of conventional optimization techniques, such as probabilistic mathematical programming and fuzzy logic [3]. Another research approach explores the use of evolutionary programming, such as Genetic Algorithms (GA), for large scale systems that require the consideration of many aspects of the problem, specially when involving mixed integer and continuous variables [4,5].

This paper presents an algorithm dedicated to the static expansion planning of distribution systems using Genetic Algorithms, where conventional expansion alternatives are considered together with the exploitation of Distributed Generation. The problem is formulated as a multi-objective optimization problem, where the objective function to be minimized is composed by the annualized costs relative to the energy losses, the expected customer interruption cost (ECOST) and the investments in the system, together with the voltage drop in the network. The expansion alternatives considered are the installation of DG units based on different energy sources, the capacity enlargement (reinforcement) of cables, the network reconfiguration and the installation of new switching devices. In the GA evolutionary process, all individuals' fitness is analyzed and for each feasible (radial) configuration, a non-linear power flow problem is solved and reliability aspects are taken into consideration by the calculation of the cost of the expected energy not supplied. The fitness value of each individual is obtained by a weighted sum of its objectives function values and a penalization strategy is applied if any of the constraints are violated. This penalization process varies with the stages of the evolutionary process in order improve the solution.

A system composed of 33 nodes [6] was used to validate the developed algorithm. The algorithm supplied a radial configuration that minimizes the objective function specified and satisfies all the operational constraints.

PROBLEM FORMULATION

The static expansion planning of distribution system can be formulated as a mixed non linear programming problem, containing continuous variables, such as voltages, angles, generated active and reactive power , and discreet variables, such as switch status (open or closed), the power capacity of DG units to be installed in the system, cables reinforcement indicators, etc. In this paper, the problem is formulated as:

$$\text{Min fob} = t_1 C_{loss} + t_2 \, ECOST + t_3 \, MVD + t_4 C_{invest} \quad (1)$$

subject to:

$$Pg_i - PL_i - \sum_{j \in \Omega_i} p_{ij} = 0 \quad (2)$$

$$Qg_i - QL_i - \sum_{j \in \Omega_i} q_{ij} = 0 \quad (3)$$

$$V_i^{min} \le V_i \le V_i^{max} \quad (4)$$

$$Pg_i^{min} \le Pg_i \le Pg_i^{max} \quad (5)$$

$$Qg_i^{min} \le Qg_i \le Qg_i^{max} \quad (6)$$

$$-p_{ij}^{max} \le p_{ij} \le p_{ij}^{max} \quad (7)$$

Radial network topology (8)

where:

fob	objective function;
$t_1 \ t_2 \ t_3 \ t_4$	normalization parameters;
C_{loss}	energy losses annualized cost;
ECOST	expected customer interruption cost;
MVD	maximum network voltage drop;
C_{invest}	system investment annualized cost;
Pg_i , Qg_i	active and reactive power generated at node i, respectively;
PL_i , QL_i	active and reactive load at node i, respectively;
p_{ij} , q_{ij}	active and reactive power flow at line i-j, respectively;
Ω_i	group of lines connected to node i;
V_i, V_j	voltage module at nodes i and j, respectively;
V_i^{min}, V_i^{max}	minimum and maximum voltage module at node i, respectively;
p_{ij}^{max}	maximum active power flow at line i-j;
Pg_i^{min}, Pg_i^{max}	minimum and maximum active power generation at node i, respectively;
Qg_i^{min}, Qg_i^{max}	minimum and maximum reactive power generation at node i, respectively.

PROPOSED METHODOLOGY

The methodology developed in this work is based on the theory of Genetic Algorithms, where conventional alternatives of expansion are considered together with the exploitation of Distributed Generation. GA work with individuals codified in a chromosome structure over which genetic operators are applied. Each gene represents a variable in the individual's formation. The code is necessary for the application of the genetic operators. In this work the binary code is used. The structure of the chromosome adopted in this work is shown in Figure 1.

(1) - Network Reconfiguration	(2) - Distributed Generation	(3) - Cable Reinforcement

Figure 1: Chromosome Structure

The first part of the chromosome refers to the possibility of network reconfiguration through the modification of the status of some switches already installed or through the installation of new switching devices. Whenever a normally-opened switch is closed, a normally-closed switch belonging to the same mesh must be opened in order to keep the radial topology of the network. This is accomplished by a reconfiguration algorithm included in the methodology.

In order to maintain the size of the chromosome reduced, only the switch that should be opened is represented for each mesh of the system, since the others will remain closed. This analysis is valid for switches already available in the system and for new switching devices candidate for installation. The network reconfiguration cost related to already installed switches is only due to the cost of the operation, while for new switches it is combined the acquisition investment and the operation cost.

The second part of the chromosome refers to the possibility of installation of DG units. In this case, 3 bits are used for the representation of each new DG, allowing a total of 8 possible values of installed capacity, including the possibility of not installing. In this work, thermal and wind energy generators were considered by appropriate models.

The third part of the chromosome refers to the possibility of reinforcement of the cables. In this case, 1 bit was used for the representation of each line candidate for reinforcement, indicating if it has to be reinforced or not.

Figure 2 shows the flowchart of the methodology developed in this paper.

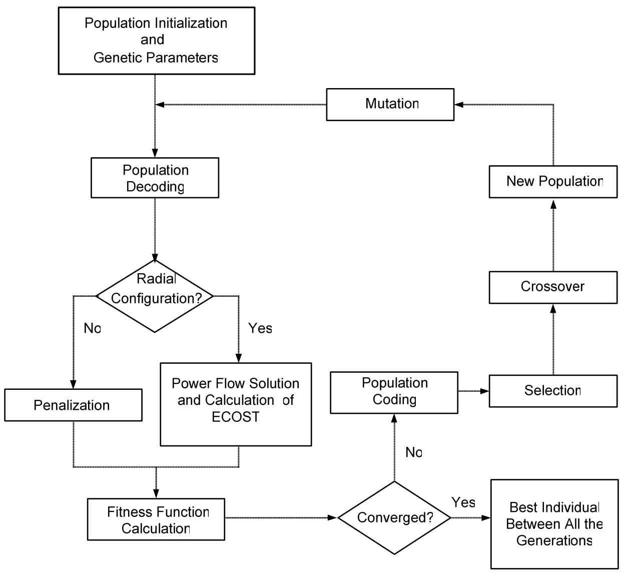

Figure 2: Flowchart of the Proposed Methodology

For each expansion alternative corresponding to a chromosome with no operational constraint violation, a non linear power flow is solved by the Newton-Raphson method in order to calculate the losses, voltages, power flows, etc. The ECOST is also calculated for each expansion alternative (chromosome), considering the failure rate and average outage time of the network components [7], the protection and switching equipments present in the distribution network, such as reclosers, fuses, etc, and specific customer damage functions (CDF) for each costumer class [8]. The uncertainties regarding the wind generators power availability is considered through the representation of the wind generation probability distribution function developed in [9].

A penalization strategy is applied if any of the constraints are violated. This penalization process varies with the stages of the evolutionary process, allowing that in the initial generations, even unfeasible solutions have the possibility to transmit their genetic characteristics for the following generations, while in the final generations only feasible solutions are found. After exhaustive tests of the genetic operators, the Roulette method was adopted for the Selection, the Two Points technique for the Crossover, Mutation by changing of 1 bit and the Elitism was implemented. With the objective of increasing the efficiency of the algorithm and to avoid the stagnation in local minima, it was adopted a variable and growing tax of mutation along the evolutionary process, varying as a function of the number of analyzed generations.

The fitness value of each individual is obtained by a weighted sum of its objectives function values, according to equation (1). The normalization parameters are calculated in the first generation and are kept constant in the rest of the evolutionary process. These parameters are introduced with the intention of maintaining all the terms of the objective function with the same order of magnitude and close to the unitary value. The choice of these parameters is complex and influences directly in the quality of the solution found by the algorithm. After exhaustive tests, it was decided to consider the normalization parameters as being the maximum value of each objective among all the chromosomes of the first generation.

RESULTS

A system composed of 33 nodes [6] was used to validate the developed algorithm. Figure 3 shows its initial configuration, where dashed lines represent normally-opened switches or candidate locals for new switching device installation. The total load is 3,715 MW and 2,3 MVAr. The unitary costs adopted in this paper are shown in Table 1, which are based on actual data.

Table 1: Losses, Operation and Investment Unitary Costs

	Annualized Costs
Losses	0.125 R$ / kW
Switch Operation	13.40 R$
Switch Acquisition	334.70 R$
Distributed Generation	215.50 R$ / kW
Cable Reinforcement	1004.10 R$ / km

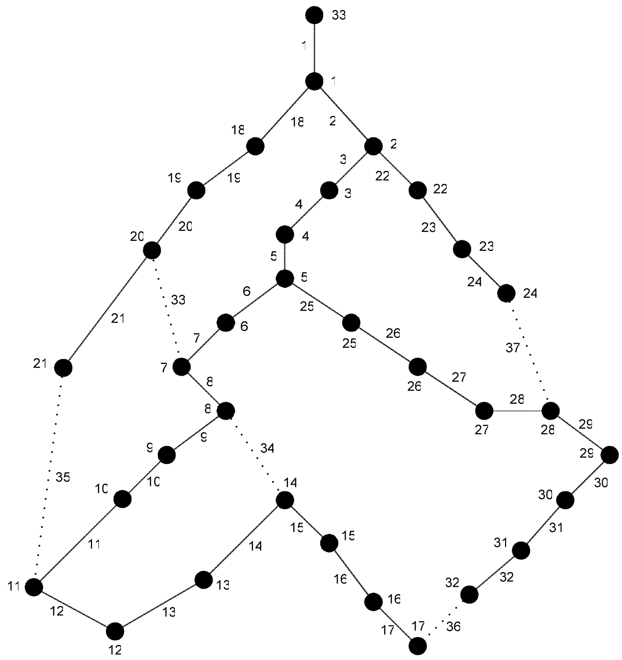

Figure 3: Initial Configuration

The annualized costs regarding losses, ECOST and their sum are shown in Table 2 for the initial configuration. The maxim voltage drop is 0.087 p.u.

Table 2: Annualized Costs – Initial Configuration

Losses Cost	ECOST	Total Cost
R$ 221,734	R$ 1,146,381	R$ 1,368,115

The following expansion alternatives were simultaneously considered for this system:

1) Reconfiguration of the network through the operation of the normally-opened switches in lines 34, 35 and 36;

2) Installation of new normally-opened switches in lines 33 and 37 and further reconfiguration of the network;

3) Cable reinforcement of lines 5, 6, 7, 16, 17, 20, 21, 22, 23, 24, 28, 29, 30, 31 and 32;

4) Installation of Distributed Generation in nodes 6, 7, 17, 21, 23, 24, 29, 31 and 32. The DG capacity possibilities are 120, 240, 360, 480, 600, 720 and 840 kW.

The optimal solution obtained by the methodology indicates the reinforcements and network reconfiguration presented in Table 3 and the installation of DG shown in Table 4.

Table 3: Reinforcements and network reconfiguration

	Line
New Switch Installed	37
Opened Switches	11, 14, 15 e 28
Lines Reinforced	5, 6, 7, 20, 21, 22, 23, 24, 29, 31 e 32

It can be observed that there is no need to install a switch in line 33 and that the new switch installed in line 37 should stay closed, provoking the opening of the switch in line 28.

Table 4: Distributed Generation Installed

Node	Capacity (kW)
17	480
21	120
24	840
29	120
32	480
Total	2,040

The total DG capacity installed correspond to a very low penetration degree (about 0,06%), which can be more easily handled by the network operation utility.

The annualized costs regarding losses, ECOST, investment and the total are shown in Table 5 for the optimal solution. The cost reduction with respect to the initial configuration is shown in Brazilian monetary unit and in percentage. The maxim voltage drop is 0.021 p.u., which represents a reduction of about 76%.

Table 5: Annualized Costs – Optimal Expansion Solution

	Cost	Reduction (R$)	Reduction (%)
Losses	R$ 58,918	162,816	73.43
ECOST	R$ 490,140	656,241	57.24
Investment	R$ 461,207	---	---
Total	R$ 1,010,266	357,849	26.16

It can be observed that a significant total reduction of about 26% was achieved by the investments in the network indicated by the methodology. Figure 4 shows the final optimal expansion solution.

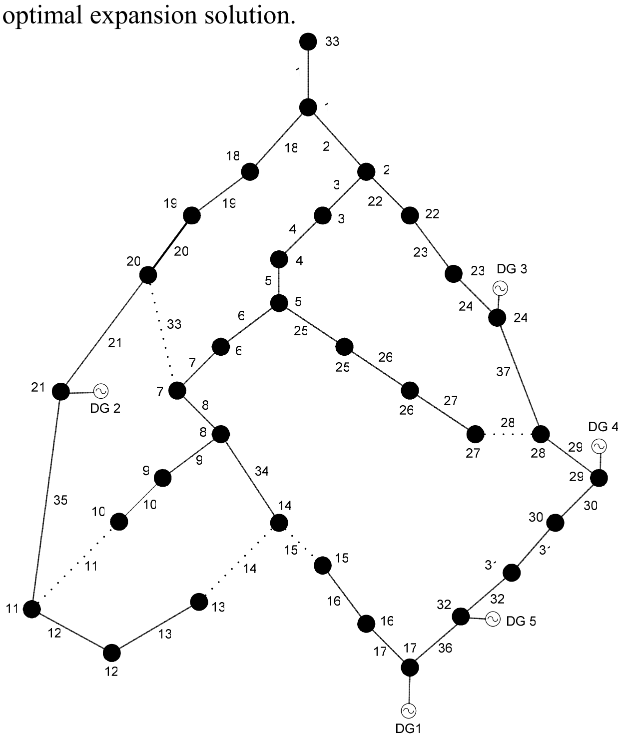

Figure 4: Optimal Expansion Configuration

CONCLUSIONS

This paper presented a new methodology dedicated to the problem of static expansion planning of distribution systems using Genetic Algorithms. Conventional alternatives of expansion were considered together with the installation of Distributed Generation, with the purpose of obtaining a radial configuration that minimizes the overall cost relative to losses, reliable energy supply and investments in the system. The results presented by the algorithm for a small system are of great quality and suggest its applicability to actual large scale distribution networks.

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