IMPACT OF EMBEDDED GENERATION ON DISTRIBUTION NETWORK PLANNING USING EVOLUTIONARY PROGRAMMING

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ABSTRACT

It is presented an algorithm for the allocation, sizing and operation of generators in radial distribution systems in order to maximize the reduction on the load supply costs. The generators operation is given by their operational schedules for all feeder load levels. Evolutionary programming is used as the optimization technique. The method was evaluated using a feeder with high losses index and the proposed distributed generation scheme provided a reduction on total costs.

NOMENCLATURE

$C_{G_i}^{\text{ope}}$ ($C_{G_i}^{\text{acq}}$)	*i*-th bus generator operational (acquisition) costs, \$/MWh (\$)
c_P (c_Q)	Active (reactive) generation index
C_S	Substation energy tariff, \$
C_T^B (C_T^A)	Total load supply costs before (after) the generators installation, \$
df_k	*k*-th segmented curve level demand factor
Δt_k	*k*-th segmented curve level duration, h
l_v	Relative voltage variation tolerance, %
λ_v	Cost conversion factor, \$
n_c	Number of characteristics of the individual
n_d	Number of days of the study horizon time
$n_g^{\max}$	Maximum number of generators
n_l	Number of levels of the segmented curve
n_P (n_Q)	Number of divisions of the active (reactive) generation power interval
$pf_{G_i}^{\min}$ ($pf_{G_i}^{\max}$)	Minimum (maximum) *i*-th bus generator power factor
pf_{Li}	*i*-th bus load power factor
$P_{G_i}^{\text{nom}}$	*i*-th bus generator nominal active power, MW
P_{Gik} (Q_{Gik})	*i*-th bus active (reactive) generation power at the *k*-th segmented curve level, MW (Mvar)
P_{ik} (Q_{ik})	*i*-th branch active (reactive) flow, MW (Mvar)
P_{Lik} (Q_{Lik})	*i*-th bus active (reactive) load at the *k*-th segmented curve level, MW (Mvar)
$P_{S_k}^B$ ($P_{S_k}^A$)	Active power coming from the substation at the *k*-th segmented curve level before (after) the generators installation, MW
P_v	Value proportional to the voltage variation limits violations at all generation buses during all segmented curve levels
$Q_{G_{ik}}^{\min}$ ($Q_{G_{ik}}^{\max}$)	Minimum (maximum) *i*-th bus generator reactive power at the *k*-th segmented curve level, Mvar
R_i (X_i)	*i*-th branch resistance (reactance), Ω
S_i^{nom}	*i*-th bus installed nominal power, MVA
V_{ik}^B (V_{ik}^A)	*i*-th bus voltage magnitude at the *k*-th segmented curve level before (after) the generators installation, kV
Ω_G	Set of generation buses
ξ_{ik}	Penalty for voltage variation limits violation for the *i*-th bus generator at the *k*-th segmented curve level

INTRODUCTION

Distributed generation (DG) can be defined as an electrical power source connected directly to the distribution network or on the consumer side of the meter [1]. The optimal placement and sizing of generators on distribution networks has been continuously studied in order to achieve different aims. The objective can be the minimization of the active losses of the feeder [2], [3]; or the minimization of the total network supply costs, which includes generators operation and losses compensation [4], [5]; or even the best utilization of the available generation capacity [6].

As a contribution to the methodology for DG economical analysis, it is presented an algorithm for the allocation and sizing of generators in distribution networks, in order to minimize the load supply costs. Evolutionary programming technique has been used as the optimization method.

DISTRIBUTED GENERATION

With distributed generation, utilities are able to delay higher infra-structure investments and can also diversify their energy sources. This sort of investment can also provide reduction on losses and voltage profile improvement, while alleviates substation overload at peak demand hours. Nevertheless, DG may cause some disturbs to the system, such as: possible power quality deterioration, voltage regulation modifications, and need for protection system rearrangement.

Due to the importance of allocation, utilities are interested in methods which allow them to evaluate the impact of generating power in some points of their feeders. In load flux problems for distribution systems with generators, the generation buses can be modeled as PV, PQ or PX buses. Depending on the capacity of the generators relatively to the network dimensions, they may not be properly modeled as PV buses, as they may not be robust enough to control voltage levels. When using PQ model, the generator is considered a negative load, which is more adequate when modeling synchronous machines [7]. Asynchronous generators are more properly modeled as a PX bus, represented by an active generated power and a linear or non-linear reactance [8].

EVOLUTIONARY PROGRAMMING

Evolutionary algorithms are efficient methods used to solve optimization problems, for which the search for the optimal solution is based on the evolution theory. They can be divided in three groups: genetic algorithms, evolutionary strategies and evolutionary programming. As some others heuristic techniques used to solve combinatorial optimization problems, the evolutionary algorithms do not guarantee that the best solution founded is the global optimal of the problem; however, it is quite likely that the best solution is a good approximation of that optimal.

Evolutionary programming is an emulation of the evolution process of a population of individuals along a number of generations. In this population, each individual represents one possible solution of the optimization problem. In general, there are four steps that should be followed to create an evolutionary programming algorithm [9]: determine the solution codification; create the initial population; define the combination rule; and define the selection rule. The algorithm is iterative and the most used stopping criterion is the maximum number of generations. The combination rule generates new individuals from others already existent, what allows the exploration of new regions of the search space. The selection rule is used to determine which individuals of a generation will pass to the next one, by a comparison of their fitness values. The *fitness* of an individual is defined as the objective function value for the solution codified in it.

PROBLEM FORMULATION

The allocation and sizing of generators in distribution systems is faced with the aim of minimizing the *supply costs*, i.e., the total costs paid by the utility in order to supply the feeder loads. Two scenarios are compared:

1) the energy that supplies the feeder (loads and losses) comes uniquely from the substation;
2) the energy has two origins: the substation and the installed generators.

The energy provided by DG, being more expensive than that provided by large central generators, will only be worth if the allocation and sizing of the generation units leads to a significant reduction on feeder losses.

The active and reactive powers generated by each unit must be located into its operational limits. Another constraint is that the units operation must not cause significant changes on the voltage levels previously existent. The maximum number of generators to be installed is previously defined. One problem solution must contain the position, nominal capacity and operational schedule for each generator to be installed. The generator *operational schedule* indicates the active and reactive powers that should be generated by each unit at different feeder load levels. The supply costs of the proposed DG scenario will be compared to the present one, which does not contemplates DG. The optimal solution is the one for which the costs reduction is maximum.

SOLUTION METHOD

Load and Feeder Models

The distribution feeder model adopted is shown in Figure 1, as suggested in [10], which allows the installation of loads and generation in all buses. Each branch has the following properties: origin bus, destiny bus, impedance per length unit, length, apparent power installed, and load power factor. The load model is the constant power one.

It is used the modified power summation method proposed in [10] for the power flow calculation. There can be a load ($P_{Lik}+\mathrm{j}Q_{Lik}$) and a power generation ($P_{Gik}+\mathrm{j}Q_{Gik}$) at any bus. The substation is the feeder swing bus, while all the others, including those where generators are found, are PQ buses. The load daily variation is considered by the use of the segmented load duration curve, as defined in [11]. This curve is characterized by some feeder power demand levels and by their respective duration. The ratio between the demand level of the curve and the total apparent power installed in the feeder results in the demand factor of each level. A unitary diversity factor is considered if there is not more information about the feeder loads behavior. Thus, the substation demand factor is applied to all buses to determine their active and reactive loads:

$$P_{L_{ik}} = S_i^{\mathrm{nom}} df_k \, pf_{L_i} \tag{1}$$

and

$$Q_{L_{ik}} = S_i^{\mathrm{nom}} df_k \sin(\arccos(pf_{L_i}))\,. \tag{2}$$

Generator Model

Each generator is considered a negative constant load. The reactive power generated by the unit installed at the *i*-th bus at the *k*-th segmented curve level must be such that:

$$Q_{G_{ik}}^{\min} \le Q_{G_{ik}} \le Q_{G_{ik}}^{\max}\,, \tag{3}$$

where

$$Q_{G_{ik}}^{\min} = P_{G_{ik}}.\mathrm{tg}(\arccos(pf_{G_i}^{\max})) \tag{4}$$

and

$$Q_{G_{ik}}^{\max} = P_{G_{ik}}.\mathrm{tg}(\arccos(pf_{G_i}^{\min}))\,. \tag{5}$$

In order to match the discrete nature of the chosen optimization method, the possible generation intervals are

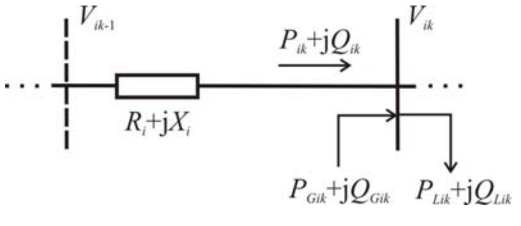


Figure 1. *i*-th feeder branch model

divided into discrete levels, as shown in Figure 2. Thus, the active and reactive generated powers are:

$$P_{G_{ik}} = c_P \frac{P_{G_i}^{\text{nom}}}{n_P} \qquad (6)$$

and

$$Q_{G_{ik}} = Q_{G_{ik}}^{\min} + c_Q \frac{(Q_{G_{ik}}^{\max} - Q_{G_{ik}}^{\min})}{n_Q} . \qquad (7)$$

The numbers n_P and n_Q are previously defined integers used to divide the possible generation intervals into discrete values. The numbers c_P and c_Q are integers between 0 and n_P and between 0 and n_Q, respectively.

Solution Codification

The individual must contain the following information: installation bus, generator type and active and reactive generation indexes for all segmented curve levels. A *type* is a set of data that characterizes each kind of generator available to be installed. These information are repeated in the individual for each generator to be installed.

An example of individual is presented in Figure 3, when the segmented curve has three levels and there are up to two generators to be installed. As indicated in the figure, the c_P and the c_Q values of each segmented curve level are considered an unique characteristic of the individual.

Fitness Function

The fitness of each individual is determined by the reduction on the supply costs considering the DG configuration codified in it. The fitness function is:

$$f = C_T^B - C_T^A - \lambda_v P_v . \qquad (8)$$

The first term, which represents the load supply costs before the generators installation, is expressed by:

$$C_T^B = n_d C_S \sum_{k=1}^{n_l} P_{S_k}^B \Delta t_k . \qquad (9)$$

The supply costs after the generators allocation, corresponding to the second term of (8), is given by:

$$\begin{aligned} C_T^A &= n_d C_S \sum_{k=1}^{n_l} P_{S_k}^A \Delta t_k + \\ &+ \sum_{i \in \Omega_G} [n_d C_{G_i}^{ope} \sum_{k=1}^{n_l} (P_{Gik} \Delta t_k) + C_{G_i}^{acq}] \end{aligned} . \qquad (10)$$

The last term of (8) is a penalty function that is applied to those solutions in which generators operation makes the generation buses voltages exceed the specified variation tolerance, for every load level. In this term, P_v is:

$$P_v = \sum_{k=1}^{n_l} \sum_{i \in \Omega_G} \xi_{ik} , \qquad (11)$$

where ξ_{ik} can be given by:

$$\xi_{ik} = 0, \text{ if } \left| \frac{V_{ik}^A}{V_{ik}^B} - 1 \right| \le \frac{l_v}{100} \qquad (12)$$

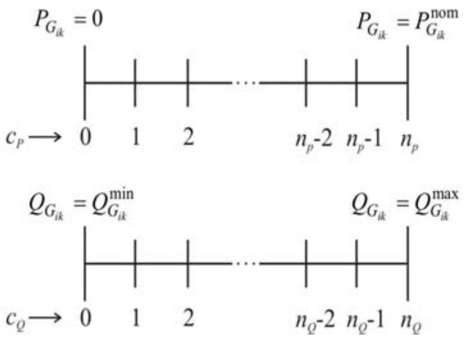


Figure 2. Active and reactive generated powers intervals

or by

$$\xi_{ik} = \left| \frac{V_{ik}^A}{V_{ik}^B} - 1 \right|, \text{ if } \left| \frac{V_{ik}^A}{V_{ik}^B} - 1 \right| > \frac{l_v}{100} . \qquad (13)$$

Evolutionary Programming Steps

The stopping criterion in this work is the number of generations, and the population size is kept constant in the end of each generation. Next, each step of the evolutionary programming technique is described, as schematized in the diagram of Figure 4.

Initial population creation. The characteristics of each individual of the initial population are chosen randomly, but always from the possible interval, what avoids ill-formed individuals. The active and reactive powers generated in each segmented curve level are proportional to its loading situation, i.e., they are interdependent characteristics.

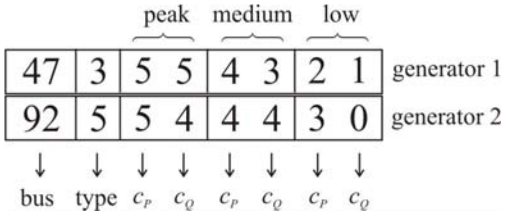
Combination stage. Mutation was the combination operator used. One randomly selected individual generates another by randomly substituting one of its characteristics value by other that belongs to the set of possible options.

Selection stage. The selection scheme adopted was the competition. To each individual of the increased population is associated its fitness. Then, each individual competes with randomly chosen opponents, by a simple comparison of their fitness. In the end, those with the greater number of victories are selected to pass to the next generation.

Statistics. In the end of each generation, three indexes are stored: the smaller and the greater fitness values founded, besides its medium value among the individuals.

EXAMPLE CASE

In order to evaluate its performance and efficiency, the proposed method was applied to a feeder with high losses



bus	type	c_P	c_Q	c_P	c_Q	c_P	c_Q	
47	3	5	5	4	3	2	1	generator 1
92	5	5	4	4	4	3	0	generator 2

Figure 3. Example of individual

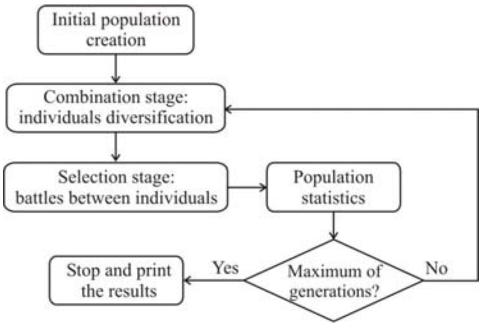


Figure 4. Evolutionary programming diagram

index, a situation in which DG becomes an attractive option to reduce the load supply costs. The chosen feeder is part of the distribution system of a Brazilian utility. In Table 1 there are some information about this feeder. The horizon time considered for the evaluation of the proposed DG scenarios is five years. It is admitted that it will be installed up to two generators in the feeder, among the five types whose characteristics are presented in Table 2. Those data are from hypothetic machines.

In Table 3 are presented the evolutionary programming and the objective function parameters. The best individual founded by the algorithm suggests the solution shown in Table 4 and in Table 5 it is presented a comparison between some feeder indexes, before and after the generators installation. The optimal allocation of the units provided a reduction of about $ 242.000 on the supply costs during the five years. As required, the generators operation did not violate the voltage variation limits at the generation buses in none load level.

Table 1. Feeder information

Substation voltage (kV)	13,80
Number of branches	167
Installed apparent power (MVA)	9,72
Load power factor	0,85
Substation energy tariff ($/MWh)	60,00
Supply voltage limits (%)	±10

Table 2. Generators data

Type	$P_{G_i}^{nom}$ (MW)	$pf_{G_i}^{\min}$	$pf_{G_i}^{\max}$	Acquisition ($)	Operation ($/MWh)
1	0,20	0,80	0,98	35.000,00	75,00
2	0,30	0,80	0,98	45.000,00	72,50
3	0,40	0,80	0,98	52.000,00	72,50
4	0,60	0,80	0,98	61.000,00	70,00
5	0,80	0,80	0,98	76.000,00	70,00

Table 3. Optimization method parameters

Number of individuals	100
Number of generations	200
Number of opponents per individual	10
Cost conversion factor λ_v ($)	$3,5.10^5$
Divisions of generation intervals n_P, n_Q	5

Table 4. Best solution founded

Characteristics		Generator 1	Generator 2
Bus		128	116
Type		4	4
Peak	(MW)	0,60	0,60
	(Mvar)	0,45	0,45
Medium	(MW)	0,60	0,60
	(Mvar)	0,45	0,45
Low	(MW)	0,36	0,00
	(Mvar)	0,27	0,00

Table 5. Comparison of feeder indexes

Parameters	Before	After
Losses (MWh/day)	14,89	7,91
Active losses (peak) (%)	13,35	8,73
Supply costs ($)	$16,41.10^6$	$16,16.10^6$

CONCLUSIONS

The proposed method for distributed generation economical analysis has shown good efficiency. Its applicability has been tested in a feeder with high losses index. The generators allocation and sizing proposed by the algorithm could reduce the total load supply costs, in spite of generators installation costs and their more expensive energy price. In addition, the evolutionary programming technique was adequate to solve the problem in the way it was formulated.

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