GENETIC ALGORITHM FOR THE OPTIMAL LOCATION OF CAPACITORS IN DISTRIBUTION SYSTEMS

Diego Moitre, José Luis Hernandez, Luis Aromataris, Gustavo Rodriguez

Grupo de Análisis de Sistemas Eléctricos de Potencia (GASEP)
Facultad de Ingeniería - Universidad Nacional de Río Cuarto
Ruta Nacional 36 Km. 601 - (5800) Río Cuarto
Córdoba – Argentina
Tel / Fax: + 54 358 4676252
E-mail: dmoitre@ing.unrc.edu.ar ; jlh@ing.unrc.edu.ar ; laromataris@ing.unrc.edu.ar ; grodriguez@ing.unrc.edu.ar

INTRODUCTION

In Electric Systems of different countries in South America and Central America, the losses of global power in the distribution reach values into range from 10 to 18% of the whole generation. A way of attacking this problem consists in the location of the capacitor banks so as to change the profile of distribution voltage in the system regulating the flow of reactive power in which they are installed. The choice of the necessary location has a fundamental role with direct economic benefits.
The objective of the present work is to find a scheme of location of capacitors in a given distribution system so that it could diminish the global losses taking into account the established limits for the distribution voltage.

ELECTRIC ENERGY MARKETS

The idea of an open access to the networks was developed by American economists in the 70s and early 80s for economic networks in general. This new approach in the economy of networks has been proposed as a new model for air transport, telecommunications, gas and electricity. The physical infrastructure of the networks remains as natural regulated monopolies (airports, cables, piping, lines). With the open access to these networks, the rest can be subdued to a competitive scheme (airlines, services with added value, gas production and electric energy). Three elements converge to make up a model to deregulate the electric industry: the idea that greater scale economies in the production do not exist, the theory that the open access to networks enables the maintenance of competence and the growing public concern for the environment.
An Electric Energy Market (EEM) model completely segmented is based on the following hypotheses [1]:

- The scale and scope economies of the generation plants are not meaningful in relation to industry. The property and control of the generation are widely distributed among the agents.
- The scale and scope economies of the transmission and distribution system are meaningful in relation to the industry, conforming natural monopolies which must be regulated.
- The centralized coordination of the economic dispatch of the generation is essential to supply the demand from consumers, keeping the stability and integrity of the system in a short-term. The dispatch is a natural monopoly which must be regulated.
- All other service and/or product exhibits limited scale or scope economies and could be segmented and supplied by many suppliers in a competitive environment.

They suggest a segmentation of the generation, transmission and distribution areas of the market in functions developed under a competitive scheme when there is no natural monopoly, or, in case it exists, under a regulated scheme which maintains and facilitates competence among the rest of the areas. This segmentation separates the potentially competitive functions in the generation and distribution sectors. In those segments to which the present technology demands coordinated activities, control or property separation and free access to the media, a regulated scheme is proposed.

THE ARGENTINE ELECTRIC ENERGY MARKET

The electric Argentine industry is constituted by some services in the Southern region, the Patagonic Subsystem and by a subsystem in the Central region, both conforming the Interconnection Argentine System (SADI). The installed capacity of the Patagonic Subsystem is made up by gas turbines which total 331 MW, and by 494 MW of the F. Ameghino and Futaleufú hydroelectric plants. The load, interconnected by a transmission network of an extension of 2.217 km., with voltage levels of 330 and 132 KV, has an important industrial component mainly due to aluminum production and oil extraction that covers 82% of it. The consumption in 1996 was in the order of 4.406 GWh. Of a greater importance, the Central Subsystem, with the consumption of 60.549 GWh in 1996, is supplied through a transmission network of an extension of 7.000 km., with voltage levels of 500, 220 and 132 KV., by an installed capacity of about 17.109 MW; out of which 8.230 MW correspond to hydroelectric plants; the remaining 8.879 MW are composed by: 4.783 MW steam turbines, 2.943 MW gas turbines, 1.005 MW nuclear, 144 MW combined cycle and 4 MW diesel engines. From the generated energy, approximately, 42% is of an hydraulic origin, 43% conventional thermal and 15% nuclear; 59% of the consumption is situated in the area of Gran Buenos

Aires, 13% in the Litoral, 9% in the Central region, 6% in Cuyo, 6% in the Argentine Northwest (NOA), 4% in the Comahue and 3% in the Argentine Northeast (NEA) [2].

This market, conformed by the wholesale electric market of the Central System (MEM) and the wholesale Patagonic market (MEMSP), includes different commercial and financial agreements by means of contracts of different type and duration, shared risks, short-term transactions, etc. The kernel of these agreements is a “spot” market in which the electric energy is valued and traded requiring for its functioning, communication between its agents and the control center, a task that is carried out in our country by CAMMESA, as an Organism in charge of the SADI dispatch.

The optimal administration of an hydro-thermal system, in any moment, is based on the comparison of fuel costs of the thermal plants with the water values of dams and determine the dispatch of thermal and hydraulic units. The complexities of the operation programming of an hydro-thermal system are considered through “chains” of models with different horizons of programming [3]. For the highest level of the chain the objective is to find an operation strategy so that for each stage of the horizon of programming, and knowing the state of the system at its beginning, it would give the generation for the different plants of the system. The programming of the economic dispatch of the SADI at this level, is made by CAMMESA via the MARGOT model with the objective of minimizing the expected value, over the hydrology, of the operation cost plus failure in the generation plants. It also calculates for each trimester of the year the Seasonal Programming which defines the Seasonal Price of Energy which is the price at which the Distributors buy up to 60% of its demand, with the possibility of the remnant to be bought in the spot market or in the term market (contracts), to be later sold at the seasonal price plus the distribution costs (regulated “cap price”).

Once incorporated as a EEM agent, an generator will be able to sell its remnants or buy its shortages; for the estimate of the distribution price of electric energy, the generators will have to send to CAMMESA, their prevision of offer for the indicated period. The losses of global power in the distribution reach values which range from 10 to 18% of the whole generation. A way of attacking this problem consists in the location of the capacitor banks so as to change the profile of distribution voltage in the system regulating the flow of reactive power in which they are installed. The choice of the necessary location has a fundamental role with direct economic benefits.

OPTIMUM CAPACITOR ALLOCATION

The optimum application of shunt capacitors on distribution feeders to reduce losses has been studied by means of classical techniques [4-6]. An approach by Gönen [4] supply a solution considering uniformly distribution load (UDL) and provide an analytic expression for determine an optimal capacitors allocation.

However this hypothesis can be, in some cases, too restrictive and an analysis without precedent UDL consideration should be made. Its involves solving a non-linear optimization problem with integer variables, where the decision variable is the location and capacity of capacitor banks to connect in the distribution system.

The objective function is the cost (sum of all banks cost allocated in the distribution system) but under certain constraints: the real loses must be less than an admissible value and an adequate voltage profile should be observed.

Under its considerations, the mathematical model of the problem can be described as follow:

$$
\begin{aligned}
&\text{Minimize} \quad \sum_{i \in NB} C_i \\
&\text{subject to:} \\
&\text{for} \quad i \in N_0 \\
&PG_i = PD_i + V_i \sum_{j \in Ni} V_j \left[G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right] \\
&\text{for} \quad i \in N_{PQ} \\
&QG_i = QD_i + V_i \sum_{j \in Ni} V_j \left[G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right] \\
&\text{for} \quad i = 1, \ldots, N_{PV} \\
&QG_i^{Min} \le QG_i \le QG_i^{Max} \\
&\text{for} \quad i = 1, \ldots, NB \\
&V_i^{Min} \le V_i \le V_i^{Max}
\end{aligned}
\tag{1}
$$

Where:

NB = set of numbers of total buses
Ni = set of numbers of buses adjacent to bus i, including bus i.
N_0 = set of numbers of total buses excluding slack bus.
N_{PQ} = set of numbers of PQ bus.
N_{PV} = set of numbers of PV bus.
N_E = set of numbers of network branches.

The following considerations settle down:

- Exists NC banks of capacitors of different types
- Exists T types of banks each one has a cost associated C_i (i=1,2 ..T)

This type of problems, in which the objective function is neither linear nor differential can be faced with success by means of techniques of evolutionary computation in general and, in particular, with genetic algorithms.

The decision variable is the location of capacitors while the fitness is estimated by a software package of calculation of power flow and a later analysis of the fulfillment of restrictions which will give place to penalties of the potential solution in case there is a violation of some of the mentioned restrictions.

GENETIC ALGORITHM

The genetic algorithms (GA) are included within evolutionary computation techniques. The philosophy that underlies is the one that tries to simulate the mechanisms of the natural evolution to solve the optimization problems that result from the adaptation of living organisms to the environment. The simulation has to establish analogies between GA and the mechanisms which nature provides looking for the adaptation of potential solutions (chromosome or individuals) to an environment considering their fitness or adjustment (given by the individuals merit to the population).

The functioning of the GA is based on the iterative modification of a population of individual that is candidates to a solution by means of the use of genetic operators.

The theory on which the GA support themselves is explained in [7]. The problems of optimization of real functions, without the necessary demand of neither continuity nor derivability can be solved by the GA using, among others, a representation of the potential solutions in form of bit chains in each of the chromosomes which conforms the population. The scheme of a canonic GA is the following:

```
Procedure GA {
t=0
initialize p(t)
evaluate p(t)
while (no detention) {
        t = t + 1;
        select p (t);
        cross p (t);
        mutate p (t);
        evaluate p(t)
 }
```

The sequential problems present an additional difficulty since their representation does not adjust, a priori, to the GA. However, an adequate re-design of the representation and of such operators makes it possible the solution of problems such as the commercial traveler, the rucksack problem, the coloring of graphs, problems of routing in nets, etc.

The following aspects have to be taken into account in the design of the AG:

- Representation of chromosomes
- Adjustment function (fitness)
- Selection method
- Genetic operators (crossing, mutation)
- External parameters which govern the evolution

Representation of chromosomes

In this case the representation by means of strings of bits was chosen. Each component j of the vector can store a 0 (what indicates absence of capacitors bank in the node j) or an integer different from 0 that indicates the bank type that is placed in the node j. This way a chromosome C will be represented by a vector:

$$C= (C_1, C_2, C_3, \dots , C_N)$$

where:

$$C_i = \{0,k\} ;k=1,..., NC$$

Fitness function

The objective function is subject to restrictions, in this problem in particular. The GA provides a solution to the problem without restrictions. To take them into account, one of the possible methods that are the one that is used here, consists in penalizing the objective function. The penalty can be as severe as the capital punishment (openly discard the chromosome assigning an infinite cost) or take into account the violating degree of the restriction.

Representation

Binary representation, traditionally, are used in GAs. However it has some drawbacks when applied in certain types of problems of optimization. Additionally, the system representation and the optimization problem are strongly related and both have influence to genetics operators

Binary representation allows represent then variable of decision in both, real and integers numbers. Floating point representation is often faster than binary representation. Integer vectors representation is used successfully in optimization problems in which the solution is a permutation, such optimal allocation capacitors in a distribution power system. This is the reason for choose, precisely, a vector of integers as representation method. Each gene of chromosome is an integer representing the node affected and the type of bank that will be allocated in this node.

Selection method

An important aspect to consider in GAs is then inability, under certain conditions, to find optimal solutions; such failures are caused by a premature convergence to a local optimum. If the convergence occurs too rapidly, then the valuable information developed in part of the population is often lost: there is an excessive selective pressure or a degree of genetic diversity.

These factors are strongly related: an increase in the selective pressure, decrease the diversity of the population and vice versa. The selection method that is chosen determines the degree of genetic diversity that is shown by the evolving population. The loss of genetic diversity can lead to premature convergence. On the other hand, the excess of diversity brings about greater times of convergence.

In this work proportional selection is used: each individual is selected to procreate with a proportional probability to its fitness.

Genetic Operators

The operators that are used to generate the offspring are the ones of crossing and mutation. Uniform crossing was used to use the advantage that grants the elected representation. If C_1 and C_2 are the chromosomes parents:

$$C_1 = C_1^{1}, C_1^{2}, C_1^{3}, \ldots , C_1^{N}$$
$$C_2 = C_2^{1}, C_2^{2}, C_2^{3}, \ldots , C_2^{N}$$

A son is generated component to component the mother's gene or the selected father random:

$$H_1 = C_2^{1}, C_1^{2}, C_2^{3}, \ldots , C_1^{N}$$
$$H_2 = C_1^{1}, C_2^{2}, C_1^{3}, \ldots , C_2^{N}$$

The used mutation was the macro-mutation, consistent in the regeneration of a valid individual.

To reach the solution to the problem posed, the process is initiated with a first population of individuals generated randomized. The fitness function is applied to these individuals evaluating the ones which show the best performance, which will have a greater probability of survival while the individuals of a less quality will tend to disappear as evolution advances.

Having selected the best individuals, the crossing and mutation operators are applied to generate a new population to which the same operators will be applied. The criterion of detention of the algorithm was established in a maximum number of iterations. It was considered with a fixed population of 15 individuals, 1 elite individual, probability of crossover 0.65 and probability of variable mutation: base Pm=0.001y until a maximum of Pm=0.05**.**

STUDY CASE

In this section an example on a testing system is presented to show the behavior of the GA developed in applications to the optimum capacitors allocation.

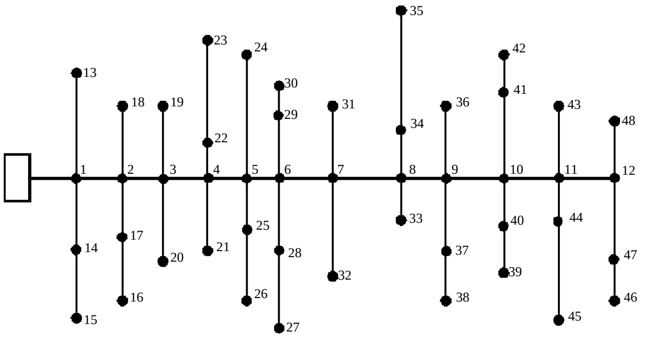

Fig 1. 48 nodes system

The loads associated to each node are tabulated in the following table:

Table 1

Node	Real [Kw]	Reactive [KVAr]
1	-	-
2	80	10
3	40	5
4	60	4
5	70	8
6	40	6
7	20	4
8	50	15
9	29	3
10	25	7
11	20	6
12	30	3
13	45	4
14	20	6
15	22	4
16	12	3
17	10	3
18	15	3
19	20	3
20	10	4
21	10	3
22	20	2
23	29	3
24	25	5
25	20	2
26	10	6
27	15	5
28	20	4
29	22	2
30	12	2
31	10	1
32	15	5
33	15	5
34	30	5
35	10	2
36	10	5
37	20	6
38	29	4
39	25	3
40	20	3
41	10	4
42	15	3
43	20	1
44	22	3
45	12	2
46	10	2
47	15	3
48	15	2
49	15	5

It was supposed for this case, three types of banks of capacitors: 10, 30 and 50 KVAr. We assume costs of banks shows in Table 2.

Table 2

Bank Capacity	Cost [ℜ]
10	100
30	200
50	300

The representation system used is an integer vector for each individual. Each chromosome is separated in two halves. In first half are stored the nodes in which capacitors banks are connected and second half stores the type of bank connected. A typical chromosome is shown in the figure 2. In this example three banks are connected: 10 KVAr at node 2, 30 KVAr at node 4 and 30 KVAr at node 7.

2	4	7	0	0	....	....	2	1	1	0	0

First half
Nodes 2 4 y 7
With banks

Second half
bank type 2 at node 2
bank type 1 at node 4
bank type 1 at node 7

Fig 2. an example of a valid chromosome.

For each chromosome proposed, its fitness is calculated through a power flow that determine real loses and voltage profile, which are used to penalize the objective function, the cost. Such penalization, consist in to increase cost in a value dependent of the degree of constraints violation.

The limit for the real loses was 59 KW . A population of 30 individual, Elitism=1, probability of crossoveer=0.65 and macro-mutation was parameters used for government the evolution cycle. Results of experiments are shown in table 3.

Table 3

Nodes with comp.	Bank Type	Cost [ℜ]
8, 11, 12	2	600

Totals real lost reach 58.6 KW for optimal allocation.

CONCLUSIONS

The behavior of the GA was analyzed on a concrete example of application to the electric power distribution systems and the results were compared with classic techniques. As a result of this comparison it can be concluded that the study of the techniques of evolutionary calculation presents alternative ways to the resolution of problems of optimization. Another of the advantages of the GA is the obtaining, not only of the best chromosome but of a group of solutions.

The GA has the advantage of not incorporating any restriction to the function objective. The same one can not be continuous neither derivable, but having any characteristic.

A disadvantage of the GA rests in that the good one global it can not always be reached with any precision. When a particular problem this associated with a method that finds solutions with a smaller error to the acceptable one in acceptable times, is convenient the application of this method.

ACKNOWLEDGMENTS

The authors wants to express their acknowledgement to the CONICOR, and the Secretary of Science and Technique of the UNRC, for all the economic support provided in the frame of the Research Program, years 1999/2000.

REFERENCES

[1] H. Rudnick, R. Varela, W. Hogan, “Evaluation of alternatives for power system coordination and pooling in a competitive environment”. *IEEE Trans. on Power Systems,* Vol 12, No 2. ,1997, pp. 605-613.

[2] CAMMESA *Annual Report.* Bs. As., Argentina. (1996).

[3] M. Pereira, "Optimal scheduling of hydrothermal systems : an overview". 1985 *IFAC Electric Energy Systems*. Rio de Janeiro, Brazil.

[4] T. Gönen and F. Djavashi, "Optimum Shunt Capacitors Allocation on Primary Feeders", in *Proceedings 1980 IEEE MEXICO International Conference.*

[5] J. Grainger and S. Lee, "Optimum Size and Location of Shunt Capacitors for reduction of losses on Distribution Feeders", *IEEE Trans. Power Appar. Syst.,* vol. PAS-100, March 1981, pp. 1105-1118.

[6] S. Lee and J. Grainger, "Optimum Placement of fixed and switched Capacitors on Primary Distribution Feeders", *IEEE Trans. Power Appar. Syst.,* vol. PAS-100, January 1981, pp. 345-351.

[7] Z. Michalewicz, *Genetic Algorithms + Data Structure = Evolution Programs,* Springer-Verlag (1995).