Evolutive algorithm to optimize the power flow in a network using series compensators.

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***Abstract*—The actual lines have many operation problems like oscillations, a important reactive power flow in the lines... other kind of problems are the planification of the network (power of the generators, reactive power flow in the lines...) or the bad distribution of the power flow in the lines of the network, for example one line overloaded and the other lines below their nominal power, this case happens, for example, in a network when a line falls. Many techniques have been used to solve this second type of problems, actually techniques based in the evolution and natural selection (like genetic algorithms or evolutionary algorithms) are being used combined with electronic equipment.**

The FACTS are a good electronic equipment to be used in these problems, because the converter can stay in bypass until a line falls, in this moment the converter can be used to solve the problem. The line impedance can be changed using SSSC converters, because they can inject a voltage in quadrature with the line current, so the effect of the converter is a capacitive or a inductive reactance in series with the line impedance. This paper presents an evolutive algorithm that solves the problem of placing SSSC converters in a network to optimize the power flow across all the lines of those network, minimizing the total installed power. The number of converters to be placed and their power will be chosen by the algorithm too.

I. Introduction

As deregulation of the electric system becomes an important issue in many countries, Flexible AC Transmission System (FACTS) [1], [2] devices become more and more commonly used. They may be used to improve the transient responses of the power system and can also control the power flow (both active and reactive power), this is very important because the reactive power also increases the transmission losses [3] and the control of active power flow requires "series VAR" solutions, that can alter the impedance of the power lines or change the angle of the voltage applied across the line.

Static Series Synchronous Compensator (SSSC) is based on a solid-state controllable voltage source inverter that is connected in series with power transmission lines. SSSC has become an effective tool for power flow control [4], [5], because it can inject a voltage in quadrature with the line current, so the line reactance can be changed from capacitive to inductive or from inductive to capacitive, using this converter.

Series reactive compensation has rarely been used other than on long transmission lines due to the high cost and complexity of implementation. The main advantages of FACTS are enhancing system flexibility and increasing the loadability. Although FACTS devices have many advantages, they are handicapped due to the high cost of the components.

Many techniques have been used for the planning of series compensation: heuristic [6], artificial intelligence techniques such as: Simulated Annealing [7], Tabu Search [8], Evolutive Programming [9], Fuzzy Logic and Evolutive Programming [10], Fuzzy logic and micro-GA [6] and Genetic algorithms [11],[12],[13]. These techniques have been used recently to locate capacitor banks [14], [15].

For complicated networks the heuristic methods that try to minimize the cost of the investment and the genetic algorithm based on techniques [16] are good solutions. But when the problem becomes more complicated, evolutionary algorithms based on techniques have provided better results [17]. The evolutive strategies (EE) are probabilistic optimization techniques [18] based on natural selection and evolution of living beings.

This paper presents an algorithm based on evolutionary techniques to do a series compensation in a network that has a line loaded above their nominal value, trying to minimize the installed power. The number of converters to be placed and their power will be chosen by the algorithm. This problem is proposed by Red Elctrica de España (R.E.E.) to distribute the power flow across the network lines when one of these lines falls, to ensure that no line is above its nominal value in a real situation, that situation is prediction of R.E.E.

II. Approach to the problem.

R.E.E. proposed a network that is used in general situations, Fig. 1 represents the general diagram of the system. The network consists of three nodes, with five interconection lines. In node 3, there is a load represented by their impedance. It is posible that line 5 falls, in that situation the power flow in line 1 and line 2 will be increased so the algorithm studies this case, to ensure that no line is above its nominal value using a series compensation.

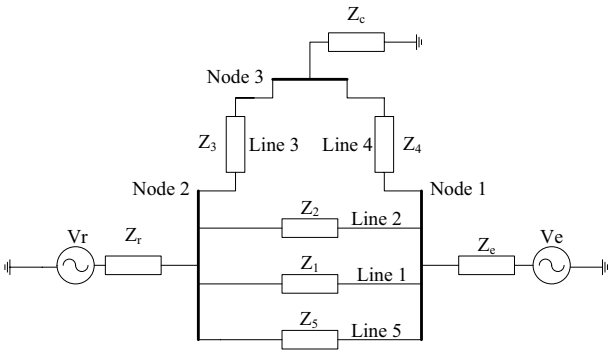


Fig. 1. Electric system.

Table I shows the powers (nominal and actual) flowing across the lines in a normal situation, that is without a line fall. Table II represents the powers (nominal and actual) flowing across the lines when line 5 falls, so the problem of this network is that the line 1 is overloaded (its rated power is 42 MVA and the power flow that crosses it, is 55.958 MVA)while the other lines are below their nominal power values, so the objetive of the algorithms is to modify the power flow distribution in this network using SSSC converters to ensure that all lines are below their load limit.

TABLE I
TABLE OF POWERS WITHOUT LINE5 FALL.

Line	$S_{nominal}$	S_{real}
1	42 MVA	41.77 MVA
2	81 MVA	50.86 MVA
3	81 MVA	11.95 MVA
4	81 MVA	49.05 MVA
5	72 MVA	50.86 MVA

TABLE II
TABLE OF POWERS.

Line	$S_{nominal}$	S_{real}
1	42 MVA	55.958 MVA
2	81 MVA	71.452 MVA
3	81 MVA	6.3349 MVA
4	81 MVA	59.309 MVA

III. PROPOSED EVOLUTIVE ALGORITM.

Fig. 2 shows the structure of the proposed algorithm:

One of the most important things in these types of algorithms is the codification of chromosomes, the proposed algorithm uses the codification shown in Table III, where ΔX_i are the equivalent impedance of the SSSC converter in the line "i", σ_i the standard deviation of a normal distribution which determines the mutation of the impedance in the line "i". This represents the structure of a chromosome and every individual is represented in this way.

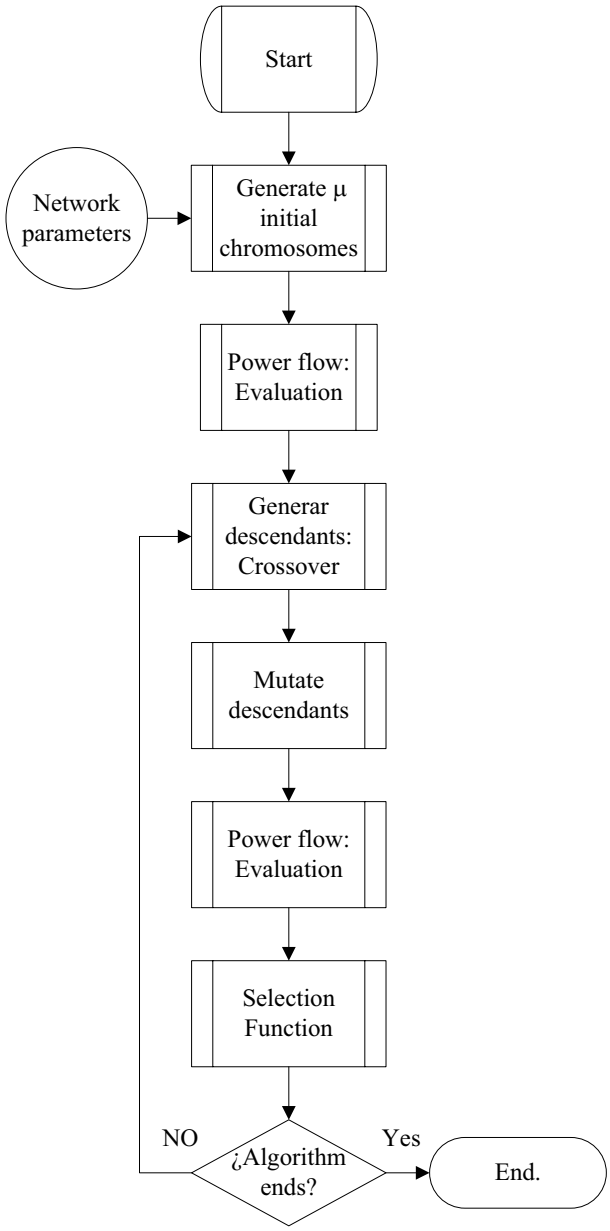


Fig. 2. Structure of the algorithm.

TABLE III
TABLE CHROMOSOMES CODIFICATION.

ΔX_1	ΔX_2	ΔX_3	ΔX_4
σ_1	σ_2	σ_3	σ_4

With the lines impedances and the increase or decrease of this impedance produced by the converter, the other paremeters to solve the problem: S_i, S_{ci}, S_{TC} can be calculated.

A. Generate initial chromosomes

At first, the initial μ individuals must be generated. The proposed algorithm is an $(\mu + \lambda)$ evolutive algorithm, with $\mu < \lambda$, that is because in this techniques is recommended to

use more generated population than initial population. In this example μ and λ are small numbers too, because this problem is a small one (the network has only three nodes), so it is not necessary to use a big number of individuals.

The initial choromosomes paremeters: ΔX_i and σ_i are generated randomly, this is for all the initial population.

B. Solving Power Flow: Evaluation of the solutions

Now, the other chromosomes parameters Table IV must be calcultated. With the value of the increased or decreased impedance in each line, a power flow is solved to obtain the power in each line, the power of the converters and the total power installed.

TABLE IV
TABLE OF THE NETWORK PAREMETERS TO SOLVE THE PROBLEM.

S_1	S_2	S_3	S_4
S_{c1}	S_{c2}	S_{c3}	S_{c4}

With the power flow, the voltages on the nodes: V_{N1} and V_{N2}, and the line currents: i_1, i_2, i_3 and i_4 can be calculated. So finally, the powers of the lines are calculated as follows Eq. 1, Eq. 2, Eq. 3, Eq. 4:

$$S_1 = |V_{NE} \cdot I_1^*| \quad (1)$$
$$S_2 = |V_{NE} \cdot I_2^*| \quad (2)$$
$$S_3 = |V_{NR} \cdot I_3^*| \quad (3)$$
$$S_4 = |V_{NE} \cdot I_4^*| \quad (4)$$

To complete the parameters of the network, the power of the SSSC converters and the total installed power should be calculated Eq. 5, Eq. 6, Eq. 7, Eq. 8, Eq. 9:

$$S_{C1} = |V_{C1} \cdot I_1^*| \quad (5)$$
$$S_{C2} = |V_{C2} \cdot I_2^*| \quad (6)$$
$$S_{C3} = |V_{C3} \cdot I_3^*| \quad (7)$$
$$S_{C4} = |V_{C4} \cdot I_4^*| \quad (8)$$
$$S_{CTot} = \sum S_{Ci} \quad (9)$$

Finally this calculus is done with all the initial population to obtain all the parameters of the initial space. To evaluate wich solution is the best, a "fitness function" assingns a cost to each chromosome.

$$cost = \sum S_{ci} + \Psi \quad (10)$$

The Eq. 10 shows the form of the fitness function which has two terms: the total installed power, and a term Ψ which represents the cost assigned to each chromosome to overcome the nominal power value of the lines, called as: "penalization function".

In another point of the algorithm another power flow equal to this one is solved by the λ new individuals asigning their cost too.

C. Generate descendants: Crossover operation

Now the λ chromosomes "descendants" should be generated from crossings between the chromosomes μ "parents". First, two parents are selected randomly, these chromosomes generate two descendants; to create the first column of the "Descendant 1" randomly the first column of the "Parent 1" or for the "Parent 2" was selected (randomly). The first column of the "Descendant 2" is the first column of the other parent (the no selected).

This is done with all the columns and until all the chromosomes "descendants" λ are created. The Eq. 3 shows an example of de generation of two descendants by the crossover operation.

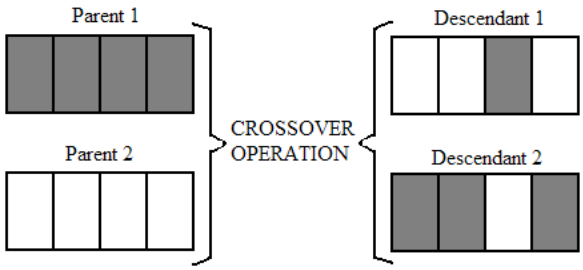


Fig. 3. Crossing operator.

D. Mutation of the descendants

To solve the problem, its necessary that the impedance associated with the converters varies, so it is value must change. In this section it will be explained how this variation is done. First, two random variables z_0 and z_i with a normal distribution with average zero and typical desviation τ_0 and τ_i respectively, are defined as shown in Eq. 11. The bibliography recommends the values τ_0=0.1 and τ_i=0.3.

$$z_0 = \tau_0 \cdot N(0,1)$$
$$z_i = \tau_i \cdot N(0,1) \quad (11)$$

z_0 will remain fixed while z_i varies with the expression Eq. 12 where N(0,1) is a normal distribution with average zero and typical deviation one:

$$z_{i_{n+1}} = z_{i_n} + N(0,1) \quad (12)$$

After this, the values of the cumulative probability of the variation of the impedances: σ Eq.13 and the new impedances values ΔX (Eq. 14) are calculated.

$$\sigma_{i_{n+1}} = \sigma_{i_n} \cdot \exp(z_0 + z_{i_{n+1}}). \quad (13)$$

$$\Delta X_{i_{n+1}} = \Delta X_{i_n} + \sigma_{i_{n+1}} \cdot N(0,1). \quad (14)$$

This calculation is done for all the values of each chromosome impedances, and for all the λ chromosomes obtained by the crossing operation.

IV. Selection function

In this point, the new μ initial population should be selected (between the $\mu+\lambda$ chromosomes). The "fitness function" was asigned a cost to all the individuals so the μ chromosomes with the lower cost are selected to create the new initial population.

The cost of each solution ((Eq.10)) is calculated with two terms: the penalization funcion Ψ asigns a very big cost if the difference between the nominal powers in the lines and the powers that flow across the lines is big. This does not mean that chromosomes that do not comply the power criterion can not be selected, if there are less than μ individuals that comply this criterion, the initial population is completed with chromosomes that do not meet it, but whose error is the smallest of it.

As the number of iterations grows, more chromosomes satisfy the criterion of powers, then the chromosomes that cause the minimum installed converters power, will be selected to create the new initial population, that is the first term of the fitness function.

V. Finalization of the algorithm

To end the algorithm, it is necessary to fulfil two conditions. First, more than μ chromosomes meets that with their injected power, all the powers in the lines are below their nominal value. And second one, the difference between the total injected power of the best chromosome (this is the one whose installed power is lower), the average from all the installed powers of the chromosomes and the the total injected power of the worse chromosome (this is the one whose installed power is greater), is less than a certain value ϵ Eq.15 and (Eq.16).

$$\left| S_{T_{BestParent}} - \frac{1}{n}\sum S_{T_i} \right| \leq \epsilon \tag{15}$$

$$\left| \frac{1}{n}\sum S_{T_i} - S_{T_{WhorseParent}} \right| \leq \epsilon \tag{16}$$

Using this approach ensures that if the algorithm is ending, is because it has found an overall minimum, and not a local one. At the first iterations the difference between those paremeters is very big, but as the algorithm is doing iterations that difference is decreasing.

VI. Experimental results

This algorithm has been programmed in Matlab and its results have been validated with PsCad. After the algorithm is executed, the results of the best chormosome are represented in Table V.

TABLE V
Best chromosome.

$\Delta X_i(\Omega)$	0.0274	1.2156e-15	-3.6313e-13	-2.9358e-15
σ_i	2.6518e-14	1.9565e-14	6.2943e-12	1.1020e-14

The parameters of this chromosome indicate that only one converter in the line 1 is necessary to solve the problem, because only the impedance of the line 1 has a significant value. With these values the solution of the power flow of the network is represented in Table VI.

TABLE VI
Other parameters results.

$S_{C_i}(VA)$	4.3380e5	6.9573e-8	2.6397e-7	-1.0792e-7
$S_{L_i}(VA)$	4.2e7	7.9801e7	7.9875e6	6.3955e7

And the total installed power, that is, the total power of the converters: S_{CT}=4.3380e5 VA. In this case to solve the problem it is necesary a converter of aproximately 434 kVA per phase placed in the line 1.

To see the convergence of the algorithm is possible to see the evolution of the total installed power in the line 1 Fig.4, in this figure are represented the solutions obtained by the best chromosome, the worse chromosome and the mean value of all the chromosomes.

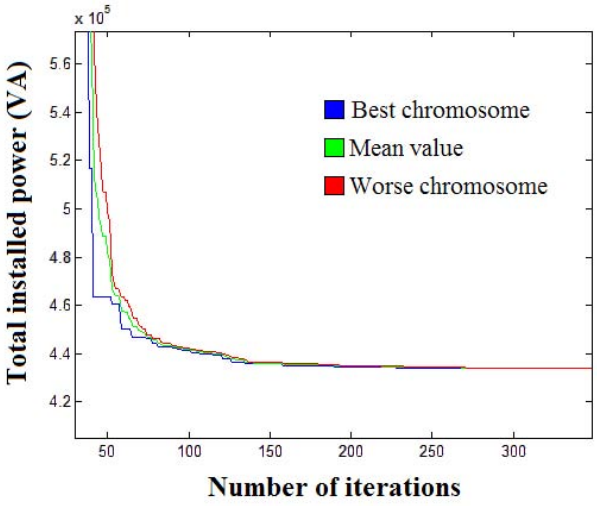


Fig. 4. Line 1 converter installed power for the first iterations.

Another possible figure is the power flow across line 1, Fig.5 represents this power for the best chromosome, the worse chromosome and the mean value of all the chromosomes.

And finally, in Fig.6 it is represented the fitness function value for the best chromosome and the mean value of all the chromosomes, so it is posible to see the algorithm evolution.

VII. Conclusions

This paper presents an evolutive algorithm for choosing the best placement for a series compensator in order to redistribute power flow under N-1 contigency. When line 5 falls down the algorithm recommends to place a series compensator in the line 1 in order to get a new power flow with all the lines under their thermal limits.

Besides, this algorithm finds a solution with a small number of iterations and with good convergence. The next step in developing is the application of this algorithm to more complex electric grid systems.

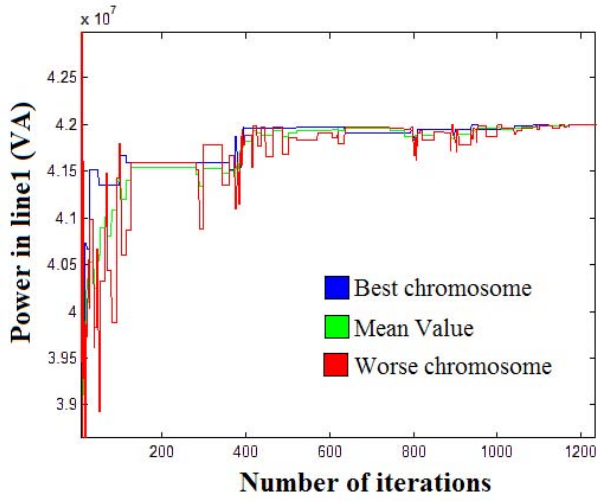


Fig. 5. Power flow across the line 1.

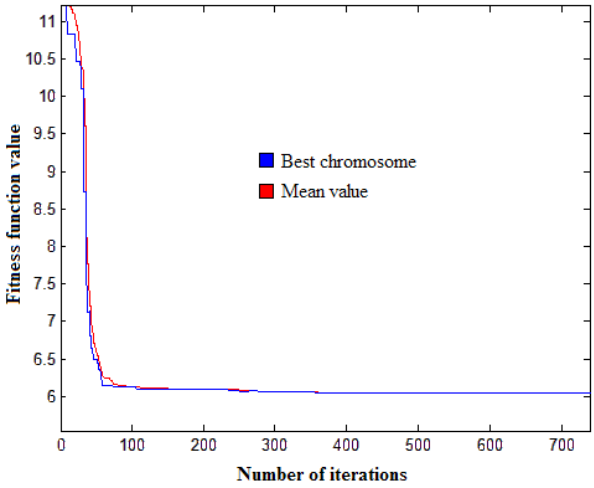


Fig. 6. Evolution of the algorithm: fitness function.

ACKNOWLEDGEMENT

This work was supported by the Spanish Ministry of Education and Science under Project ENE2006-02930. The authors want to thank Red Electrica de España for the technical support.

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