INTRODUCTION

The optimal control of voltage profile with mono-phase voltage regulators banks in radial distribution feeders is presented. The formulation is made as a combinatorial optimization problem and solved by a Genetic Algorithm. The used optimization criteria are: voltage profile centred in the normal range, losses and costs reductions. The proposed method determine: the location and optimal adjustments of mono-phase regulator banks in maximum and minimum load conditions, and the maximum regulation.

THE CONTROL OF VOLTAGE PROFILE

The control of voltage profile and reduction of losses in radial distribution feeders usually has been treated with installation of capacitor banks and voltage regulators by electric power utilities. Voltage regulators are mainly applied in extensive and loaded feeders, where the reactive compensation does not have satisfactory effect. These are low cost solution in comparing to others which are demanded whether the problems of that nature are too intense, such as: conductors resizing, network reconfiguration, implantation of new feeders, construction or amplification of substations.

In [1], is presented the application of voltage regulators with the integrated control of voltage and reactive power (volt/var), where are shown: the modelling of the components of the system, the analytic treatment of the objective functions and an example of application. However, one does not consider the discrete characteristic of problem, since the installation buses of the banks and the taps that the same ones should operate form a discrete and finite group. The modelling and implementation of the integrated control are presented in [2,3] too. However, they use the Gauss-Sidel load flow method with uniform distribution of load, having limitations for networks highly loaded.

In [4] an algorithm was proposed for location of voltage regulators in distribution systems that takes also into account the costs, but looks for solutions for approaches of the voltage profile, in relation to the profile without regulator, in agreement with the used tap and tries to elevate the voltage the possible maximum.

The volt/var integrated control is also done in [5], being that costs and typical load curves are considered. In [6,7] a genetic algorithm is presented for optimal location of regulators in radial distribution systems, taking into consideration the search space as a discrete and finite group. The first one uses three-phase regulators, the other using mono-phase regulator banks. The work presented here is a continuation of [7]. Now for location and optimal adjustments of mono-phase regulator banks, one takes into account the reduction of the energy losses costs originated from the installation of the banks, considering a typical load increasing of medium term, and using a genetic algorithm with reduced search space.

ADOPTED MODELS

Radial Feeder and Type of Load

As usual for radial distribution feeders, has been adopted a simplified model of the line with just impedance series. The load model of constant power, predominant in urban feeders [8], was used.

Voltage Regulator and Mono-phase Regulator Bank

The automatic voltage regulator is an autotransformer with load derivation changer, an electromechanical device controlled by voltage relay.

The mono-phase regulator bank is the most usual configuration in three-phase distribution systems. In the closed delta configuration (Fig. 1) the regulation band is 50% larger. That means if the mono-phase units have regulation range of ±10% each, then, the effective regulation of the bank is ±15%.

Another advantage is that if one of the mono-phase regulator flaws, the other two can stay in operation, in the configuration delta-opened, maintaining the voltage levels still regulated and the load capacity assisted by the bank. In that case, the regulation will be limited to ±10%.

The equations (1) – (3) relate the output voltage magnitude (V) and angle displacement (A) of the mono-phase regulator bank linked in closed delta, with the input voltage magnitude (v) and used step, d.
\[ V = \sqrt{(1 + 3a + 3a^2)} \]  
\[ \Delta = \tan^{-1}\left( \frac{\sqrt{3}a}{2 + 3a} \right) \]  
\[ a = d \left( \frac{0.1}{16} \right) \]

where, 
\[ v \] voltage magnitude at the banks entrance;  
\[ V \] voltage magnitude at the banks exit;  
\[ d \] operation step;  
\[ \Delta \] angle defasage of voltage at banks exit.

In the minimal step (-16), the output voltage of the bank is 15% smaller than input and the voltage angle is -5.8° out of phase [9,10]. In the maximum step (+16), the output voltage of the bank is 15% larger and phase angle is +4.3° out of phase. This voltage angle displacement does not affect the power flow in radial distribution feeders [11].

**CRITERIA FOR THE OPTIMAL LOCATION**

In this work it is considered the location and adjustments of two regulator banks. However, the presented method is valid for any number of banks. More than two is unusual due to coordination problems of system protection.

The principal criteria to locate voltage regulators banks are:

1. To maintain the voltage in all buses, inside of acceptable limits;  
2. To locate the banks in the main feeder;  
3. Not to locate the regulators banks on buses where exists capacitors banks;  
4. To avoid that the regulators are very close or very distant one of the other, because that would take to a larger discrepancy in the taps adjustments of one to compensate the other;  
5. The first regulator should support the power flows in the section where it, is located, which is of high magnitude in the first sections of the main feeder;  
6. The taps adjustments for the following years should be determinate based a forecast of load growth.

The attendances of those criteria demand an optimization method that is capable to contemplate the discrete characteristic of the problem and without approaches. In this context, the Genetic Algorithms [12] are well adapted to this problem.

**FORMULATION OF THE PROBLEM**

The problem of the location and adjustments of voltage regulators banks in distribution systems are formulated in this work as a problem of combinatorial optimization to be solved using genetic algorithm [6, 7].

The **Codification**

Genetic algorithms are different of other optimization and search methods because they do not deal with solutions, but with solution coding. That is, a solution of the problem, not necessarily the optimal, is codified in a sequence of bits. The necessary number of bits to represent the buses where the regulators will be installed depends on the amount of buses. Just in case of the banks be located on the main feeder, promotes a significant reduction of the search space. For main feeders that have 128 buses or less, for instance, a number of 7 bits is enough to represent the buses where each bank will be located. In other hand, six bits are enough to represent the regulator steps (32 steps plus zero-step).

The decoded chromosome in decimal representation (Fig. 2) is passed to the load flow computational routine. The first two digits represent the installation buses of the regulator banks and the others represent the taps of peak and out of peak loads, of each bank, for every year.

<table>
<thead>
<tr>
<th>Bus</th>
<th>Year 01</th>
<th>Year 02</th>
<th>Year 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>R2 1</td>
<td>R3 4</td>
<td>R4 5</td>
</tr>
<tr>
<td>R5</td>
<td>R6 2</td>
<td>R7 3</td>
<td>R8 6</td>
</tr>
<tr>
<td>21  77 4</td>
<td>2  5  2</td>
<td>6 4 7</td>
<td>8 5 9</td>
</tr>
</tbody>
</table>

Fig.2 Structure of the decoded chromosome, in decimal representation.

For each chromosome, six load flows are calculated: one for peak load and other for out of peak load for each year and therefore the energy losses are determined for every year. The profile of annual voltage on the two conditions of feeder loading is determined too.

The **Fitness Function**

The implemented genetic algorithm seeks for a solution that implicates in the smallest possible error, being this error defined in agreement with the following fitness function (objective function to be maximized by genetic algorithm):

\[
f(c) = -\frac{\Delta}{\sqrt{ny}} \sum_{k=1}^{nc} \sum_{i=1}^{nb} [p(v_{i,k}) (v_{med} - v_{i,k})^2 + p(u_{i,k}) (v_{med} - u_{i,k})^2]
\]

\[ v_{med} = \frac{1}{2} (v_{s\text{up}} + v_{\text{inf}}) \]

where,  
\[ k \] year in that the deviation of the voltages is being calculated;  
\[ ny \] number of years foreseen for the location and adjustments of the banks;  
\[ nb \] number of buses of the distribution feeder;  
\[ c \] chromosome: sequence of bits in that the solution is codified;  
\[ v_{i} (u_{i}) \] voltage in the bar \( i \) in conditions of peak (out of peak) load with installed regulators and operating as codified in \( c \);
\( v_{\text{sup}}(v_{\text{inf}}) \) superior and inferior limits of the voltage strip (kV), respectively;

\( p_c \) low penalty variable, which depends of energy losses of actual chromosome related to energy losses of the best chromosome of actual population;

\( p \) penalty function, to inhibit the solution choice that implicates out in bar voltage of the superior or inferior limits, defined as:

\[
p(v_i) = p(u_i) = \begin{cases} 
1 & \text{if } v_i(u_i) \in I = (v_{\text{inf}}, v_{\text{sup}}) \\
\beta & \text{if } v_i(u_i) \notin I 
\end{cases}
\]  

Typical values of \( \beta \) are in the interval \([1, 1.2]\).

**THE PROPOSED ALGORITHM**

The proposed algorithm is schematized in Fig. 4. The following observations are made:

- the definition of the chromosomal structure is made starting from the number of bars of the main feeder;
- the selection for crossing is made using the roulette method;
- before apply the mutation, the population is reduced to the initial number of individuals, using the tournament method;
- in the mutation scheme, the chromosomes and genes are randomly chosen;
- the homogeneity index of population is evaluated at each generation, being verified the difference among the bits of each chromosome in relation to the bits of the best chromosome of the population;
- the stop criterion tests if the homogeneity index \( h \) of the population is superior to the established parameter (for instance: \( h = 98\% \));
- in each generation the best chromosome is maintained (elitism) together with your aptitude value.

In this work are also considered 552 kVA as a limit of power.

**IMPLEMENTATION**

A Matlab\textsuperscript{6} implementation has been made in a microcomputer with Athlon XP 2000 processor.

A distribution feeder of 13.8 kV and 103 buses whose line and load data are found in [13] has been considered.

As an application of the proposed method, the optimal location and adjustments of two mono-phase regulator banks have been done. A rate of load growth from 5\% a year, for three years has been supposed. The adopted parameters by the AG are showed in Table I. Was established a limit of 1000 generations.

### TABLE I – Parameters of the Genetic Algorithm.

<table>
<thead>
<tr>
<th>Rate of crossover</th>
<th>Rate of mutation</th>
<th>Rate of equality</th>
<th>Penalty in load of peak</th>
<th>Penalty in load of out of peak</th>
<th>Low Penalty cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>55%</td>
<td>2.5%</td>
<td>98%</td>
<td>6%</td>
<td>8%</td>
<td>3%</td>
</tr>
</tbody>
</table>

The medium voltage was considered the own nominal voltage. The voltage regulation was calculated on peak and out of peak load conditions, being defined the regulation as the percentile difference between the voltages with and without regulator bank in the bus where the bank of regulators will be installed.

As voltage limits one considered 4\% above or below the nominal voltage (1.0 p.u.). In Table II the optimal values are presented for location and adjustments of the regulator banks. The obtained medium time of processing with the reduced search space was about 8 times less than the time considering the full search space (all feeder buses).

### TABLE II – Location, adjustments and regulation values.

<table>
<thead>
<tr>
<th>Bank</th>
<th>Bus</th>
<th>Year 01</th>
<th>Year 02</th>
<th>Year 03</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 )</td>
<td>08</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>25</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>( R_1 % )</td>
<td>08</td>
<td>4,7</td>
<td>1,9</td>
<td>4,7</td>
<td>2,8</td>
</tr>
<tr>
<td>( R_2 % )</td>
<td>25</td>
<td>8,0</td>
<td>4,9</td>
<td>9,1</td>
<td>6,9</td>
</tr>
</tbody>
</table>

\[ \text{Time} = 250 \text{ seconds} \]

It is important to verify in the table II that the adjustments of both regulators grow of one year for the other, since it was made the supposition of load growth.

The reduction of the costs of the losses of energy was of the order of 0.5\%, due to the installation of the two banks and the voltage profile stayed inside of the admitted range for the two loading conditions during the three years, as showed in figure 5. The maximum voltage drop is 8.6\%, in the bus 38. After the installation of the banks it is maintained in 1.0 p.u.
With the obtained results, the proposed algorithm can be successfully applied to studies of voltage regulators and coordination of automatic capacitors banks in distribution systems, although very extensive and high loaded feeders.

**REFERENCES**


