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A Specialized Genetic Algorithm to Solve the Short Term Transmission Network Expansion Planning

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Abstract — **In this paper, the short term transmission network expansion planning (STTNEP) is solved through a specialized genetic algorithm (SGA). A complete AC model of the transmission network is used, which permits the formulation of an integrated power system transmission network expansion planning problem (real and reactive power planning). The characteristics of the proposed SGA to solve the STTNEP problem are detailed and an interior point method is employed to solve nonlinear programming problems during the solution steps of the SGA. Results of tests carried out with two electrical energy systems show the capabilities of the SGA and also the viability of using the AC model to solve the STTNEP problem.**

Index Terms — **Transmission network expansion planning, AC model of the transmission network, specialized genetic algorithm, mixed integer nonlinear programming, interior point method.**

I. INTRODUCTION

THE aim of the Transmission Network Expansion Planning (TNEP) problem is to determine the optimal number of lines, transformers and capacitors to be added to the system, so that it can operate under steady state normal conditions in a defined planning horizon. The expansion plan must determine *where*, *how many* and *when* to install new elements with minimum investment cost and attending the forecasted demand. [1]

The planning of the transmission system consists of determining the best investment options based on information related to the current network structure, the candidate elements to be added and the characteristics of the electricity market. The solution must be the best under the technical and economical point of view. Basically, the transmission expansion problem has been solved minimizing investment costs, assuring certain reliability levels and minimizing the load shedding. With regard to the horizon of planning, the transmission expansion planning problem can be or a one-stage problem [2], or a multi-stage problem [3]. The former is called static planning and considers a single planning horizon, while the later takes into account a horizons of planning separated in several stages.

Currently, the transmission planning plays a decisive roll in the new electricity market environment, since it has a direct influence in the efficiency of the market through the congestion of the transmission lines. In the new regulatory framework of the electricity markets, the mathematical models must accurately represent the behavior of the system. There are several mathematical models that have been used to solve the TNEP problem. Some of them are: a) the transport model, b) the hybrid model, c) the disjunctive lineal model, and d) the DC model. The TNEP problem is solved both by classical optimization techniques [4]-[7] and by meta-heuristics, such as simulated annealing [8], genetic algorithms [9][10], tabu search [11], GRASP [12].

The DC model presents several advantages that make it an efficient tool to solve the TNEP problem, especially to solve the long term transmission expansion planning problem. However, it presents some disadvantages such as: a) it allows only the expansion planning of the active power, making necessary a second phase to optimally allocate capacitor banks in the system; b) the expansion plans obtained with the DC model usually require a posterior reinforcement phase (lines and/or transformers) to operate appropriately with the AC model of the transmission system.

The use of AC model in the TNEP problem has advantages such as (1) efficiently carrying out the reinforcement stage, when the expansion plans obtained for the DC model are used in the reactive planning phase; (2) using an integrated mathematical model that allows transmission network expansion planning problems and the optimal allocation of simultaneous reactive power (in a unique phase) avoiding the use of simplified models such as the DC model; (3) incorporating precisely the transmission losses in a trivial way and as a sub-product of the optimization process; (4) incorporating other non-linear operation characteristic devices, for example FACTS controllers; and (5) the possibility of carrying out other types of studies, after solving the AC integrated TNEP problem, as example: voltage stability, nodal analysis, transient stability analysis, etc. The approach has been labeled short term transmission network expansion planning (STTNEP).

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The mathematical model and an initial optimization technique for solving the STTNEP problem is presented in [13], where a constructive heuristic algorithm (CHA) is used to add a circuit (transmission line or transformer) to the system and an index based on the optimization dual variables is used to help the allocation of reactive power sources. In [14] a CHA for solving the STTNEP problem is presented, in each step of the CHA a sensitivity index is used to add a circuit (transmission line or transformer) or a capacitor bank (fixed or variable) to the system. It must be observed that the least efficient module of the proposal presented in [13] and [14] is the general technique of optimization used, that is, the CHA used to find a good quality topology for the STTNEP problem.

In this paper, the specialized genetic algorithm (SGA) presented in [15] is used to solve the STTNEP problem. This work is a natural extension of the methodologies presented in [13] and [14]. An interior point method is employed to solve nonlinear programming (NLP) problems during the solution steps of the SGA. Results tests carried out with two electrical energy systems show the capabilities of the SGA and also the viability of using the AC model to solve the STTNEP problem.

II. MATHEMATICAL MODEL

The short term transmission network expansion planning problem can be formulated as follows [14]:

$$\min \qquad v = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} + \sum_{o\in O}\sum_{j=1}^{nto} c_{oj} q_{oj} + \sum_{s\in s}\sum_{j=1}^{nts} c_{sj} q_{sj} \tag{1}$$

s.a

$$P_i(V,\theta,n) - P_{Gi} + P_{Di} = 0 \tag{2}$$

$$Q_i(V,\theta,n) - Q_{Gi} - V_i^2 \sum_{j=1}^{nts} (q_{sji} + q_{sji}^o) b_{sji}^{sh} - \sum_{j=1}^{nto} (q_{oji} + q_{oji}^o) Q_{oji}^{sh} + Q_{Di} = 0 \tag{3}$$

$$(n_{ij} + n_{ij}^o)(S_{ij}(V,\theta) - S_{ij}^{\max}) \le 0 \tag{4}$$

$$(n_{ij} + n_{ij}^o)(S_{ji}(V,\theta) - S_{ji}^{\max}) \le 0 \tag{5}$$

$$(q_{oj} + q_{oj}^o)(Q_{sh_{oj}} - Q_{sh_{oj}}^{\max}) \le 0 \tag{6}$$

$$(q_{oj} + q_{oj}^o)(Q_{sh_{oj}}^{\min} - Q_{sh_{oj}}) \le 0 \tag{7}$$

$$P_{G_k}^{\min} \le P_{G_k} \le P_{G_k}^{\max} \tag{8}$$

$$Q_{G_k}^{\min} \le Q_{G_k} \le Q_{G_k}^{\max} \tag{9}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{10}$$

$$0 \le n_{ij} \le n_{ij}^{\max} \tag{11}$$

$$0 \le q_{oj} \le q_{oj}^{\max} \tag{12}$$

$$0 \le q_{sj} \le q_{sj}^{\max} \tag{13}$$

θ_j unbounded

$n_{ij}, q_{oj}\ q_{sj},$ interger

$i\,j \in \Omega, i \in N,\ j \in L,\ k \in \Gamma, o \in O,\ s \in S$

where *ij* represent lines or circuits between buses *i* and *j*; c_{ij}, c_{oj} and c_{sj} represent the costs of the candidate circuit, the variable type *j* capacitors, and fixed type *j* capacitors, respectively, to be installed; n_{ij}, n_{ij}^0 and n_{ij}^{max} represent, the number of circuits to be added, the number of circuits from the base case, and the maximum number of circuits, respectively, that can be added between buses *ij*; *nto* and *nts* represent the number of types of variable and fixed capacitor banks that will be considered in the planning process, respectively; q_{oji}, q_{oji}^0, q_{oji}^{max} and Q^{sh}_{oji} represent, the number of variable type *j* capacitors to be installed in bus *i,* the number of variable type *j* capacitors installed in bus *i* from the base case, the maximum number of variable type *j* capacitors that can be installed in bus *i* and the reactive power generation of the variable type *j* capacitors installed in bus *i* respectively; q_{sji}, q_{sji}^0, q_{sji}^{max} and b^{sh}_{sji} represent the number of fixed type *j* capacitors to be installed in bus *i*, the number of fixed type *j* capacitors installed in bus *i* from the base case, the maximum number of fixed type *j* capacitors that can be installed in bus *i*, and the susceptibility of the fixed type *j* capacitor to be installed in bus *i* respectively. *n* is a vector of all added circuits and *v* is the total investment. *i* and *k*, represent the number of buses; P_{Gi}, *and* Q_{Gi}, are the generation of active and reactive power; ; P_{Di}, *and* Q_{Di}, are the demand of active and reactive power; *V* is a vector with components V_i, which are the voltage magnitudes; θ is a vector with components θ_i, which are the voltage angles; $P_{Gk}^{\min}$ and $P_{Gk}^{\max}$ are the limits of the active power generated in bus *k*; $Q_{Gj}^{\min}$ and $Q_{Gj}^{\max}$, are the limits of the reactive power generated in bus *k*; $V_i^{\min}$ and $V_i^{\max}$, are the limits voltage magnitude for the buses (between 105% and 95% of the nominal voltage); S_{ij}, S_{ji}, S_{ji}^{max} , is the power flow in MVA in circuits *ij* and the superior limit. Ω is the set of all branches, *N* is the set of all buses, Γ is the set of generation buses, *O* is the set of candidate buses for the allocation of variable capacitor banks, *S* is the set of candidate buses for the allocation of fixed capacitor banks. For more information about the mathematical model see [13] and [14].

The STTNEP problem formulated with the mathematical model presented in this paper can be solved using many optimization techniques, such as heuristics algorithms, classical optimization techniques like branch and bound algorithms, Benders decomposition, and metaheuristics. In this paper, we use a specialized genetic algorithm [15] that belongs to the metaheuristic group. Given an investment proposal to the STTNEP problem (n_{ij}^k, q_s^k, q_o^k, chosen within their limits and generated by the metaheuristic), the cost of adding these elements to the system can be defined as:

$$v^k = \sum_{(i,j)\in\Omega} c_{ij} n_{ij}^k + \sum_{o\in O}\sum_{j=1}^{nto} c_{oj} q_{oj}^k + \sum_{s\in s}\sum_{j=1}^{nts} c_{sj} q_{sj}^k \tag{14}$$

where v^k represents the total cost of the elements added to the initial configuration by the metaheuristic. To determine the unfeasibility of the investment proposal, the NLP problem (15) – (27) is solved adding elements proposed by the metaheuristic to the current configuration (n_{ij}^0, q_s^0, q_o^0), if the objective function v^c of the investment proposal is zero, then the investment proposal is a feasible solution, does not mean that the investment proposal is the optimal solution of the planning problem, just means that satisfies the constraints of the power system. Otherwise, the investment proposal is an unfeasible solution, and the solution of the NLP problem is used to improve its unfeasible, see [14].

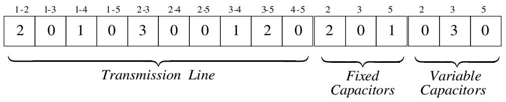

Fig. 1. Proposed codification.

$$\min \qquad v^c = \sum_{(i,j)\in\Omega} c_{ij} n_{ij}^c + \sum_{o\in O}\sum_{j=1}^{nto} c_{oj} q_{oj}^c + \sum_{s\in s}\sum_{j=1}^{nts} c_{sj} q_{sj}^c \tag{15}$$

s.a

$$P_i(V,\theta,n^c) - P_{Gi} + P_{Di} = 0 \tag{16}$$

$$Q_i(V,\theta,n^c) - Q_{Gi} - V_i^2 \sum_{j=1}^{nts} (q_{sji}^c + q_{sji}^o) b_{sji}^{sh} - \sum_{j=1}^{nto} (q_{oji}^c + q_{oji}^o) Q_{oji}^{sh} + Q_{Di} = 0 \tag{17}$$

$$(n_{ij}^k + n_{ij}^c + n_{ij}^o)(S_{ij}(V,\theta) - S_{ij}^{\max}) \le 0 \tag{18}$$

$$(n_{ij}^k + n_{ij}^c + n_{ij}^o)(S_{ji}(V,\theta) - S_{ji}^{\max}) \le 0 \tag{19}$$

$$(q_{oj}^k + q_{oj}^c + q_{oj}^o)(Q_{sh_{oj}} - Q_{sh_{oj}}^{\max}) \le 0 \tag{20}$$

$$(q_{oj}^k + q_{oj}^c + q_{oj}^o)(Q_{sh_{oj}}^{\min} - Q_{sh_{oj}}) \le 0 \tag{21}$$

$$P_{G_k}^{\min} \le P_{G_k} \le P_{G_k}^{\max} \tag{22}$$

$$Q_{G_k}^{\min} \le Q_{G_k} \le Q_{G_k}^{\max} \tag{23}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{24}$$

$$n_{ij}^c \ge 0 \tag{25}$$

$$0 \le q_{oj}^c \le q_{oj}^{\max} \tag{26}$$

$$0 \le q_{sj}^c \le q_{sj}^{\max} \tag{27}$$

θ_j unbounded ,

$n_{ij}^c, q_{oj}^c, q_{sj}^c$ continuous

$i\,j \in \Omega, i \in N,\ j \in L,\ k \in \Gamma,\ o \in O,\ s \in\ S$

The NLP problem must be solved for each solution proposal identified by the metaheuristic. In this way, the NLP problem consumes most of the processing time of the metaheuristic. To solve the NLP problem, it is necessary an efficient and robust algorithm. In this paper, the interior point algorithm proposed in [16] is used to solve the NLP problem. The decision variables of the NLP problem are the voltage magnitude and angles, the number of circuits added in branch *ij*, the number of fixed capacitors banks, the number of variable capacitors banks and the active and reactive power generation.

III. SPECIALIZED GENETIC ALGORITHM

The Chu-Beasly genetic algorithm (CBGA) was initially designed to solve the generalized assignment problem (GAP) [17]. There are also reports of the adaptation of the CBGA to the electrical planning problem [15],[18],[19]. The CBGA is based on the fundamental theory of the genetic algorithm (GA). However, it presents some differences that make it competitive in evaluating large problems. The main features of the CBGA are: 1) it uses a *fitness* function to identify the value of the objective function. 2) The main difference between the GA proposed by Holland and the one proposed by Chu-Beasly is that the later only substitutes one individual at a time in the population for each generational cycle. 3) Additionally, the new individual can not be repeated in the current population; this avoids the homogeneity in the population and conserves the diversity of the individuals.

A. Codification of the problem

In the power system transmission planning problem, an individual of the population is represented by a vector of size *nlc+2nbc* (*nlc*: number of candidate lines to be added and *nbc*: number of candidate buses for the allocation of capacitors*)*. In this case, every element of the vector represents the number of lines, transformers and fixed or variable capacitor banks of the system. This number ranges form zero until the maximum number of elements allowed.

Fig. 1 shows the codification used in this paper. For instance: in branch 1-2 two lines were added to the initial configuration, in branch 1-4 only one line was added to the initial configuration, etc. Regarding the case of fixed capacitors, 2 capacitors were added to bus 2 and one to bus 1. Finally, regarding the case of variable capacitors 3 of them were added in bus 3.

B. Initial Population

To solve planning problems using a GA is necessary to have an initial population. Depending on the type of problem there might be different ways to generate the individuals of the initial population. In problems with high complexity, their own characteristics determine the way of generating the individuals. Generally heuristic methods are used to generate individuals of good quality to form the initial population. In systems with low or medium complexity the initial population can be randomly generated, nevertheless if it is possible to use some knowledge of the problem to generate the initial population, this knowledge must be used. In this paper the initial population was implemented as suggested in [9], and the constructive heuristic algorithm presented in [14] was used. There are two characteristics that distinguish one initial population from another: the *quality* and *size*. These two characteristics are decisive in the solution of problems with high complexity.

C. Objective function

The objective function (*fitness*) must be evaluated for each individual of the population by the Eq. (14). The objective function represents the total cost of the elements that must be added to the initial network.

Once the CBGA proposes the elements to be added to the system, it must be verified whether such proposal is feasible. To do this the NLP problem represented by equations (15)-(27) must be solved. An investment proposal can be feasible for the NLP problem, but from the economic point of view it can represent a very high investment cost. Then, the optimal investment proposal for the planning problem consists of finding a feasible investment proposal with minimum investment cost. In the CBGA the objective function is used to implement the mechanism of selection and to substitute an individual in the population.

D. Selection

The selection mechanism consists of randomly choosing a reduced number of *k* configurations of the current population to compete among them, with the aim of choosing one configuration denominated as father. This selection procedure must be done twice with the objective of selecting two fathers.

According to the fundamental theory of GA there are several proposals of selection: 1) *roulette selection,* this is a proportional selection mechanism where each individual of the reduced list of proposals have the chance to be chosen as father depending of its fitness function. Therefore, those configurations with better objective functions have higher probability to be chosen as fathers. 2) *Tournament selection*, in this case, the configuration with the best objective function of the reduced list of k configurations is chosen. This procedure is executed twice to select the two parents. In this mechanism the value of k must be properly chosen to suit to each problem. This value must be chosen considering the problem size, complexity and initial population size. A high value of k and a small population might lead the algorithm to a premature convergence, achieving local solutions. On the other hand, a small value of k might cause a high computational burden. Once the selection mechanism is executed, two parents are available; these will be used in the recombination mechanism.

E. Recombination

The two chosen configurations in the selection mechanism are subject to recombination. In GA theory the recombination consists of interchanging information of two vectors to form two new vectors. In this case one of the new vectors will have elements of the previous ones. This is also defined as crossing over. In this way one can affirm that two vectors are crossed or recombined to form two new vectors. Generally, the original selected configurations are designated as parents, and the new ones are designated as offspring.

There are several ways of recombination and the simplest one is the recombination of one point that consists of selecting one only point to perform the recombination. Given a configuration of L elements or binary cells, then, once the configurations to perform the recombination are selected, a random number between 1 and (L-1) is generated. This number will indicate the point of recombination. The right part of both configurations is interchanged to form the two new configurations. It is also possible to perform recombination with multiple points.

Fig. 2 shows the recombination used in this paper. In this case three recombination points are used: one for the transmission lines, and the other two for the fixed and variable capacitors respectively. These three reconfiguration points were adopted because lines and capacitors must remain separated as they are two different types of elements.

F. Mutation

Mutation terminates the process in the obtaining of the new offspring. In the binary codification, mutation implies changing the value of a variable form 0 to 1 o vice versa.

Consider the case in which all configurations have a value of 0 in position k, however, the optimal configuration has a value of 1 in this position. In this case the recombination mechanism is not able to change the value of this single position, but the mutation mechanism can perform this change.

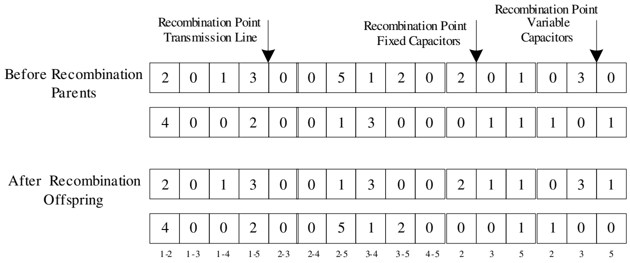

Fig. 2. Recombination Process

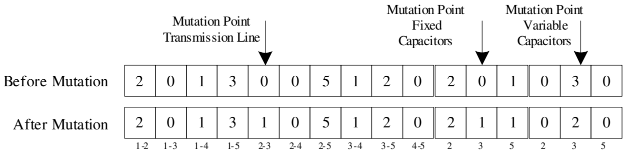

Fig. 3. Mutation process

According to empiric experience of researchers, in transmission network expansion planning problems, the typical range of mutation rate varies from 0.001 to 0.050.

Fig. 3 illustrates the process of mutation. In the transmission lines vector a new line was added in branch 2-3. Regarding fixed and variable capacitors, one of the former was added in bus 3 and one of the later was removed form the same bus. If the value of the selected cell is zero, the only option in this case is to add an element, since negative elements are not considered in the model. On the other hand, if the value of the cell is different from zero an element can be added or removed. Elements are added until the maximum number of elements in a branch or bus is reached.

G. Improving the unfeasibility

A configuration is feasible if the investment proposal value (v^c) is equal to zero. Otherwise the configuration is unfeasible. The first case does not mean that the configuration is optimal. Additionally this configuration must accomplish the electrical constraints of the AC model of the network. When the offspring is unfeasible and it has already passed through the mechanisms of selection, recombination and mutation, the constructive heuristic algorithm presented in [14] is used to eliminate this unfeasibility. If the proposed configuration has a value of v^c lower than any current configuration, then, it is included in the population. Additionally it is necessary to verify if this configuration is present in the current population.

H. Improving optimality

When the offspring is feasible (with $v^c = 0$) and has already passed through the selection, recombination and mutation mechanisms, there might be unnecessary elements that increase the value of the objective function. To determine the elements to be removed in this configuration, these elements are ordered according to their cost and the costlier elements are removed since that the feasibility is preserved. In the case of several paralleled elements, the remove is performed one by one and preserving the feasibility.

I. Modification of the Population

In the CBAG only one feasible individual is created in every generational cycle. The new feasible offspring is incorporated to the current population according to the following criteria:

- The offspring substitutes the one with the worst fitness function, if and only if the offspring has a better fitness function than the worst individual of the current population.
- The offspring must be different form all the individuals of the current population, if not, the substitution is discarded.

J. Pseudocode of the specialized CHGA

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1) Specify the control parameters
2) Create the initial population
3) Perform selection: choose two parent configurations using tournament selection.
4) Perform recombination: recombine parents and choose the best configuration (offspring)
5) Perform mutation: apply the mechanism of mutation to the selected offspring.
6) Improving the unfeasibility
7) Improving optimality
8) Apply acceptation criteria: if the stopping criteria are satisfied, then stop, otherwise go back to step 3.
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The process stops if the incumbent (best solution found during the process) does not improve after a determined number of iterations, or when a maximum number of NLP problems have been solved.

IV. TESTS AND RESULTS

To test the efficiency of the proposed methodology, the Garver [20], and the IEEE 24 bus systems have been used.

A. Garver System

The system has 6 buses, 15 candidate lines for addition, a total demand of 760 MW, 190 MVAr and a maximum number of 5 lines that can be added per branch. For this network there are two study cases: with and without the original topology. The data of the transmission lines and buses are presented in the appendix. It was considered that only on buses 2, 4 and 5 could have variable and fixed capacitor banks to be installed. Three types of different fixed and variable capacitors banks that can be installed on the candidate buses were considered. In appendix I, data on fixed and variable capacitor buses are presented.

1) Garver system with the original topology

The solution found by the CBAG for this study case, has a total investment cost of v = 134.0 US$ and the following items should be added to the basis topology: a) transmission lines: $n_{2\text{-}3} = 1$, $n_{2\text{-}6} = 1$, $n_{3\text{-}5} = 1$, and $n_{4\text{-}6} = 2$, with an investment cost of v = 130.00 US$; and b) two fixed capacitor banks of type 1 ($q_{4\text{-}s1} = 2$) with an installed power of 38.38 MVAr in bus 4 and with an investment cost of v = 4.0 US$. The active and reactive power losses were 33.49 MW and 129.14 MVAr, respectively. Fig. 4 shows the operation point of the network for this study case.

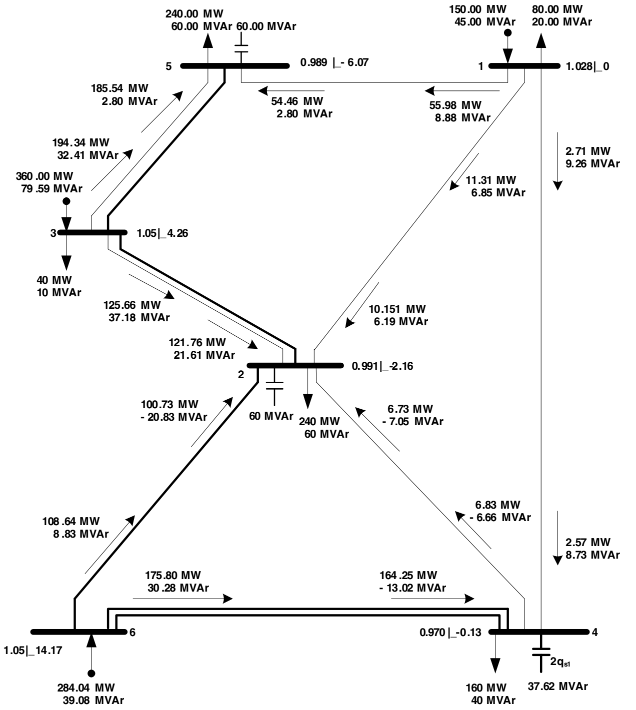

Fig. 4. Solution found by the CBGA for the Garver System with the original topology.

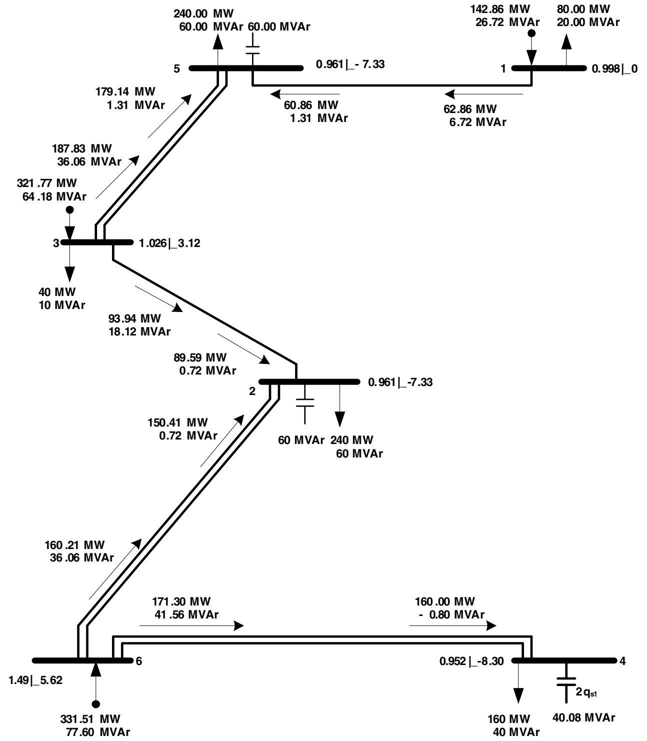

Fig. 5. Solution found by the CBGA for the Garver System without the original topology.

2) Garver system without the original topology

The solution found by the CBAG has an investment cost of v = 205.0 US$ and the following elements must be added to the basis topology: a) transmission lines: n_{1-5} = 1, n_{2-3} = *1*, n_{2-6} = 2, n_{3-5} = 2, and n_{4-6} = 2 with an investment cost of v = 200.0 US$; b) two fixed capacitor banks of type 1 (q_{4-s1} = *2*), with an installed power of 36.28 MVAr, and one of type 3 (q_{4-s3} = *1*) with an installed power of 4.53 MVAr, both in bus 4, with an investment cost of v = 5.0 US. The real and reactive power losses are 35.18 MW and 135.55 MVAr, respectively. Fig. 5 presents the operation point of the network for this study case.

B. IEEE 24 Buses System

This network contains 24 buses, 41 lines, a total demand of 8550 MW, and a maximum of 3 lines can be added per branch, the data of the network can be accessed in [21], and the data of the fixed and variable capacitor banks used in this work is presented in Appendix II. It was considered that only in buses 3-6, 8-12, 14, 17, 19 and 20 can variable and fixed capacitors be installed.

The solution found by the AGCB for this network, has an investment cost of v = US$ 55.2 million and the following elements must be added to the basis topology: a) transmission lines: n_{6-10} = 1, and n_{7-8} = *2*, with an investment cost of v = US$ 48.0 million; and b) a type 1 fixed capacitor with a power of 222.62 MWAr (q_{3-s1} = 1), and one of type 2 with a power of 57.31 MVAr (q_{3-s2} = 1), both in bus 3. Three fixed capacitor with power of 147.45 MVAr (q_{9-s2} = 3), in bus 9. Two type 1 capacitors with a power of 445.01 MVAr (q_{12-s1} = 2), and three of type 2 with a power of 166.88 MVAr (q_{12-s2} = 1), in bus 12. A type 1 capacitor with a power of 220.48 MVAr (q_{24-s1} = 1), and one type 2 capacitor with a power of 55.12 MVAr (q_{24-s2} = 1), in bus 24. With a total investment cost of v = US$ 7.2 million. The total reactive power generation injected by all the capacitor banks is 1314,87 MVar. The real and reactive power losses are 278.85 MW and 1766.08 MVAr, respectively.

V. COMPARATIVE ANALYSIS OF RESULTS

In reference [14] the TNEP problem using the integrated AC model of the network was solved using CHA, with the following results:

1. *Garver system with the original topology:* in this system the total investment cost was v = 138.50 US$, with a cost of transmission line installation of v = 130.00 US$, and a cost of fixed and variable capacitor banks of v = 8.5 US$
2. *Garver system with the original topology:* for this system the total investment cost is v = 214.00 US$, with a cost of transmission line installation of v = 201.00 US$, and a cost of fixed and variable capacitor banks of v = 13.00 US$.
3. *IEEE of 24 Buses System:* for this system the total investment cost is v = 90.50 US$, with a cost of transmission line installation of v = 86.00 US$, and a cost of fixed and variable capacitor banks of v = 4.50 US$.

It can be noted that the results of this paper, using a specialized genetic algorithm, are better when compared with those presented in reference [14] in which a constructive heuristic algorithm was employed. In the first two cases involving the Garver system with and without the original topology, the solutions obtained with the CBGA and the CHA had many elements in common, resulting in similar proposals barely improved by the CBGA. However, for the IEEE 24 bus test system there were remarkable differences between the two techniques. In spite of the fact that both techniques found an equal number of transmission lines to be added to the system, it was observed that the location of these lines was better when using the CBGA. It is worth to notice that the cost of the transmission lines in this last case was US$ 48 million as compared with US$ 86 million proposed by the CHA. This shows a quite important reduction in the investment cost. However, as a trade-off, it was necessary a higher power injection of the capacitors. Despite of this, the investment proposal found by the CBGA was still cheaper.

VI. CONCLUSIONS

In this paper a methodology to solve the STTNEP problem has been proposed. Its main contribution is the use of the integral AC model of the power system what makes possible to consider transmission lines, transformers and fixed and variable capacitor banks as planning elements. Among the advantages of using the integrated AC model of the network are: a) the possibility of active and reactive power planning in one single stage and b) the active and reactive losses can be optimally found as a sub-product of the solution of the NLP problem.

A specialized genetic algorithm is used to solve the STTNEP problem. The GA is based in the fundamental ideas of natural evolution (selection, recombination and mutation). The GA presented by Chu-Beasley to solve the generalized assignation problem was specially adapted to solve the expansion planning problem. The specialized GA presented in this paper has several advantages that make it a very competitive algorithm and within these advantages one can point out the preservation of diversity of all individuals in the population and the avoiding of homogeneity among these individuals.

The results obtained with this GA are better than those obtained with a constructive heuristic algorithm.

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APPENDIX I

Data of buses, lines and fixed and variable compensation banks, for the Garver network, are presented.

TABLE I
Data of the Garver system with the original topology

Data of buses

Bus	Type	P_D [MW]	Q_D [Mvar]	P_G^{max} [MW]	P_G^{min} [MW]	Q_G^{max} [Mvar]	Q_G^{min} [Mvar]	bsht
1	Vθ	80	20	150	0	48	-10	-
2	PQ	240	60	-	-	-	-	60
3	PV	40	10	360	0	101	-10	-
4	PQ	160	40	-	-	-	-	-
5	PQ	240	60	-	-	-	-	60
6	PV	0	0	600	0	183	-10	-

Data of lines

Bus	R_{ij} (p.u)	X_{ij} (p.u)	b_{ij}^{sh} (p.u)	C_{ij} [US$]	S_{ij}^{max} [MW]	n_{ij}^{o}	n_{ij}^{max}
1 – 2	0.10	0.40	0.00	40	100	1	5
1 – 3	0.09	0.38	0.00	38	100	0	5
1 – 4	0.15	0.60	0.00	60	80	1	5
1 – 5	0.05	0.20	0.00	20	100	1	5
1 – 6	0.17	0.68	0.00	68	70	0	5
2 – 3	0.05	0.20	0.00	20	100	1	5
2 – 4	0.10	0.40	0.00	40	100	1	5
2 – 5	0.08	0.31	0.00	31	100	0	5
2 – 6	0.08	0.30	0.00	30	100	0	5
3 – 4	0.15	0.59	0.00	59	82	0	5
3 – 5	0.05	0.20	0.00	20	100	1	5
3 – 6	0.12	0.48	0.00	48	100	0	5
4 – 5	0.16	0.63	0.00	63	75	0	5
4 – 6	0.08	0.30	0.00	30	100	0	5
5 – 6	0.15	0.61	0.00	61	78	0	5

TABLE II
Data on the Fixed Compensation Banks

Type	b_{shs} [MVAr]	n_{qsm}	c_{qs} [US$]
1	20	5	2.0
2	-20	5	2.0
3	5	5	0.5

TABLE III
Data on the Variable Compensation Banks

Type	q_{omi} [MVAr]	q_{oma} [MVAr]	n_{qom}	c_{qo} [US$]
1	-10	10	5	2.0
2	-20	20	5	4.0
3	-50	50	5	10.0

APPENDIX II

Presentation of the data on the variable and fixed compensation banks for the IEEE network of 24 buses.

TABLE IV
Data on the Fixed Compensation Banks

Tipo	b_{shs} [MVAr]	n_{qsm}	c_{qs} [million US$]
1	200	5	1.2
2	50	5	0.3
3	-50	5	0.3

TABLE V
Data on the Variable Compensation Banks

Tipo	q_{omi} [MVAr]	q_{oma} [MVAr]	n_{qom}	c_{qo} [million US$]
1	-300	0	5	6.0
2	-150	600	5	8.0
3	-500	500	5	9.0

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