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A Combinatorial Approach for Transmission Expansion & Reactive Power Planning

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Abstract--**A metaheuristic technique for solving short-term transmission network expansion planning and reactive power planning in regulated power system using the AC model is presented. The problem is solved using Real Genetic Algorithm (RGA). Fitness function is calculated using cost of each configuration as well as an AC optimal power flow in which the minimum reactive generation of new VAR sources and active power losses are as objectives. New VAR sources are defined for each topology through an L indicator. This indicator tries to find week buses for reactive allocation. In this way the circuit capacity increases and the cost of installation can be decreased. The results of the test systems show the capability of the method.**

Index Terms-- **L indicator, Reactive Power Planning, Real Genetic Algorithm, Transmission Expansion Planning, VAR sources, weak Buses**.

I. Nomenclature

$\boldsymbol{c}$ circuit costs vector

$\boldsymbol{n}$ added circuit vector

$\boldsymbol{N}$ diagonal matrices containing vector $\boldsymbol{n}$

$\boldsymbol{N}^0$ diagonal matrices containing the existing circuits

K_e converted real power to cost

D system operating time

P_{Loss} total real power loss

$f(Q_G)$ cost function of VAR sources

Q_G MVAr size of VAR sources vector

v_0 investment on new transmission line

v_1 total cost of active power losses and VAR sources

$\bar{\boldsymbol{n}}$ vector of maximum number of circuits that can be added

θ phase angle vector

$\boldsymbol{P}_G$ existing real power generation vector

$\boldsymbol{Q}_G$ existing reactive power generation vector

$\boldsymbol{P}_D$ real power demand vector

$\boldsymbol{Q}_D$ reactive power demand vector

$\boldsymbol{V}$ voltage magnitude vector

$\bar{\boldsymbol{P}}_G$ vector of maximum limit of generation of real power

$\bar{\boldsymbol{Q}}_G$ vector of maximum limit of generation of reactive power

$\bar{\boldsymbol{V}}$ vector of maximum limit of voltage

$\underline{\boldsymbol{P}}_G$ vector of minimum limit of generation of real power

$\underline{\boldsymbol{Q}}_G$ vector of minimum limit of generation reactive power

$\underline{\boldsymbol{V}}$ vector of minimum limit of voltage

$\boldsymbol{S}^{\text{from}}$ apparent power flow vector "from" the bus

$\boldsymbol{S}^{\text{to}}$ apparent power flow vector "to" bus

$\bar{\boldsymbol{S}}$ Maximum apparent power flow vector

k load bus

Ω_l set of all load buses

c_{0k} installation cost of VAR source at bus k.

c_{1k} unit cost of VAR source at bus k

Q_{Gk} MVAr size of VAR source at bus k

Y_{ij} magnitude of the admittance of the line connected between bus i and bus j

ϕ_{ij} angle of the admittance of the line connected between bus i and bus j

V_i magnitude of voltage at bus i

θ_i angle of voltage at bus i

N_B set of all buses

θ_{ij} difference in phase angle between buses i and j

g_{ij} conductance of the transmission line or transformer ij

b_{ij} susceptance of the transmission line or transformer ij

b_{ij}^{sh} shunt susceptance of the transmission line or transformer ij

b_i^{sh} shunt susceptance at bus i

V_L, I_L voltage and current vectors at the load buses

V_G, I_G voltage and current vectors at the generator buses

H hybrid representation of transmission system

$Z_{LL}, F_{LG}, K_{GL}, Y_{GG}$ sub-matrices of the hybrid matrix H.

L voltage stability limit indicator

V_{0j} an equivalent generator comprising the contribution from all generators.

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S_{jcorr} contributions of the other loads in the system to the index evaluated at the node j.
N individuals in the population
P position of each individual in the population.
P_1, P_2 two parents
O_1, O_2 two offspring
$\lambda, \lambda_1, \lambda_2$ randomly generated numbers
a_k lower band of P_k
b_k upper band of P_k
r uniform random number between zero and one
t number of current generation
T maximum number of generation
c a parameter determining the degree of non-uniformity
$h_i(f(\overline{X}))$ strictly monotonically decreasing function
w_1, w_2, w_3 tuning weights
d_V voltage deviation from Voltage limits
d_G power generation deviation from power generation limits
d_S branch flow deviation from branch flow limits

II. INTRODUCTION

The objective of the power system transmission expansion and reactive power planning problem is to determine 'where', 'how many' and 'when' new devices, Transmission lines, reactive power sources, transformer, must be added to a network in order to make its operation viable for a pre-defined horizon of planning, at a minimum cost The system network of the base year, the candidate circuits, the power generation and power demand of the planning horizon and investment constraints are the basic data for the problem.

In the traditional approach, the long-term transmission network planning problem is solved first, using simplified system models. The transportation model, the hybrid model, the linear disjunctive model, DC model [1], among others, have been used in this first phase and the problem is solved both by classical optimization techniques [2–5] and by meta-heuristics, such as simulated annealing [6], genetic algorithms [7], tabu search [8], GRASP [9]. In a subsequent stage, the expansion plan obtained is checked for other operational constraints (reactive power planning) where the AC load flow and stability analysis are the basic tools.

The use of the (complete) AC model of the transmission network in the first phase is incipient and there are practically a few technical literatures on the subject[10]. The use of the DC model has the following disadvantages, among others: (1) the transmission expansion planning problem must be separated from the reactive power allocation problem; (2) it is frequently necessary to reinforce an expansion plan obtained using the DC model, when an operation with the AC model is considered; and (3) the difficulty of taking into account the power losses in the initial phase of the planning.

In this paper, an AC integrated transmission network expansion planning (real and reactive power planning) is used. The use of this model has advantages, such as (1) efficiently allocating reactive power sources during the planning and consequently decreasing the cost of installation of new lines (2) using an integrated mathematical model that allows transmission network expansion planning problems and the optimal allocation of reactive power (simultaneously, in a unique stage), dispensing the use of simplified models such as the DC model; (3) incorporating the determination of the transmission system's precise real losses in a trivial way and as a sub-product of the optimization process; (4) incorporating other nonlinear operation characteristic devices in the TNEP problem, for example, the FACTS controllers; and (5) the possibility of carrying out other types of studies, after solving the AC integrated TNEP problem, for example: voltage stability, nodal analysis, transient stability analysis and so on.

In this work, a Real Genetic Algorithm (RGA) can be used to solve the planning problem using the AC model transmission system. The Genetic Algorithm (GA) technique is suitable for multi-objective optimization problems resulting into good solutions whilst maintaining low computational costs. Similar to other metaheuristics solutions, the GAs are more efficient in terms of computational time and may find a better solution than the other classical optimization methods such as: Benders decomposition (BD) and Branch and Bound (BB) methods[11]. GA was initially formulated by Holland (1975) [12]. It is based on the principle of natural selection and the theory of evolution in which adaptable individuals have a better chance to survive. RGA is used for identifying potential lines for installation. For each combination of the lines (individuals) an indicator is used to identify week buses, for allocating reactive power sources, while the lines and reactive power sources embedded into initial network an AC OPF is solved the Objective of this problem is minimum active power losses and minimum reactive power sources. Another Index is used for identifying potential lines, in terms of cost and the amount of satisfaction of constraints, this index is used for fitness evaluation of each individual in RGA.

III. THE MATHEMATICAL MODELING

The mathematical model for transmission expansion planning and reactive power planning problem can be formulated as:

$$\min v_0 = c^T n \quad (1)$$

$$\min v_1 = K_e P_L D + f\ (Q_G) \quad (2)$$

s.t.

$$P(V, \theta, n) - P_G + P_D = 0 \quad (3)$$

$$Q(V, \theta, n) - Q_G - Q_G{}^0 + Q_D = 0 \quad (4)$$

$$\underline{P}_G \le P_G \le \overline{P}_G \quad (5)$$

$$\underline{Q}_G \le Q_G \le \overline{Q}_G \quad (6)$$

$$\underline{Q}_G{}^0 \le Q_G{}^0 \le \overline{Q}_G{}^0 \quad (7)$$

$$\underline{V} \le V \le \overline{V} \quad (8)$$

$$(N+N^0)S^{from} \le (N+N^0)\overline{S} \qquad (9)$$

$$(N+N)S^{to} \le (N+N^0)\overline{S} \qquad (10)$$

$$0 \le n \le \overline{n} \qquad (11)$$

n integer and θ unbounded

Where c and n represent the circuit cost vector that can be added to the network and the added circuit vector, respectively. N and N^0 are diagonal matrices containing vector n and the existing circuits in the base configuration, respectively. K_e is the converted real power to cost, D is the system operating time. P_L is the total power loss to be minimized and can be defined as follows:

$$P_L = \sum [V_i^2 + V_j^2 - 2V_iV_j \cos(\theta_i - \theta_j)]Y_{ij} \cos\varphi_{ij} \qquad (12)$$

V_i and θ_i are the magnitude and angle of voltage at bus *i*, and Y_{ij} and φ_{ij} are the magnitude and angle of the admittance of the line from bus *i* to bus *j*.

$f(Q_G)$ is the installation cost of new reactive power sources that can be defined as follows:

$$f(Q_G) = \sum_{k \in \Omega_l} (c_{0k} + c_{1k} Q_{Gk}) \qquad (13)$$

Where: Q_G is the Vector of all new VAR sources. $k \in \Omega_l$ represents load buses while Ω_l is the set of all load buses, c_{0k} and c_{1k} are the installation costs and unit costs for a VAR source at bus k respectively. Q_{Gk} is the MVAr size of a VAR source installed at bus k.

v_0 is the investment due to the addition of circuits to the networks, v_1 is the total cost of active power losses and new reactive power sources. $\overline{n}$ is the vector containing the maximum number of circuits that can be added. θ is the phase angle vector. P_G and $Q_G{}^0$ are the existing real and reactive power generation vectors. P_D and Q_D are the real and reactive power demand vectors; V is the voltage magnitude vector; $\overline{P}_G, \overline{Q}_G{}^0$, $\overline{Q}_G$ and $\overline{V}$ are the vectors of maximum limits of generation of real power, reactive power of existing and new sources and voltage magnitudes, respectively; $\underline{P}_G, \underline{Q}_G{}^0$, $\underline{Q}_G$ and $\underline{V}$ are the vectors of minimum limits of generation of real power, reactive power of existing and new sources and voltage magnitudes, respectively; 105 and 95% of the nominal value are used for the maximum and minimum voltage magnitude limits, respectively; S^{from}, S^{to} and S are the apparent power flow vectors (MVA) in the branches in both terminals and their limits.

The limits for real power is represented by 5, for reactive power of new and existing sources by (6) and (7) respectively; and for the voltage magnitudes by (8). The limits (MVA) of the flows are represented by (9) and (10). The constraints in the capacities of the added circuits are represented by (11). Equations (3) and (4) represent the conventional equations of AC power flow considering n, the number of circuits (lines and transformers), as variables. The elements of vectors $P(V,\theta,n)$ and $Q(V,\theta,n)$ are calculated by (14) and (15), respectively.

$$P_i(V,\theta,n) = V_i \sum_{j \in N_B} V_j [G_{ij}(n)\cos\theta_{ij} + B_{ij}(n)\sin\theta_{ij}] \qquad (14)$$

$$Q_i(V,\theta,n) = V_i \sum_{j \in N_B} V_j [G_{ij}(n)\sin\theta_{ij} - B_{ij}(n)\cos\theta_{ij}] \qquad (15)$$

Where $i, j \in N$ represent buses and N is the set of all buses, ij represents the circuit between buses i and j. $\theta_{ij} = \theta_i - \theta_j$ represents the difference in phase angle between buses i and j. The bus admittance matrix elements (G and B) are

$$\boldsymbol{G} = \begin{Bmatrix} G_{ij}(\boldsymbol{n}) = -(n_{ij}g_{ij} + n_{ij}^0 g_{ij}^0) \\ G_{ii}(\boldsymbol{n}) = \sum_{j \in \Omega_l} (n_{ij}g_{ij} + n_{ij}^0 g_{ij}^0) \end{Bmatrix} \qquad (16)$$

$$\boldsymbol{B} = \begin{Bmatrix} B_{ij}(\boldsymbol{n}) = -(n_{ij}b_{ij} + n_{ij}^0 b_{ij}^0) \\ B_{ii}(\boldsymbol{n}) = b_i^{sh} + \sum_{j \in \Omega_l} [n_{ij}(b_{ij} + b_{ij}^{sh}) \\ + n_{ij}^0 (b_{ij}^0 + (b_{ij}^{sh})^0)] \end{Bmatrix} \qquad (17)$$

Where V_i represents the set of all buses directly connected to bus i; g_{ij}, b_{ij} and b_{ij}^{sh} are the conductance, susceptance and shunt susceptance of the transmission line or transformer ij (if ij is a transformer $b_{ij}^{sh} = 0$), respectively, and b_i^{sh} is the shunt susceptance at bus i. Note that in (16 and 17), the possibility of a different transmission line or transformer being added in parallel with an existing one (in the base case) is considered, although the equivalent circuit parameters may be different. It should be noted that off-nominal transformer taps are not considered and in this case both transmission lines and transformers have similar equivalent circuits. The present model does not consider the phase shifters. Elements (ij) of vectors S^{from} and S^{to} of (9) and (10) are given by:

$$S_{ij}^{from} = \sqrt{(P_{ij}^{from})^2 + (Q_{ij}^{from})^2}$$

$$P_{ij}^{from} = V_i{}^2 g_{ij} - V_iV_j(g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij})$$

$$Q_{ij}^{from} = -V_i{}^2(b_{ij}^{sh} + b_{ij})$$

$$-V_iV_j(g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij})$$

$$S_{ij}^{to} = \sqrt{(P_{ij}^{to})^2 + (Q_{ij}^{to})^2}$$

$$P_{ij}^{to} = V_j^{\,2} g_{ij} - V_i V_j (g_{ij} \cos\theta_{ij} - b_{ij} \sin\theta_{ij})$$

$$Q_{ij}^{to} = -V_j^{\,2} (b_{ij}^{sh} + b_{ij}) + V_i V_j (g_{ij} \sin\theta_{ij} + b_{ij} \cos\theta_{ij})$$

The investment n, the number of circuits added in branch ij, is the most important decision variable and a feasible operation solution of the electric power system depends on its value. The remaining variables only represent the operating state of a feasible solution. For a feasible investment proposal, defined through specified values of n, one can have several feasible operation states.

IV. WEAK BUS IDENTIFICATION

An indicator L is used for identifying weak buses [13]. The indicator uses information of the normal load flow, the advantages of the method lies in the simplicity of numerical calculation. Since the nature of calculation is non-iterative, the computation time is short. The indicator L is a quantitative measure for the estimation of the distance of the actual state of the system to the stability limit. The local indicators L permit the determination of those nodes from which a collapse may originate. Weak busses can be identified through this Index. For calculating L the transmission system is represented using a hybrid representation, by the following set of equations:

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = H \begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (18)$$

V_L, I_L are the voltage and current vectors at the load buses V_G, I_G are the voltage and current vectors at the generator buses $Z_{LL}, F_{LG}, K_{GL}, Y_{GG}$ are the sub-matrices of the hybrid matrix H.

The H matrix can be evaluated from the Y bus matrix by a partial inversion, where the voltages at the load buses are exchanged against their currents. This representation can then be used to define a voltage stability indicator at the load bus, namely L_j which is given by,

$$L_j = \left| 1 + \frac{v_{0j}}{v_j} \right| \quad (19)$$

Where

$$v_{0j} = -\sum_{i \in G} F_{ji} V_i \quad (20)$$

The term V_{0j} is representative of an equivalent generator comprising the contribution from all generators.

The index L_j can also be derived and expressed in terms of the power terms as the following.

$$L_j = \left| \frac{\overset{*}{S}_{j+}}{Y_{jj} + V_j^{\,2}} \right| \quad (21)$$

Where

$$S_{j+} = S_j + S_{jcorr}$$

*indicates the complex conjugate of the vector

$$S_{jcorr} = \left(\sum_{\substack{i \in Loads \\ i \neq j}} \frac{\overset{*}{Z}_{ji}}{\overset{*}{Z}_{jj}} \frac{S_i}{V_i} \right) V_j \quad (22)$$

$$Y_{jj+} = \frac{1}{z_{jj}} \quad (23)$$

The S_{jcorr} complex power term component represents the contributions of the other loads in the system to the index evaluated at the node j.

V. REAL GENETIC ALGORITHM

Mathematically, GA can be considered as a technique for optimization combinatorial large and complex problems with high probability of finding the global optimum among many local optimal solutions. RGA has the following special characteristics:

- It does not require any binary coding and decoding stages;
- It is faster and more accurate than binary GA;

The proposed method comprises of five stages i) problem codification, ii) selection, iii) recombination, iv) Mutation, and vi) fitness evaluation, each explained in the following sections.

A. Problem codification

One of the most important factors in representing a candidate solution in the proposed method is codification. A proper codification may prevent complications in the implementation of the RGA algorithm. The individual is a solution proposal for the planning problem, or better, is the topology made up of all the lines added to the system corresponding to an investment proposal. In the AC TNEP, the individual of the RGA is represented by a vector size. Each vector is constructed the number of new lines that are proposed to be added to respective branches . Each member can vary its value from zero to the maximum number of lines. Thus, in the codification shown in Fig. 1, branch 2–6 has two new lines; branch 3–5 has one new line, etc.

1-2	1-4	3-5	2-6	4-6
0	0	1	2	1

Fig. 1. Codification proposal

The method proposed in this paper does not demand that the characteristics of the lines between two buses be equal, they can work with various types of circuits between two buses. In this case, the lines are selected similar to the pervious form of line. The number of individuals in the RGA population, for the transmission network expansion problem, depends on the dimension of the system. Similar to ordinary GA, RGA operators are: selection, recombination and mutation. These terms are explained in the following sections.

B. Selection

The chromosome selection procedure is based on a random process where one of the selection operators is known as the roulette-wheel. Individual chromosomes are mapped to the adjacent segments of a line. The length of each segment on this line corresponds to the levels of fitness (i.e. fitness values) of each individual. As part of the trial process a random number is generated and the individual chromosome position on the line that corresponds to the random number is selected. This technique is analogous to a roulette wheel where each slice is proportional in size to the fitness value. For chromosome selection we use ranking process. In the selection ranking process, the population is sorted in accordance with their corresponding fitness values. The fitness levels assigned to each individual chromosome only depends on its ranking position and not on the actual fitness value. It is assumed that the number of individuals in the population is N, while P is the position of each individual in the population.

Equation 24 can be used to calculate the rank of each individual. In this equation, minimum and maximum values of P are respectively 1 and N. SP is a random number between 1 and 2 [14].

$$Rank(P) = 1 - SP + \frac{2(SP-1)(P-1)}{N-1} \qquad (24)$$

C. Recombination

At the recombination stage next generation is created. This process makes it different from typical binary Genetic Algorithm approach. There are three kinds of recombination criteria [14] adopted in this process, denoted by following equations.

$$O_1 = \lambda P_1 + (1-\lambda)P_2$$
$$O_2 = \lambda P_2 + (1-\lambda)P_1 \qquad \lambda \in \{0,1\}$$
$$O_1 = \lambda_1 P_1 + (1-\lambda_1)P_2$$
$$O_2 = \lambda_2 P_2 + (1-\lambda_2)P_1 \qquad \lambda_1, \lambda_2 \in [-0.25, 1.25]$$
$$O_1 = \lambda P_1 + (1-\lambda)P_2$$
$$O_2 = \lambda P_2 + (1-\lambda)P_1 \qquad \lambda \in [\text{-}0.25, 1.25]$$

Where P_1, P_2 are the two parents, O_1, O_2 are their two offspring and λ_1, λ_2 are two randomly generated numbers. A typical individual chromosome with two genes, in which two parents can merge based on three forms that are shown in Fig. 2 (a, b and c).

The recombination process shown in Fig. 2 (a) generates the offspring that is located on the corners of the hypercube defined by the parents. The line recombination shown in Fig. 2 (b) can generate any offspring by the parents on the specified line. Fig. 2 (c) shows the intermediate recombination capable of producing any point within the hypercube that is slightly larger than the one defined by the parents. The line recombination is similar to intermediate recombination, except that only one λ value is used for all variables [14, 15].

D. Mutation

The reason for the mutation stage in the process is to introduce artificial diversification in the population and to avoid premature convergence to a local optimum. Arithmetic mutation operators are dynamic or non-uniform mutations that have been successfully used in a number of studies [16].

In order to achieve a high degree of precision in the proposed method a dynamic mutation is designed for fine-tuning the mutations. This is to provide a degree of control of those mutations. For example, in the mutation process, if gene P_k is selected from parent P, then there is an equal chance that the resulting gene to be either of the following choices:

$$\begin{Bmatrix} O_K = P_K - r(P_K - a_K)(1 - \frac{t}{T})^c \\ O_K = P_K + r(b_K - P_K)(1 - \frac{t}{T})^c \end{Bmatrix} \qquad (25)$$

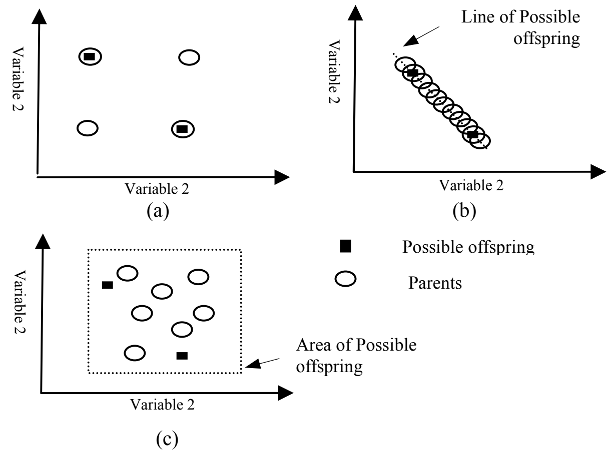

Fig. 2. Different Schemes of Recombination

E. Fitness Evaluation

The main objective in TNEP is to minimize the cost of installation new lines in such that all the constraints are satisfied we make our fitness evaluation upon this sentences i.e.

$$\text{Fitness} = -(w_0 v_0 + w_1 d_V + w_2 d_G + w_3 d_S) \qquad (26)$$

Where w_0, w_1, w_2 and w_3 are constant and can be set by decision maker, v_0 is the total cost of new lines and d_v, d_G and d_s are the sum of deviations from voltage bounds, power generation bounds and branches flow bounds respectively. RGA tries to maximize the fitness function. When the fitness value is equal to zero ,maximum value, it means that cost of installation is zero ($v_0 = 0$) and deviation from constraint is zero in another word all the variable are inside their bounds ($d_V = 0; d_G = 0; d_S = 0$)

VI. IMPLEMENTATION

The overall procedure of using RGA in Transmission expansion planning considering reactive power allocation is shown in Fig. 3, the steps to find optimum solution for TNEP is as following:

1. Initialize first generation at random

Each individual is chosen at random. As in Fig. 1 shows the data of an individual is the number and location of new lines. For the first Generation about 100 individual is chosen at random.

2. Feasibility checking

Each chromosome is checked in terms of cost. Those individuals that their investments are too high will be pruned.
3. the data of each individual, consisting number and location of new lines, read out and the new network is constructed.
4. AC power flow is solved for constructed network and L indicator is determined for each load bus, buses are ranked in terms of weakness, the more weak buses are chosen for allocating reactive power sources, the numbers of buses that can be assumed to install reactive power sources is depend on decision maker.

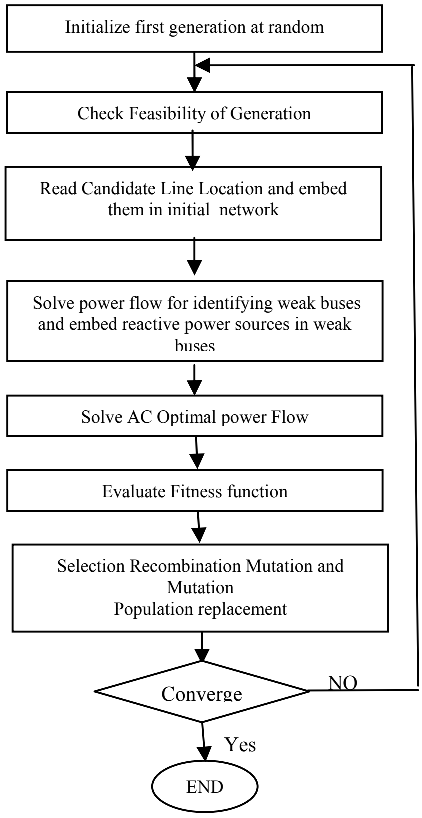

Fig. 3. Flowchart of the TNEP considering reactive power allocation with RGA

5. AC Optimal Power flow with real power and reactive power sources as an objective is solved for each individual. In this step the problem that is solved is as follows:

$$\min v_1 = K_e P_L D + f(Q_G)$$

s.t.

$$P(V,\theta) - P_G + P_D = 0$$

$$Q(V,\theta) - Q_G - Q_G{}^0 + Q_D = 0$$

$$\underline{P}_G \le P_G \le \overline{P}_G$$

$$\underline{Q}_G \le Q_G \le \overline{Q}_G$$

$$\underline{Q}_G{}^0 \le Q_G{}^0 \le \overline{Q}_G{}^0$$

$$\underline{V} \le V \le \overline{V}$$

$$S^{from} \le \overline{S}$$

$$S^{to} \le \overline{S}$$

θ Unbounded

When new lines embedded in the initial network there is no need to separate existing lines and new lines in formulation so In this formulation there is no integer variable and we just need to solve an AC OPF. Since the cost of new reactive power sources is one of the objectives of OPF new and existing reactive power sources must be separated in formulation. In the objective function reactive power sources and active power losses competes each other.

6. The results of OPF is used to calculate d_v, d_G and d_s, and their combination with the cost of installation lines makes the fitness function.

7. When OPF solved for the entire individual and fitness of each is calculated, the Selection, Recombination and Mutation of RGA carried out and New Generation of individual is constructed. When all the individuals are the same and there is no new individual and the process can be stopped, another stop criterion is the number of generation. In the implemented software the first criteria is used.

8. Depend on the convergence of RGA, stop criteria, the process will be stop or continued into step 2.

Since in the genetic algorithm new generation might consists of previous individuals, for speeding up the process a pool of all individual constructed, and for calculation the fitness function for repetitive individuals we do not carry out all calculation and just simply pull out the fitness value from the pool. It is clear for the new individuals all calculation carried out and finally their data and fitness function will insert to the pool.

VII. Illustrative Test

The algorithm was implemented in MATLAB. For the illustrative test, the Modified Garver 6-bus system was used. This system has six buses and 15 branches candidates, the total demand of 760 MW, 152 MVAr and maximum 5 lines can be added to each branch. The Garver system data is given in [10]. The main objective of the test was to show that active and reactive power planning can be carry out simultaneously. Four different tests have been carried out. Two different base cases have been used: Base case 1 – with the base topology proposed by Garver and Base case 2 – without the base topology proposed by Garver . For each case two tests are carry out, TNEP without reactive allocation and then TNEP with reactive power allocation.To implement RGA for optimum TNEP, a population with the size of 100 individual individuals is used, while mutation and mutation rates are 76 % and 3 % respectively the selection process would be terminated when there is no new individual in the population. In test 3 and 4 we consider that VAR fixed cost of installation is $c_0 = 100\$$ and VAR variable cost is 0.3 \$ / kvar also $k_e D$ is set to 1.

Test-1 Modified Garver system without reactive power allocation with Base case 1:

The algorithm is converged after 10 Generation, the planning process resulted in Line investment of US\$140000 and the following lines are added: $n_{2-6} = 2; n_{3-5} = 1; n_{4-6} = 2$

Active and reactive power losses are 12.292 MW and 122.92

Fig. 4 shows the complete results of the test.

Test-2 Modified Garver system with reactive power allocation with Base case 1:

For this test the final solution is found after 11 generation the planning process resulted in line investment of US$110000 and the following lines are added: $n_{2-6} = 1; n_{3-5} = 1; n_{4-6} = 2$. Active and reactive power losses are 13.925MW and 139.25Mvar and a total 43.7 reactive power source must be installed at bus 2 and bus 4. These buses are weak buses and can be defined by L indicator. Table I shows load buses in ascending order of L indicator. Fig. 5 shows the result of the test.

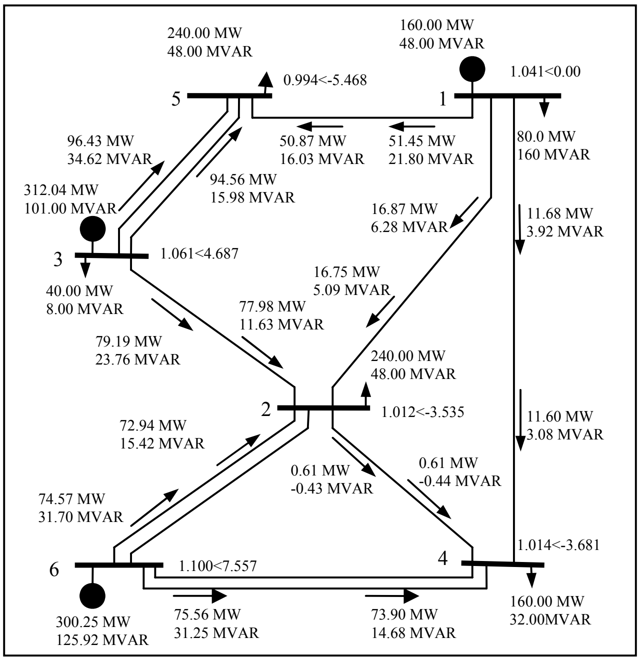

Fig. 4. Garver system without reactive power allocation with Base case 1

TABLE I

L INDICATOR FOR SYSTEM IN TEST-2

Bus	5	4	2
L Indicator	0.2882	1.3064	1.5058

Test-3 Modified Graver system without reactive power allocation with Base case 2:

This test is implemented considering no line is constructed. Only Generator and load buses are defined. The algorithm is converged after 12 Generation, the planning process resulted in line investment of US$200000 and the following lines are added: $n_{1-5} = 1; n_{2-3} = 1; n_{2-6} = 2; n_{3-5} = 2; n_{4-6} = 2$ Active and reactive power losses are 12.635MW and 126.35Mvar

Fig. 6 shows the complete results of the test.

Test-4 Modified Garver system with reactive power allocation with Base case2:

The final test is carried out considering no line is constructed and no new reactive power sources is installed just generator and loads are defined, we assume one of the buses can be allocated for reactive power installation, RGA converge after 13 generation with us$190000 Line investment as following: $n_{1-5} = 1; n_{2-3} = 2; n_{2-6} = 1; n_{3-5} = 2; n_{4-6} = 2$. The total active and reactive power losses are: 13.306MW and 133.06Mvar. in comparison with the test-2 one line is added between bus 2-3 and one is omitted between 2-6 and with Installation of a total 18.59 Mvar at bus 2, 10000us$ in transmission lines is saved. The results of this test are shown in Fig. 7. Table II shows the weak bus indicator for each bus.

TABLE II

L INDICATOR FOR SYSTEM IN TEST-4

bus	4	5	2
L Indicator	0.3161	0.4033	1.5884

The optimal solution for the last four examples proposed in [10]. For all examples the solution quality is approved, in example 1 the active power losses is decreased, in example 3 the line investment decreased from 260000$ to 250000$, in example 2 and 4 the amount of VAR sources is decreased. Table III shows the total cost including line cost, VAR cost and Power losses cost for each test. Comparing Test-1 with test-2 and test 3 with test 4 we can found that when VAR source allocation is carryout during planning process the total cost will be decreased significantly.

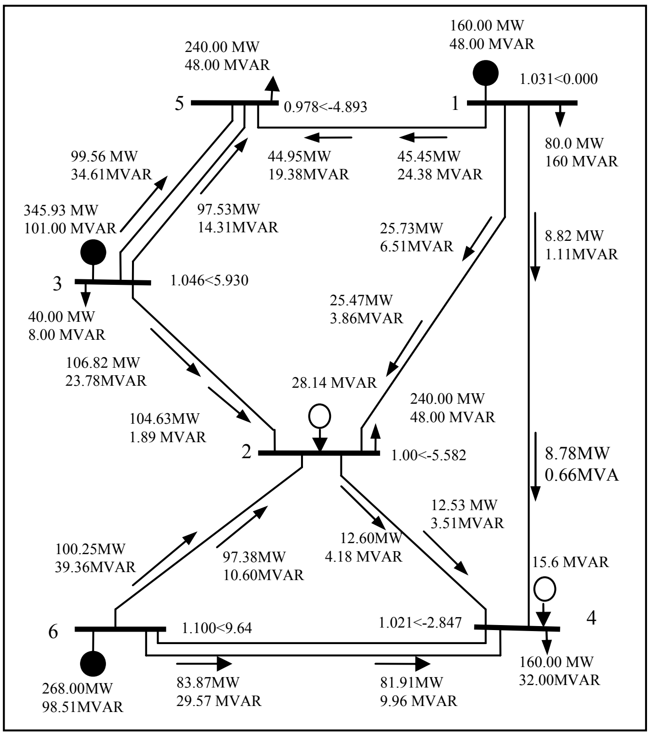

Fig. 5. Modified Garver system with reactive power allocation with Base case1

VIII. CONCLUSIONS

A mathematical model and a metaheuristic technique for solving the TNEP problem and reactive power planning using an AC model for the transmission system are presented in this paper. The main contribution of this paper is to show that active and reactive power planning can be carry out simultaneously. A real Genetic Algorithm was used to solve the problem. For each individual, combination of new lines, An L indicator is used base on the power flow to help the allocation of reactive power sources. Fitness function is calculated from the investment of new lines, in combination with the results of AC OPF. AC OPF tries to minimize reactive power losses and the amount of new reactive power sources. A set of tests and a general analysis of the results are presented. Results with the Garver system shows the performance of the proposed model.

TABLE III

TOTAL INVESTMENT

costs	Test 1	Test2	Test3	Test4
Power Losses	12292	13925	12635	13306
Line	140000	110000	200000	190000
Var source	……..	13310	………	5656
Total	152292	137235	212635	208962

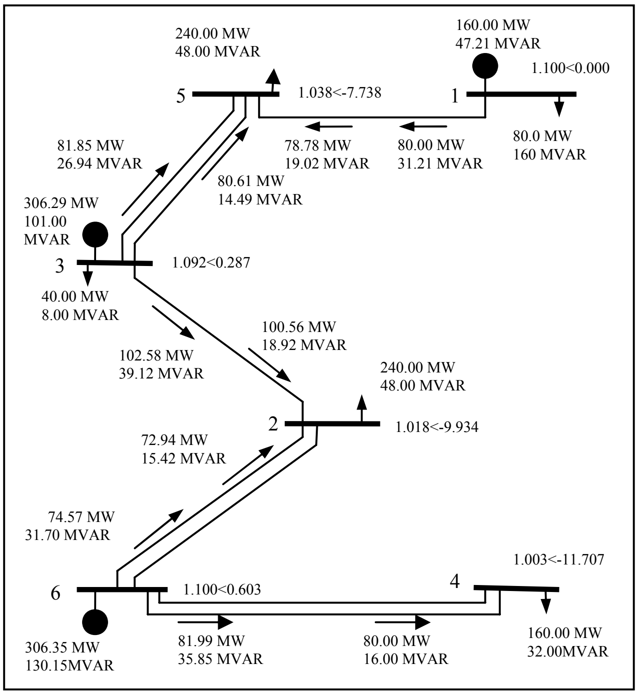

Fig. 6. Modified Graver system without reactive power allocation with Base case 2

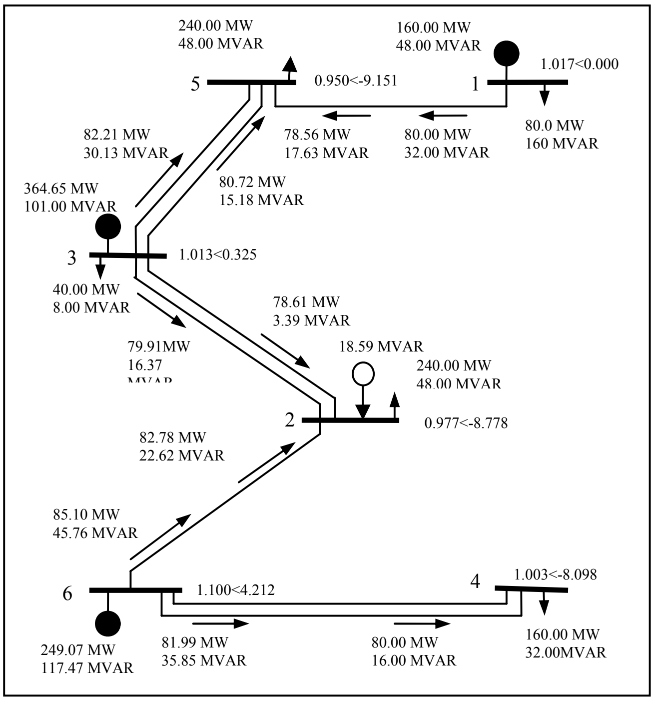

Fig. 7. Modified Garver system with reactive power allocation with Base case2.

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