Abstract: This paper proposes an integrated approach of Genetic Algorithms, Tabu Search and Simulated Annealing for multi-stage (dynamic) transmission network expansion planning. The proposed algorithm integrates the most interesting and best features of the above individual algorithms. The efficiency and reliability of the proposed algorithm is proved with the modified Garver’s 6 bus network. Finally, a real-world application (Sri Lanka transmission network) of the integrated algorithm is presented for multi-stage transmission expansion planning.

Keywords: Transmission expansion planning, Multi-stage planning, Genetic Algorithms, Tabu Search, Simulated Annealing

1. INTRODUCTION

A Transmission Expansion Planning (TEP) model determines the timing and the type of the new transmission facilities that should be added to an existing network in order to ensure adequate transmission network capacity with future generation options and load requirements [1].

A detailed definition of the transmission expansion planning problem can be found in [2]. The TEP problem is a hard multi-criteria combinatorial optimization problem. The key objective is to minimize the long range capital investment costs and operating costs while maintaining adequate level of reliability and service quality. This planning problem is generally handled by an optimization model. Transmission expansion planning models are generally categorized as (1) Heuristic Models (2) Single-stage optimization Models (3) Time-phased/Multi-stage Optimization Models. Different authors have suggested different approaches to cope with the TEP problem both under single stage and multi-stage planning.

The techniques used in handling TEP problem can be divided in two categories:

- Techniques based on mathematical programming, such as linear programming [3, 5], dynamic programming [1], and sensitivity analysis [6, 7]

- Techniques based on non-convex optimization approaches such as Genetic Algorithms (GA) [8], Simulated Annealing (SA) [9, 10], hybrid approaches: neural networks hybridized with genetic algorithms [11], hybridized approach of Simulated Annealing (SA), Genetic Algorithms (GA) and Tabu Search (TS) [12].

Usually, the network topologies proposed by those planning models will be analyzed and improved by technical tools such as load flow, short circuit and stability studies.

In this paper we present an integrated algorithm of three non-convex (GA, SA and TS) optimization approaches. It combines the most interesting features of each one of the three approaches. These are all meta-heuristics and the interesting characteristic is that GA and SA exhibit proved probabilistic convergence characteristics. We are therefore not using probabilistic models, but adopting probabilistic tools.

The paper outline is as follows. First, we present a review of three non-convex approaches (GA, SA and TS) and proposed integrated algorithm. Second, the paper describes the formulation of TEP problem along with optimal capacitor placement. Third, the results of validation tests and a real world application are summarized. Finally some relevant conclusions are outlined.

It must be said that a complete TEP model should also include a reliability model. This has not been dealt with in this paper, because the main concern has been to prove the effectiveness of the new algorithm proposed. Furthermore, the new context of a regulated market of power generation is living side by side, in many countries and regions, namely in Europe, with monopolistic operation of the transmission system, and there is not a clear unanimous view on how reliability should be accounted for, in the new frame of events. Therefore, we have opted to keep out of this problem and to avoid that a discussion on the adequacy of the reliability model would blur the main achievements reported in the paper.

2. REVIEW OF COMBINATORIAL OPTIMIZATION METHODS

Genetic Algorithms

Genetic Algorithms (GA) are search and optimization algorithms of probabilistic convergence based on natural evolution and genetics [13]. GA optimize a function (objective) or a process with respect to encoded problem variables (individuals). Initially, the algorithm generates randomly a population of encoded finite-length strings of bits called “Chromosomes”. Each Chromosome represents a possible solution to the problem. Thereafter each Chromosome is evaluated by the objective function (called “fitness function”). The genetic algorithm determines which individuals should survive, which should reproduce, and which should be eliminated. When a GA is run, the Evaluation and Reproduction operators work together to produce the evolution of a population of chromosomes [14]. New populations are generated by the evolution mechanism comprising selection, crossover, fitness proportionate reproduction and mutation.
3. THE PROPOSED INTEGRATED ALGORITHM

The proposed integrated algorithm combines some of the main features of the GA, TS and SA algorithms. This was proposed in the literature [16] for unit commitment application. The main objective of using this algorithm is to improve the convergence speed as well as the quality of the final solution of the TEP problem. TS is implemented in the reproduction stage of the GA to generate some percentage of new members to the new population. This prevents falling into local minima and premature convergence of GA. A SA technique is employed in accepting the members of the new generation over the old generation. This ensures the higher probability of acceptance for good solutions.

Figure 1 depicts a schematic representation of the above algorithm.

4. PROBLEM FORMULATION

The dynamic transmission network expansion planning problem can be formulated as a minimization problem as described below.

Cost of transmission facility additions

This includes the total discounted capital investment in adding new links (transmission lines or substation links) over the planning horizon.

$$C_T = \sum_{i=0}^{T-1} \sum_{k=1}^{N_{ij}} C_{k,ij} \cdot X_{kl,ij}$$  \hspace{1cm} (2)

where:
- $C_{k,ij}$: Capital cost of adding a new link $k$ between node $i$ and $j$.
- $X_{kl,ij}$: No. of new additions for the link $k$, between nodes $i$ and $j$, at stage $t$.
- $d$: Discount rate for the planning horizon.
- $T$: Total no. of stages in the planning horizon.
- $n$: Number of years per stage.

Cost of power and energy losses

The cost of power and energy loss is calculated using the LRMC values of capacity and energy at transmission level. This is summated throughout the planning horizon.

$$C_L = C_{\text{EL}} + C_{\text{PL}}$$

$$= \sum_{t=1}^{T-1} \sum_{i=0}^{n} \sum_{k=1}^{N_{ij}} P_{\text{loss},i+1} \cdot \left( k_p + 8760 \cdot \text{LLF} \cdot k_E \right) \cdot \frac{1}{(1+d)^{t+1}}$$  \hspace{1cm} (3)

where:
- $P_{\text{loss},i+1}$: Peak power loss in $kW$ in the stage $t$, $i^{th}$ year.
- $\text{LLF}$: Loss Load Factor.
- $k_E$: LRMC value of energy at transmission level in $$/kWh$.
- $k_p$: LRMC value of capacity at transmission level in $$/kW/year.$
Initialize GA, TS and SA parameters

Generate randomly the initial population of the GA.
Let the initial population be the current population

Calculate the fitness values for the current population

Is \( \text{gen} \geq \text{max. gen} \) ?

No

Use TS algorithm to generate new members in the new population, as neighbors to randomly selected members in the current population

Apply crossover and mutation operations to the current population to complete the new population members

Calculate the new temperature of the SA algorithm cooling schedule. Apply SA test to accept or reject the members of the new population (one by one) with current solution;

Update the current population = new population

Start

Copy the best members in the current population to the new population

 Penalty due to bus voltage magnitude violations

\[
P_v = \begin{cases} 
0.05 & \text{if } |v_k| > 1.05 \\
0.95 - |v_k| & \text{if } |v_k| < 0.95
\end{cases}
\]  

(6)

where:

\( N_{bi} \) : No. of bus nodes at the stage \( t \)
\( K_v \) : Penalty Coefficient
\( v_k \) : Bus voltage magnitude in p.u.

Overall problem formulation

The dynamic transmission expansion planning problem can be formulated as the following minimization problem.

\[ 
\min_{X_t, Z} \left( C_c(X_t) + C_e(X_t) + P_f(X_t) + C_p(X_t) \right) 
\]  

(7)

where:

\( X_t \) : represents the number of line additions and the no. of capacitor banks to be added at each planning stage.

Coding of the Problem

A direct coding method was adopted to code the above variables into a binary chromosome. Figure II shows the chromosome coding of the dynamic TEP problem.

Fitness Function Evaluation

Fitness function must reflect both the desired and undesired properties of a solution, rewarding the former strongly and penalizing the later. Fitness function evaluation scheme for the dynamic TEP problem is shown in the Fig. III.

5. TEST RESULTS

The test results shown in this section illustrate the performances of the proposed algorithm. Three-stage (03) network expansion study was carried out for the Modified Garver’s 6-bus, in order to validate the developed model and to determine the various parameters used in this algorithm. A real-world application of the proposed algorithm is presented next with Sri Lanka transmission network.
Modified Garver’s 6-bus network

The network topology is as shown in the Figure 4, where solid lines represents the existing network, and dotted lines represent possible future expansions. A complete network data may be obtained from the authors. Other important details can be inspected below.

<table>
<thead>
<tr>
<th>Number of stages</th>
<th>3 stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate</td>
<td>10 %</td>
</tr>
<tr>
<td>Candidate buses for reactive power compensation</td>
<td>2,3,4</td>
</tr>
<tr>
<td>Per km line construction cost</td>
<td>60,000 US$/km</td>
</tr>
<tr>
<td>Cost of 10 MVAr Capacitor Bank</td>
<td>75,000 US$</td>
</tr>
<tr>
<td>LRMC Energy value</td>
<td>0.05 US$/kWh</td>
</tr>
<tr>
<td>LRMC Capacity value</td>
<td>80.0 US$/kW/year</td>
</tr>
</tbody>
</table>

The following tabulation shows the best solution with the proposed algorithm. It shows the line requirement at each transmission corridor and reactive power compensation required at each candidate bus. However, the steady state members of the population shows comparatively good sub optimal solutions. Figure 5 shows the convergence of the algorithm for 6-bus case.

<table>
<thead>
<tr>
<th>Stage I</th>
<th>Stage II</th>
<th>Stage III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line No. 0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Line No. 1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Line No. 2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Line No. 3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Line No. 4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Line No. 5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Line No. 6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Line No. 7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Line No. 8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Line No. 9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus No. 2</td>
<td>30 MVAr</td>
<td>0</td>
</tr>
<tr>
<td>Bus No. 3</td>
<td>30 MVAr</td>
<td>0</td>
</tr>
<tr>
<td>Bus No. 4</td>
<td>30 MVAr</td>
<td>20 MVAr</td>
</tr>
</tbody>
</table>

Figure 3 - Fitness Evaluation Scheme

The following tabulation shows the best solution with the proposed algorithm. It shows the line requirement at each transmission corridor and reactive power compensation required at each candidate bus. However, the steady state members of the population shows comparatively good sub optimal solutions. Figure 5 shows the convergence of the algorithm for 6-bus case.

Sri Lankan Transmission Network

The model developed was tested also with the Sri Lanka Transmission network in order to carry out a two- (02) stage network planning exercise along with optimal capacitor placement.

Figures 6 and 7 display the network configuration of the Sri Lanka Transmission System – there is not space enough to display the full data set in this paper.
The planning year stages were considered as 2001 and 2004. After running the algorithm, we observed the emergence of interesting results from the point of view of planning the system. In this particular case, capacitor placements were more predominant than line additions – a fact of relevance in a country that must carefully plan the use of its financial resources.

The optimal network configurations along with required reactive power compensations are shown in Fig. 6 and 7. These two network configurations show the optimal networks with lowest capital investment and lowest power and energy losses.

6. CONCLUSIONS

Transmission expansion planning is a complex problem and several models have been proposed to solve it. Some recent models have relied on the general properties of Evolutionary Computing. However, authors have reported difficulties in obtaining convergence for a stable solution or problems in algorithm efficiency.

Because of the complexity of the problem, which includes discrete decisions and the consideration of dynamic solutions (time dependent), it remains a matter of research to find ways to improve algorithm efficiency and the robustness of solutions (or reliability of the method).

This paper presents a hybrid approach aiming at improving algorithm performance in the dynamic transmission expansion planning problem, based on positive results from applying the same type of strategy to unit commitment problems.

The work reported demonstrates that the proposed integrated (GA, TS and SA) algorithm is both feasible and advantageous for dynamic transmission expansion planning. It allows reaching a time-ordered investment decisions which optimizes the total capital investment and cost of power and energy losses.

The model presented lacks a reliability evaluation model; however, this will not be difficult to add and it does not invalidate the conclusions reached: hybrid models, profiting from the best characteristics of each contributor, are a promising answer to build a decision aid tool for planning activities.

REFERENCES

Fig. 6 - Network Solution for the year 2001
Fig. 7 - Network Solution for the year 2004