Transmission Expansion Planning considering Contingency Criteria and Network Utilization

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Abstract—The basic transmission expansion planning problem addresses the network adequacy criteria. Conventionally, additional criteria such as security, efficiency, reliability are post planning studies to strengthen the initial basic plan. This paper presents a automated way of finding the minimum cost expansion plan while considering security constraints during the planning stage itself with prior importance to utilization level of the lines. The objective is to minimize the present cost of building additional lines which will make the system secure due to single contingencies, subject to the technical constraints. A Z-bus based genetic algorithm considering investment cost, overload, underload in the fitness function is developed. This heuristic method utilizes the DC load flow model and incremental load flows to monitor security constraints. The proposed method is tested on a standard 46 bus TEP test case and the results are discussed.

I. NOMENCLATURE

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEP</td>
<td>Transmission Expansion Planning</td>
<td></td>
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</tr>
<tr>
<td>ROW</td>
<td>Right-of-Way</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Fitness of the individual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f1</td>
<td>Investment cost for building the network (in million $)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f2</td>
<td>Net overload of the network considering all the contingency cases individually (in MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f3</td>
<td>Net underload of the network considering all the contingency cases individually (in MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α</td>
<td>Weightage factor for Overload (in $/MW)</td>
<td>Ν</td>
<td>Maximum allowable new circuits in between ROW ij</td>
</tr>
<tr>
<td>β</td>
<td>Weightage factor for Underload (in $/MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>γ</td>
<td>Under-utilization parameter (in pu)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>κ</td>
<td>Set of new planned lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>τ</td>
<td>Set of contingencies considered</td>
<td></td>
<td></td>
</tr>
<tr>
<td>φ</td>
<td>Set of all overloaded lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ψ</td>
<td>Set of all underloaded lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c_{ij}</td>
<td>Cost of adding a new circuit between buses i and j</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n_{ij}</td>
<td>Number of lines planned between buses i and j</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{flow}</td>
<td>Column vector of power flows over existing and planned lines (in MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{max}</td>
<td>Maximum flow over the line i-j (in MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{cont}</td>
<td>Flow over the line i-j under contingency (in MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{inj}</td>
<td>Column vector of power injections at all buses (in MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{cont}</td>
<td>Vector of powerflows under contingency case (in MW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[b]</td>
<td>Diagonal matrix of susceptances of all lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[K]</td>
<td>Branch-node incidence matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[X_{bus}]</td>
<td>Bus reactance matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X_{pq}</td>
<td>pth row and qth column element of X_{bus}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔX_{qp}</td>
<td>Difference of qth column and pth column of the X_{bus}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X_{new}</td>
<td>Modified Bus reactance matrix as per the contingency case studies</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

II. INTRODUCTION

The purpose of a power transmission network is to transfer power from generation plants to load centers securely, efficiently, reliably and economically. Any practical transmission network is ever expanding and thus, the transmission expansion planning (TEP) problem is identifying where to construct new transmission lines in future so that the growing load demand can be met by transfer of power from existing and upcoming generation in a given time horizon. TEP problem is studied extensively in the literature since early 1970's and is still an active research area. Reference gives the basic definition of TEP, its classification based on the solution methods, the treatment of the planning horizon, and consideration of restructuring in the power sector. Another significant paper organizes and classifies existing TEP algorithms in both regulated and deregulated environment.

Input data for the basic TEP problem comprises of a existing network, future generation, future loads and a set of Right-of-ways (ROWs) available for system expansion. Thus the solution of a typical TEP problem is thus combinatorial in nature which involve choosing the optimal combination of new lines.
lines from among the available ROWs with an objective of minimizing the investment cost and meeting all the demands without overload of any component of the network. Two broad solution approaches are reported in the literature i.e., (1) Mathematical optimization [1], [4]–[7] and (2) Heuristics [8]–[11]. The former uses rigorous mathematical modeling and optimization techniques whereas the later uses empirically derived heuristics for modeling and artificial intelligence techniques for solutions. A review on these approaches can be found in [12], [13]. Owing to their ability to handle large search spaces, heuristic approaches such as genetic algorithms [14], simulated annealing [10], expert systems [11], are known to be better suited for application to expansion planning of practical real world power systems.

The basic TEP problem addresses only the adequacy criteria, whereas there exist additional criteria such as security, reliability and efficiency, against which the plans have to be subsequently validated. If these additional criteria are not satisfied at the planning phase, they may emerge as hurdles in the operational phase. For example, (n–1) contingency criteria is a security criteria which requires that the planned system should be able to operate adequately in the event of outage of any one component of the network. The traditional utility practice is to deal with the above additional criteria on a short term basis, while only the adequacy criteria is considered over a longer time horizon. This paper reports a methodology for incorporating (n-1) contingency criteria in TEP.

Literature on expansion planning considering security constraints is limited. Reference [15] uses two phase planning method, in which the planned networks obtained with adequacy criteria in phase one are further augmented in phase two to accommodate security criteria. This may lead to sub-optimal solutions, since the problem is inherently not decoupled. Reference [16] incorporates security criteria within the TEP problem, but uses non-robust approaches. For example, approaches such as local improvement of solutions [17], non-random means of generating initial population [18], intervention into natural progression of search algorithms through meta-heuristics [9], may result in non-generic and non-robust methodologies. Thus, there is always a scope for convergence to a local, sub-optimal solution. However these above references provide knowledge on critical issues dealing with formulation and implementation of security based TEP methodologies.

Even for a medium sized system, the search space for a security incorporated TEP explodes to a large combinatorial space as each plan has to be evaluated for each contingency. Despite the size, we believe that overall computational time should not be a constraining issue, since this is a planning exercise. We also suggest that accurate and innovative means of reducing the computational effort have to be devised to solve TEP, but not at the cost of sacrificing generality and robustness of the solution method. With these considerations this paper proposes an elegant and robust “Overload minimization approach” for solving TEP problem, as opposed to conventional “Load curtailment minimization approach”. The reasons for these claims are as follows:

1) Former uses “simple DC load flow” as basic unit of computation whereas the later uses “LP optimization” as basic unit of computation which is computationally heavier and thus limits the size of the problem.

2) Former approach is driven by “overload signal” which occurs within the network whereas the later is driven by “load curtailment signal” which occurs external to the network.

In essence, overload minimization approach quantifies the overloads occurring in the network through simple DC load flow and takes the overload as driving signal for system expansion. The issue of convergence of DC load flow in the presence of isolated nodes is obvious but a different problem, and it is addressed by modeling isolated nodes as nodes connected to reference bus with high impedance low, capacity lines. The detailed description and analysis of these two approaches is provided in [12], [19].

The rest of the paper is organized as follows. Section III gives the overview of the GA based TEP algorithm with explanation on each component. Derivation of mathematical equations for quantifying overload and underload in the system along with a numerical example is presented in section IV. Section V applies the proposed method on a standard 46 bus TEP test system and results are presented. Section VI concludes the paper.

### III. IMPLEMENTATION OF GA BASED TEP INCORPORATING SECURITY CRITERIA

In literature, genetic Algorithms have been implemented in various forms to solve TEP. This section describes specific implementation features like representation of the individuals, selection, crossover, mutation, fitness function and a convergence criteria. This is followed by discussion on fitness function and penalty factors for overload and underload.

#### A. Features of GA for TEP

1) Representation of the individuals: Integer representation is adopted for this problem as the solution of TEP is the number of lines to be constructed in the given right-of-way. The solution is represented by assigning one gene per ROW so that the size of each individual in the population is equal to the number of ROWs. The value of each gene will give the number of new circuits to be constructed in the corresponding ROW. The value of each gene may range from 0 to $n_{i,j}$, which is the maximum permissible new circuits that can be added between buses i-j.

2) Selection: Roulette Wheel Selection is used by which the individuals to be included in the initial population are chosen according to the fitness value. The probability $p_i$, of selecting the individual i is equal to the ratio $F_i / \sum F_i$, where $F_i$ is the fitness of individual i. This roulette wheel with its slots sized according to the fitness values, is spun as many times as the population size N.

3) Crossover: Crossover is usually not applied to all pairs of individuals, however, in the TEP problem, it is important to stimulate a higher exchange of genetic information among the individuals by using a larger crossover rate value. The pairs of individuals not selected for the crossover mechanism are passed directly to the next generation. In this implementation.
two point crossover method is used, where in, the parent genes are cut at two randomly selected points and the genes interchanged.

4) 

**Mutation:** 
Mutation mechanism leads the search to regions possibly not yet explored, thus acting as a source of diversity. By this mechanism, for each individual, a uniform random number is generated into the interval [0,1]. If this number is lower than the mutation rate, one of the gene is changed with a random integer, chosen between 0 to \( n_{ij} \).

5) 

**Inversion:** 
Inversion operator is not extensively used in a typical genetic algorithm. Reference [20] investigates the effective role of inversion operator for solving problems where the optimum consists of juxtaposed symmetric building blocks. Since TEP solution is the combination of many localized network expansions, it is observed that inversion operator is suitable for solving the TEP problem. Inversion operation involves reversing the order of randomly selected portion of genes of an individual. A small percentage represented by “Inversion rate” of population in each generation is chosen for this operation.

6) 

**Fitness calculation:** Calculation of fitness is the major computational work carried out by GA apart from selection, crossover and mutation operations. In the next sub-section the formulation of the fitness function for considering security constraints and utilization levels of lines is described in detail.

### B. Fitness function

We have also observed that upon accommodating security criteria, the resulting plans contain certain corridors which are severely underloaded. This is expected since the underloaded corridors are not explicitly penalized, but this is not desired because these corridors result in poor utilization of the transmission line and higher investment cost. To address this issue the objective function is extended, with an additional term to penalize underloaded lines. Thus, in this paper, the proposed TEP methodology comprises expanding the network by satisfying the (n-1) security criteria and achieving the triple objective of

1) Eliminating all the overloads in the network
2) Minimizing underloading of all components in the network
3) Minimizing overall investment cost

For the proposed problem, the fitness function is given in equation (1).

\[
F = \frac{1000}{f_1 + \alpha f_2 + \beta f_3}
\]  

(1)

In the above equation, the investment cost \( f_1 \) for building the network, can be readily calculated using equation (2) in which the gene itself represents the number of new circuits. The calculation of net overload \( f_2 \) and net underload \( f_3 \) are detailed in section IV. To evaluate the net overload and underload we need to get a load flow solution, which is always assured, since the problem of isolated nodes has been handled by modeling high impedance low capacity fictitious lines.

The above load flow solution is to be obtained for each case of contingency from a predefined list of contingencies. \( f_2 \) and \( f_3 \) are defined as per the equations (3) and (4).

\[
f_1 = \sum_{n} c_{ij} n_{ij}
\]

(2)

\[
f_2 = \max_{\phi} \left( \sum_{n} \left( |P_{ij\text{-cont}}| - P_{ij}^{\text{max}} \right) \right)
\]

(3)

\[
f_3 = \max_{\psi} \left( \sum_{n} \left( \gamma P_{ij}^{\text{max}} - |P_{ij\text{-cont}}| \right) \right)
\]

(4)

### C. Discussion on fitness function

It is obvious that the code for fitness calculation has to be as optimized as possible so that the computational effort and time are minimized. For example, if GA is implemented using initial population of 100 and run for 500 generations considering 10 individual contingencies, we would require to solve 5,000,000 load flows.

For fitness function, we are considering outage of one line at a time and find overload for each case. Incremental Z-bus [21] is used. The net overload \( f_2 \) will be the most severe overload out of all the contingencies considered. This tends to addressing the (n-1) contingency criteria at planning stage itself and not as a “post planning” study.

The fitness of the individual is inversely proportional to the weighted sum of investment cost, net overload, and net underload in the system. The weights \( \alpha \) and \( \beta \), imposed on \( f_2 \) and \( f_3 \) respectively, are chosen so as to assign a corresponding monetary value in $ for every MW of overload and underload. These weights define priorities among the three objectives in the search for optimum plan. However, \( \alpha \) is given higher value as compared to \( \beta \), since overloading is penalized severely than underloading. This is shown in Fig.1. The concept of penalizing underloaded lines is exactly similar to penalizing overloaded lines. Here we can define \( \beta \) (underload penalty) which will increase as the loading level of line goes below \( \gamma \). Thus between \( \gamma \) to 1 pu both \( f_2 \) (overload penalty) and \( f_3 \) (underload penalty) will be zero. \( f_2 \) increases above 1 pu loading and \( f_3 \) increases below \( \gamma \). These factors \( f_2 \) and \( f_3 \) are evaluated by considering n-1 criteria as outlined in above point. Thus, we are addressing the under utilization problem during the planning stage itself.

The sole consideration of network security in the planning process will result in under utilization of lines which inturn results in high investment cost [22]. So, there is a need to
consider the under utilization aspect in the planning to reduce the investment cost. To serve this purpose, a factor \( \gamma \), which is the under utilization factor of the line, is introduced in calculating the term \( f_3 \) of the fitness function.

In this paper, the under utilization factor (\( \gamma \)) is taken as equal for all lines. But in generally, the network has following types of lines

- Line connecting new generation
- Line connecting new load with old bus
- Line connecting two new buses
- Line connecting two old buses

These lines have different considerations in defining the respective utilization levels. For example, a line connecting a new generation is very important and its utilization has to come high. So, for giving proper consideration to different types of lines, here, in this proposed methodology there is a flexibility of defining under utilization factor for different lines to different values. This way, the proposed methodology becomes more richer and addresses more issues than what are currently doing.

IV. QUANTIFICATION OF OVERLOAD AND UNDERLOAD

For reducing the computational burden, actual loadflow is not performed for every case instead the powerflows are arrived at using incremental DC load flow. In incremental DC loadflow the entire Z-Bus is not formed but only the changes in the Z-bus are considered and from that incremental line flows are calculated. The resulting line flows would be the sum of original line flows and the incremental line flows. This results in greatly reducing the computational effort for solving a load flow. Mathematically, this is explained as follows:

\[
[P_{flow}] = [b][K][X_{bus}][P_{inj}]
\]

(5)

here,

\( X_{bus} \)

is the bus reactance matrix in which the row and column corresponding to reference bus are made zeros. In the context of using DC load flow model in which we assume there is zero resistance, the bus reactance matrix is the same as imaginary component of bus impedance matrix (Z-bus).

Henceforth we use X-bus, which is obtained by simply dropping the “i” from the Z-bus. This is needed to keep the solution real.

Let

\[
[b][K] = [I]
\]

(6)

substituting equation (6) in equation (5), we get

\[
[P_{flow}] = [I][X_{bus}][P_{inj}]
\]

(7)

In the equation (7) \([I]\) and \([X_{bus}]\) change whenever there is a change in the network parameters or topology, for example, outage of a line. \( P_{inj} \) would remain unchanged as long as there is no generation rescheduling and load curtailment. By writing equation (7) as a difference equation, we obtain

\[
[\Delta P_{flow}] = ([I][\Delta X_{bus}] + [\Delta I][X_{bus}^{new}])[P_{inj}]
\]

(8)

where,

\[
X_{bus}^{new} = X_{bus} + \Delta X_{bus}
\]

(9)

\([\Delta X_{bus}]\) can be found by modeling the outaged line as addition of negative reactance line to the basecase \([X_{bus}]\).

Mathematically, if a line between buses p, q with reactance \( x_{pq} \) is outaged the change in X-bus can be found by equation (10).

\[
[\Delta X_{bus}] = \frac{\Delta X_{qp} \Delta X_{T_{pq}}}{-X_{pq} + X_{pp} + X_{qq} - 2 * X_{pq}}
\]

(10)

[\(\Delta I\)] represents the outage of one circuit of reactance \( x_{pq} \) in the \( i^{th} \) corridor between bus p and q. Hence, only two elements of \( \Delta I \) would be non-zero, which are

\[
[\Delta I]_{(i,p)} = \frac{-1}{x_{pq}}
\]

(11)

\[
[\Delta I]_{(i,q)} = \frac{1}{x_{pq}}
\]

(12)

Thus, substituting equation (11) and equation (12) in the second term of equation (8), we get

\[
[\Delta I][X_{bus}^{new}] = \frac{1}{x_{pq}}[X_{bus}^{new}]_{(q,h,row−p,h,row)}
\]

(13)

Substituting equation (13) and equation (10) in equation (8), we obtain the change in power flows on all corridors. Thus the resulting powerflows due to contingency can be calculated as

\[
[P_{cont}] = [P_{flow}] + [\Delta P_{flow}]
\]

(14)

From this overload \( f_2 \) and \( f_3 \) can be calculated using equation (3) and (4). Finally fitness is calculated using equation (1). The procedure for quantification of overload and underload is summarized in the flowchart in Fig. 2.

A. Numerical Example

This section presents a numerical example demonstrating how overload and underload are quantified in a system which contains isolated as well as radial buses. For this purpose a modified Garver’s 6 bus system is taken with one line between bus 2 and 4 removed. For convenience, the bus data and the line data of the system are shown in Table I and II respectively. It can be observed from the data that, considering only the existing lines Bus 6 is an isolated bus and Bus 4 is a radial bus. Bus 4 will become isolated if a contingency on line 1 to 4 is considered. Hence both buses are connected to the reference bus (Bus 1) through a high impedance fictitious lines. Also lines in two corridors 1-3 and 2-6 are added as per a randomly chosen plan.

On this system a base case load flow was carried out and the line flows are shown in last column of Table II. Table III

---

TABLE 1

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Pgen (MW)</th>
<th>Pload (MW)</th>
<th>Pinj (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>80</td>
<td>-30</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>240</td>
<td>-240</td>
</tr>
<tr>
<td>3</td>
<td>165</td>
<td>40</td>
<td>125</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>160</td>
<td>-160</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>240</td>
<td>-240</td>
</tr>
<tr>
<td>6</td>
<td>545</td>
<td>0</td>
<td>545</td>
</tr>
</tbody>
</table>

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TABLE II

**BUS DATA OF MODIFIED GARVER’S SYSTEM**

<table>
<thead>
<tr>
<th>No. (MW)</th>
<th>(MW)</th>
<th>(MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>240</td>
</tr>
<tr>
<td>3</td>
<td>165</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>160</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>240</td>
</tr>
<tr>
<td>6</td>
<td>545</td>
<td>0</td>
</tr>
</tbody>
</table>

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**TABLE III**

**BUS DATA OF MODIFIED GARVER’S SYSTEM**

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Pgen (MW)</th>
<th>Pload (MW)</th>
<th>Pinj (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>80</td>
<td>-30</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>240</td>
<td>-240</td>
</tr>
<tr>
<td>3</td>
<td>165</td>
<td>40</td>
<td>125</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
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<tr>
<td>5</td>
<td>0</td>
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<td>-240</td>
</tr>
<tr>
<td>6</td>
<td>545</td>
<td>0</td>
<td>545</td>
</tr>
</tbody>
</table>
shows the powerflows under four contingency cases considered one at a time. These power flows are obtained by performing incremental load flows as explained above. Table IV shows the overload or underload occurring in the given corridor. Underload figures are marked using *. From the table the maximum overload of 784.2 MW occurs for case 2 and maximum underload of 64 MW occurs for case 4. In this way, overload and underload are quantified.

In the section III and IV, the implementation of GA for TEP, its fitness function, quantification of overload and underload are described. Algorithm 1, summarizes the entire security constrained Genetic Algorithm implementation for TEP.

Algorithm 1 Overview of Genetic Algorithm for TEP considering the security constraints
- Read network data and GA parameters
- Build initial Z-bus by handling isolated nodes
- Create incidence matrix for existing network
- Generate initial population
while (Generation count < Maximum generations are not processed) do
  while (All individuals are not processed) do
    - Initialize fitness calculation process of each individual in the population
    - Define contingency list
    while (All lines are not processed) do
      - Find \( \Delta X_{bus} \)
      - Calculate power flow using equation (14)
      - Calculate Overload and Underload of line outage
end while
- Store plans with zero Overload and Underload
- Calculate \( f_2 \) and \( f_3 \) using equations (2-3)
- Evaluate fitness of the individual
end while
- Perform Crossover of individuals
- Perform Mutation of individuals
- Select individuals for next generation from roulette wheel
end while
- Print the plans

Underload values are marked by *
The underload factor of \( \gamma = 0.5 \) is chosen for above calculations
TABLE V
LIST OF CONTINGENCY CASES CONSIDERED

<table>
<thead>
<tr>
<th>1-2</th>
<th>1-7</th>
<th>2-4</th>
<th>2-5</th>
<th>4-5</th>
<th>4-9</th>
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<td>42-43</td>
<td>42-44</td>
<td>44-45</td>
<td>46-6</td>
<td>46-10</td>
<td>46-11</td>
</tr>
</tbody>
</table>

The pairs of numbers above indicate the 'from' and 'to' buses of the contingency case considered. The total number of contingency cases considered are 64.

TABLE VI
LIST OF ROW’S CONSIDERED

<table>
<thead>
<tr>
<th>2-4</th>
<th>46-10</th>
<th>4-11</th>
<th>5-11</th>
<th>5-11</th>
<th>5-11</th>
<th>21-25</th>
<th>31-32</th>
<th>28-31</th>
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<tr>
<td>28-30</td>
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<td>26-29</td>
<td>40-45</td>
<td>46-11</td>
<td>24-25</td>
<td>29-30</td>
<td>5-6</td>
<td></td>
</tr>
<tr>
<td>9-10</td>
<td>20-23</td>
<td>4-9</td>
<td>12-14</td>
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V. CASE STUDY ON 46 BUS TEP TEST SYSTEM

The proposed methodology is applied to a standard TEP 46 bus test system. The system data is available in [23] and the single line diagram of original network is given in [24]. This system is chosen for the case study since its a reasonably large and practical system reported in the literature. The test system consists of 46 buses, 11 isolated buses with an active power demand of 6,880 MW and with maximum generation capacity of 10,545 MW. The list of Rows considered for expansion are shown in table VI. Plans are searched considering no generation re-dispatch and maximum new circuit additions allowed in each corridor is restricted to three.

For comparison purpose, the standard genetic algorithm was also implemented to solve the planning problem without security constraints. The necessary investments to solve the basic planning problem without generation re-dispatch and without security constraints is US $166.9 million with the following circuit additions:

• $n_{14-22}=1$, $n_{32-43}=1$, $n_{20-21}=1$, $n_{42-43}=2$, $n_{46-66}=1$, $n_{25-32}=1$, $n_{31-32}=1$, $n_{28-31}=1$, $n_{24-25}=2$, $n_{905-66}=2$.

Next, the (n-1) security criteria is considered and the planning is carried out using 64 contingency cases. Table V shows the set of lines which are outaged one at a time to obtain contingency case studies.

The GA was run using the following parameters: Population size = 2000; Number of generations = 200; $\alpha = 10000$; $\beta = 1000$; $\gamma = 0.2$; Crossover rate = 0.8; Mutation rate = 0.95; Initial population rate = 0.5; Mutation threshold rate = 0.7; Inversion rate = 0.15; Figures 3, 4 and 5 show the convergence characteristics of the implemented genetic algorithm. The following new lines are proposed so as to make the system adequate to serve the loads while satisfying (n-1) security criteria for all the contingency cases considered.

• $n_{5-11}=3$, $n_{17-19}=1$, $n_{19-21}=1$, $n_{21-25}=1$, $n_{23-24}=1$, $n_{32-43}=1$, $n_{42-44}=1$, $n_{44-45}=1$, $n_{46-16}=1$, $n_{20-21}=2$, $n_{24-25}=2$, $n_{28-31}=2$, $n_{31-32}=2$, $n_{46-11}=2$, $n_{42-43}=3$.

A total investment cost of US $ 412 Million is needed for building the 24 lines as per the above plan.

VI. CONCLUSION

A TEP methodology incorporating (n-1) contingency criteria with the objective of minimizing investment cost as well as the under-utilization of the network elements is presented. The framework of overload minimization approach is chosen. A Z bus based genetic algorithm with a fitness function incorporating investment cost, overload and underload is developed. The incremental DC load flow was employed to track the security constraints. One of the main features of the methodology is that the security constraint criteria is accounted for at the planning stage itself rather than the ex-post testing of the optimal plan for network security. The developed TEP
methodology is applied on a standard 46 bus TEP test system and results are presented.

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REFERENCES


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