A Comprehensive Two Level Heuristic Approach to Transmission Expansion Planning

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Abstract—The transmission expansion planning (TEP) has long term effects on system performance. The effects are irreversible. The conventional optimization techniques have convergence problems for large system and heuristic methods reported so far are not holistic in nature. This paper proposes a two level approach. At first level, the usual static solution using linear approach is proposed. The objective is to minimize the cost along with overloads. The isolated nodes are handled by ZBUS formulation as described. The Genetic Algorithm (GA) is used as a heuristic approach to arrive at results. The plans are shortlisted with no overloads and least cost. The performance is tested for high rank contingencies and appropriate system strengthening is suggested. At second level, further strengthening of the network on short term basis is done with due consideration to reactive power balance in the grid. The reactive power support has to be incorporated since the AC model with reactive power limits can impose convergence problems. To overcome this, Reactive Power Compensation (RPC) enhanced FDLF module with integrated reactive power planning based on set of heuristics is implemented. The TEP plans need to be evaluated for reactive power balance. This is accomplished by evaluating voltage stability margin index (VSMI). It identifies weaker lines prone to reactive power imbalance. The TEP plan reinforces grid to improve the weaker section. The proposed methodology is applied to IEEE 46-bus test system and results are discussed. Power System Simulator (PSS/E) package along with visualization tools are used for validating and portraying the results.

Index Terms— contingency analysis, Power System Simulator (PSS), VSIM, Transmission expansion planning, Tuned FDLF Module.

I. INTRODUCTION

Conventional transmission expansion planning is carried out for a future horizon year, where the available data is base year topology, candidate circuits for expansion, planned generation and forecasted demand. Reference [1] gives the basic definition of TEP, its classification based on the solution methods, treatment of the planning horizon, and consideration of restructuring in the power sector. Another significant paper [2] organizes and classifies existing TEP algorithms in both regulated and deregulated environment. Expansion planning is a complex problem as it is dynamic in nature and it is simplified by solving as static transmission planning. Traditionally, DC model is used and planning is done only for active power. The problem has been approached in different ways, including usage of optimization [3]–[6] and heuristic methods [7]–[10] where, the objective is to arrive at a minimum investment cost plan as best plan while satisfying the capacity constraints. The usage of the DC model restricts the planning studies from considering reactive power planning and losses in the network. References [11], [12] have presented the formulation of the planning problem using AC model to address reactive planning issues. Reference [12] presents a relaxed Short Term Transmission Network Expansion Planning (STTNEP) formulation in conjunction with constructive heuristic algorithm. The system operators are confronted with chronic reactive power imbalance in some major parts of the network. This may be either due to improper reactive power support or due to improper expansion planning.

This paper gives a two level comprehensive approach to planning by considering future active power needs along with contingency studies in Level-1 and reactive power needs in Level-II. The motivation is to present a comprehensive methodology incorporating an end to end approach with multiple criteria in a sequential manner. Alternatively, an integrated approach can be followed where both active, reactive planning can be done simultaneously in a coordinated way. Although this approach in principle is more accurate, but for a long time horizon this may lead to high computation effort and prone to errors owing to uncertainties. The loss of accuracy can thus be justified in adopting a sequential approach. Moreover, in this approach instead of relying on a single “best” plan, we start with a set of plans and gradually improve to meet further criteria. Based on a consolidated view of all the plans, a comparative study is done to choose the final expansion plan. PSS/E package is used for validating and visualization of results.

Section-II gives overview of the comprehensive Two Level Heuristic Approach for TEP. Section-III suggests active power planning using Z-bus based genetic algorithm and is termed as Level-1 of planning. Section-IV explains integrated reactive power planning and is termed as Level-2 of planning. In Section-V, implementation of the proposed method on a standard TEP test case (46 bus system) is done and the results are compared with those reported in the literature. Section-VI concludes the paper.

II. OVERVIEW OF COMPREHENSIVE TWO LEVEL HEURISTIC APPROACH FOR TEP

This section gives an overview of comprehensive two level heuristic approach for TEP in the form of a flowchart shown
in Fig 1. This comprehensive approach towards TEP has following advantages:

- Issues dealing with comprehensive TEP planning are addressed in a logical order wherein the planning methodology tends to satisfy various operational constraints while building the network, one after the other. First, capacity constraints are satisfied followed by security constraints, then by voltage limit constraints and finally voltage stability constraints.
- The methodology is sequential and follows a repeating input-process-output format, as seen in the flowchart.
- The methodology works on a set of plans and strengthens them subsequently in every process. The final plan can be chosen as per planner’s overall criteria.
- The methodology is organized into two broad levels i.e., active power planning and reactive power planning.
- Each component (or process) is implemented as an independent module and hence there is a scope for further optimizing specific module in future without disturbing the overall planning process.

The next two sections will detail the proposed methodology with various intermediate steps shown in the above flowchart for active and reactive power planning respectively.

### III. LEVEL 1: ACTIVE POWER PLANNING

Medium and Long term TEP mainly focuses on the following three criteria. 1) Minimization of investment cost of transmission expansion, 2) Supplying all the future load demand and 3) satisfying n-1 contingency criteria. Criteria 1 and 2 are met in the basic TEP formulation. Additional considerations suggest contingency analysis have to be carried out to address criteria 3. In this paper, the first level TEP carries out the active power planning which is then followed by contingency analysis to obtain a set of feasible plans with necessary strengthening to address the (n-1) contingency criteria. The plans are arranged in increasing order of investment cost which will be further processed.

Input data is the base year topology, future planned generation capacity additions, future load growth and available right-of-ways for expansion. DC load flow analysis suffices for the purpose of planning at this stage as it mainly focuses on the building the network to carry real power. In this paper a Z-bus based genetic algorithm method is used to carry out the conventional expansion planning. This method is explained in reference [13], [14]. The salient features of this approach are:

1. Adopting overload minimization approach to GA
2. Use of Z-bus for handling isolated nodes. Isolated nodes are the nodes where a new generation plant or a new load center is planned in future and there is no initial connectivity.
3. The overload quantified by simple DC loadflow is used as a driving signal for genetic algorithm search.
4. The fitness of an individual (plan) is inversely proportional to weighted sum of investment cost and net overload in the system.

GA provides a set of best solutions with zero overloads and in increasing order of investment cost.

The next step would be to perform contingency analysis for each of the expansion plans. This paper proposes a Contingency ranking based heuristic rule for suggesting necessary improvements so as to make each plan (n-1) secure. The heuristic is described in Algorithm. 1.

Power System Simulator (PSS/E Version 30.2) is used for performing above contingency studies and generating contingency ranking reports. Thus, by the end of Level-1, a set of secure plans addressing active power planning requirements is achieved. The next section describes the reactive power planning process which is further carried on these set of plans.

### IV. LEVEL 2: REACTIVE POWER PLANNING

Along with Active power planning, Reactive power planning should also be considered as an integrated problem while formulating a planning process because inappropriate reactive power compensation can lead to either 1) nonconvergence of the AC loadflow program or 2) unrealistic results due to Q absorption by generators or 3) unacceptably low voltages in
the system. The planning so far has only considered the real power aspects. The power network is meant to carry active power and if significant reactive power flows are observed on the transmission lines then valuable transmission resource is wasted in carrying reactive power [15]. Hence the reactive power demand is best met locally.

At this stage the future reactive power demand and the reactive power capabilities of the future planned generators are also considered as the input data for the algorithm. The reactive power flow on a line is mainly determined by the voltage levels of the buses at the either ends of the line. If there is a demand for reactive VARs at a bus, its voltage dips and the lines connecting it will have to carry reactive power to this bus from the adjacent buses, leading to lowering of bus voltage of adjacent buses as well. Conversely, if the supply of VARs at bus is excessive, its voltage rises and this extra reactive power is pushed over the lines to adjacent bus, spreading high voltage. Hence to minimize the reactive flows over the lines, the bus voltages must be as close to each other as possible and also ideally be equal to 1.0 pu.

Reference [16] uses optimal power flow for carrying out reactive planning for the system and reference [17] uses enhanced Fast Decoupled Load Flow (FDLF) module for short term expansion planning. In this work, we extend these methods to address long term expansion planning issues which involve the problem of incorporating a large number of reactive power sources which are not already existing in the network. Thus, apart from the consideration of time horizon, the main difference between short-term and medium or long-term planning is the consideration of new Right-of-Ways (ROWs) and new buses. In the medium or long-term, new ROWs and new buses are considered for the planning. Reactive Power Compensation (RPC) enhanced FDLF Module is elaborated in algorithm 2.

Algorithm 1 Contingency Ranking Based Heuristic Rule

\[
\text{while (All plans are not (n-1) secure) do} \\
- Choose a plan which is to be strengthened \\
- Perform Contingency Analysis on the plan \\
\text{while (Overloads are detected) do} \\
- Rank the contingencies based on severity of overloads \\
- Identify most severely overloaded contingency as location for system strengthening \\
- Strengthen the system at the identified location \\
- Again, Perform Contingency Analysis on the plan \\
\text{end while} \\
\text{end while} \\
- Print the results of strengthening of plans required to make the system (n-1) secure
\]

A. RPC Enhanced FDLF Module:

In the AC Loadflow program using FDLF Algorithm, low or high voltage pockets in the system are known only after initial couple of iterations. To handle this issue, we start monitoring the voltages after two iterations of the load flow program. In particular, we track minimum and maximum voltage at each iterations. If the limiting voltage is beyond permissible value, then a synchronous condenser is attached at the corresponding bus which regulates the voltage to the limiting values. For a bus with over voltage, the synchronous condensor output will be equal to inductive compensation required to maintain the voltage at the upper limit. Conversely, the limiting node with lower voltage, output of synchronous condensor is the amount of capacitive VARs required to maintain voltage at the minimum value. To avoid overcompensation in the system, a tuning variable is defined in the program, which is used to change the compensation level at each iteration. Depending on planning scenario, this may or may not be adequate. The process terminates either when the load flow convergence criteria is met or when for three successive iterations, the maximum mismatch consecutively increases. RPC Enhanced FDLF Module is elaborated in algorithm 2.

Algorithm 2 RPC Enhanced FDLF Module

\[
\text{while (All plans are not processed) do} \\
- Choose a plan for reactive compensation \\
- Append reactive power data to the chosen plan \\
- Perform AC load flow \\
\text{while (AC loadflow not converged) do} \\
- Initiate RPC-FDLF based loadflow algorithm and run for two iterations \\
\text{if (voltage violations are identified) then} \\
\text{Perform tuning of reactive compensation at that bus} \\
\text{while (Voltage violations exist) and (Subsequent iterations do not diverge) do} \\
- Increment reactive compensation in steps at buses with voltage violations \\
- Continue RPC-FDLF based loadflow algorithm for one iteration \\
- Compare with previous iterations and check for convergence error \\
- Continue this loop until voltage violations are eliminated with sufficient accuracy. If divergence is detected restart the loop \\
\text{end while} \\
\text{end if} \\
\text{end while} \\
- Print the results of Reactive Compensation of plans
\]

So far reactive power compensation issue is addressed for the chosen plans. However, the issue of voltage stability is not yet considered. According to [18] Voltage instability occurs when the reactive demand at a certain bus increases to a large value, which results in voltage dip, which further results in increase of reactive demand at that bus. This situation builds until the voltage value goes very low and the system can
no longer meet the reactive demand at that bus, leading to a voltage collapse. Once the list of reactive supports is found, we can take one more step ahead and quantify the voltage stability margin for the network. Reference [19] defines a Voltage Stability Margin Index (VSMI) which can be used to identify weak lines and buses of the network prone to voltage instability (indicated by low values of VSMI). VSMI of a line is based on the relationship between voltage stability and prevailing angle difference between sending-end and receiving-end buses. The advantage of VSMI is that it doesn’t require the continuation powerflows for estimation of stability margin and thus involves lesser computational effort and is aptly suitable for planning studies. The implementation of VSMI based voltage stability improvement module is detailed in the algorithm 3.

**Algorithm 3 VSMI based voltage stability improvement**

```plaintext
while (All plans are not processed) do
  - Choose a plan for voltage stability assessment
  - Read bus angles and active, reactive power flows over the lines
  - Calculate VSMI indices for all lines
if (VSMI is low) then
  - Add a reactive source to supply the corresponding reactive sink locally
end if
- Generate list of reactive compensation required to improve voltage stability
- Identify weak areas in terms of voltage instability for operational use
end while
- Print the results of Reactive Compensation of plans
```

Although enhancement of reactive compensation for voltage stability may be relatively uncommon, calculation of VSMI index is still useful in identification of weak areas which are prone to voltage instability and hence this information gives insights for operational purposes.

**V. RESULTS AND DISCUSSION**

The proposed methodology is applied to a standard TEP 46 bus test system. The system data is available in [3] and the single line diagram of initial network is given in [20]. This system is chosen for the case study since its a reasonably large and practical system reported in the literature. But the data concerning real power planning is only given in the above reference. In this paper the resistance of lines is derived from the reactance of the line assuming an X/R ratio of 20. Also the reactive loading at each bus is not specified for the standard test system and hence reactive power load is assumed to be 30% of real power load which approximately corresponds to a power factor of 0.95. The values are chosen in the above two assumptions as are valid in a typical practical power transmission network. The test system consists of 46 buses, 12 isolated buses and 79 ROWs for new circuit additions with a active power demand of 6,880 MW, reactive power demand of 2,064 MVAR, with maximum generation capacity of 10,545 MW. Plans are searched considering no generation re-dispatch and maximum new circuit additions allowed in each corridor is restricted to three.

As described in Section I, Comprehensive Two Level Heuristic Approach for TEP was preformed on this test system. The steps followed are as per the flowchart in Fig 1. At the end of Active Power Planning five plans were obtained as shown in Table I. Next Contingency ranking based heuristic is applied to arrive at 5 plans which are (n-1) secure. As per this, the additional new lines required at various ROWs along with total cost are also shown in Table I. With this level 1 of planning is completed. The network single line diagram with low investment cost (as per plan 1) at this stage is shown in Fig 2.

The five plans are further improved with addition of reactive power support upon implementing the RPC enhanced FDLF module on these plans. Table II. shows the reactive compensation needed as per the RPC enhanced FDLF module for each plan, so as to satisfy voltage limit criteria. Voltage limits of 0.98 pu. to 1.05 pu. are enforced. Table II. also shows the results reported in literature according to Reference [12]. It can be observed that although the methodology used in this paper and [12] are different, the results are more or less confirming.

Fig. 3 shows the comparison of total investment cost of these five plans for both levels. It is observed that the Plan-5 is evolved as the optimal plan at the end of Level-2. The optimum investment plan at the end of planning is shown in the fig 4. The real and reactive power losses are 45.9MW and 918MVAR. These are optimum as compared to reference [12].

**VI. CONCLUSION**

A comprehensive two level heuristic approach to transmission expansion planning is proposed in this paper. The
### TABLE II
**Reactive Compensation Required**

<table>
<thead>
<tr>
<th>Bus no.</th>
<th>Amount of Reactive compensation in MVAR (all are capacitive V ARS)</th>
<th>Results from Ref [12]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plan No</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>54</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>92</td>
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<tr>
<td>13</td>
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<td>180</td>
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<td>20</td>
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<td>92</td>
</tr>
<tr>
<td>45</td>
<td>76</td>
<td>54</td>
</tr>
</tbody>
</table>

| Total (MVAR) | 1710 | 1822 | 1628 | 1668 | 1866 | 1700 |
| Cost (mn $)  | 7.372 | 7.855 | 7.019 | 7.191 | 8.045 | 6.500 |

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**Fig. 2.** Optimal Network for 46 bus system at the end of Active Power Planning.

**Fig. 4.** Final Optimal Network for 46 bus system at the end of both Active and Reactive Power Planning.

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The main contribution of the paper is to show that in a sequential manner it is possible to work with the AC system model for transmission expansion planning and also the so mentioned optimal plans in the literature may not be optimal by considering other aspects as explained. The above method can
be further improved by incorporating other factors like angle stability, loss of load, inclusion of FACTS devices, etc. The method has sequential steps viz, planning for active power, contingency planning, reactive planning, and voltage stability evaluation. The initial best multiple plans arrived in the first step are carried forward and improved on in the later steps. The sequential approach can be converted to combined integrated approach, where all the above criteria are simultaneously evaluated and the best set of plans is arrived at. The authors believe that if the described planning methodology is applied to a real world system it would yield good overall insight by virtue of its holistic nature.

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REFERENCES

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