Using a Novel Heuristic Objective Function in Transmission Expansion Planning.

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ABSTRACT

Electric system planning is a process of evaluating, monitoring, and updating, which makes the reliability and risk assessment for the development of a reliable, economically efficient power system expansion and operation plan an invaluable process. The technique proposed in this paper is a "novel but classic" technique. We classify the transmission planning into two dimensions including economic and technical criteria with detailed definitions. Transmission Planning Index (TPI) is the main focus of this paper and can be used as an important criterion for decision making and transmission planning in the planning horizon. This paper is aimed at developing a flexible decision method to select a favorable plan among various transmission system expansion alternatives, based on economic and technical criteria, and system constraints studies under normal and contingency conditions. The six bus system case study results demonstrate that the proposed method is practical for solving the power system expansion planning problem.

(Keywords: transmission expansion planning, technical criterion, economical criterion)

INTRODUCTION

The optimal design of transmission system expansion planning is an important part of the overall planning task of electric power system. The transmission expansion planning (TEP) problem of electrical power systems consists in finding the transmission lines and/or transformers that should be constructed so that the system can operate in an adequate way and in a specified planning horizon. The objective of the ensemble planning, transmission programming, heuristic of transmission network planning functions is to determine the installation plans of new facilities (lines and other network equipment) so that the resulting bulk power system may be able to meet the forecasted demand at the lowest cost, while satisfying prescribed technical, financial, and reliability criteria.

The data of the TEP problem are the topology of the transmission network of a base year, the candidate's circuits, the generation and demand data of the planning horizon, investment constraints, etc. The expansion plan (solution of the expansion planning problem) must specify where, how many and when the new equipment must be installed. Usually, the expansion planning horizon is divided into short-, medium-, and long-term periods in accordance with the type of decisions to be made and with the quality of the available data and information involved in the planning process. If we have only one horizon of planning, then we have the so called static or one-stage planning [1]. If the horizon is separated in more stages (years), there is the multi-stage planning [2].

Due to technological complexity and great cost of the procedure, hundreds of papers have been published, have tried to provide a model for this problem, and solve it optimally. In regulated systems, the goal of TEP is to find the least-cost plan for network expansion, in order to provide consumers with reliable energy. In the beginning of studies, large simplifications had been considered. For example, the circuitry laws of network were underestimated by transportation or dc models. Most of these models had been optimized by mathematical tools like linear programming [3-8].

By evolution in computers, and development of heuristic optimization methods, some of the simplifications have been eliminated [9-11] (e.g., AC power flow instead of a DC one). Many researches were concentrated on more precise models for TEP, and methods to optimize them. These techniques including branch and bound, sensitivity analysis, bender decomposition, simulated annealing, genetic algorithms, tabu search, and GRASP (Greedy Randomized Adaptative Search Procedure) have been used to study the problem [12-19]. It is difficult to obtain the optimal solution of a composite power system considering the generators and transmission lines simultaneously in an actual system, and therefore transmission system expansion planning is usually performed after generation expansion planning under individual planning standards.

In this paper, a new methodology is proposed for deciding the optimal economical and technical criteria for an optimal transmission system expansion planning. A deterministic planning index, TPI, is used in this study. Starting from a reference plan, alternative expansion plans are derived based on postponement/anticipation of circuit implementations. These plans are then ranked by using the TPI index is obtained. This study aims at a method for decision making that allows selecting a favorable plan among multiple options for power transmission system expansion with a limited amount of investment. For this purpose, the aforementioned approach has been employed.

This paper is outlined as follows: the proposed TEP model and solution methodology are described below, followed by discussion of transmission planning index (TPI) and contingency analysis, the algorithm of the problem, the case study of the Garver's six-bus system, and the conclusions drawn from the study.

THE TRANSMISSION SYSTEM EXPANSION PLANNING PROBLEM

Transmission planning is the key to keeping the power system capacity ahead of increasing demand. Transmission planning therefore ensures that the transmission infrastructure can deliver power from the generators to the loads, and that all the equipment will remain within its operating limits in both normal operation and during system contingencies. The TEP problem consists of defining when and where new circuits should be installed to serve, in an optimal way subject to a set of electrical, economic, financial, social, and environmental constraints. Any plan can become technically and economically obsolete. A good plan should take into accounts for all kinds of uncertainties that could happen in the future. In this paper, both economics and technical considerations are considered in the appraisal of the most desirable transmission network.

Economic Criterion

The economics of alternate facilities play a major role in the decision making process for transmission system expansion planning, therefore, should be consider for transmission planning. The economic considerations can be consisting of investment, maintenance, operational, outage and loss costs. The economic criterion of transmission system expansion problem can be stated as follows:

$$C_i = \sum_{i=1}^{T} \left(I_{it} + M_{it} + O_{it} + U_{it} + L_{it} \right) \quad \textbf{(1)}$$

where:

C_i : The total cost of plan *i*;

I_{it} : Total investment cost;

M_{it} : Maintenance cost of plan *i*;

O_{it} : Operational cost;

U_{it} : Outage cost of unserved load;

L_{it} : Loss cost of plan *i*;

T : The horizontal years of planning.

Here, we consider the total investment cost (the installation cost of lines or substations) as the economic criterion.

Technical Criterion

Technical criteria are another of major considerations in system operation and planning. Permissible operating ranges of voltage and lines loading are the essential constraints in power networks operation and design, one of the essential tasks power network designers maintain these constraints at a level appropriate to the electric power systems in different conditions. Here, we classify the technical criterion into three dimensions including Voltage Profile Index (PI), Line Loading Index (LI), and Expected Energy Not Supplied (EENS) Index with detailed definitions as follows:

Voltage Profile Index (PI)

One of the primary reasons for numerous blackouts across the globe has been inadequate voltage planning. Considering the influence of voltage quality on the customers equipment performance and also the increase on efficiency and lifetime of network equipment, the magnitude and status of voltage in power networks is one of the important parameters that it is necessary for power system engineers to become familiar with them. In various references, different versions of a voltage profile index are used. The limits of the acceptable voltage levels are determined according to the exigencies of a secure operation of the available system electrical equipment. In this paper, the PI for the overall system is defined as [20]:

$$PI^L = \sum_{i \in N_{Low}} |V_i - 0.95|$$
$$PI^H = \sum_{i \in N_{High}} |V_i - 1.05| \qquad \textbf{(2)}$$
$$PI = PI^L + PI^H$$

where:

PI: voltage profile index
PI^L: voltage profile index when bus voltage falls below 0.95
PI^H: voltage profile index when bus voltage rises above 1.05
V_i: the voltage magnitude of i^{th} bus
N_{LOW}: A set of bus with allowable voltage at each bus, typically 0.95 Pu
N_{HIGH}: A set of bus with allowable voltage at each bus, typically 1.05 Pu.

Line Loading Index (LI)

For desirable operation of power system should guarantee that current flow into the all network facilities are in permissible ranges. In this section, with attention to the lines loading status in power networks, a criterion is brought for the overall assessment of system's lines loading status. The limits of the acceptable current levels are determined according to the exigencies of a secure operation of the available system electrical equipment. The *LI* for the overall system is defined as:

$$LI = \sum_{i \in SB} \frac{I_i}{I_{i\,max}} \qquad \textbf{(3)}$$

Where:

LI : Line loading index
: The current magnitude of i^{th} branch I_i
I_{imax}: The maximum current magnitude of i^{th} branch
: Set of branches with current over %80 SB

Expected Energy Not Supplied (EENS) Index

EENS is the expectation of the energy loss caused to customers by insufficient power supply. The EENS index for the overall system is defined as:

$$EENS = \sum_k \sum_i L_{ki} F_{fi} D_{ki}$$

where*:*

L_{ki}: the load curtailment at bus *k* or the load not supplied at an isolated bus *k*;
F_{ki}: the frequency of occurrence of outage *i* at bus *k*;
D_{ki}: the duration in hours of the load curtailment.

TRANSMISSION PLANNING INDEX (TPI)

The increase in technical criteria due to the various alternatives is evaluated together with the investment cost associated with each scheme. The objective functions of transmission planning can be update to the following optimization problem.

$$Min \quad C_i = \sum_{i=1}^{T} (I_{it})$$
$$Min \quad PI = PI^L + PI^H$$
$$Min \quad LI = \sum_{j \in OL} \frac{I_i}{I_{i\,max}}$$
$$Min \quad EENS = \sum_k \sum_i L_{ki} F_{fi} D_{ki} \qquad \textbf{(5)}$$

Subject to:

$$P_{min} \le P \le P_{max}$$
$$Q_{min} \le Q \le Q_{max} \qquad \textbf{(6)}$$
$$V_{min} \le V \le V_{max}$$

Where:

V_{min} *and* V_{max} are the limits voltage magnitude for the buses (between 105% and 95% of the nominal voltage in normal condition and 110% and 90% of the nominal voltage in contingency analysis);

$P_{min}, P_{max}, Q_{min} and Q_{max}$ are the limits of the active and reactive powers (between $\pm 80\%$ of the nominal power in normal condition and $\pm 100\%$ of the nominal power in contingency analysis).

The multi-objective optimization problem can be transformed into a scalar optimization problem by weighted sum approach [21]. This method consists of adding objectives together using different weighing, which is shown in Equation (7).

$$Min \quad \begin{Bmatrix} TPI = W_c * C_i + W_p * PI + \\ W_r * LI + W_f * EENS \end{Bmatrix} \qquad \textbf{(7)}$$

Where W_c, W_p, W_r *and* W_f are weighting factors for cost, voltage profile, line loading, and Expected Energy Not Supplied Indexes, which enable reflect the planner's preference, and $W_c + W_p + W_r + W_f = 1$. The plan that has the minimum target value will be chosen as the final expansion plan. In order to get reasonable results, it would be better to normalize the data over a wide range. The method used for normalization as shown in Equation (8):

$$F_n = \frac{F_j}{max\{F_j\}} \qquad \textbf{(8)}$$

where F_n is the normalized value of cost, voltage profile, line loading, and EENS indexes.

CONTINGENCY ANALYSIS

Contingencies in this context mean unexpected failures of any system element; for example a generator or a transmission line could have an unexpected outage, which would force the remainder of the system (6) sition to a new operating point. Studying (6) transitions and ensuring that a stable operating point can be reached after any contingency is an essential part of transmission system planning. A network can be designed for single contingency outages, double contingency outages or for any specified multiple outage criteria.

Currently, utilities, and independent system operators employ a single contingency method (N-1 contingency analysis) to determine system restrictions and identify upgrades to alleviate the restrictions. The N-1 contingency analysis examines contingencies that will result in a transmission path being overloaded. Applying contingency analysis for all single outage case with considering the reliability standard based on the N-1 rule (which has been proposed to be adopted by NERC in USA). Here, we have employed a single contingency analysis to plan its transmission system. The transmission network was built with enough excess capacity along the planning horizon to withstand an unexpected outage of any component during system peak conditions without thermal overloads or voltage violations. According to the planning methodology adopted, the transmission system is to be reinforced when it can no longer feed the peak demand without equipment overload in a single contingency.

ALGORITHM FOR OPTIONAL EXPANSION PLANS

Figure 1 shows the framework of the proposed planning model. In this figure, an initial set of proposed plans and candidates is identified in the preliminary study. The selection of candidate lines in proposed plans is based on the results of power flow and contingency analysis, as illustrated in Figure 1.

This technique is quite general, and any known operating conditions can be included. The solution algorithm for the proposed approach follows:

Step 1. Prepare system data which includes system parameters, network topology data, component outage data, bus characteristic data, and determine the upper and lower limiting states. The load data comes from the load prediction for the horizon year to be studied.

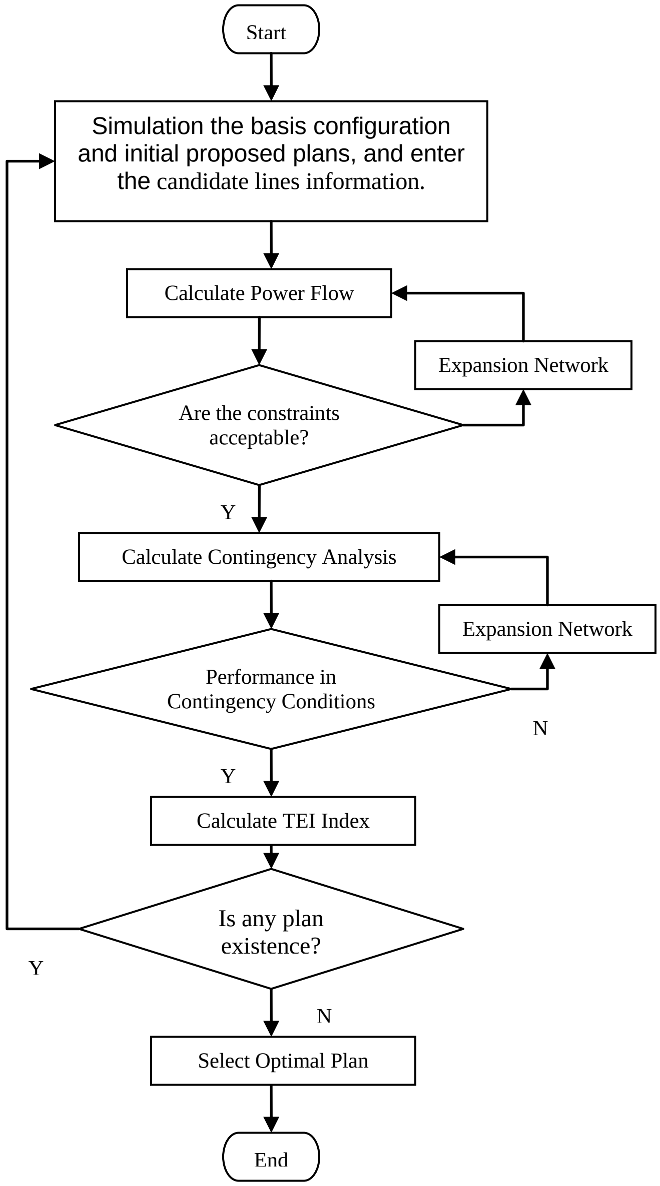

Figure 1: Flow Chart Proposed Method.

Step 2. Solve power flow and check the need for transmission expansion for the system, if the solution indicates that satisfy constrains go to step 3. Otherwise, update the current topology with the addition of the candidate and chosen circuit and go to step 2.

Step 3. Conduct contingency analysis, if the solution indicates that satisfy constrains go to step 4. Otherwise, expand and suggest preferred reinforcement alternatives using the candidate equipments and go to step 3.

Step 4. Calculate economical and technical indexes and Rank alternatives based on TPI index.

Step 5. Is any plan existence? If the response is ok, go to step 2, otherwise go to step 6.

Step 6. Select optimal plan based on TPI index.

Step 7. End of process.The optimum and sub-optimum alternatives that will minimize the overall system objective function and satisfy the system requirements under normal operation and the contingency condition are obtained. The proposed planning algorithm satisfies system security based on N-1 contingency along the planning horizon.

CASE STUDY

The characteristics and effectiveness of this methodology are illustrated by the case study using Matlab. A modified six buses Garver system for the expansion planning problem was used to show the performance of the methodology.

Six Buses Garver System

The modified Garver system has 6 buses, three generators and five branches, 13 candidate lines for addition, a maximum generation of 1100 MW and a total demand of 760 MW (Figure 2). In the Appendix I, there is data on the transmission lines and buses that were used.

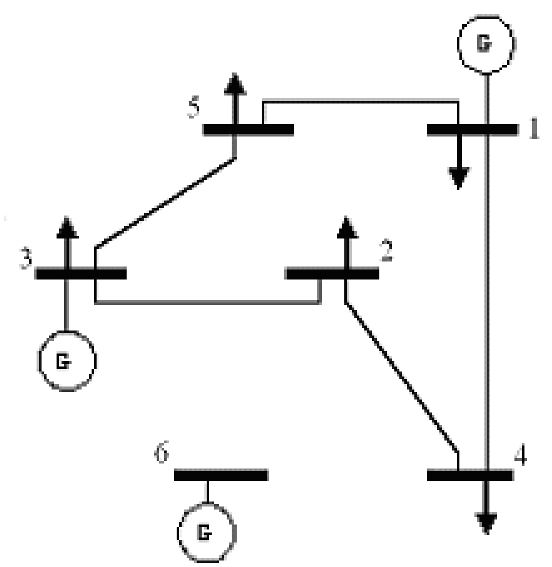

Figure 2: Initial Configuration of Garver's Network.

Test and Results

In this section, we use the proposed algorithm for deciding the optimal reliability criteria for an optimal transmission system expansion planning. TPI index is used in this study. Starting from a reference plan, alternative expansion plans are derived based on postponement/anticipation of circuit implementations and satisfy the demand requirements under normal operation and the contingency condition. These plans are then ranked by using TPI index set is obtained through the aforementioned analyses. The plan that has the minimum target value will be chosen as the final expansion plan.

Here, there are 6 expansion plans under consideration (Figure 3). The planning results are shown in Table 1 and the normalized results from Table 2 are represented in Table 3. Suppose that the four parameters are equal important for, the weighting factors for each parameter will be same, and then they will be set as:

$W_c = W_p = W_r = W_f = 0.25$ from Equations 7 and 8, we have:

$$TEI1 = 0.25*(1.000+0.631+1.000+) = 0.9077$$
$$TEI2 = 0.25*(0.875+1.000+0.969+) = 0.8932$$
$$TEI3 = 0.25*(0.611+0.000+0.921+) = 0.6193$$
$$TEI4 = 0.25*(0.708+0.502+0.931+) = 0.7647$$
$$TEI5 = 0.25*(0.152+0.000+0.826+) = 0.4892$$
$$TEI6 = 0.25*(0.500+0.000+0.878+) = 0.5892$$

It can be seen that Plan 3 has the minimum T value of 0.4892. Thus, it will be chosen as the final decision. Different planner may set different weight factor for cost, line loading, voltage profile and Expected Energy Not Supplied Indexes then the final decision may be changed. Consequently, without this analysis it is difficult to make decision from these plans. From this point of view, TPI can help planner or decision maker to make final decision.

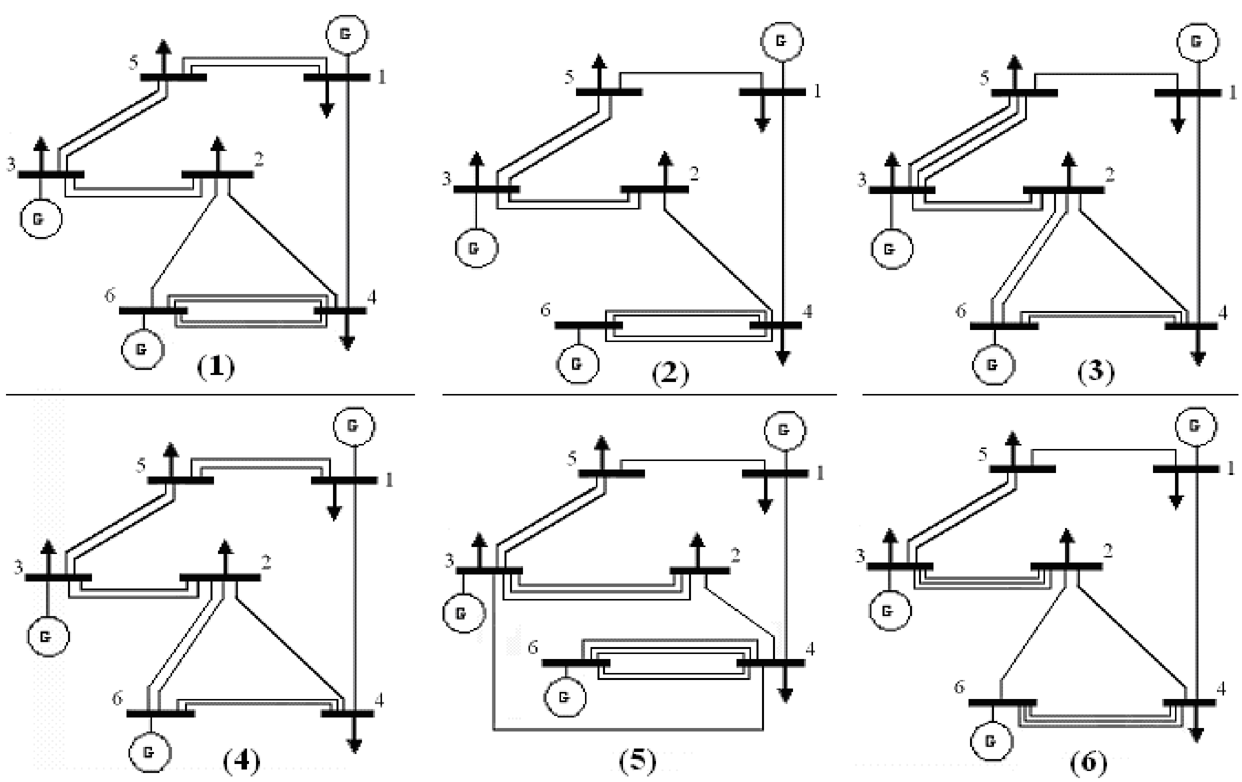

Figure 3: Proposed Plans for Future Expansion of Garver's Network.

Table 1: All Test Results for Proposed Method.

	PI	LI	EENS	Cost(M$)
Plan1	0.072	0.103	35.67	74.0
Plan2	0.063	0.163	34.58	54.0
Plan3	0.044	0.00	32.86	70.0
Plan4	0.051	0.095	33.24	68.0
Plan5	0.011	0.00	29.47	72.5
Plan6	0.036	0.00	31.32	72.5

Table 2. Normalized Results.

	PI	LI	EENS	Cost
Plan1	1.000	0.631	1.000	1.000
Plan2	0.875	1.000	0.969	0.729
Plan3	0.611	0.000	0.921	0.945
Plan4	0.708	0.502	0.931	0.918
Plan5	0.152	0.000	0.826	0.979
Plan6	0.500	0.000	0.878	0.979

Table 3: Data from the Modified Garver System.

Bus	Type	P_D (MW)	Q_D (Mvar)	P_G^{max} (MW)	P_G^{min} (MW)	Q_G^{max} (Mvar)	Q_G^{min} (Mvar)
1	$V\theta$	80	16.0	160.0	0.0	48.0	-10.0
2	PQ	240	48.0	-	-	-	-
3	PV	40.0	8.0	370.0	0.0	101.0	-10.0
4	PQ	160.0	32.0	-	-	-	-
5	PQ	240.0	48.0	-	-	-	-
6	PV	0.0	0.0	610.0	0.0	183.0	-10.0

Data of the lines

Bus from	Bus to	r_{ij} pu	x_{ij} pu	b_{ij} pu	S_{ij}^{max} MVA	n_{ij}^0	n_{ij}^{max}
1	2	0.040	0.400	0.000	120.0	0	0
1	3	0.038	0.380	0.000	120.0	0	0
1	4	0.060	0.600	0.000	100.0	1	1
1	5	0.020	0.200	0.000	120.0	1	2
1	6	0.068	0.680	0.000	90.0	0	0
2	3	0.020	0.200	0.000	120.0	1	3
2	4	0.040	0.400	0.000	120.0	1	1
2	5	0.031	0.310	0.000	120.0	0	0
2	6	0.030	0.300	0.000	120.0	0	2
3	4	0.059	0.590	0.000	102.0	0	1
3	5	0.020	0.200	0.000	120.0	1	3
3	6	0.048	0.480	0.000	120.0	0	0
4	5	0.063	0.630	0.000	95.0	0	0
4	6	0.030	0.300	0.000	120.0	0	5
5	6	0.061	0.610	0.000	98.0	0	0

CONCLUSIONS

Planning for power systems is essentially a projection of how the system should grow over a specific period of time, given certain assumptions and judgment about the future loads and the size of investment in generating capacity additions and transmission facilities expansion and reinforcements.

This paper proposes a methodology for choosing the best transmission expansion plan considering various types of economical and technical criteria. The cost index combining with PI, LI, and EENS indexes has been treated as transmission planning objectives. By using weighted sum approach, the transmission planning objectives (multi-objectives) optimization problem has been transformed to a single objective optimization problem. Reinforcement alternatives are evaluated considering their influence on system reliability studies under normal and contingency conditions. The technique is quite general and also a "novel but classic" technique, and any known operating conditions can be included.

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