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Heuristic method for transmission expansion planning based on reliability criteria

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ABSTRACT

The optimal design of transmission system expansion planning is an important part of the overall planning task of electric power system. One of main keys of the successful grid expansion planning comes from optimal reliability level/criteria decision, which should be given for constraint in the optimal expansion problem. However, it's very difficult to decide logically the optimal reliability criteria of a transmission system as well as generation system expansion planning in a society. The technique proposed in this paper is a "novel but classic" technique. We classify the transmission planning into three dimensions including Line Loading Index (LI), Voltage Profile Index (PI), and Expected Energy Not Supplied (EENS) Index with detailed definitions. Transmission Expansion Index (TEI) 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. The 6 bus system case study results demonstrate that the proposed method is practical for solving the power system expansion planning problem.

Introduction

The objective of the transmission expansion planning (TEP) problem of electric energy systems is to find the optimal expansion plan to the power system (that is, the transmission lines and/or transformers that must be constructed to permit the viable operation of the system) in a pre-defined horizon of planning. 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.

Generally, transmission network expansion planning can be classified as static or dynamic. Static expansion determines where and how many new transmission lines should be installed up to the planning horizon. If in the static expansion, the planning horizon is separated into several stages, we have dynamic planning [1]–[3]. In this paper, only the static planning problem is analysed. However, this methodology can be extended to multistage planning.

The recent blackouts that have occurred in countries worldwide suggest that more reliable grid structures may be needed to establish successful deregulated electricity markets. These incidents call for the development of new tools that can address system uncertainties and significantly enhance the effectiveness of transmission planning [4], [5]. However, the basic objective of strengthening a transmission grid is relevant for most countries.

Transmission expansion planning addresses the problem of augmenting an existing generation and transmission network to optimally serve a growing electric load while satisfying a set of economic and technical constraints. The problem is to minimize the cost of expansion subject to the constraints needed to meet an explicit reliability level [6].

The analysis and comparison of various reliability criterions are necessary in order to induce the agreement of customers successfully. Normally, the power system expansion planning problem, which is generation and transmission expansion planning, is analyzed using a macro approach in view point of adequacy and then a detail micro approach considering the stability, and dynamic characteristics of the new system.

A main reason of the separated work process in powers system expansion planning comes from too much computation time to obtain the global optimal solution if all constraints (stability, voltage violation and dynamic characteristics) are considered simultaneously [7]-[8]. The transmission expansion planning macro approach problem is to minimize the cost subject to a reliability level constraint.

Various 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 [9]-[18]. 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.

This study knocks a new door carefully with a new methodology for deciding the optimal reliability criteria for an optimal transmission system expansion planning. A deterministic reliability index, TEI 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 a Reliability index set is obtained through the aforementioned analyses.

The rest of the paper is organized as follows. The proposed long-term multi-year TEP model and solution methodology are described in Section 2. Section 3 discusses contingency analysis. The algorithm of the problem is provided in Section 4. Section 5 presents and discusses the case study of the Garver's six-bus system which enables easy understanding of the contribution of

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this paper. The conclusion drawn from the study is provided in Section 6.

The Transmission Expansion Planning Problem

Transmission system planning is a continual process of evaluating, monitoring and updating, which makes the reliability and risk assessment for the development of a reliable, economically efficient transmission system expansion and operation plan an invaluable process. 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 transmission planning 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 [19]:

$$\begin{aligned} PI^L &= \sum_{j \in N_{Low}} \left| V_j - 0.95 \right| \\ PI^H &= \sum_{j \in N_{High}} \left| V_j - 1.05 \right| \\ PI &= PI^L + PI^H \end{aligned} \tag{1}$$

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_j: 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:

$$LI = \sum_{i \in SB} \frac{I_i}{I_{i\,max}} \tag{2}$$

Where:

LI : Line loading index

: The current magnitude of i^{th} branch I_i

: The maximum current magnitude of i^{th} branch $I_{i\,max}$

: Set of branches with current over %80 SB

EENS (Expected Energy Not Supplied) 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:

$$EENS = \sum_k \sum_i L_{ki} F_{fi} D_{ki} \tag{3}$$

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 Expansion Index (TEI)

The objective functions of transmission planning can be update to the following optimization problem.

$$\begin{aligned} &Min \quad PI = PI^L + PI^H \\ &Min \quad LI = \sum_{j \in OL} \frac{I_j}{I_{j\,max}} \\ &Min \quad EENS = \sum_k \sum_i L_{ki} F_{fi} D_{ki} \end{aligned} \tag{4}$$

Subject to:

$$\begin{aligned} P_{min} &\le P \le P_{max} \\ Q_{min} &\le Q \le Q_{max} \\ V_{min} &\le V \le V_{max} \end{aligned} \tag{5}$$

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 [20]. This method consists of adding objectives together using different weighing, which is shown in equation (6).

$$Min \quad \{TEI = W_c * PI + W_r * LI + W_f * EENS\} \tag{6}$$

Where W_c, W_r *and* W_f are weighting factors for Voltage Profile, Line Loading and Expected Energy Not Supplied Indexes, which enable reflect the planner's preference, and $W_c + W_r + W_f = 1$. 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 (7):

$$F_n = \frac{F_j}{max\{F_j\}} \tag{7}$$

Where F_n is the normalized value of PI, LI and EENS indexes.

Contingency Analysis

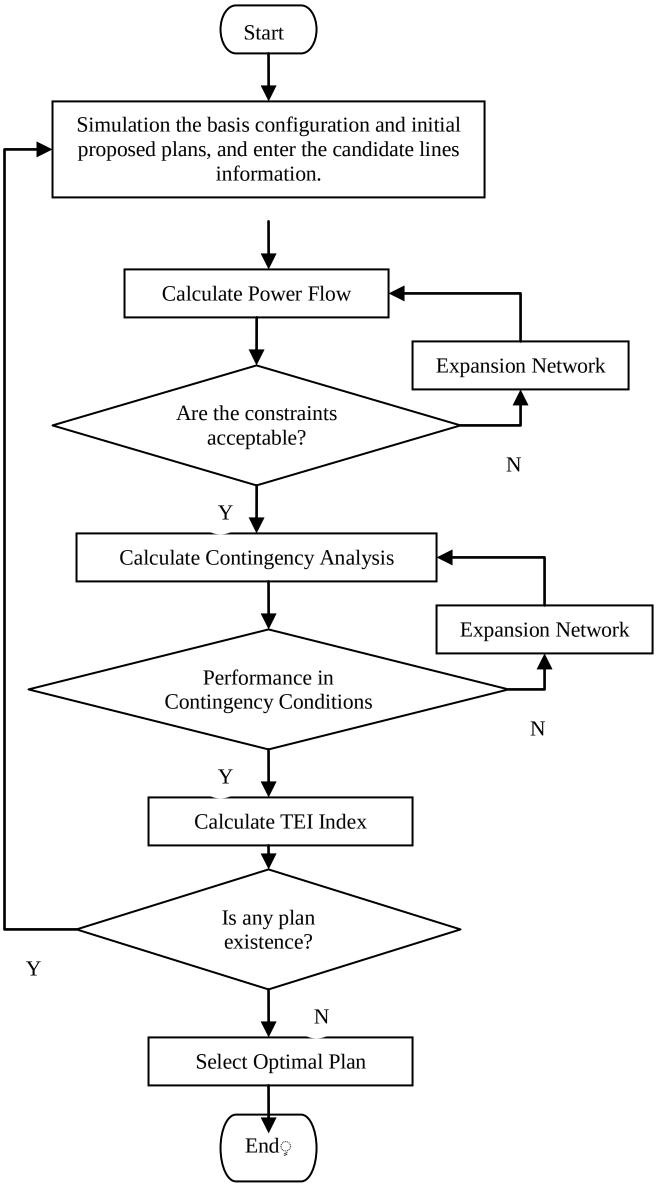
A network can be designed for single contingency outages, double contingency outages or for any specified multiple outage criteria. None of these transmission adequacy criteria, however, provide a quantitative measure of the level of system reliability. Currently, utilities and independent system operators 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. Here, we have employed a single contingency to plan its transmission system. Based on this single contingency, the transmission network was built with enough excess capacity to withstand an unexpected outage of any component during system peak conditions without thermal overloads or voltage violations. In this study, in the contingency analysis for transmission outages, all single outage cases are considered. We apply 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); it is shown by using the power flow calculations.

Algorithm for Optional Expansion Plans

Fig. 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 Fig. 1.

Fig.1. Flow chart proposed method



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

Step1. 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.

Step2. 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.

Step3. 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.

Step4. Calculate reliability indexes and Rank alternatives based on TEI index.

*Step5. I*s any plan existence? if the response is Ok, go to step 2, otherwise go to step 6.

Step6. Select optimal plan based on TEI index.

Step7. End.

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.

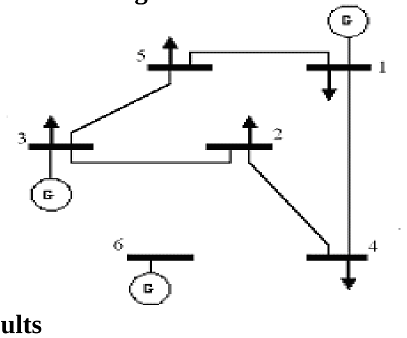
Case Study

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 (Fig.1). In the Appendix I, there is data on the transmission lines and buses that were used.

Fig.2. Initial configuration of Garver's network



Test and Results

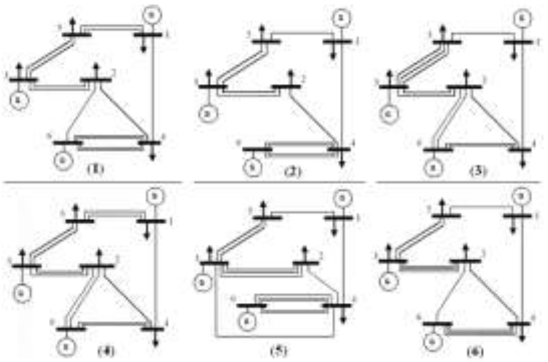
In this section, we use the proposed algorithm for deciding the optimal reliability criteria for an optimal transmission system expansion planning. TEI index is used in this study. Starting from a reference plan, alternative expansion plans are derived based on postponement/anticipation of circuit implementations and satisfy the demand requirements under normal operation and the contingency condition. These plans are then ranked by using TEI 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 (Fig.3). The planning results are shown in Table 1 and the normalized results from Table 1 are represented in Table 2. Suppose that the three parameters are equal important for, the weighting factors for each parameter will be same, and then they will be set as: $W_c = W_r = W_f = 0.333$ from equations 7 and 8, we have,

$$TEI1 = 0.333*(1.000+0.631+1.000) = 0.8764$$
$$TEI2 = 0.333*(0.875+1.000+0.969) = 0.9471$$
$$TEI3 = 0.333*(0.611+0.000+0.921) = 0.5102$$
$$TEI4 = 0.333*(0.708+0.502+0.931) = 0.7402$$
$$TEI5 = 0.333*(0.152+0.000+0.826) = 0.3259$$
$$TEI6 = 0.333*(0.500+0.000+0.878) = 0.4588$$

It can be seen that plan5 has the minimum *TEI* value of 0.3259. Thus, it will be chosen as the final decision. Different planner may set different weight factor for Line Loading, Voltage Profile and Expected Energy Not Supplied Indexes then the final decision may be changed. Consequently, without so analysis it is difficult to make decision from these plans, TEI can help planner or decision maker to make final decision.

Fig.3 Proposed plans for future expansion of Garver's network



Conclusions

Transmission planning is the key to keep the system capacity ahead of increasing demand in the future. A good plan should take into accounts for all kinds of uncertainties that could happen in the future. The technique proposed in this paper is a "novel but classic" technique. The PI index combining with 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 any known operating conditions can be included.

The characteristics and effectiveness of this methodology are illustrated by the case study using Matlab. The results shown, systems may have different TEI value even with similar weighting factors. The plan that has the minimum target value will be chosen as the final expansion plan. Therefore, the TEI offers another criterion and an opportunity, for planners and operators to compare alternative plans.

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Table 1. All Test Results for Proposed Method

	PI	LI	EENS
Plan1	0.072	0.103	35.67
Plan2	0.063	0.163	34.58
Plan3	0.044	0.00	32.86
Plan4	0.051	0.095	33.24
Plan5	0.011	0.00	29.47
Plan6	0.036	0.00	31.32

Table 2. Normalized Results

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

Appendix I

Table I- 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