International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:7, No:10, 2013

Transmission Expansion Planning with Economic Dispatch and N-1Constraints

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***Abstract*—**This paper proposes a mathematical model for transmission expansion employing optimization method with scenario analysis approach. Economic transmission planning, on the other hand, seeks investment opportunities so that network expansions can generate more economic benefits than the costs. This approach can be used as a decision model for building new transmission lines added to the existing transmission system minimizing costs of the entire system subject to various system's constraints and consider of loss value of transmission system and *N*-1 checking. The results show that the proposed model is efficient to be applied for the larger scale of power system topology.

***Keywords*—**Transmission Expansion Planning, Economic Dispatch, Scenario Analysis, Contingency.

I. Introduction

TRANSMISSION planning is an important part of power system planning. Its task is to determine an optimal network configuration according to load growth and a generation planning scheme for the planning period so as to meet the requirement of delivering electricity safely and economically.

Transmission planning can be used to correct the original generation planning schemes. Therefore, generation planning and network planning should be made on the basis of decomposition and co-ordination in order to optimize the overall power system planning. The basic principle of network planning is to minimize the network construction and operational cost satisfying the following requirements of delivering electric power safely and reliably to load centers. Here the reliability requirements include [1]-[2]:

– Normal operation requirements. When power system equipment is operated under good conditions, various operating standards are ensured. For example, line transmission powers, generator output, voltage level, spinning reserve and so on are within the rated range.
– Contingent operation requirements. When an equipment fault or load disturbance occurs, the electricity supply reliability requirements are satisfied.

The transmission expansion planning problem consists of defining when and where new circuits are needed and should be installed to serve, in an optimal way, the growing electrical, economic, financial, social and environmental constraints. Strictly speaking, such a problem has a dynamic nature, since the requirements of transmission facilities should be defined over time within a given horizon. The availability of the transmission expansion plan is quite important for new generating plant investor, since they need to know, in advance, about future transmission facilities which, consequently, will allow them to make decisions regarding attractive location for their plants.

One of the first approaches for solving the transmission expansion planning problem was proposed by Garver [3], who developed an iterative method, which consisted of formulating power flow equations as a linear programming problem and selecting the new circuit additions based on the largest overloads found in the optimization problem's solution. Although the most important circuit additions can be identified by this approach, the final solution thus found large scale systems need to be improved, since it usually involves loss of load. Moreover, the others mathematical programming package [4], Hierarchical decomposition [5] and branch and bound algorithm [6]. The challenge for the solution approach is solve large scale problem. The integrality nature of the expansion decisions leads to mixed integer programming formulations which can only be solved for small and medium size power system.

The main objective of transmission planning is to find an optimal long-term expansion through the construction of new lines or the upgrade of existing facilities to increase the amount of power to meet load growth and a generation planning scheme over the planning period. The transmission planning model presented in this paper is based on a scenario analysis method and takes into account an economic dispatch constraint.

II. Problem Formulation

A. Heuristic Method

The heuristic method is based on intuitive analysis. It is relatively close to the way that engineers think. It can give a good design scheme based on experience and analysis. However, it is not a strict mathematical optimization method. In network planning, the heuristic approach finds wide application because of its straightforwardness, flexibility, speed of computation, easy involvement of personnel in decision making and ability to obtain a comparatively optimal solution which meets practical engineering requirements. The heuristic method consists of overload checking, sensitivity analysis and scheme formation [7].

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B. Power Flow Problem

Network equations can be formulated systematically in a variety of forms. The node voltage method, which is the most suitable form for many power system analyses, can be used to calculate voltages and phase angles at various nodes. Thus, the resulting equations in terms of power, known as the power flow equations, become nonlinear and must be solved by iterative techniques. The most common techniques used for the iterative solution of nonlinear algebraic equations are Gauss-Sidel, Newton-Raphson, and the Fast Decouple methods [8], [9].

Power flow studies, commonly referred to as load flow, are the backbone of power system analysis and design. They are necessary for planning, operation, economic scheduling and exchange of power between utilities. In addition, power flow analysis is required for many other analyses such as transient stability and contingency.

C. N-1 Checking and Contingency

Network design has to satisfy certain operational security requirements. As discussed earlier, the common network operational security requirement is to satisfy *N-1* checking; i.e. when one of *N* line fails, the system operation criteria remain within given requirements. At the initial stage of forming a network configuration, the principle is to ensure that there is no overloading in the network; i.e. the network satisfies requirements of securely transmitting power. To this end, one has carry out the overload check for successive line outages. If outage of a line causes overloading or system disconnection, then the network does not satisfy *N*-1 checking. In such circumstances, the network has to be expanded using one of the network planning methods until the *N*-1 checking is satisfied [10], [11].

The *N*-1checking on all line needs *N* line outage analyses, resulting in a large amount of computing. In practice, some line outages do not cause system overloading. Therefore, a contingency ranking is carried out according to the probability of system overload being caused by line outage; then the checking is performed on the lines with higher probability.

III. Methodology

The presented methodology starts by selecting a set of feasible scenarios to be analyzed. With a given scenario and an existing generation composition, the economic dispatch problem is performed to find a transmission loss and line flows, subject to power balance and power flow equations. A transmission investment problem will employ the resulting line flows to determine an optimal number of transmission lines to be added into the system, subject to a line capability constraint [12]. After a new transmission configuration has been obtained; the line flows and system loss will be updated.
Economic dispatch problem

$$\text{Min } F_T = \sum_{i=1}^{N_G} F_i(P_{Gi}) = \sum_{i=1}^{N_G} (a_i P_{Gi}^2 + b_i P_{Gi} + c_i) \qquad (1)$$

Subject to

$$V_i \sum_{j=1}^{N} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) - P_{Gi} + P_{Di} = 0 \qquad (2)$$

$$V_i \sum_{j=1}^{N} V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) - Q_{Gi} + Q_{Di} = 0 \qquad (3)$$

$$\sum_{i=1}^{N} P_{Gi} - \sum_{i=1}^{N} P_{Di} - P_{loss} = 0 \qquad (4)$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad i = 1,2,\ldots,N \qquad (5)$$

where

F_T	=	generation cost parameters
P_{Gi}	=	power output of unit *i*
P_{Di}	=	load at bus *i*
a_i, b_i, c_i	=	generation cost parameters of unit *i*
N_G	=	number of generating units *i*
N	=	number of buses
V_i	=	voltage magnitude at bus *i*
Y_{ij}	=	admittance magnitude of transmission line connected bus *i* and bus *j*
$\delta_i,\ \delta_j$	=	voltage angle at bus *i* and bus *j*
θ_{ij}	=	admittance angle of transmission line connected bus *i* and bus *j*
P_{loss}	=	power system loss
$P_{Gi}^{\min}, P_{Gi}^{\max}$	=	minimum and maximum power output of unit *i*

Transmission investment problem

$$\text{Min V} = \sum_{(ij)} C_{ij} n_{ij} \qquad (6)$$

Subject to

$$\left|f_{ij}\right| \le (n_{ij}^0 + n_{ij})\overline{f}_{ij} \qquad (7)$$

where

V	=	total cost of transmission investment
C_{ij}	=	cost of transmission line connected between bus *i* and bus *j*
n_{ij}	=	number of transmission lines to be added between bus *i* and bus *j*
n_{ij}^0	=	number of existing transmission lines between bus *i* and bus *j*
$\overline{f}_{ij}$	=	line flow limits between bus *i* and bus *j*

IV. Cases Study

Simulation results to verify the planning ability of the proposed method, we perform simulation for case I: transmission expansion planning and case II: *N-1* checking and contingency. Table I gives the data of a 5-bus network. Fig. 1 shows the single line diagram of the 5-bus system [8]. The system has three generating units. The generation costs and power limits of the three units are shown in Tables I and II. Table III illustrates all investigated scenarios.

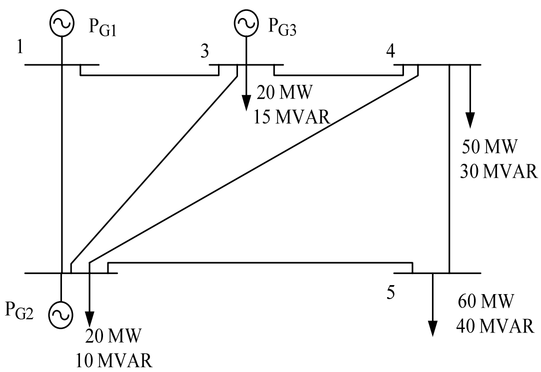

Fig. 1 Single line diagram of 5-bus system

TABLE I
DATA FOR 5–BUS SYSTEM (100 MVA BASE)

Bus	R	X	½B	Capacity(MW)	Investment Cost (10^3\$)
1-2	0.02	j0.06	0.030	50	25
1-3	0.08	j0.24	0.025	50	35
2-3	0.06	j0.18	0.020	50	45
2-4	0.06	j0.18	0.020	50	50
2-5	0.04	j0.12	0.015	50	30
3-4	0.01	j0.03	0.010	50	20
4-5	0.08	j0.24	0.025	50	40

TABLE II
GENERATION COSTS AND POWER LIMITS

Power Generation	Cost Function Coefficients			P_G^{min}	P_G^{max}
	a_i	b_i	c_i	(MW)	(MW)
$F_1(P_{G1})$	0.008	7.0	200	10	85
$F_2(P_{G2})$	0.009	6.3	180	10	80
$F_3(P_{G3})$	0.007	6.8	140	10	70

TABLE III
SCENARIOS FOR TRANSMISSION EXPANSION PLANNING

Scenario	Added circuit (i-j)						
1	1-3	2-3	2-5	3-4	4-5	-	-
2	1-2	2-3	2-5	3-4	4-5	-	-
3	1-2	2-3	2-4	2-5	4-5	-	-
4	1-2	2-3	2-4	2-5	3-4	4-5	-
5	1-2	1-3	2-3	2-5	3-4	4-5	-
6	1-2	1-3	2-3	2-4	2-5	4-5	-
7	1-2	1-3	2-3	2-4	2-5	3-4	4-5

Case I: Transmission Expansion Planning with Economic Dispatch

The results for all the scenarios are shown in Tables IV, V. As can be seen, scenario 1 gives the minimum investment cost of transmission.

This scenario requires 6 transmission lines in total to be installed, as indicated in Table IV. However, as far as the system operating cost is concerned, scenario 5, where 8 transmission lines need to be installed and the investment cost of transmission is $55,000 higher than that of scenario 1, would be the most attractive in the long run because it has the lowest generation cost and also transmission loss. Therefore, such a generation cost will occupy a large portion of the total system cost over the course of a study period. The mathematical model presented in this paper can be further improved to include some other related constraints such as demand uncertainty, network reliability and network stability.

TABLE IV
RESULTS OF FOR NUMBER OF ADDED CIRCUITS OF CASE I

Scenario	Number of added circuits (i-j)						
	n_{1-2}	n_{1-3}	n_{2-3}	n_{2-4}	n_{2-5}	n_{3-4}	n_{4-5}
1	0	1	1	0	1	2	1
2	1	0	0	0	2	2	1
3	1	0	1	1	2	0	1
4	1	0	1	1	1	1	1
5	1	1	1	0	2	2	1
6	1	1	1	1	2	0	1
7	1	1	1	1	1	2	1

TABLE V
RESULTS OF TRANSMISSION EXPANSION PLANNING WITH ECONOMIC DISPATCH

Scenario	Total generation cost \$/h	Investment cost of transmission (10^3\$)	Total system loss (MW)
1	1,604.60	190	2.461
2	1,598.11	210	1.643
3	1,620.13	220	4.505
4	1,596.32	210	2.129
5	1,590.39	245	1.306
6	1,616.92	255	4.088
7	1,595.47	265	1.954

Case II: *N*-1 Checking and Contingency

This case bring the first case study 's result from scenario 5 and 7 as shown in Table III for *N*-1 checking and comparison by increasing demand 20 % at bus 2, 3, 4 and 5 are as follows: 24 MW 12 Mvar, 24 MW 18 Mvar, 60 MW 36 Mvar and 72 MW 48 Mvar. From the test results shown in Table VI: scenario 5, if there is line outage *N*-1 checking, the rest of transmission enable to work normally. Table VII: scenario 7, do the same test for *N*-1 checking. When the transmission line 2-5 outage, the loss is higher and economic patch is not optimal. Table VIII: scenario 7, add transmission line 2-5 for stability increment of transmission system.

TABLE VI
RESULTS OF *N-1* CHECKING AND CONTINGENCY FOR SCENARIO 5

Line outages	Total generation cost \$/h	Total system loss (MW)
1-2	1,832.33	3.095
1-3	1,829.98	2.783
2-3	1,831.25	2.950
2-4	-	-
2-5	1,836.83	3.692
3-4	1,828.77	2.622
4-5	1,827.52	2.456

TABLE VII
RESULTS OF *N-1* CHECKING AND CONTINGENCY FOR SCENARIO 7

Line outages	Total generation cost $/h	Total system loss (MW)
1-2	1,841.14	4.264
1-3	1,840.41	4.167
2-3	1,835.87	3.568
2-4	1,836.83	3.629
2-5	-	25.218
3-4	1,838.19	3.873
4-5	1,842.50	4.443

TABLE VIII
RESULTS OF *N-1* CHECKING AND CONTINGENCY FOR SCENARIO 7
ADD LINE 2-5 = 1 CIRCUIT

Line outages	Total generation cost $/h	Total system loss (MW)
1-2	1,830.58	2.863
1-3	1,828.82	2.629
2-3	1,825.88	2.238
2-4	1,826.41	2.309
2-5	1,834.37	3.366
3-4	1,826.37	2.303
4-5	1,826.26	2.289

V. CONCLUSION

Transmission expansion planning with economic dispatch constraint and *N*-1 checking results show that the proposed method gives rise to the optimal investment, considering the reasonable amount of transmission losses, as well as the proper pattern of generation dispatch. It is envisaged that the proposed method for planning of transmission system expansion is efficient to be applied for the larger scale of power system topology.

ACKNOWLEDGMENT

The authors would like to express his gratitude to Rajamangala University of Technology Phra Nakhon, Thailand for support.

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