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분기 한정법에 의한 송전계통의 확충 계획

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Transmission System Expansion Planning Using Branch and Bound

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Abstract- This paper proposes a method to solve expansion problem for a transmission network, given future generation and load strategy, and alternative types of lines available, subject to load, reliability and right of way constraints, the problem is formulated as a series of zero one integer programs which are solved by an efficient branch and bound algorithm. A study test result on the 63-buses test system shows that the proposed method is practical and efficiently applicable to the transmission expansion planning.

1. Introduction

Transmission network expansion is a complicated nonlinear mathematical optimization problem [1]. The most desirable expansion plan is one which results in the minimum present worth of the incurred cost over an extended period time. Starting from Garver's paper in 1970, a variety of techniques such as branch and bound algorithm sensitivity analysis, Benders decomposition, simulated annealing, genetic algorithms (GAs), tabu search algorithms, and GRASP were used to study the transmission network expansion planning problem [2-6].

In this paper, a new approach to the transmission system expansion planning is proposed. It uses branch and bound algorithm which includes the network flow theory and the maximum flow-minimum cut set theorem is proposed to obtain the optimal solution. The effectiveness of the proposed approach algorithm is demonstrated by testing it on the 63-buses test system. Following are assumption used [11].

(a) A network flow method considering active power is used.
(b) The network flow method is sufficient for the long term planning problem.
(c) Set of draft plans/scenarios are used as candidate plans.
(d) The problem is limited to a static expansion planning problem for a single-stage or horizon-year.

2. The Transmission Expansion Planning Problem

The static transmission expansion problem can be stated as follows. Given the generation and load patterns in a target in the future, find a set of transmission line additions to minimize the total investment cost, subject to load constraints, reliability constraints, and right of way constraints. The transmission expansion planning can be formulated as a Integer Programming (IP) problem as follows (see Appendix for details)

$$minimize\ C^T = \sum_{(x,y)\in B} [\sum_{i=1}^{m(x,y)} C^i_{(x,y)} U^i_{(x,y)}] \qquad (1)$$

where, C^T is the total construction cost of new equipment

No shortage power supply requires that the total capacity of branches involved in the minimum cut-set should be greater or equal to the total load of the system. This is also referred to as the bottleneck capacity *Fm* (or the maximum flow of the network) in Table A.1 in the Appendix. Therefore, a no shortage power supply constraint can be expressed by eq. (3)

$$P_c(X,\overline{X}) \ge L \qquad (s \in X,\ t \in \overline{X}) \qquad (2)$$

The demand constraint can be formulated by eq. (3)

$$\sum_{(x,y)\in(X_k,\overline{X}_k)} [P^{(0)}_{(x,y)} + \sum_{i=1}^{m(x,y)} P^{(i)}_{(x,y)} U^i_{(x,y)}] \ge L \qquad (3)$$

Where,

$$C^{(i)}_{(x,y)} = \sum_{j=1}^{i} \Delta C^{(j)}_{(x,y)} \qquad (4)$$

$$P^{(i)}_{(x,y)} = \sum_{j=1}^{i} \Delta P^{(j)}_{(x,y)} \qquad (5)$$

$$\sum_{i=1}^{m(x,y)} U^i_{(x,y)} = 1 \qquad (6)$$

$$U^i_{(x,y)} = \begin{cases} 1, P_{(x,y)} = P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \\ 0, P_{(x,y)} \ne P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \end{cases} \qquad (7)$$

$$P_{(x,y)} = P^{(0)}_{(x,y)} + \sum_{i=1}^{m(x,y)} P^{(i)}_{(x,y)} U^{(i)}_{(x,y)} \qquad (8)$$

L: total demand
$P_{(x,y)}$: power of transmission line or generator between node x and node y
$\Delta C^{(j)}_{(x,y)}$:construction cost of #j parallel element of branches between node x and node y
$\Delta P^{(j)}_{(x,y)}$: capacity of #j parallel element of branches between node x and node y
k: cut-set subscript number (=*1, 2, k, n*)
B: a set of all branches
$m(x,y)$: the number of new branches between nodes x and y.

3. Solution Algorithm

The objective in the conventional branch and bound method is to minimize the total construction cost subject to a specified reliability level, delivery power reserve rate. The solution algorithm for the proposed approach follows.

Step 1. Check the necessary and possibility of transmission system expansion planning from given system and candidate lines.

Step 2. Set up j=1, $jopt$ =0, $jmax$ =0, C^T_{opt} = and $ENNOD_j$=0. Where, the #1 system means initial system and $ENNOD_j$ means whether the #j system is end node(=1) or not(=0).

Step 3. Check whether $ENNOD_j$ = 1 or not for the #j system. If it is one, the #j system is end node in solution graph which is used for obtaining the optimal solution using branch and bound method and any solution graph following to the #j system does not need to be considered any more in solution graph of branch and bound method. Therefore, go to step 15.

Step 4. Calculate minimum cut-set using maximum flow method for #j system which can be called as #j solution in the solution graph.

Step 5. Choice a #i branch/line of the candidate branches/ lines set (Sj) involved in minimum cut-set and add to the #j system. The new system is called temporary as #ji system in followings.

Step 6. Check whether the #ji system has been already considered in solution graph or not. If it was already considered, go to step 14.

Step 7. Calculate total cost C^T_{ji} = C^T_j + $C(P^{(i)}_{(x,y)})$ for the #ji system.

Step 8. Calculate the minimum cut-set capacity, $P_{cji}(X,\overline{X})$using maximum flow and minimum cut-set theorem for the #ji system.

Step 9. Calculate C^T_{ji} = minimum{ C^T_{ji} , C^T_{opt}}.

Step 10. Compare C^T_{opt} and C^T_{ji}. If the C^T_{ji} is lower than C^T_{opt}, it is not necessary to consider the solution graphs following to this #ji system. Because the costs of the following systems are always higher than this cost (C^T_{ji}) and the cost of the following systems will be surely higher than the optimal solution (C^T_{opt}) obtained until now. Hence, go to step 14.

Step 11. Set up $jmax$ = $jmax$ +1.

Step 12. If C^T_{ji} is lower than C^T_{opt}, set up C^T_{opt} = C^T_{ji} and $jopt$ = $jmax$ and go to step 14.

Step 13. If Fm is higher than L, set up C^T_{jmax} = C^T_{ji} and $ENNOD_{jmax}$ =1 and go to step 15. If Fm is lower than L, go to next step.

Step 14. Add this #$jmax$(#ji) solution to the solution graph.

Step 15. Whether the all candidate branches/lines involved in set Sj have been considered or not? If no, set up i=i+1 and go to step 5. If yes, go to step 16.

Step 16. Check whether j = $jmax$ or not. If no, set up j = j +1 and go to step 4.

Step 17. For j = $jmax$, the solution graph has been made entirely and the optimal solution, $jopt$ with C^T_{opt} of the lowest construction cost of a decision maker has been obtained at step 12. Therefore, stop this process.

The flow chart for this algorithm is show in Fig. 1

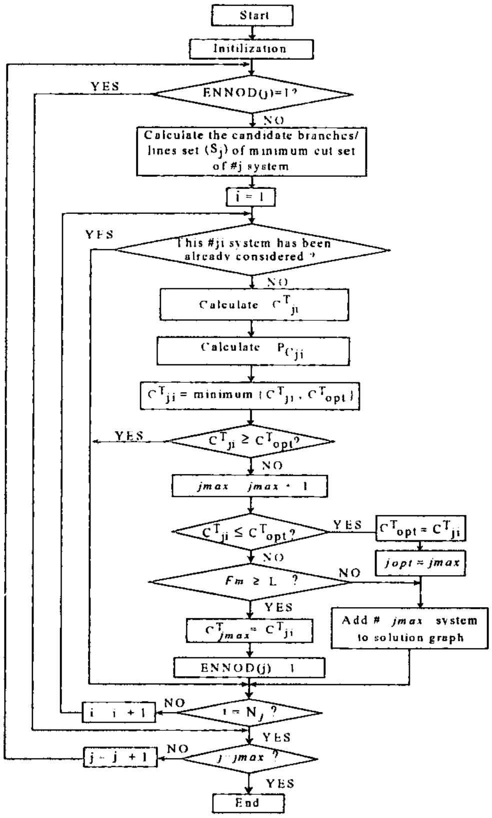

Fig. 1 Flow chart

4. Case Study

The proposed method was tested on the 63-buses radial style test system shown in Figure 2. Considering a forecasted future system load and generation expansion increasing from 7147 MW to 8433 MW and from 7647 MW to 9135 MW, respectively. The amount new load and generation expansion installed capacity are presented in Table 1 and Table2.

On the other hand, Table 3 shows the system data with GN, TF, TL and LD representing generators, transformers, transmission lines and loads respectively. SB and EB are start and end bus, respectively. P(0) and C(0) are the capacity and cost of constructed original transmission lines or generators. P(i) and C(i), for I = 1,2,3,4 are respectively, the capacity and cost of the candidate line.

Table 1 Load demand at status and load forecasted

Load Bus	Original Load [MW]	New Load [MW]	Increasing Load [MW]
Bus 25	350	550	200
Bus 32	101	201	100
Bus 44	105	305	200
Bus 46	125	525	400
Bus 61	270	656	386
Other Buses	6196	6196	0
Total	7147	8433	1286

Table 2 Generation capacity installed and capacity expansion

Generation Bus	Original generation [MW]	New Generation [MW]	Increasing Capacity [MW]
Bus 3	325	625	300
Bus 12	157	607	450
Bus 14	627	771	144
Bus 16	275	419	144
Bus 17	215	665	450
Other Buses	6050	6050	0
Total	7649	9135	1488

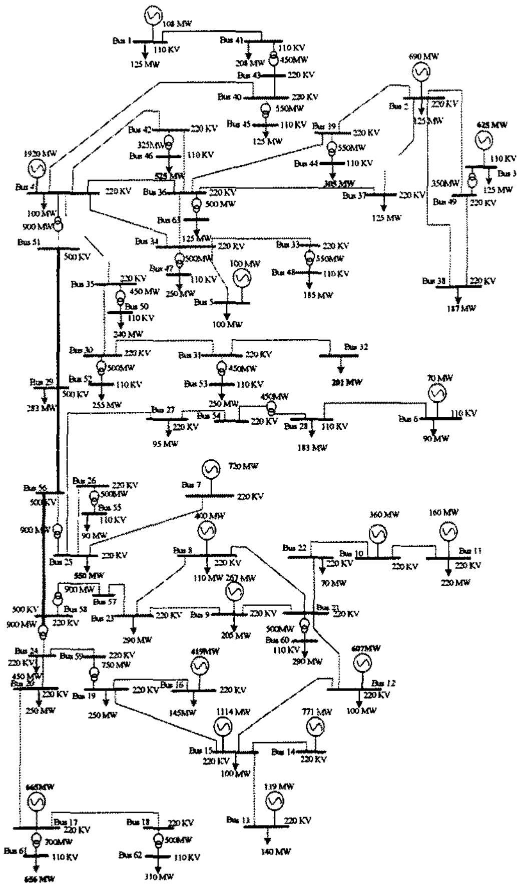

Fig.2 The configuration of 63 buses test system

Table 3 System Capacity and Cost Data

NL	SB	EB	ID	P(0)	P(1)	P(2)	P(3)	P(4)	C(0)	C(1)	C(2)	C(3)	C(4)
1	0	1	GN	108	0	0	0	0	0	0	0	0	0
2	0	2	GN	690	0	0	0	0	0	0	0	0	0
3	0	3	GN	625	0	0	0	0	0	0	0	0	0
:	:	:	:	:	:	:	:	:	:	:	:	:	:
21	42	46	TF	325	325	0	0	0	0	450	0	0	0
22	36	63	TF	500	0	0	0	0	0	0	0	0	0
23	33	48	TF	550	0	0	0	0	0	0	0	0	0
24	3	49	TF	350	350	0	0	0	0	500	0	0	0
:	:	:	:	:	:	:	:	:	:	:	:	:	:
44	4	36	TL	450	450	450	450	450	0	60	60	60	60
45	36	39	TL	550	127	0	0	0	0	40	0	0	0
46	36	37	TL	750	103	0	0	0	0	35	0	0	0
47	2	39	TL	450	127	0	0	0	0	40	0	0	0
:	:	:	:	:	:	:	:	:	:	:	:	:	:
122	45	64	LD	125	0	0	0	0	0	0	0	0	0
123	41	64	LD	208	0	0	0	0	0	0	0	0	0
124	46	64	LD	525	0	0	0	0	0	0	0	0	0

P(*): (MW) and C(*): (M$)

Discussion of Results

Optimal solution for new system are shown in Table 4 and status of the new system is introduced at Table 5. It is shown *that the delivery reserve rate(HLII) of new system is different* from supply reserve rate(HLI) from Table 5 because of capacity constraint of transmission system. The results configuration of the 63 buses system is shown in Fig. 3. Reserve rates of the generators and transmission lines of new system are shown in Fig 4. The Fig. 4 shows that the #33(57-58), # 37(17-61), #56(4-35), #58(35-30), #64(7-25), #68(24-20), #72(9-21), #73(8-23), #76(12-21) and #84(15-19) lines have reserve rates under 10%.

Table 4 The optimal expansion planning of the system

	Optimal Solution of New System	Cost [M$]
TF	$TF_{42\text{-}46}^{1}$, $TF_{3\text{-}49}^{1}$	950
TL	$T_{4\text{-}35}^{1}$, $T_{4\text{-}35}^{2}$, $T_{4\text{-}35}^{3}$, $T_{35\text{-}30}^{1}$, $T_{24\text{-}20}^{1}$, $T_{24\text{-}59}^{1}$, $T_{57\text{-}3}^{1}$, $T_{9\text{-}23}^{1}$, $T_{12\text{-}21}^{1}$	445
Total Cost		1395

(Number of subscript and superscript mean bus number and new transmission line, respectively)

Table 5 The reliability of expansion planning

	Original system	New system
Total generation power [MW]	7647	9135
Total Load demand [MW]	7147	8433
Total maximum delivery power [MW]	7647	9114
Supply reserve rate (HLI)	6.99%	8.32%
Delivery reserve rate (HLII)	6.99%	8.08%

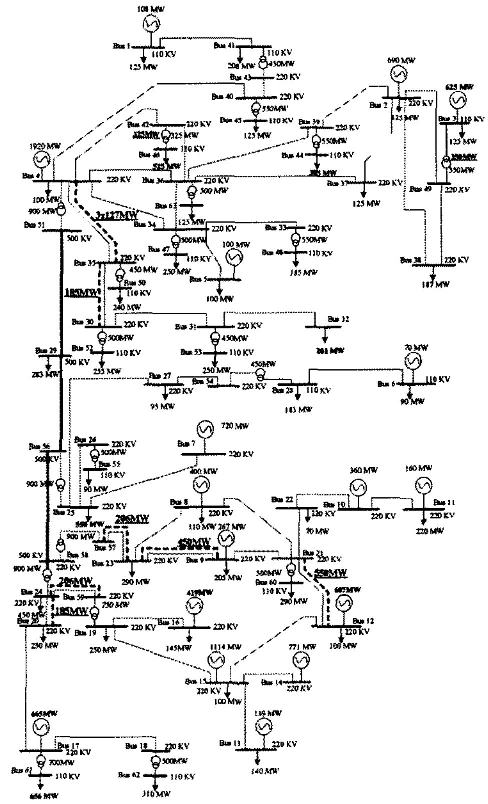

Fig. 3 The result configuration of 63 buses test system of the expansion planning

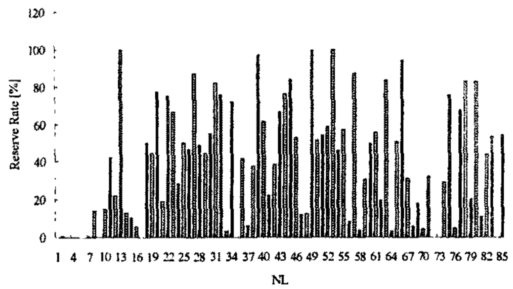

Fig.4 Reserve rate of generations and transmission lines of the new system

5. Conclusions

A new method for solving a single-stage or static transmission expansion problem has been proposed in this paper using an efficient branch and bound algorithm. The discrete nature of the problem is tackled directly on 63 buses test system. Single contingency criteria is recognized in the design. Furthermore, a special procedure is available to design a network, when new buses are introduced. The method has been implemented in a computer program which can handle a system with one hundred buses.

This paper addresses the problem of transmission expansion planning when a very small database for the evaluations of reliability and economics. A proposed branch and bound algorithm, which includes the network flow method, and the maximum flow-minimum cut set theorem is proposed to solve the problem.

Acknowledgments

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Appendix

A.1 Network Modeling of Power System

The generators, substations, and load points have limited capacities. It is difficult to check a shortage power supply of the system because these elements are presented as nodes in a real system model. Network modeling of the system makes it convenient to check a shortage of power supply because the network elements mentioned above are presented as branches with a capacity limitation. Aspects of a shortage of power supply according to a bottleneck are as given in Table 1.

Table A.1 Various aspects of power supply BottleNeck.

$Fm \cdot L \leq G$	No shortage of supply
$Fm \cdot G \quad L$	Shortage of power generation
$Fm \cdot L \leq G$	Shortage of transmission delivery capacity
$Fm \cdot G \cdot L$	Shortages of power generation and transmission delivery capacity

Where,

Fm: maximum flow of the network

G: total power generation

L: total system load

A.2 Integer Programming (IP)

The total cost minimization objective transmission systems expansion planning can be formulated as an ordinary integer problem with only 0 or 1 as follows

$$\begin{aligned} &\text{minimize } F(x) \\ &s.t. \quad Ax \quad b \\ &x = \{0, 1\} \end{aligned} \qquad (A.1)$$

where,

x : decision vector

F : coefficient vector of the objective function(1 x n)

A : coefficient matrix of the constraints(p x n)

b : constant vector of constraints (RHS) (p x 1)

p : number of constraints

Biographies

Trungtinh Tran was born in Mochoa, Vietnam in 1973. Obtained B.Sc. degrees from Cantho University in 1997. His research interest includes Transmission Expansion Planning using Fuzzy Set Theory and Reliability Evaluation of Power Systems. He is now working forward a M.Sc. degrees at Gyeongsang National University.

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