Transmission System Expansion Plans in View Point of Deterministic, Probabilistic and Security Reliability Criteria

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Abstract

This paper proposes three methods for choosing the transmission system expansion plan considering three reliability constraints, which are deterministic reliability criterion, probabilistic reliability criterion and security criterion based on N-α contingency in order to give more successful market operation. The proposed method minimizes total investment cost It models the transmission system expansion problem as an integer programming one. The method solves for the optimal strategy using a branch and bound method that utilizes a network flow approach and the maximum flow-minimum cut set theorem. The 21 bus system case study results demonstrate that the proposed method is practical for solving the power system expansion planning problem subject to practical future uncertainties.

1. Introduction

The one of successful operation of the power system market may come from the preventive operation from sudden accidents of system in operation mode. It is based on expert and preventive control system as well as reasonable strength of grid originally. Because investment for power system expansion is very huge, the problem, "how is the investment money?" is one of very difficult policies work. Therefore, the reasonable investment budget should be decided from grid owner's considering the various reliability criteria, which has relationship with investment. Furthermore, not only conventional reliability criterion code but also the agreement of customer, who is most important factor in the competitive electricity market, is necessary for deciding the investment budget. The analysis and comparison of various reliability criterion 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 [1]-[3]. 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 [4]-[13]. 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.

NERC Planning Standards continue to define the reliability of the interconnected bulk electric systems using the following two terms [14].

- Adequacy: The ability of the electric systems to supply the aggregate electrical demand and energy requirements of their customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.
- Security: The ability of the electric systems to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements

Adequacy standards may be used for first macro approach stage and then security standards is applied to second micro checking stage in panning problem. A deterministic reliability criteria such as load balance constraint or a probabilistic reliability criterion or a N-1 (or N-2) contingency criteria in view point of adequacy in first stage are used in most transmission system planning because of computation time problems. With the processing, transmission system expansion planning addresses the problem of broadening and strengthening an existing generation and transmission network to optimally serve a growing electricity market while satisfying a set of economic and technical constraints [2].

In a deregulated environment, electric utilities are expected to be winners in competition. Successful electricity market operation in such an environment depends on the transmission system and nodal (bus) reliability management. Deregulated electricity markets, therefore, call for nodal based indices in system operation and planning. Nodal reliability indices together with related information can be used for the management and control of congestion and reliability by ISO and TRANSCO in deregulated markets [15],[16]. This environment makes it important to assess and provide reasonable reliability criteria at the load points [15]. In such an environment, there is more variability in the investment budget for construction and higher uncertainty in the transfer reliability of the transmission system. This is because profit maximization for the system owner is the major focus while, for a conventional power system, the primary function is to provide electrical energy to its customers economically and with an acceptable degree of continuity and quality. System planners and owners are therefore expected to evaluate the reliability and economic parameters with more detail in grid planning where the problem involves many uncertainties including those of the investment budget, reliability criterion, load forecast and system characteristics, etc. [17],[18]. Furthermore, the recent blackouts that have occurred in countries worldwide, call for strengthening the grid structure in order to establish successful deregulated electricity markets. The incidents call for the development of tools that can address and diagnoses uncertainties and significantly enhance the ability to conduct effective transmission planning [19].

This paper proposes and compares three methods for choosing the best transmission system expansion plan considering three reliability constraints, which are deterministic reliability criterion, probabilistic reliability criterion and a security criterion based on N-α contingency in first macro analysis stage[2],[21]. The proposed method minimizes the investment budget for constructing new transmission lines subject to three kinds of reliability criteria. It models the transmission system expansion problem as an integer programming problem. It solves for the optimum mix of transmission network expansion using a branch and bound method that utilizes a network flow approach and the maximum flow-minimum cut set theorem [20]-[25].

2. The transmission system expansion planning problem

A composite power system that includes generation and transmission facilities is shown in Figure 1. *TS* refers to the transmission system, *NG* is the number of generators, ${}_k\Phi_0$ is the inverted load duration curve at load point *k*, and *NL* is the number of load points. In this paper, a composite power system is designated as HLII (Hierarchical level II) and HLI (Hierarchical level I) is used to designate generation and load components only [26]. It is assumed that the generation system and transmission system plans are separated and the construction of new generators is determined independently by GENCOs.

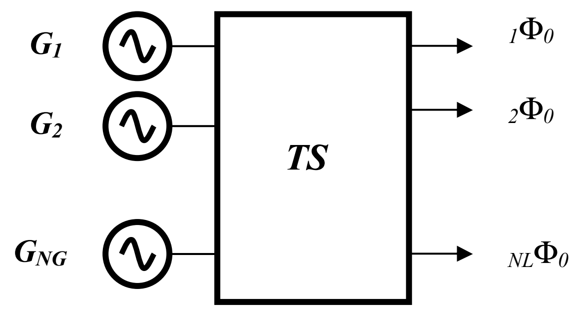


Figure 1. A composite power system including the transmission system

2.1. The Objective function

The conventional transmission system expansion planning problem is to minimize the total construction cost C^T associated with investing in new transmission lines as expressed in (1) [21]-[25].

$$\min imize\, C^T = \sum_{(x,y)\in\rho}\left[\sum_{i=1}^{m(x,y)} C_{(x,y)}^{(i)} U_{(x,y)}^{(i)}\right] \qquad (1)$$

where,

ρ: the set of all branches (transmission lines)

$m(x,y)$: the number of new candidate branches connecting nodes *x* and *y*

$C_{(x,y)}^{(i)}$: sum of the construction costs of the new lines *1st* through *i-th* that connect buses *x* and *y*

$C_{(x,y)}^{(i)} = \sum_{j=1}^{i} \Delta C_{(x,y)}^{(j)}$

with $\Delta C_{(x,y)}^{(j)}$: construction cost of the new *j-th* line connecting nodes *x* and *y*,

$U_{(x,y)}^{(i)}$: the decision variable associated with the line (1 if from 1st to *i-th* lines are to be constructed, and 0 otherwise).

with $\sum_{i=1}^{m(x,y)} U_{(x,y)}^{(i)} = 1$

$$U_{(x,y)}^{(i)} = \begin{cases} 1 & P_{(x,y)} = P_{(x,y)}^{(0)} + P_{(x,y)}^{(i)} \\ 0 & P_{(x,y)} \neq P_{(x,y)}^{(0)} + P_{(x,y)}^{(i)} \end{cases} \quad (2)$$

$$P_{(x,y)}^{(i)} = \sum_{j=1}^{i} \Delta P_{(x,y)}^{(j)}$$

with

$P_{(x,y)}^{(i)}$: sum of the capacities of new branches (new transmission lines) between nodes x and y

$\Delta P_{(x,y)}^{(j)}$: capacity of the *j-th* element of the candidate branches connecting nodes x and y

$P_{(x,y)}^{(0)}$: capacity of the existing lines that connect nodes x and y.

2.2. Constraints

In this paper, three types of constraints, which are a deterministic adequacy reliability criterion (demand balance), security criterion and probabilistic reliability criterion are tried.

2.2.1. Deterministic adequacy reliability constraint. In a deterministic approach, no shortage of power supply requires that the total capacity of the branches involved in the minimum cut-set should be greater than or equal to the system peak load demand, L_p. This is also referred to as the bottleneck capacity. Therefore, a no shortage power supply constraint can be expressed by (3)[21]-[24].

$$P_c(S, T) \geq L_p \quad (s \in S,\ t \in T) \quad (3)$$

Where, $P_c(S, T)$ is the capacity of the minimum cut-set of two subsets, S and T, containing source nodes s and terminal nodes t respectively when all nodes are separated by a minimum cut-set.

The demand constraint (3) can be expressed by (4) with k being the cut-set number (k = 1,…,n), where, n is number of cut-set.

$$\sum_{(x,y)\in(X_k, \bar{X}_k)} \left[P_{(x,y)} = P_{(x,y)}^{(0)} + \sum_{i=1}^{m(x,y)} P_{(x,y)}^{(i)} U_{(x,y)}^{(i)} \right] \geq L_p \quad (4)$$

2.2.2. Security constraint in view point of adequacy. In a security constraint approach in view point of adequacy, no shortage of power supply requires that the total capacity of the branches involved in the minimum cut-set under N-α contingency should be greater than or equal to the system peak load demand, L_p. This is also referred to as the bottleneck capacity. Therefore, a no shortage power supply constraint under N-α contingency can be expressed by (5) [2].

$$P_c(S, T)_{N\text{-}\alpha} \geq L_p \quad (s \in S,\ t \in T) \quad (5)$$

Where, $P_c(S, T)_{N\text{-}\alpha}$ is the capacity of the minimum cut-set of two subsets(S and T)containing source nodes s and terminal nodes t respectively when all nodes are separated by a minimum cut-set under N-α contingency.

2.2.3. Probabilistic reliability constraint. In the probabilistic approach, the probabilistic reliability criterion index, *LOLE* (Loss of Load Expectation), can be used as in (6) [27],[28].

$$LOLE_{TS}(P_{(x,y)}^{(i)}, \Phi) \leq {}_{R}LOLE \quad (6)$$

Where, ${}_{R}LOLE$ is the required transmission reliability criterion for the new system. The ${}_{R}LOLE$ is ${}_{R}LOLE_{TS}$ for the transmission system reliability criterion case and it is ${}_{R}LOLE_{Bus}$ for the bus/nodal reliability criterion case. Φ is a function of the load duration curve. A detailed discussion of Φ and *LOLE* is presented in Section III.

3. Composite power system probabilistic reliability evaluation for reliability constraint

The following is a brief introduction to the methodology used to determine the transmission system reliability indices and the bus/nodal reliability indices. The methodology is based on the composite power system effective load model developed by authors [29]-[30].

3.1. Reliability evaluation at HLI

Reliability indices of $LOLE_{HLI}$ (Loss of load expectation) and $EENS_{HLI}$ (Expected energy not served) at HLI considering only the generation system are calculated using the effective load duration curve (ELDC), ${}_{HLI}\Phi(x)$ of HLI as in (7) and (8) respectively.

$$LOLE_{HLI} = {}_{HLI}\Phi(x)\big|_{x=IC} \quad \text{[hours/yr]} \quad (7)$$

$$EENS_{HLI} = \int_{IC}^{IC+Lp} {}_{HLI}\Phi(x)dx \quad \text{[MWh/yr]} \quad (8)$$

where,

IC : total installed generating capacity [MW]

L_p : system peak load [MW]

And,

$$_{HLI}\Phi_i(x_e) = {}_{HLI}\Phi_{i-1}(x_e) \otimes {}_{HLI}f_{oi}(x_{oi}) = \int {}_{HLI}\Phi_{i-1}(x_e - x_{oi})\,{}_{HLI}f_{oi}(x_{oi})dx$$

where,

$\otimes$: operator meaning convolution intergral

$_{HLI}\Phi_0(x_e - x_{oi}) = {}_{HLI}\Phi(x_L)$

$_{HLI}f_{oi}(x_{oi})$: the probability distribution function of outage capacity of generator #i

3.2. Reliability evaluation at HL II (composite power system)

The reliability indices at HLII can be classified as load point indices and bulk system indices depending on the object of the evaluation. The reliability indices can be evaluated using a Composite power system Equivalent Load Duration Curve (CMELDC) of HLII based on the composite power system effective load model in Figure 2 [29]-[31]. *CG, CT* and q and q_l in Figure 2 are the capacities and forced outage rates of the generators and transmission lines respectively.

3.2.1. Reliability indices at the load points (buses).

The load point reliability indices, $LOLE_k$ and $EENS_k$ can be calculated using (9) and (10) with the CMELDC, $_k\Phi_{NG}(x)$

$$LOLE_k = {}_k\Phi_{NG}(x)\Big|_{x=AP_k} \quad \text{[hours/yr]} \qquad (9)$$

$$EENS_k = \int_{AP_k}^{AP_k+Lp_k} {}_k\Phi_{NG}(x)dx \quad \text{[MWh/yr]} \qquad (10)$$

where, L_{pk}: peak load at load point k[MW]

AP_k: maximum arrival power at load point k[MW]

$$_k\Phi_i(x_e) = {}_k\Phi_o(x_e) \otimes_k f_{osi}(x_{oi}) = \int {}_k\Phi_o(x_e - x_{oi})\,{}_k f_{osi}(x_{oi})dx_{oi} \qquad (11)$$

with,

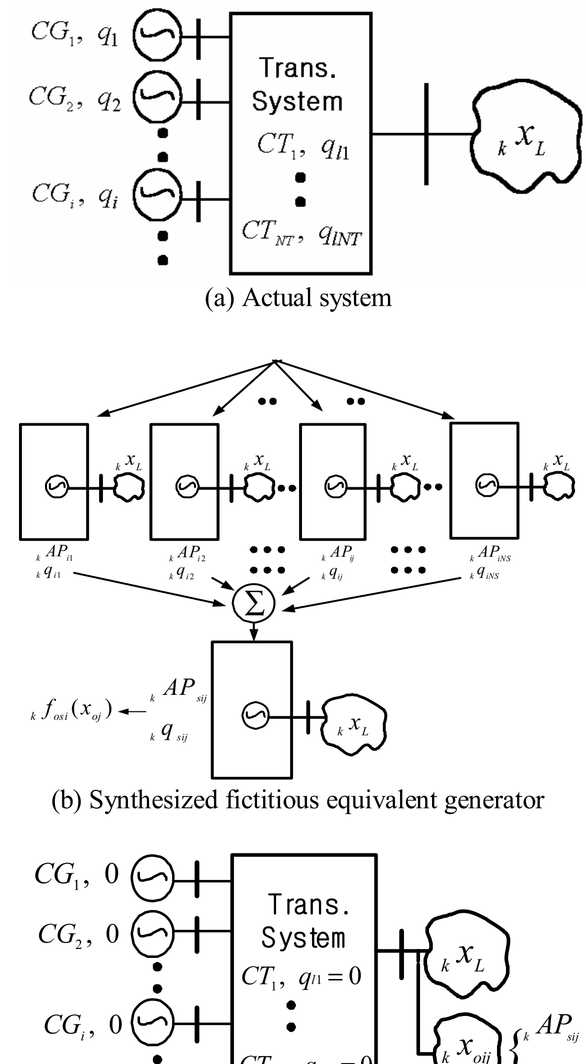
$\otimes$: the operator representing the convolution integral

$_k\Phi_0$ = original load duration curve at load point #k

$_kf_{osi}$: outage capacity *pdf* of the synthesized fictitious generator created by generators *1* to *i,* at load point #*k*.

3.2.2 Reliability indices of the bulk system.

While the $EENS_{HLII}$ of a bulk system is equal to the summation of the $EENS_k$ at the load points as shown in (12), the *LOLE* of a bulk system is entirely different from the summation of the $LOLE_k$ at the load points. The ELC_{HLII} (Expected load curtailed) of bulk system is equal to the summation of ELC_k at the load points. The $LOLE_{HLII}$ of the bulk system can be calculated using (14).



(a) Actual system

(b) Synthesized fictitious equivalent generator

(c) Equivalent system

Figure 2. Composite power system effective load model at HLII

$$EENS_{HLII} = \sum_{k=1}^{NL} EENS_k \quad \text{[MWh/yr]} \qquad (12)$$

$$ELC_{HLII} = \sum_{k=1}^{NL} ELC_k \quad \text{[MW/cur.yr]} \quad (13)$$

$$LOLE_{HLII} = EENS_{HLII} / ELC_{HLII} \quad \text{[hours/yr]} \quad (14)$$

$$EIR_k = 1\text{-}EENS_k/DENG_k \quad \text{[PU]} \quad (15)$$

where, NL : number of load points

$ELC_k = EENS_k / LOLE_k$

$DENG_k$: demand enegy at bus $\#_k$

3.3 Reliability evaluation of transmission system

The reliability indices of a transmission system can be expressed as the difference between the HLII and HLI reliability indices as shown in (16) and (17).

$$EENS_{TS} = EENS_{HLII} - EENS_{HLI} \quad \text{[MWh/yr]} \quad (16)$$

$$LOLE_{TS} = LOLE_{HLII} - LOLE_{HLI} \quad \text{[hrs/yr]} \quad (17)$$

4. Maximum flow under contingency analysis for security constraint

In order to consider the security constraints in view point of adequacy in this study, it is evaluated that the power flow under $N\text{-}\alpha$ contingency of system elements satisfy the peak load whether or not.

The power flow in the network of each arc (transmission line) $(i,j) \in B$ is associated with its a non-negative real number C_{ij} that is called the transmission line capacity from node i to node j. The static power flow value, K from s (source) to t (terminal) in branch set, B of branch set can be formulated by (18) [21]-[23],[31].

$$\sum\left(-x_{ij} + x_{ij}\right) = \begin{cases} -K, & i = s \\ 0, & i \neq s,t \\ K, & i = t \end{cases} \quad (18)$$

$$0 \leq xij \leq Cij \qquad (ij) \in B_{N\text{-}\alpha}$$

where,

$B_{N\text{-}\alpha}$: branch set under $N\text{-}\alpha$ contingency

K: total load (= L_p)

c_{ij} : branch (generator and line) capacity ($c_{ij} > 0$) between nodes i and j

The maximum power flow using branch set, $B_{N\text{-}\alpha}$ under $N\text{-}\alpha$ contingency can be calculated by LP and it means the bottleneck capacity under $N\text{-}\alpha$ contingency. It can be expressed by (19). Where, the $F_{m\ N\text{-}\alpha}$ is the maximum power flow obtained by using branch set, $B_{N\text{-}\alpha}$ under $N\text{-}\alpha$ contingency.

$$P_c(S,\ T)_{N\text{-}\alpha} = F_{m\ N\text{-}\alpha} \quad (19)$$

5. Solution algorithm

The objective in the conventional branch and bound method is to minimize the total construction cost subject to a specified reliability criterion. The proposed probabilistic branch and bound-based method minimizes the total cost subject to the required probabilistic transmission system reliability criteria, ${}_RLOLE_{TS}$ or/and ${}_RLOLE_{BUS}$ [24],[28].

The solution algorithm for the proposed approach follows.

1. Check the need for transmission expansion for the system and its possibility using the candidate lines. Need and possibility can be checked respectively by the reliability evaluation for systems considering no candidate lines and considering all candidate lines.
2. Set j=1 (initial system), $jopt$ =0, $jmax$ =0, C^T_{opt}=∞ and $ENNOD_j$=0.
3. If $ENNOD_j$=1, the #j system is an end node at which the branch operation of a branch and bound is finished (bound) in the solution graph used to obtain the optimal solution, and there is no need to consider any of the other graphs following this system. Go to 13.
4. Calculate the minimum cut-set using the maximum flow method for system j (solution j in the solution graph.)
5. Select a #i branch/line of the candidate branches/ lines set (S_j) involved in the minimum cut-set and add to the #j system. In what follows, the new system is named the system ji.
6. If the system ji is already considered in the solution graph. Go to step 13.
7. Calculate the total cost $C^T_{ji} = C^T_j + C(P^{(i)}_{(x,y)})$ for the system ji and evaluate the transmission system reliability index, $LOLE_{TSji}$ of the system.
8. If $C^T_{ji} < C^T_{jopt}$, the current system (ji) with a cost of C^T_{ji} can be optimal. If not, go to 11.
9. Set $jmax = jmax$ +1.
10. 1) For deterministic reliability criterion; If $P_c(S,T) > L_p$, set $C^T_{opt} = C^T_{ji}$, and $F_{m\ opt} = P_c(S,T)$, $jopt = jmax$, and go to 12.
    2) For security criterion; If $P_c(S,T)_{N\text{-}\alpha} > L_p$, set $C^T_{opt} = C^T_{ji}$, and $F_{moptN\text{-}\alpha} = P_c(S,T)_{N\text{-}\alpha}$, $jopt = jmax$, and go to 12.

    3) For probabilistic reliability criterion; If $LOLE_{TSji}$ (or $LOLE_{BUSji}$)<${}_RLOLE_{TS}$, set $C^T_{opt} = C^T_{ji}$, and ${}_RLOLE_{opt} = LOLE_{ji}$, $jopt = jmax$, and go to 12.
11. Set $C^T_{jmax} = C^T_{ji}$, $ENNOD_{jmax}$ =1, and go to 13.

12. Add the solution $jmax(ji)$ to the solution graph.
13. If all the candidate branches/lines in the cut-set S_j have been considered, go to 14. Otherwise, set $i=i+1$ and go to 5.
14. If $j = jmax$, continue the next step. Otherwise, set $j = j+1$ and go to 4.
15. For $j = jmax$, the solution graph has been constructed fully and the optimal solution $jopt$ with C^T_{jopt} being the lowest cost and satisfies the required reliability criteria is obtained in 10.

6. Case study

The proposed method was tested on the 21-bus model system shown in Fig. 3. This is a part of the south-east area (Youngnam) in Korea. Considering a future forecast system load, the proposed deterministic reliability criterion and the probabilistic reliability and security approaches were applied and the case studies compared [24],[28].

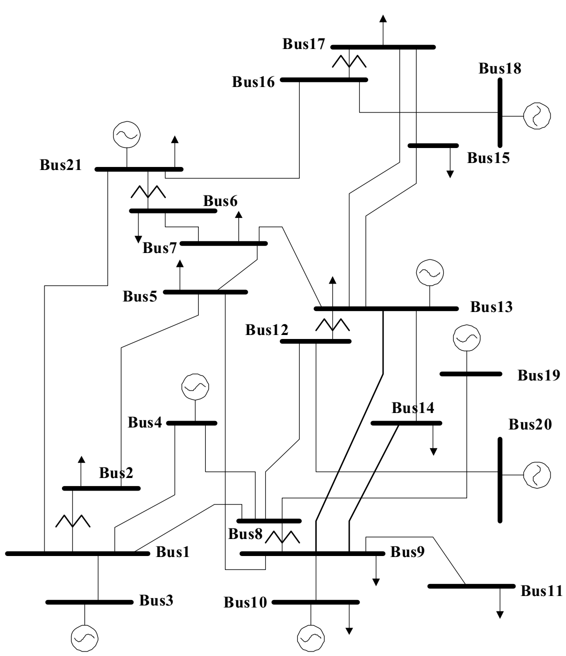


Figure 3. 21-Bus model system

Table 1 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 buses of the line, respectively. $\Delta P_{(x,y)}^{(0)}$ and $\Delta C_{(x,y)}^{(0)}$ are respectively, the capacities and costs of existing lines that connect nodes x and y. In this study, four candidate generators and lines are considered as it is, it means $m(x,y)= 3$ in (1) and (4). In Table 1, parentheses in $\Delta P_{(x,y)}^{(j)}$ and $\Delta C_{(x,y)}^{(j)}$ are omitted for convenience. The cost unit, M$ in this table stands for million dollars. Table 2 shows the forced outage rate of the generators and transmission lines. Fig. 4 shows the inverted load duration curves at the buses with the four largest loads.

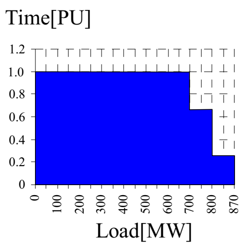
Table 1. System capacity and cost data P(*): (MW) and C(*): (M$)

NL	SB	EB	ID	NN	ΔP^0_{xy}	ΔP^1_{xy}	ΔP^2_{xy}	ΔP^3_{xy}	ΔC^0_{xy}	ΔC^1_{xy}	ΔC^2_{xy}	ΔC^3_{xy}
1	0	3	GN	1	850	0	0	0	0	0	0	0
2	0	21	GN	1	900	0	0	0	0	0	0	0
3	0	4	GN	1	850	0	0	0	0	0	0	0
4	0	10	GN	1	900	0	0	0	0	0	0	0
5	0	20	GN	2	1200	0	0	0	0	0	0	0
6	0	18	GN	1	850	0	0	0	0	0	0	0
7	0	13	GN	1	760	0	0	0	0	0	0	0
8	0	19	GN	1	950	0	0	0	0	0	0	0
9	6	21	TF	2	510	510	510	0	0	132	132	0
10	16	17	TF	2	510	510	510	0	0	124	124	0
11	12	13	TF	2	510	510	510	0	0	123	130	0
12	8	9	TF	1	800	800	0	0	0	155	0	0
13	1	2	TF	1	800	800	0	0	0	151	0	0
14	21	1	TL	1	500	500	500	0	0	29	29	0
15	2	5	TL	2	220	220	0	0	0	54	0	0
16	1	4	TL	2	300	300	0	0	0	73	0	0
17	1	8	TL	2	400	400	0	0	0	70	0	0
18	1	3	TL	4	250	250	250	250	0	20	20	20
19	4	8	TL	2	300	300	0	0	0	63	0	0
20	5	9	TL	1	220	220	0	0	0	82	0	0
21	5	7	TL	2	220	220	0	0	0	77	0	0
22	7	6	TL	2	220	220	0	0	0	85	0	0
23	21	16	TL	4	250	250	250	250	0	30	30	30
24	7	13	TL	1	220	220	0	0	0	88	0	0
25	13	17	TL	1	220	220	0	0	0	69	0	0
26	13	15	TL	1	220	220	0	0	0	83	0	0
27	16	18	TL	4	330	330	330	330	0	32	32	32
28	9	13	TL	2	220	220	0	0	0	71	0	0
29	9	14	TL	2	220	220	0	0	0	65	0	0
30	8	19	TL	2	620	620	0	0	0	64	0	0
31	12	20	TL	4	310	310	310	310	0	28	28	28
32	12	8	TL	2	400	400	0	0	0	62	0	0
33	9	10	TL	2	240	240	0	0	0	81	0	0
34	9	11	TL	1	340	340	0	0	0	45	0	0
35	15	17	TL	2	220	220	0	0	0	80	0	0
36	13	14	TL	2	220	220	0	0	0	80	0	0
37	21	22	LD	1	785	0	0	0	0	0	0	0
38	6	22	LD	1	750	0	0	0	0	0	0	0
39	2	22	LD	1	850	0	0	0	0	0	0	0
40	9	22	LD	1	595	0	0	0	0	0	0	0
41	10	22	LD	1	17	0	0	0	0	0	0	0
42	11	22	LD	1	550	0	0	0	0	0	0	0
43	14	22	LD	1	190	0	0	0	0	0	0	0
44	13	22	LD	1	710	0	0	0	0	0	0	0
45	15	22	LD	1	450	0	0	0	0	0	0	0
46	17	22	LD	1	870	0	0	0	0	0	0	0
47	7	22	LD	1	290	0	0	0	0	0	0	0
48	5	22	LD	1	70	0	0	0	0	0	0	0

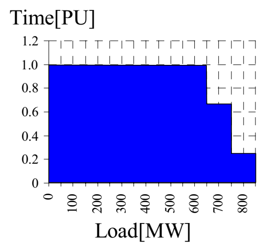
(#0 and #6 represent source and terminal nodes,)

Table 2. Forced outage rates of generators and lines

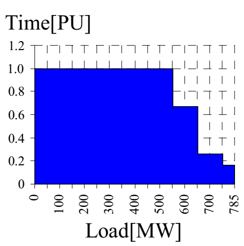
NL	FOR	NL	FOR	NL	FOR
1	0.012	13	0.0012	25	0.0014
2	0.015	14	0.0015	26	0.0020
3	0.010	15	0.0015	27	0.0018
4	0.015	16	0.0012	28	0.0022
5	0.010	17	0.0015	29	0.0020
6	0.012	18	0.0014	30	0.0025
7	0.0125	19	0.0015	31	0.0012
8	0.0155	20	0.0016	32	0.0015
9	0.0015	21	0.0018	33	0.0011
10	0.0020	22	0.0012	34	0.0011
11	0.0015	23	0.0012	35	0.0021
12	0.0012	24	0.0012	36	0.0022



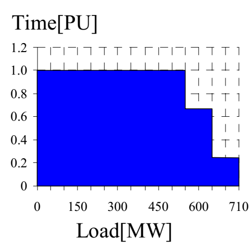
(a) ILDC at Bus 17



(b) ILDC at Bus 2



(a) ILDC at Bus 21



(b) ILDC at Bus 13

Figure 4. Inverted load duration curves at the buses with the four largest loads

In the first case study, the deterministic reliability criterion approach was tried (case 1). Figure 5 shows the new system with dotted lines presenting new lines obtained by deterministic reliability constraints. An optimal system which has the construction cost of 74[M\$] and the new construction elements of $T_{21\text{-}1}^{1}$ and $T_{9\text{-}11}^{1}$ is obtained. An other deterministic case (case 2) has been studied using a deterministic bus/nodal reliability criterion, BRR_k is defined in [28] as $BRR_k = (AP_k\text{-}L_{pk})\text{x}100/L_{pk}$. Where, AP_k and L_{pk} are the maximum arrival power and peak load respectively at the k load point. It will be shown in Table 4 later.

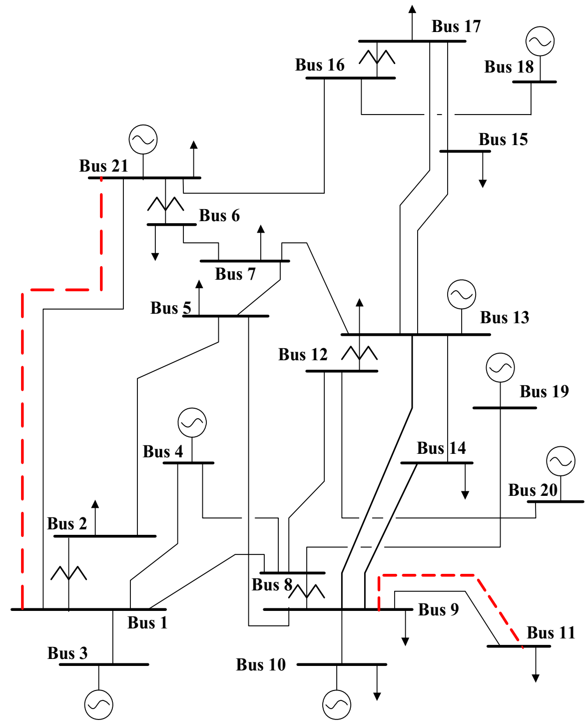


Figure 5. Optimal system by the deterministic reliability criterion approach (case 1)

In the second case study, the probabilistic transmission system reliability criterion method was approached. $_{R}LOLE_{TS}$=30[hrs/yr] is assumed for the probabilistic reliability criterion (case 3). The new optimal system is shown in Figure 6 with dotted lines presenting new lines also. An optimal system which has the construction cost of 265[M\$] and the new construction elements of $T_{1\text{-}2}^{1}$, $T_{13\text{-}17}^{1}$ and $T_{9\text{-}11}^{1}$ is obtained. The actual reliability level, $LOLE_{TS}$ of the optimal system was evaluated as 26.84[hrs/yr] and this level is satisfied with a required probabilistic reliability criterion level (constraint), $_{R}LOLE_{TS}$=30 [hrs/yr]. Table 3 shows the reliability indices at the load buses in the case of $_{R}LOLE_{TS}$ =30[hrs/yr]. The other case using $_{R}LOLE_{TS}$=60[hrs/yr] has been studied (case 4) and the result will be shown in Table 4 later.

Finally, the security criterion approach with (N-1) contingency is applied to same system (case 5). Figure 7 shows the obtained new system by the security criterion approach. An optimal system which has the construction cost of 503[M\$] and the new construction elements of $T_{1\text{-}2}^{1}$, $T_{21\text{-}1}^{1}$, $T_{13\text{-}17}^{1}$, $T_{13\text{-}15}^{1}$, $T_{9\text{-}10}^{1}$, $T_{9\text{-}11}^{1}$and $T_{9\text{-}11}^{2}$ is obtained.

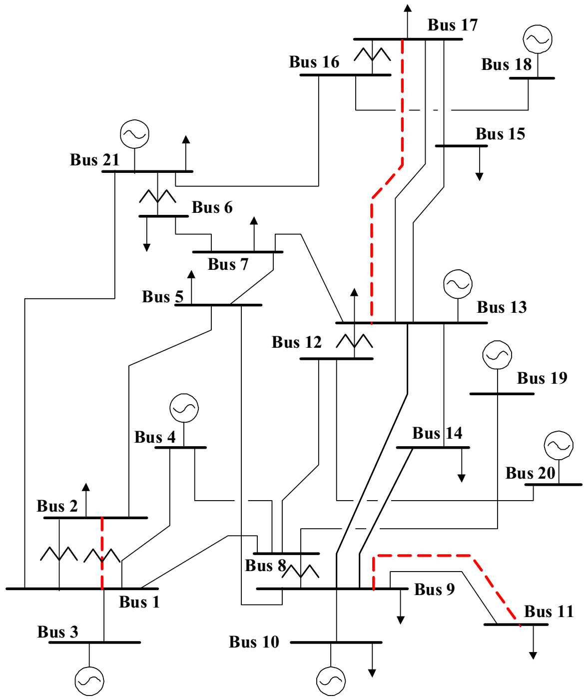


Figure 6. Optimal system by the probabilistic reliability criterion approach (case 3) ($_{R}LOLE_{TS}$=30[hrs/yr])

Table 3. Reliability indices at the load buses in the case of $_{R}\ LOLE_{TS}$ = 30[hrs/yr]

Load Bus Number	$LOLE_{Bus}$ [hrs/yr]	$EENS_{Bus}$ [MWh/yr]	EIR_{Bus} [PU]	Remark (*LOLE*)
21	26.47	3388	0.9994	
6	32.64	4441	0.9992	
2	33.29	5320	0.9992	
9	23.05	2660	0.9994	
10	0.00	0	1.0000	
11	25.22	2643	0.9993	
14	7.12	357	0.9997	
13	34.68	4589	0.9992	
15	24.4	2006	0.9993	
17	35.69	5657	0.9992	Highest
7	7.73	472	0.9997	
5	1.98	99	0.9998	

Table 4 shows the results and investment costs obtained for six cases with different constraint types. Where, D, P and S are the deterministic, probabilistic and security criterion approaches. In this table, the N-1T security criterion means a case with contingency constraint considering the transmission lines contingency only, as it is, the generators contingency not considered. The Table 4 shows characteristics that security criterion is inquiring the highest investment cost for grid expansion plan. It is interesting that the line$T_{9\text{-}11}^{1}$ is selected by all kind constraints approaches because load point/bus 11 has some large load and the existing line supplying to the bus 11 has one cct only. It may be expected a fact that the probabilistic reliability criterion has a middle criterion characteristics between N-0 (deterministic) criterion and N-1 (security) criterion.

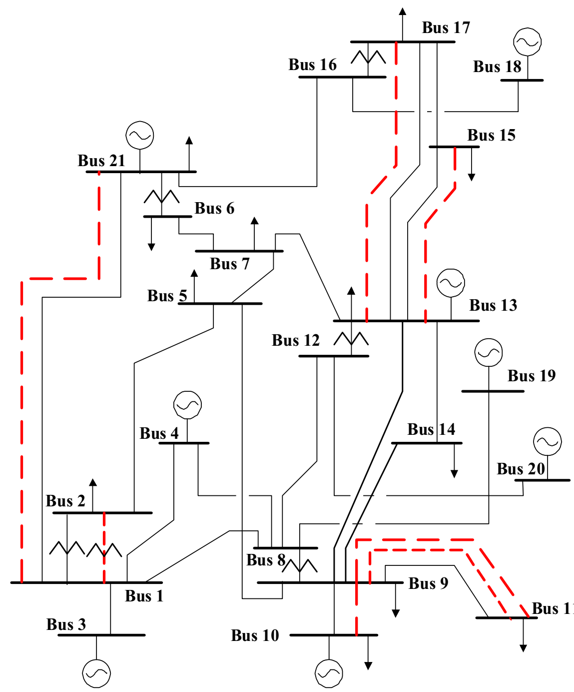


Figure 7. Optimal system by the N-1 security criterion approach (case 5)

Table 4. Optimal expansion plans due to changing constraints type

Cases	Construction of new lines	$Cost_T$ [M$]	Appro-ach	Criterion
case 1	$T_{21\text{-}1}^{1}$ and $T_{9\text{-}11}^{1}$	74	D	*BRR*=0%
case 2	$T_{21\text{-}1}^{1}$, $T_{21\text{-}1}^{2}$ and $T_{9\text{-}11}^{1}$	103	D	*BRR*=10%
case 3	$T_{1\text{-}2}^{1}$, $T_{13\text{-}17}^{1}$ and $T_{9\text{-}11}^{1}$	265	P	$LOLE_{TS}$ =30[hrs/yr]
case 4	$T_{13\text{-}15}^{1}$ and $T_{9\text{-}11}^{1}$	128	P	$LOLE_{TS}$ =60[hrs/yr]
case 5	$T_{1\text{-}2}^{1}$, $T_{21\text{-}1}^{1}$, $T_{13\text{-}17}^{1}$, $T_{13\text{-}15}^{1}$, $T_{9\text{-}10}^{1}$, $T_{9\text{-}11}^{1}$ and $T_{9\text{-}11}^{2}$	503	S	N-1 contingency
case 6	$T_{1\text{-}2}^{1}$, $T_{21\text{-}1}^{1}$, $T_{13\text{-}17}^{1}$, $T_{13\text{-}15}^{1}$, $T_{9\text{-}11}^{1}$ and $T_{9\text{-}11}^{2}$	422	S	N-1T contingency

7. Conclusions

Electricity system operators are being challenged to maintain the reliability of the grid and support economic transfers of power as the industry's structure changes and market rules evolve. Meanwhile, the US economy depends more than ever on reliable and high quality electricity supplies. New technologies are needed to prevent major outages. As previous commented in introduction, the one of successful operation of the power system market may come from the preventive operation from sudden accidents of system in operation mode. It is based on expert and preventive control system as well as reasonable strength of grid originally. Because investment for power system expansion is very huge, the problem, "how is the investment money?" is one of very difficult policies work. Therefore, the reasonable investment budget should be decided from grid owner's considering the various reliability criteria, which has relationship with investment.

This paper addresses transmission system expansion planning and investment evaluation using a deterministic and probabilistic reliability criteria and security criterion for supplying some various reliability criteria to the grid company and the relative national policy. The proposed procedure is a first stage in preparing a transmission system expansion plan employing various reliability assessment methods to ensure the reliability of the electric power grid. Optimal locations and capacities of transmission lines can be determined using the proposed method. The paper presents three practical approaches that should serve as a useful guide for the decision maker in selecting a reasonable expansion plan prior to checking system stability and dynamics in detail. In this paper, the deterministic reliability criterion, firstly, has been approached. The second proposed method finds the optimal transmission system expansion plan considering uncertainties associated with the forced outage rates of the grid elements (transformers and lines). The probabilistic approach models the problem as a probabilistic integer programming one and considers problem uncertainties through probabilistic modeling. A probabilistic branch and bound algorithm, which includes the network flow method, and the maximum flow-minimum cut set theorem is used to solve the problem. Finally, security criterion approach with N-1 contingency was tried. The various case studies show that quite different planning alternatives can be determined from the use of the deterministic and probabilistic reliability approaches and security criteria. It is interesting a fact that security criterion is requiring the highest investment cost for transmission system expansion planning in this case study of 21-bus test system. The paper suggests that the probabilistic reliability criterion and security criterion can be used in collaborate for more reasonable investment in grid expansion planning in order to operate the power system market successfully more under competitive electricity market environment with more uncertainties in future. It will be expected that the proposed method and comparison in this paper is useful for the successful electricity market planning.

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