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A Study on Optimal Reliability Criterion Determination for Transmission System Expansion Planning

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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 under competitive electricity market environments. 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. This paper approaches a methodology for deciding the optimal reliability criteria for an optimal transmission system expansion planning. A deterministic reliability criteria, BRR (Bus Reserve Rate) is used in this study. The optimal reliability criteria, BRR*, is decided at minimum cost point of total cost curve which is the sum of the utility cost associated with construction cost and the customer outage cost associated with supply interruptions for load considering bus reserve rate at load buses in long term forecasting. The characteristics and effectiveness of this methodology are illustrated by the case study using IEEE-RTS.

Keywords: Transmission expansion planning, Optimal reliability criteria, Transmission system reliability, Utility cost, Customer outage cost

1. Introduction

This study opens a new door with a methodology for deciding the optimal reliability criteria for a transmission system expansion planning. A deterministic reliability index, BRR (bus reserve rate) is used in this study. The optimal reliability criterion, BRR*, for a transmission system is determined at the minimum cost point of the total cost curve, which is the sum of the utility cost associated with the construction cost and the customer outage cost associated with supply interruptions for the load bus reserve rates. It's an extension of the conventional concept of optimal reliability criterion for generation system expansion planning. The two curves, utility cost (reliability cost) and customer outage cost (reliability worth) are required in this methodology.

The first step is creating utility cost (reliability cost) curve. In this study, TranExp.For v5.1, a transmission system expansion planning program, developed in 1986 year by Gyeongsang National University (GSNU) is used to compose the utility cost curve. This program uses Integer Program (IP) with a branch and bound algorithm, which includes minimization construction cost for the objective function and network flow theory for constraints. A maximum flow-minimum cut set theorem is used to obtain the optimal solution at the objective minimization construction cost and subjective satisfaction load buses reserve rate of reliability constraints, capacity limitation and right of way constraints.

The second step is to create customer outage cost curve associated with probabilistic reliability of the transmission system. This second step is composed of two sub-steps. One sub-step is the reliability evaluation of the transmission system and the other sub-step is an assessment of the IEAR or VOLL by outage cost assessment. In this paper, TranRel.For v3.2, a transmission system reliability evaluation program developed in 2004 by GSNU is used in order to evaluate the reliability indices, EENS and LOLP of scenarios/cases with optimal investment obtained after running TranExp.For. The TranRel program uses an enumeration method that is able to consider up to eighth order contingencies (4-depth for generation and 4-depth for transmission systems) and the maximum network flow method for optimal load flow. The key concept of transmission system reliability evaluation of the program is that the reliability indices of a transmission

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system are equal to the difference in the reliability levels of the composite power systems HLII (hierarchical level II) and generation system (HLI). The effective load duration curve of the composite power system (CMELDC) developed earlier by the authors is used in order to obtain the reliability indices of composite power systems at HLII[4]-[8]. Therefore, the customer outage cost curve for the optimal scenarios can be assessed by multiplying the expected energy not supplied (EENS) and interrupted energy assessment rate IEAR given from surveys or a macro approach. In this study, outage cost assessment for assumed IEAR is used as the scope of this study is focused on optimal reliability criteria determination. The characteristics and effectiveness of this methodology are illustrated by a case study of an IEEE-RTS.

2. Optimal Reliability Criteria Determination

The economics of alternate facilities play a major role in the decision making process for transmission system expansion planning. The simplest approach, which can be used to relate economics with reliability, is to consider the investment cost only. The increase in reliability due to the various alternatives is evaluated together with the investment cost associated with each scheme. A goal for future transmission planning should be to extend this adequacy comparison within the same hierarchical structure to include security, and therefore to arrive at reliability-cost and reliability-worth evaluation. The extension of quantitative reliability analysis to the evaluation of service worth is deceptively simple but is fraught with potential misapplication.

Fig. 1 shows that utility cost will generally increase as customers are provided with higher reliability. On the other hand, customer outage costs associated with supply interruptions will decrease as the reliability increases. The total costs to society are the sum of these two individual costs. This total cost exhibits a minimum point at which an "optimal" or target level of reliability is achieved [8]-[9].

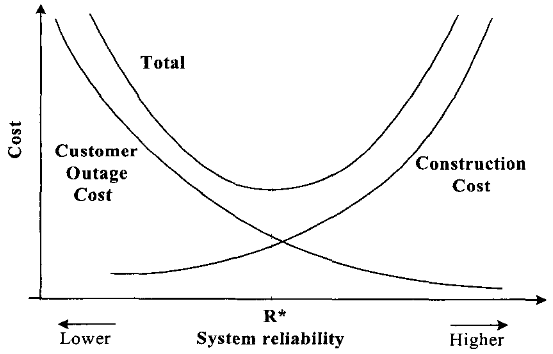


Fig. 1 Customer, utility and total cost as a function of system reliability

3. Optimal Transmission System Expansion Planing

3.1 Transmission system expansion planning formulation in TranExp.For

The static transmission system 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 an Integer Programming (IP) problem as follows

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

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

No power supply shortage requires that the total capacity of the 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. Therefore, a no shortage power supply constraint can be expressed by Eq. (2)681

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

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

$$\sum_{(x,y)\in(x_k,\overline{x}_k)} [P^{(0)}_{(x,y)} + \sum_{i=1}^{m(x,y)} P^{(i)}{}_{(x,y)} U^i_{(x,y)}] \geq L(1+BRR/100) \tag{3}$$

Where,

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

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

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

$$U^i_{(x,y)} = \left[\begin{array}{l} 1, P_{(x,y)} = P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \\ 0, P_{(x,y)} \neq P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \end{array} \right. \tag{7}$$

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

Where,

L: total demand

$P_{(x,y)}$: capacity of transmission line or generator between node x and node y.

$\Delta C^{(j)}_{(x,y)}$: construction cost of new #*j* parallel element of branches between node *x* and node *y*.

$\Delta P^{(j)}_{(x,y)}$: capacity of new #*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*.

BRR: load bus reserve rate (= $\frac{\sum AP - L}{L}$)

AP: Maximum arrival power at load bus

The conventional formulation is calculated using an educational program called TranExp.For version 5.2. It can calculate about 100 buses and 150 transmission lines. This program was developed un the power system laboratory of GSNU. The flow chart of the program is shown at Fig.2.

3.2 Flow Chart

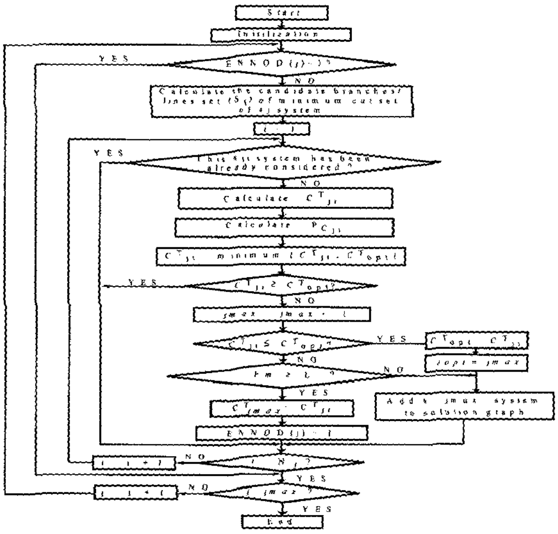


Fig. 2 Flow chart

4. Transmission System Reliability Evaluations

4.1 Reliability Evaluation of HL I

Reliability indices of $LOLE_{HLI}$ (Loss of load expectation) and $EENS_{HLI}$ (Expected energy not served) of only the generation system using the ELDC (Effective load duration curve) ${}_{HLI}\Phi(x)$ of HLI are calculated by Eq. (9) and Eq. (10) respectively.

$$LOLE_{HLI} = {}_{HLI}\Phi\ (x)\ \Big|_{x=IC} \quad \text{[days]} \qquad (9)$$

$$EENS_{HLI} = \int_{IC}^{IC+Lp} {}_{HLI}\Phi(x)dx \quad \text{[MWh]} \qquad (10)$$

Where, IC : total installed capacity of generators [MW]

$$\begin{aligned} {}_{HLI}\Phi_i(x_e) &= {}_{HLI}\Phi_{i-1}(x_e) \otimes_{HLI} f_{oi}(x_{oi}) \\ &= \int {}_{HLI}\Phi_{i-1}(x_e - x_{oi})_{HLI} f_{oi}(x_{oi})dx \end{aligned} \qquad (11)$$

Where, $\otimes$ *: operator meaning convolution integral*

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

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

L_p *: peak load of system [MW]*

4.2 Reliability Evaluation of HL II

The indices of HLII can be classified in terms of load point indices and bulk system indices according to the objective of the evaluation. The reliability indices can be evaluated from the CoMposite power system Equivalent Load Duration Curve (CMELDC) of HLII using the Synthesized Fictitious Equivalent Generator (SFEG) model shown in Fig. 3.[5]-[19]. In this Fig., ${}_kAP_{ij}$ and ${}_kq_{ij}$ are arrival power and state probability of contingency state #*j* at load point #*k* respectively.

4.2.1 Reliability indices at load points

The load point reliability indices, $LOLE_k$ and $EENS_k$ can be calculated using Eq. (12) and Eq. (13) with the nodal CMELDC, ${}_k\Phi_{NG}(x)$ of Eq. (14).

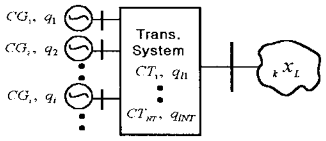
$$LOLE_k = {}_k\Phi_{NG}(x)\ \Big|_{x=AP_k} \quad \text{[day]} \qquad (12)$$

$$EENS_k = \int_{AP_k}^{AP_k+Lp_k} {}_k\Phi_{NG}(x)dx \quad \text{[MWh]} \qquad (13)$$

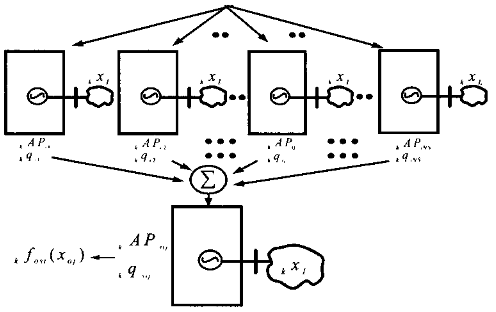
where, AP_k : maximum arrival power at load point/bus #k

L_{pk} : the peak load at load point/bus #k

$$\begin{aligned} {}_k\Phi_i(x_e) &= {}_k\Phi_o(x_e) \otimes_k f_{osi}(x_{oi}) \\ &= \int {}_k\Phi_o(x_e - x_{oi})_k f_{osi}(x_{oi})dx_{oi} \end{aligned} \qquad (14)$$



(a) Actual system



(b) Synthesized fictitious equivalent generator

Fig. 3 Synthesized Fictitious Equivalent Generator Model at HLII

Where, $\otimes$: the operator meaning convolution integral

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

$_kf_{osi}$: outage capacity *pdf* of synthesis fictitious generator operated by generators from *#1* to *#i* at load point *#k*.

4.2.2 Reliability indices of the bulk system

The $EENS_{HLII}$ of the bulk system is equal to the summation of $EENS_k$ at load points as shown in Eq.(15). The *LOLE* of the bulk system is different from summation of $LOLE_k$ at load points. The ELC_{HLII} of the bulk system is equal to the summation of the ELC_k at the load points, and therefore the $LOLE_{HLII}$ of the bulk system can be calculated as shown in Eq.(17).

$$EENS_{HLII} = \sum_{k=1}^{NL} EENS_k \quad \text{[MWh]} \qquad (15)$$

$$ELC_{HLII} = \sum_{k=1}^{NL} ELC_k \qquad (16)$$

$$LOLE_{HLII} = EENS_{HLII} / ELC_{HLII} \quad \text{[pu]} \qquad (17)$$

Where, *NL*: number of load point

R: set of states of not supplied powers

$ELC_k = EENS_k / LOLE_k$ [MW/cur.yr]

These conventional indices were calculated using the computer program TranRel.For version 3.2. It can accommodate about 100 buses, 150 transmission lines, eight deep contingencies and a 10^{-9} cut off for the state probability of a contingency. This program was developed in the power system laboratory of GSNU.

4.3 Transmission System Reliability Evaluation of TranRel.For

Compatible indices for HLII and HLI have to be used. The reliability indices of a transmission system are equal to the difference in the reliability level between HLII and HLI. Therefore, *LOLE*, *EENS*, *EDNS* and *ELC* are used in this study. The *LOLE* and *EENS* of the transmission system are calculated using Eq. (18) and Eq.(19) respectively.

$$LOLE_{TS} = LOLE_{HLII} - LOLE_{HLI} \quad \text{[days]} \qquad (18)$$

$$EENS_{TS} = EENS_{HLII} - EENS_{HLI} \quad \text{[MWh]} \qquad (19)$$

5. Flow Chart Of Optimal Reliability Criteria Determination For Transmission System Expansion Planning

A flow chart of optimal reliability criteria decision proposed in this study is shown in Fig. 4.

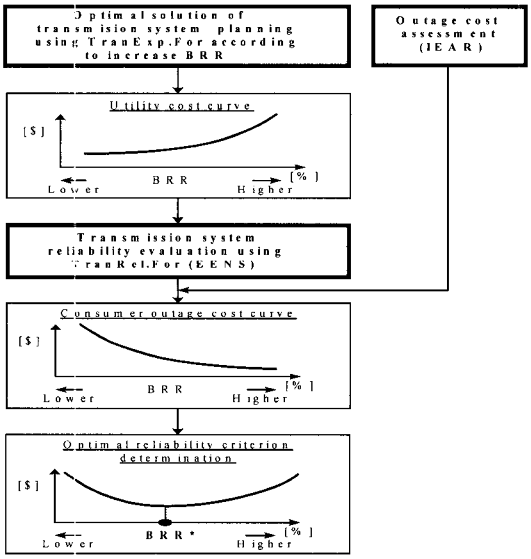


Fig. 4 Flow chart of the optimal reliability criterion determination for transmission system expansion planning as proposed in this study.

6. Case Studies

6.1 Basic Input Data

The proposed method was tested on the IEEE-RTS shown in Fig. 5. There are ten power plants with forty-eight generators, thirty-eight transmission lines and seventeen load buses. Table 1 shows the system input data with GN, TF, TL and LD representing the generators, transformers, transmission lines and loads respectively. SB and EB are the start and end buses, respectively. $T^0_{i\text{-}j}$ and $C^0_{i\text{-}j}$ are the capacity and cost of constructing the original transmission lines or generators. $T^k_{i\text{-}j}$ and $C^k_{i\text{-}j}$, for k = 1 - 4 are respectively, the capacity and cost of the candidate lines. Where subscripts I and j are numbers of starting and end buses.

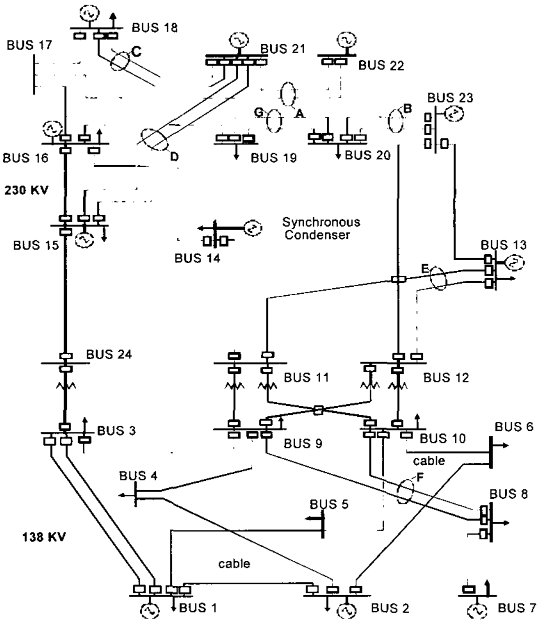


Fig. 5 IEEE-RTS for case study

Table 1 System capacity and cost data

$T^k_{i\text{-}j}$: (MW) and C(*): (M$)

NL	SB	EB	ID	$T^0_{i\text{-}j}$	$T^1_{i\text{-}j}$	$T^2_{i\text{-}j}$	$T^3_{i\text{-}j}$	$T^4_{i\text{-}j}$	$C^0_{i\text{-}j}$	$C^1_{i\text{-}j}$	$C^2_{i\text{-}j}$	$C^3_{i\text{-}j}$	$C^4_{i\text{-}j}$
1	0	1	GN	268	0	0	0	0	0	0	0	0	0
2	0	2	GN	268	0	0	0	0	0	0	0	0	0
3	0	7	GN	570	0	0	0	0	0	0	0	0	0
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11	1	2	TL	105	105	105	0	0	0	100	100	0	0
12	1	3	TL	105	105	105	105	105	0	100	100	100	100
13	1	5	TL	105	105	105	105	105	0	100	100	100	100
14	2	4	TL	105	105	105	0	0	0	100	100	0	0
15	2	6	TL	105	105	105	105	105	0	100	100	100	100
:	:	:	:	:	:	:	:	:	:	:	:	:	:
58	16	25	LD	150	0	0	0	0	0	0	0	0	0
59	18	25	LD	495	0	0	0	0	0	0	0	0	0
60	19	25	LD	270	0	0	0	0	0	0	0	0	0
61	20	25	LD	195	0	0	0	0	0	0	0	0	0

(#0 and #25 in SB and EB mean source and terminal nodes respectively)

6.2 Results of Construction Cost of Cases

Table 2 shows the results of transmission expansion planning with the objective of minimizing the construction cost with increasing load buses reserve rate obtained used TranExp.For. Fig. 6 shows that construction cost increases with increasing load buses reserve rate. It cannot, however, show optimal the optimal reliability criterion for transmission planning.

Table 2 Optimal expansion planning of the system

Cases	BRR [%]	Optimal Solution of New System	Total Cost [M$]
1	0	$T_{2\text{-}6}^1$	100
2	5	$T_{2\text{-}6}^1$	100
3	10	$T_{2\text{-}6}^1$, $T_{7\text{-}8}^1$	200
4	15	$T_{2\text{-}6}^1$, $T_{7\text{-}8}^1$, $T_{7\text{-}8}^2$	300
5	20	$T_{2\text{-}6}^1$, $T_{3\text{-}9}^1$, $T_{7\text{-}8}^1$, $T_{7\text{-}8}^2$, $T_{15\text{-}24}^1$	560
6	25	$T_{2\text{-}6}^1$, $T_{7\text{-}8}^1$, $T_{12\text{-}23}^1$, $T_{15\text{-}21}^1$, $T_{16\text{-}19}^1$	680
7	30	$T_{6\text{-}10}^1$, $T_{7\text{-}8}^1$, $T_{12\text{-}23}^1$, $T_{16\text{-}17}^1$, $T_{16\text{-}19}^1$	680
8	35	$T_{6\text{-}10}^1$, $T_{7\text{-}8}^1$, $T_{7\text{-}8}^2$, $T_{12\text{-}23}^1$, $T_{15\text{-}24}^1$, $T_{16\text{-}17}^1$, $T_{16\text{-}19}^1$	940
9	40	$T_{6\text{-}10}^1$, $T_{7\text{-}8}^1$, $T_{12\text{-}23}^1$, $T_{12\text{-}23}^2$, $T_{16\text{-}17}^1$, $T_{16\text{-}19}^1$, $T_{16\text{-}19}^2$	1160
10	45	$T_{6\text{-}10}^1$, $T_{6\text{-}10}^2$, $T_{7\text{-}8}^1$, $T_{7\text{-}8}^2$, $T_{12\text{-}23}^1$, $T_{12\text{-}23}^2$, $T_{15\text{-}21}^1$, $T_{16\text{-}17}^1$, $T_{16\text{-}19}^1$, $T_{16\text{-}19}^2$	1360

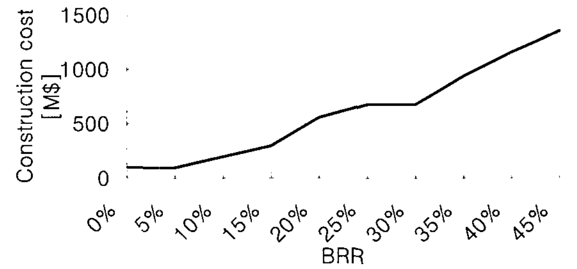

Fig. 6 Construction cost curve

6.3 Reliability Evaluation, Outage Cost Curve and Optimal BRR* in case of IEAR=5[$/kWh]: Case study A

Table 3 shows the reliability indices obtained by TranRel.For for 10 cases with the minimum construction costs obtained used TranExp.For. Customer outage costs were obtained assuming that the interrupted energy assessment rate (IEAR) is 5[$/kWh]. The non-monotonic decreasing characteristics of the customers outage cost are shown at Fig. 7. The customer outage cost curve indicates the reliability worth for each new system with minimum construction cost but it cannot give the optimal reliability level. Fig.8 shows the total cost as the sum of the construction cost and customer outage cost. The optimal reliability criterion point (BRR*) for transmission expansion

Table 3 Construction cost, reliability and outage cost at each case study

Cases	BRR	Const. Cost [M$]	EENS [MWh /Day]	LOLE Hour /Day]	EENS [MWh /Year]	Outage Cost [M$]	Total Cost [M$]	Remark
1	0	100	27.6853	0.0589	10105.13	505.26	605.26	
2	5	100	27.6853	0.0589	10105.13	505.26	605.26	
3	**10**	**200**	13.9826	0.0315	5103.65	255.18	**455.18**	**Optimal**
4	15	300	13.9599	0.0316	5095.36	254.77	554.77	
5	20	560	7.2316	0.0211	2639.53	131.98	691.98	
6	25	680	13.9800	0.0315	5102.70	255.14	935.14	
7	30	680	12.6509	0.0282	4617.58	230.88	910.88	
8	35	940	12.7603	0.0284	4657.51	232.88	1172.88	
9	40	1160	12.6500	0.0282	4617.25	230.86	1390.86	
10	45	1360	9.5333	0.0180	3479.65	173.98	1533.98	

planning of the system is given by minimum point on this curve. In this study, the total cost is 455.18[M$] at reliability criterion of 10% as shown in Table 3.

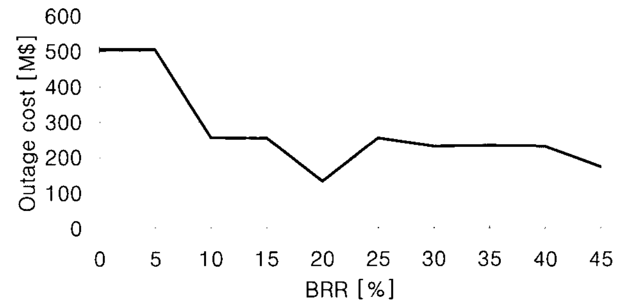

Fig. 7 Customers outage cost

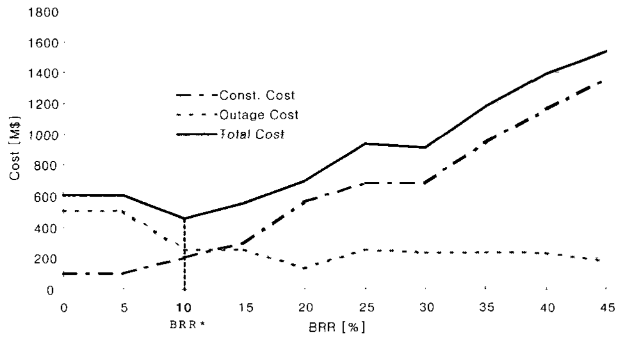

Fig. 8 Curves of construction, customer outage, total costs and optimal reliability level

6.4 Reliability evaluation, outage cost curve and optimal BRR* in case of IEAR=15[$/kWh]: Case study B

Table 4 shows the customer outage costs assuming that the interrupted energy assessment rate (IEAR) of the system is 15[$/kWh]. The construction costs and reliability indices are the same as in case study A. Fig.9 shows that the optimal reliability criteria, BRR* moves from 10% in the case of study A with IEAR=5 [$/kWh] to 20% at 15 [$/kWh]. As expected, the optimal reliability level increases as the IEAR increases.

Table 4 Construction cost, reliability and outage cost at each case study

Cases	BRR	Const. Cost [M$]	EENS [MWh /Day]	LOLE Hour /Day]	EENS [MWh /Year]	Outage Cost [M$]	Total Cost [M4]	Remark
1	0	100	27.6853	0.0589	10105.13	1515.77	1615.77	
2	5	100	27.6853	0.0589	10105.13	1515.77	1615.77	
3	10	200	13.9826	0.0315	5103.65	765.55	965.55	
4	15	300	13.9599	0.0316	5095.36	764.30	1064.30	
5	**20**	**560**	7.2316	0.0211	2639.53	395.93	**955.93**	**Optimal**
6	25	680	13.9800	0.0315	5102.70	765.41	1445.41	
7	30	680	12.6509	0.0282	4617.58	692.64	1372.64	
8	35	940	12.7603	0.0284	4657.51	698.63	1638.63	
9	40	1160	12.6500	0.0282	4617.25	692.59	1852.59	
10	45	1360	9.5333	0.0180	3479.65	521.95	1881.95	

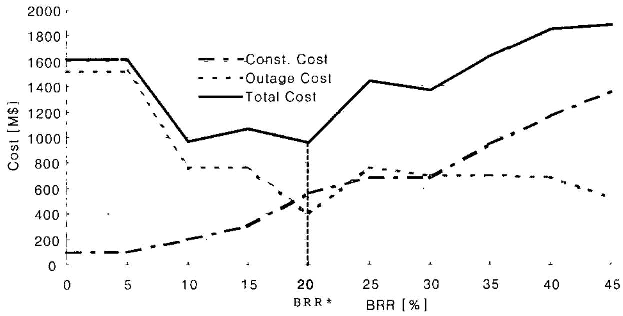

Fig. 9 Curves of construction, customer outage, total costs and optimal reliability level

7. Conclusions

This study introduces a new methodology for deciding the optimal reliability criterion for transmission system expansion planning. A deterministic reliability index, BRR (bus reserve rate) is used in this study. The optimal reliability criterion, BRR*, for a transmission system is located at minimum cost point of the total cost curve, which is the sum of the utility cost associated with construction and the customer outage costs associated with supply interruptions. A case study using a test system (IEEE-RTS) shows that an optimal deterministic reliability criterion of transmission system can be determined successfully using two basic programs, TranExp.For v5.1 for a transmission system expansion-planning and TranRel.For v3.2 in order to evaluate the reliability indices of scenarios/cases with optimal investment obtained by TranExp.For. As expected, the optimal reliability level increases as the IEAR increase. The procedure presented in this paper provides a quantitative assessment of the increase.

Acknowledgement

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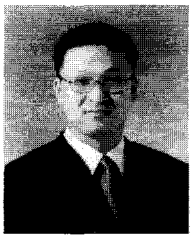

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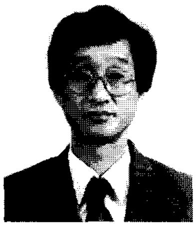

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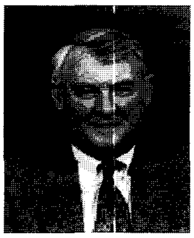

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