A Study on Transmission System Expansion Planning using Fuzzy Branch and Bound Method

Jaeseok Choi, Sungrok Kang, Hongsik Kim, Seungpil Moon, Soonyoung Lee and Roy Billinton

Abstract - This study proposes a new method for transmission system expansion planning using fuzzy integer programming. It presents stepwise cost characteristics analysis which is a practical condition of an actual system. A branch and bound method which includes the network flow method and the maximum flow - minimum cut set theorem has been used in order to carry out the stepwise cost characteristics analysis. Uncertainties of the permissibility of the construction cost and the lenient reserve rate and load forecasting of expansion planning have been included and also processed using the fuzzy set theory in this study. In order to carry out the latter analysis, the solving procedure is illustrated in detail by the branch and bound method which includes the network flow method and maximum flow-minimum cut set theorem. Finally, case studies on the 21- bus test system show that the algorithm proposed is efficiently applicable to the practical expansion planning of transmission systems in the future.

Keywords - transmission system expansion planning, fuzzy set theory, fuzzy integer programming, fuzzy branch and bound method.

1. Introduction

In the past, the primary function of a power system was that "an electric power system had to provide electrical energy to its customers as economically as possible and with an acceptable degree of continuity and quality"[1]. The conventional methods of power system expansion planning have been focused on only generation expansion planning without transmission systems. The expansion planning of the transmission system has been evaluated after planning the generation system expansion. Now the electricity industries, however, are asked to become winners of competition in the world under the capitalism social system and deregulation and restructuring of the power system[2]. It is more important to assess and construct reasonable reliability criteria at load points under a localized social system controlled by a local self government. And so, the recent problem of the power system expansion planning is focused on the composite power systems expansion planning considering the generation system as well as components of the transmission system, which are the lines, transformers, switches, etc. The power system expansion planning is an optimization problem for cost minimization under a reliability level constraint[3-5]. If no or only a very small database for the evaluation of component reliability indices is available, a method based on fuzzy theory may be a better approach for the evaluation of system reliability indices than complex statistic methods until the data base is completed reasonably[6-8]. Items considered for composite power system expansion planning are usually as follows.

Load forecasting, System characteristics, Reliability level and Economical efficiency

It is not easy to have an expansion planning solution of a power system considering all the items. In this study, a new method for the composite power systems expansion planning using the fuzzy set theory is proposed for considering the flexibility or ambiguity of investment cost and the uncertainty of the supply and delivery reserve power rate of the HLI(Hierarchical Level I) and HLII(Hierarchical Level II) [3]. The following are assumed. A network flow method for only active power instead of an AC power flow is used. The assumed network flow method is sufficient for the long term planning problem. Some draft plans/scenarios are made and come forward as candidates. And also this problem is limited to a static expansion planning problem for the single-stage or horizon-year. General methodology in order to obtain the optimal solution for the expansion planning problem formulated with Integer Programming is to select an optimal plan of some draft plans/scenarios as the candidates. It presents the stepwise cost characteristics analysis which is a practical condition of an actual system. A branch and bound method which includes the network flow theory and the maximum flow - minimum cut set theorem has been used in order to obtain the optimal solution and carry out the stepwise cost characteristics analysis. Uncertainty of the power system has also been included using the fuzzy set theory. The effectiveness of the proposed new approach is demonstrated by a case study of the 21- bus test system.

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2. Fuzzy Integer Programming

The composite power systems expansion planning is an ordinary integer problem with only 0-1 as in eq.(1)[6].

$$\begin{aligned} & \textit{maximize (minimize)}\ \mathbf{F(x)} \\ & \textit{sub. to}\ \ \mathbf{Ax \le b} \\ & \quad \mathbf{x = \{0, 1\}} \end{aligned} \tag{1}$$

Where **x** : decision vector
F : coefficient matrix of the objective function(q×n)
A : coefficient matrix of the constraints(p×n)
b : constant vector of constraints (RHS) (p×1)

In the case of the problem of some fuzzy characteristics, it can be formulated with the FIP(Fuzzy Inter Programming) as in eq.(2).

$$\begin{aligned} & \mathbf{F(x)} \lesssim \mathbf{Z_0}\ \text{(fuzzy objective functions: q)} \\ & \mathbf{Ax} \lesssim \mathbf{b}\ \text{(fuzzy constraints: p)} \\ & \mathbf{x = 0,1}\ \text{(0,1 constraints: n)} \end{aligned} \tag{2}$$

If the fuzzy mathematical programming problem consists of finding a maximum point of the membership functions according to the fuzzy optimal decision policy which is the maximization of the satisfaction level of a decision maker, the optimal solution x* for the above problem can be obtained as in eq.(3).

$$\begin{aligned} & \max_{X\ge 0}[\min\{\min_{i=1,\dots,q} \mu_i(\mathbf{F(x)}),\ \min_{i=1,\dots,p} \mu_i(\mathbf{Ax})\}] \\ & = \max_{\mathbf{x}\ge 0}[\min_{i=1,\dots,p+q} \mu_i(\mathbf{B(x)})] \end{aligned} \tag{3}$$

Where, **x*** is the optimal decision solution.
max and min are abbreviations of maximum and minimum respectively.
$\mu_i(\cdot)$: the membership function of #i-th fuzzy inequality constraints

$$\mathbf{B} = \begin{bmatrix} \mathbf{F(x)} \\ \mathbf{Ax} \end{bmatrix}$$

Using a parameter, λ, which means a satisfaction level of the decision maker, eq.(3) can be equalized to eq.(4) which is a formulation of the numerical analysis problem as follows:.

$$\begin{aligned} & \textit{maximize} \quad \lambda \\ & \textit{sub. to} \quad \lambda \le \mu_i(\mathbf{B(x)}) \\ & \qquad \mathbf{x = \{0,1\}} \\ & \qquad \lambda \ge 0 \end{aligned} \tag{4}$$

The optimal solution of the problem can be obtained by an optimization algorithm. The arbitrary shape of the membership functions is available for fuzzy integer programming because the fuzzy integer programming is originally nonlinear programming. If the membership function $\mu_i(\mathbf{B(x)})$ has linear characteristics as in eq.(5), eq.(4) can be formulated as eq.(6) where $d^{(i)}$ means the permissible width of a i-th fuzzy constraint equation.

$$\mu_i(\mathbf{Bx}) = \begin{Bmatrix} 1 & (\mathbf{B(x)})_i \le b_i' \\ 1-\{(\mathbf{B(x)})_i \le b_i'\}/d^{(i)} & b_i' < (\mathbf{B(x)})_i \le b_i' + d^{(i)} \\ 0 & b_i' + d^{(i)} < (\mathbf{B(x)})_i \end{Bmatrix} \tag{5}$$

$$\begin{aligned} & \textit{maximize} \quad \lambda \\ & \textit{sub. to} \quad \lambda \le 1 - \{(\mathrm{B(x)})_i - b_i'\}/d^{(i)} \\ & \qquad \mathbf{x = \{0,1\}} \\ & \qquad \lambda \ge 0 \end{aligned} \tag{6}$$

3. The Transmission Systems Expansion Planning Problem

3.1 Network Modeling of Power System

The generators, substations and load points have limited capacities and it is difficult to check a shortage power supply of the power system because the generators, substations and load points are presented as nodes in a real system model. Network modeling of the power system is convenient for checking a shortage of power supply because the generators, substations and load points are presented as branches with a capacity limitation[4]. Aspects of a shortage of power supply according to a bottle neck are as follow in Table 1.

Table 1 Various aspects of power supply bottle neck

Fm=L≤G	no shortage supply
Fm=G<L	shortage of the supply power of generation system
Fm<L≤G	shortage of the delivery capacity of transmission system
Fm<G<L	shortage of the supply power and delivery capacity of generation system and transmission system

where *Fm*: maximum flow of the network
G: total generation power
L: total load

3.2 Formulation of Expansion Planning

The following eq.(7) constraints for a no shortage power supply of a power system must be satisfied using the maximum flow - minimum cut set theorem.

$$P_c(X, \overline{X}) \ge L \qquad (s \in X,\ t \in \overline{X}) \tag{7}$$

Where, $P_c(X, \overline{X})$ is the maximum flow of minimum cut set of sets , X and X of branches between (Source)s and (Sink) t (=Fm)

N is a set of all branches,
$\underline{X}$ is a subset of N ,
$\bar{X}$ is a set of $N - X$.

The composite power systems expansion planning based on the minimum cutset theorem can be formulated as fuzzy integer programming as follows:

3.2.1 Objective Functions(minimization of construction cost)

$$minimize \quad C^T = \sum_{(x,y)\in B} [\sum_{i=1}^{m(x,y)} C^i{}_{(x,y)} U^i_{(x,y)}] \quad (8)$$

The fuzzy goal function with the given aspiration level, z_c^*, of the decision-maker for the construction cost, eq.(8), can be represented as follows in eq.(9).

$$C^T \lesssim z_c^* \quad (9)$$

3.2.2 Constraints

$$\sum_{(x,y)\in(x_k,\bar{x}_k)} [P^{(0)}_{(x,y)} + \sum_{i=1}^{m(x,y)} P^{(i)}{}_{(x,y)} U^i_{(x,y)}] \geq L \quad (10)$$

And also, the fuzzy constraint function with the fuzziness of the power delivery of the transmission system can be formulated as follows in eq.(11). z_R^* in eq.(11) is the aspiration level of the decision maker of the delivery power reserve rate.

$$\sum (P_{(x,y)} - L) \times 100 / L \gtrsim z_R^* \quad (11)$$

where variables and parameters are used as follows.

$$C^{(i)}_{(x,y)} = \sum_{j=1}^{i} \Delta C^{(j)}_{(x,y)} \quad (12)$$

$$P^{(i)}_{(x,y)} = \sum_{j=1}^{i} \Delta P^{(j)}_{(x,y)} \quad (13)$$

$$\sum_{i=1}^{m(x,y)} U^i_{(x,y)} = 1 \quad (14)$$

$$U^i_{(x,y)} = \left[\begin{array}{l} 1, P_{(x,y)} = P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \\ 0, P_{(x,y)} \neq P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \end{array} \right. \quad (15)$$

$$P_{(x,y)} = P^{(0)}_{(x,y)} + \sum_{i=1}^{m(x,y)} P^{(i)}_{(x,y)} U^{(i)}_{(x,y)} \quad (16)$$

L : total demand of loads
$\Delta C^{(j)}_{(x,y)}$: 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 : number of cut-set(=1, 2, 3 ... n)
B : set of all branches
$m(x,y)$: the number of new and additional branches between node x and node y

3.3 Equivalent Integer Programming and Branch and Bound Method

Eq.(8)-eq.(11), the fuzzy expansion planning problem of the composite power system, are equalized to the crisp type equivalent integer programming, eq.(17), using eq.(4).

$$\begin{array}{ll} maximize & \lambda \\ sub.\ to & C^T + d_1\lambda \leq z_c^* + d_1 \\ & \sum (P_{(x,y)} - L) \times 100 + d_2\lambda \geq z_R^* + d_2 \end{array} \quad (17)$$

where d_i : permissible width of the membership function of the i-th fuzzy inequality equation

In order to obtain the optimal solution of the problem, the branch and bound method which has merits in the case of a complex problem with many constraints has been used in this study. Therefore, the branch and bound method has been used in order to search for the optimal solution of this problem formulated with fuzzy integer programming.

4. Membership Functions

Fuzzy set theory is a useful tool for obtaining a reasonable solution for an optimization problem with subjective uncertainties. Determination of the membership function is entirely subjective for the decision maker.

In this study, the threshold values of membership function have been determined from the results of a conventional expansion planning problem with the crisp type membership function.

4.1 The membership function of the fuzzy set for the construction costs is defined as[11, 12]:

$$\mu_c\{P_{(x,y)}\} = \left\{ \begin{array}{ll} 1 & : \Delta C(\cdot) \leq 0 \\ e^{-Wc\ \Delta C\{P_{(x,y)}\}} & : \Delta C(\cdot) \rangle 0 \end{array} \right\} \quad (18)$$

where $\mu_c(\cdot)$: membership function of fuzzy set for the construction cost
$\Delta C(\cdot) = \{C(P_{(x,y)}) - Casp\} / Casp$
Casp: aspiration level for construction cost (= z_c^*)
W_c : weighting factor of the membership function for construction cost
$C(P_{(x,y)})$: construction cost at $P_{(x,y)}$

4.2 The membership function of the fuzzy set for the supply reserve rate of HLII is defined as:

$$\mu_r\{P_{(x,y)}\} = \begin{cases} 1 & : \Delta R(\cdot) \geq 0 \\ e^{W_r \ \Delta R\{P_{(x,y)}\}} & : \Delta R(\cdot) < 0 \end{cases} \quad (19)$$

where $\mu_r(\cdot)$: membership function of fuzzy sets for supply reserve rate

$\Delta R(\cdot) = \{RES(P_{(x,y)}) - Rasp\} / Rasp$

Rasp: aspiration level for supply reserve rate of composite power system (HLII) ($= z_R^*$)

W_r: weighting factor of the membership function for supply reserve rate of HLII

$RES(P_{(x,y)})$: reserve rate at $P_{(x,y)}$

5. Flow chart

The overall flow chart for the case study is as follows in Figure 1. While the objective function of the conventional crisp branch and bound method is the minimization of the total construction cost subject to the reliability level, delivery power reserve rate, the objective function of the proposed fuzzy branch and bound method, is maximization of the satisfaction level, rambda(λ) which means the reasonable solution to a decision maker for construction cost as well as the delivery power reserve rate.

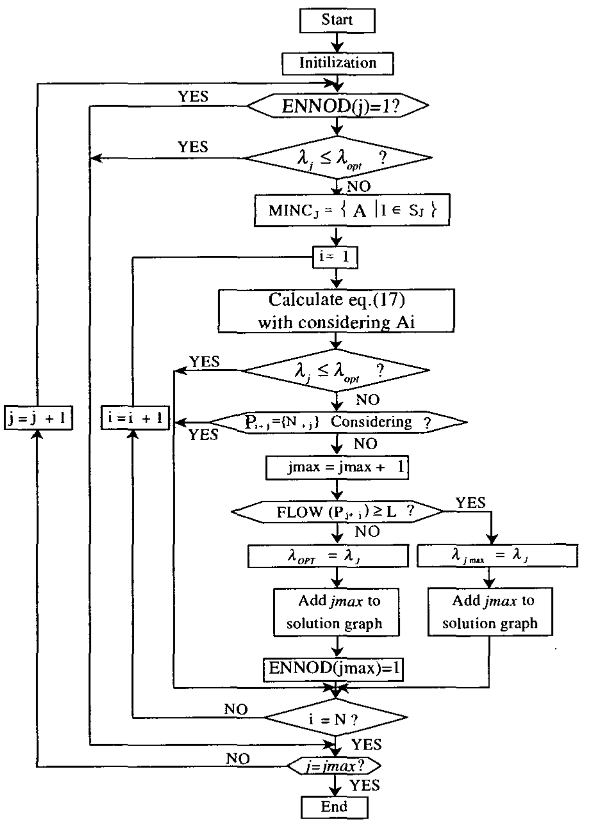

Fig. 1 Flow chart

6. Case Studies

The proposed method was applied to the 21-buses test system as in Figure 2. Table 2 shows the input data of the test system for the case studies. In Table 2, GN, TF, TL and LD represent generator, transformer, transmission and load. Also, SB and EB are starting bus and ending bus, respectively. In Table 2, P(0) and C(0) are the capacity and cost of the constructed transmission line. P(1) and C(1), P(2) and C(2), P(3) and C(3), and P(4) and C(4) are the capacity and cost, respectively, of the new candidate transmission lines for constructing. Therefore, this problem is to choose a the reasonable solution of the new transmission lines among the candidate transmission lines given in Table 2 using the proposed fuzzy branch and bound method. Table 3 shows the results of a crisp case with minimization of construction cost and four fuzzy cases with maximization of the satisfaction level of the decision maker. Z_c and Z_r are the aspired level of cost and reserve rate, respectively. W_c and W_r mean weighting factors of membership functions eq.(18) and eq.(19). For example, the configuration of the transmission system expansion planning of the crisp case study is shown in Figure 3. It is found that the result of the fuzzy case F0 with sufficient budget for construction gives the same plan as the crisp case. The supply and delivery power reserve rates and satisfaction level of the composite power system of the cases are shown in Table 4.

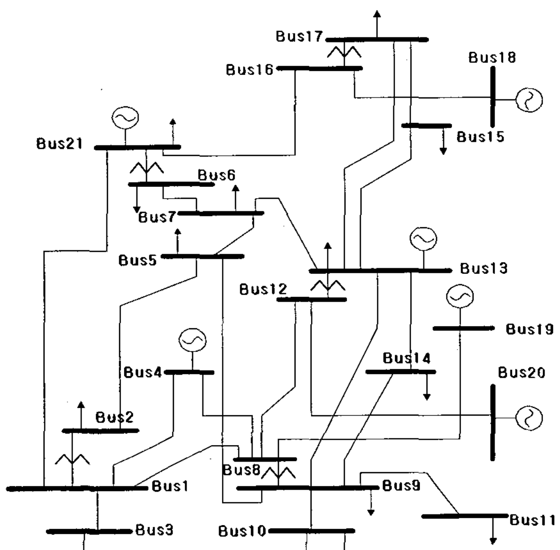

Fig. 2 21 buses test system for case studies [MW]

Table 2 Input data of capacity and cost

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	1	4	GN	850	0	0	0	0	0	0	0	0	0
2	1	22	GN	900	0	0	0	0	0	0	0	0	0
3	1	5	GN	850	0	0	0	0	0	0	0	0	0
4	1	11	GN	900	0	0	0	0	0	0	0	0	0
5	1	21	GN	1200	0	0	0	0	0	0	0	0	0

6	1	19	GN	850	0	0	0	0	0	0	0	0	0
7	1	14	GN	760	0	0	0	0	0	0	0	0	0
8	1	20	GN	950	0	0	0	0	0	0	0	0	0
9	7	22	TF	1020	510	510	0	0	0	132	132	0	0
10	17	18	TF	1020	510	510	0	0	0	124	124	0	0
11	13	14	TF	1020	510	510	0	0	0	123	130	0	0
12	9	10	TF	800	800	0	0	0	0	155	0	0	0
13	2	3	TF	800	800	0	0	0	0	151	0	0	0
14	22	2	TL	500	500	500	0	0	0	29	29	0	0
15	3	6	TL	220	220	0	0	0	0	54	0	0	0
16	2	5	TL	300	300	0	0	0	0	73	0	0	0
17	2	9	TL	400	400	0	0	0	0	70	0	0	0
18	2	4	TL	1000	250	250	250	250	0	20	20	20	20
19	5	9	TL	300	300	0	0	0	0	63	0	0	0
20	6	10	TL	220	220	0	0	0	0	82	0	0	0
21	6	8	TL	220	220	0	0	0	0	77	0	0	0
22	8	7	TL	220	220	0	0	0	0	85	0	0	0
23	22	17	TL	1000	250	250	250	250	0	30	0	0	0
24	8	14	TL	220	220	0	0	0	0	88	0	0	0
25	14	17	TL	220	220	0	0	0	0	69	0	0	0
26	14	16	TL	220	220	0	0	0	0	83	0	0	0
27	17	19	TL	1320	330	330	330	330	0	32	32	32	32
28	10	14	TL	220	220	0	0	0	0	71	0	0	0
29	10	15	TL	220	220	0	0	0	0	65	0	0	0
30	9	20	TL	620	620	0	0	0	0	64	0	0	0
31	13	21	TL	1240	310	310	310	310	0	28	28	28	28
32	13	9	TL	400	400	0	0	0	0	62	0	0	0
33	10	11	TL	240	240	0	0	0	0	81	0	0	0
34	10	12	TL	340	340	0	0	0	0	45	0	0	0
35	16	18	TL	220	220	0	0	0	0	80	0	0	0
36	14	15	TL	220	220	0	0	0	0	80	0	0	0
37	22	23	LD	785	0	0	0	0	0	0	0	0	0
38	7	23	LD	750	0	0	0	0	0	0	0	0	0
39	3	23	LD	850	0	0	0	0	0	0	0	0	0
40	10	23	LD	595	0	0	0	0	0	0	0	0	0
41	11	23	LD	17	0	0	0	0	0	0	0	0	0
42	12	23	LD	550	0	0	0	0	0	0	0	0	0
43	15	23	LD	190	0	0	0	0	0	0	0	0	0
44	14	23	LD	710	0	0	0	0	0	0	0	0	0
45	16	23	LD	450	0	0	0	0	0	0	0	0	0
46	18	23	LD	870	0	0	0	0	0	0	0	0	0
47	8	23	LD	290	0	0	0	0	0	0	0	0	0
48	6	23	LD	70	0	0	0	0	0	0	0	0	0

Table 3 Results of the crisp and fuzzy cases with maximization of the satisfaction level of decision maker

Cases	Z_c	W_c	Z_r	W_r	Solution	Total branches	Total Cost [M$]	Remark
Crisp C1	–	–	–	–	$T_{9\text{-}10}^1$ $T_{9\text{-}11}^1$, $T_{13\text{-}15}^1$	102	209	
Case F0	500	10	0.05	10	$T_{9\text{-}10}^1$ $T_{9\text{-}11}^1$, $T_{13\text{-}15}^1$	96	209	Equal to C1
Case F1	300	20	15%	5	$T_{1\text{-}21}^1$, $T_{1\text{-}4}^1$, $T_{13\text{-}15}^1$, $T_{8\text{-}19}^1$, $T_{9\text{-}11}^1$	201	294	
Case F2	370	5	17%	20	$T_{1\text{-}21}^1$, $T_{1\text{-}21}^2$, $T_{1\text{-}8}^1$, $T_{13\text{-}15}^1$, $T_{8\text{-}19}^1$, $T_{9\text{-}11}^1$	1018	383	
Case F3	315	15	15%	15	$T_{1\text{-}21}^1$, $T_{1\text{-}4}^1$, $T_{13\text{-}15}^1$, $T_{8\text{-}19}^1$, $T_{9\text{-}11}^1$	316	294	Equal to F1

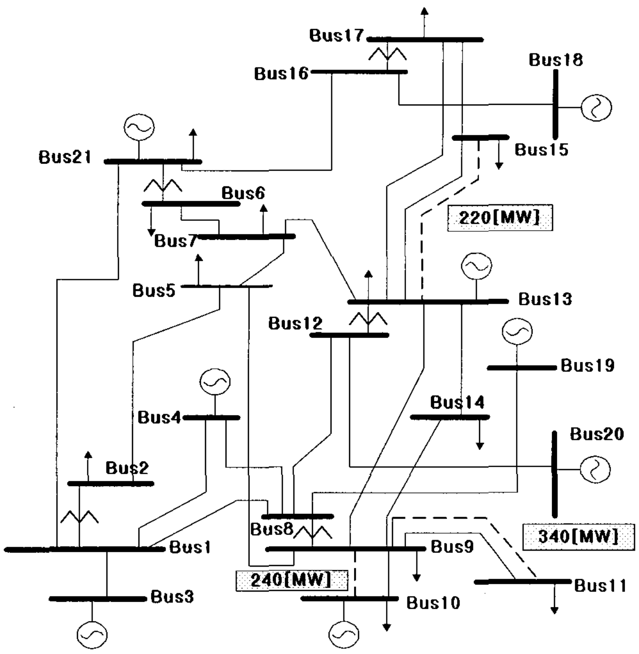

Fig. 3 The configuration of the transmission system expansion planning of the crisp case C1

Table 4 The supply and delivery power reserve rates and satisfaction levels of the composite power system

Cases	Supply reserve rate [%]	Delivery reserve rate [%]	Satisfaction Level
Case F1	18.492	14.738	0.916
Case F2	18.492	17.186	0.839
Case F3	18.492	14.738	0.770

Also, Fig. 4 and Fig.5 show the shape of membership functions for the cost and the supply and delivery reserve rate, respectively. For example, the configurations of the transmission system expansion planning of Case F1 and Case F2 are shown in Fig. 6 and Fig.7. The result of Case F3 is equal to Case F1. In these figures, the dotted transmission lines mean the configuration of the transmission system expansion planning obtained by the proposed fuzzy integer programming.

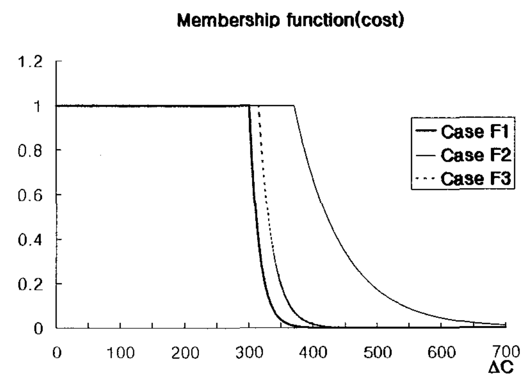

Fig. 4 Membership function of construction cost

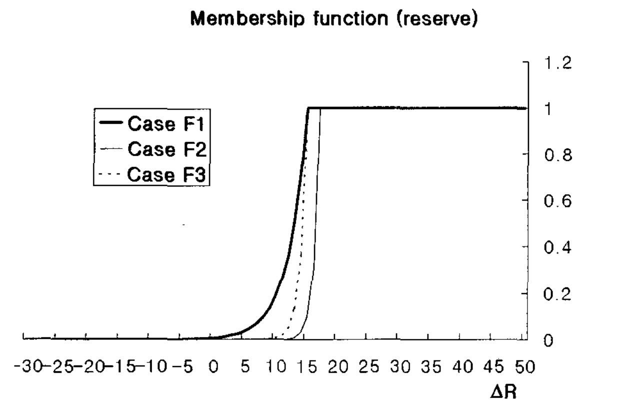

Fig. 5 Membership function of supply and delivery reserve rate

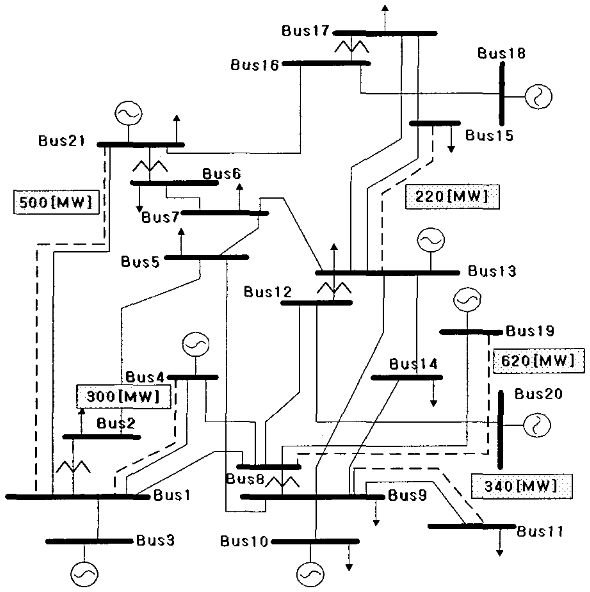

Fig. 6 The configuration of the transmission system expansion planning of the case F1

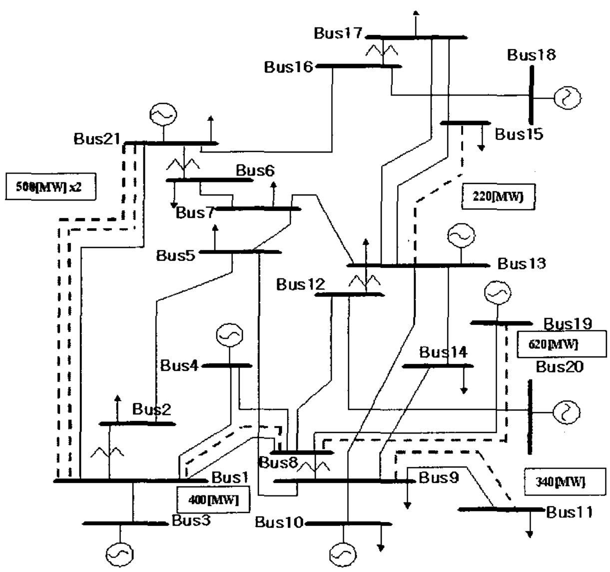

Fig. 7 The configuration of the transmission system expansion planning of the case F2

The flows and reserve powers of transmission lines of the cases are shown in Table 5.

Table 5 Flow and reserve powers of transmission lines of the three cases

No.	SB	EB	P(0)	Case C1		Case F1		Case F2	
				new	flow	new	flow	new	flow
1	6	21	1020	-	805 (215)	-	890 (130)	-	890 (130)
2	16	17	1020	-	880 (140)	-	880 (140)	-	880 (140)
3	12	13	1020	-	1020 (0)	-	980 (40)	-	940 (80)
4	8	9	800	-	800 (0)	-	755 (45)	-	755 (45)
5	1	2	800	-	800 (0)	-	800 (0)	-	800 (0)
6	21	1	500	-	500 (0)	500	935 (65)	1000	995 (505)
7	2	5	220	-	50 (170)	-	50 (170)	-	50 (170)
8	1	4	300	-	290 (10)	300	600 (0)	-	260 (40)
9	1	8	400	-	210 (190)	-	340 (60)	400	750 (50)
10	1	3	1000	-	800 (200)	-	795 (205)	-	785 (215)
11	4	8	300	-	255 (45)	-	140 (160)	-	485 (115)
12	5	9	220	-	135 (85)	-	50 (170)	-	50 (170)
13	5	7	220	-	15 (205)	-	70 (150)	-	70 (150)
14	7	6	220	-	55 (165)	-	140 (80)	-	140 (80)
15	21	16	1000	-	190 (810)	-	130 (870)	-	190 (810)
16	7	13	220	-	220 (0)	-	220 (0)	-	220 (0)
17	13	16	220	-	220 (0)	-	50 (170)	-	110 (110)
18	13	15	220	220	440 (0)	220	440 (0)	220	440 (0)
19	16	18	1320	-	850 (470)	-	800 (520)	-	800 (520)
20	9	13	220	-	90 (130)	-	170 (50)	-	170 (50)
21	9	14	220	-	90 (130)	-	30 (190)	-	30 (190)
22	8	19	620	-	595 (25)	620	855 (385)	620	840 (400)
23	12	20	1240	-	1180 (60)	-	1080 (160)	-	1120 (120)
24	12	8	400	-	160 (240)	-	100 (300)	-	180 (220)
25	9	10	240	240	480 (0)	-	240 (0)	-	240 (0)
26	9	11	340	340	550 (130)	340	550 (130)	340	550 (130)
27	15	17	220	-	10 (210)	-	10 (210)	-	10 (210)
28	13	14	220	-	100 (120)	-	220 (0)	-	220 (0)
Cost[M$]				209		294		383	
SRR[%]				18.492		18.492		18.492	
DRR[%]				6.577		14.738		17.183	

where P(0): capacity of the transmission line constructed [MW]
( ): reserve power flow of transmission lines [MW]
SRR: supply reserve rate [%]
DRR: delivery reserve rate [%]

7. Conclusions

This study proposes a new method for the expansion planning of transmission systems with uncertainties of the construction cost(economics) and supply and delivery power reserve rate(reliability) using fuzzy integer programming. The composite power system expansion planning problem with the uncertainties of the power system has been formulated. FIP(Fuzzy Integer Programming) has been used in order to obtain the optimal solution of the composite power system expansion planning problem with uncertainty. A fuzzy branch and bound method which includes the network flow method and the maximum flow - minimum cut set theorem has been used in order to obtain the optimal solution and carry out the stepwise cost characteristics analysis. An optimal plan of some candidate draft plans/scenarios can be selected by the method. The practicability and effectiveness of the proposed method have been demonstrated by simulation results of the model system.

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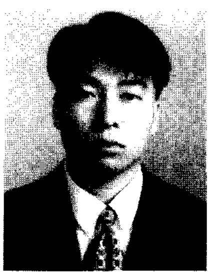

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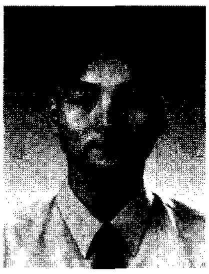

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