Transmission System Expansion Planning using Fuzzy Set Theory

H. S. Kim, J. S. Choi
Gyeongsang National University
900 Gazwa-Dong, Chinju
GN, Korea
jschoi@nongae.gsnu.ac.kr

S. P. Moon, J. B. Choo, D. H. Jeon
Korea Electric Power Research Institute
103-16, Munji-Dong, Yusung-Gu
Taejeon, Korea
spmoon@ieee.org

***Abstract* --** Recently, the electricity industries are asked for being winner of competition in the world under the capitalism social system and deregulation and restructure of power system. It is more important to assess and construct reasonable reliability criteria at load points under localization social system controlled by local self-government. Therefore, the recent problem of the power system expansion planning is focused to the composite power systems expansion planning considering generation system as well as components of transmission system, which are the lines, transformers, switches, etc. Specially, transmission system expansion planning is issued because of open transmission access and utilities divided into generation, transmission and retail segments. In this study, a new method for the transmission system 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). The effectiveness of the proposed new approach is demonstrated by case studies.

Keywords – Transmission system expansion planning, Fuzzy set theory, Fuzzy integer programming, Fuzzy branch and bound method.

I. INTRODUCTION

The past times, the primary function of 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 to only generation expansion planning without transmission systems. The expansion planning of the transmission system has been evaluated after planning the generation system expansion. Just now, the electricity industries, however, are asked for being winner of competition in the world under the capitalism social system and deregulation and restructure of power system[2]. It is more important to assess and construct reasonable reliability criteria at load points under localization social system controlled by local self government. And so, the recent problem of the power system expansion planning is focused to the composite power systems expansion planning considering generation system as well as components of transmission system, which are the lines, transformers, switches, etc. The power system expansion planning is an optimization problem for the cost minimization under a reliability level constraint[3-5]. If no or only a very small database for evaluation of component reliability indices is available, method based on fuzzy theory may be better approaches for the evaluation of system reliability indices than complex statistic methods until the data base completed reasonably[6-8]. Items considered for composite power system expansion planning are usually as following.

Load forecasting
System characteristics
Reliability level
Economical efficiency

It is not easy to have the expansion planning solution of power system considering the all 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]. Something are assumed as following. Network flow method for only active power instead of AC power flow is used. The assumed network flow method is sufficient for long term planning problem. Some draft plans/scenarios is made and come forward as candidates. And also this problem is limited to 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 a 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 systems. 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 proceed the stepwise cost characteristics analysis. Uncertainty of the power system has been also included using fuzzy set theory. The effectiveness of the proposed new approach is demonstrated by case study of the 21- bus test system.

II. Fuzzy Integer Programming

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

$$\left.\begin{array}{l} maximize\ (minimize\ )\ \mathbf{F(x)} \\ sub.to\quad \mathbf{Ax} \leq \mathbf{b} \\ \quad \mathbf{x} = \{\mathbf{0,\ 1}\} \end{array}\right\} \qquad (1)$$

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 eq.(2).

$$\left.\begin{array}{ll} \mathbf{F(x)} \lesssim \mathbf{Z_0} & \text{(fuzzy objective functions: q)} \\ \mathbf{Ax} \lesssim \mathbf{b} & \text{(fuzzy constraints: p)} \\ \mathbf{x} = \mathbf{0,1} & \text{(0,1 constraints: n)} \end{array}\right\} \qquad (2)$$

If the fuzzy mathematical programming problem consist 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 eq.(3).

$$\max_{\mathbf{X} \geq 0}[\min\{\min_{i=1,\ldots,q} m_i\,(\mathbf{F(x)}),\ \min_{i=1,\ldots,p} m_i\,(\mathbf{Ax})\}\ ]$$
$$= \max_{\mathbf{x} \geq 0}[\min_{i=1,\ldots,p+q} m_i\,(\mathbf{B(x)})\,] \qquad (3)$$

Where, **x*** is the optimal decision solution.
max and min are abbreviations of maximum and minimum respectively.
$m_i\,(\bullet)$: 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 following.

$$\left.\begin{array}{ll} maximize & l \\ sub.to & l \leq m_i\,(\mathbf{B(x)}) \\ \mathbf{x} = \{\mathbf{0,1}\} & \\ \lambda\,^3\,\mathbf{0} & \end{array}\right\} \qquad (4)$$

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 m_i(**B(x)**) has linear characteristics as like as eq.(5), the eq.(4) can be formulated as eq.(6). Where, the $d^{(i)}$ means the permissible width of a i-th fuzzy constraint equation.

$$m_i(\mathbf{Bx}) = \begin{cases} 1 & (\mathbf{B(x)})_i \leq b_i' \\ 1 - \{(\mathbf{B(x)})_i \leq b_i'\}/d^{(i)} & b_i' < (\mathbf{B(x)})_i \leq b_i' + d^{(i)} \\ 0 & b_i' + d^{(i)} < (\mathbf{B(x)})_i \end{cases} \qquad (5)$$

$$\left.\begin{array}{ll} maximize & l \\ sub.\ to & l \leq 1 - \{(\mathrm{B(x)})_i - b_i'\}/d^{(i)} \\ \mathbf{x} = \{\mathbf{0,1}\} & \\ \lambda\,^3\,\mathbf{0} & \end{array}\right\} \qquad (6)$$

III. The Transmission Systems Expansion Planning Problem

A. Network Modeling of Power System

The generators, substations and load points have the 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 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 the capacity limitation[4]. Aspects of a shortage of power supply according to bottle neck are as followings as 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

B. Formulation of Expansion Planning

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

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

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

The composite power systems expansion planning based on the minimum cut-set theorem can be formulated as fuzzy integer programming as follow.

1) Objective *Functions(minimization of construction cost)*

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

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

$$C^T \lessapprox z_c^* \tag{9}$$

2) Constraints

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

And also, the fuzzy constraint function with the fuzziness of the power delivery of the transmission system can be formulated as following eq.(11).

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

Where, variables and parameters are used as following.

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

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

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

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

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

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

C. Equivalent Integer Programming and Branch and Bound Method

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

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

Where, d_i : permissible width of 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 a merit in case of a complex problem with many constraints has been used in this study. Therefore, the general branch and bound method has been used in order to search the optimal solution of this problem formulated with fuzzy integer programming in this study.

IV. Membership Functions

A. Membership function of fuzzy set for the construction costs is defined as[11, 12]:

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

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

W_c : weighting factor of the membership function for construction cost

$C(P_{(x,y)})$: construction cost at $P_{(x,y)}$

B. Membership function of fuzzy set for the supply reserve rate of HLII is defined as:

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

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)

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

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

V. CASE STUDIES

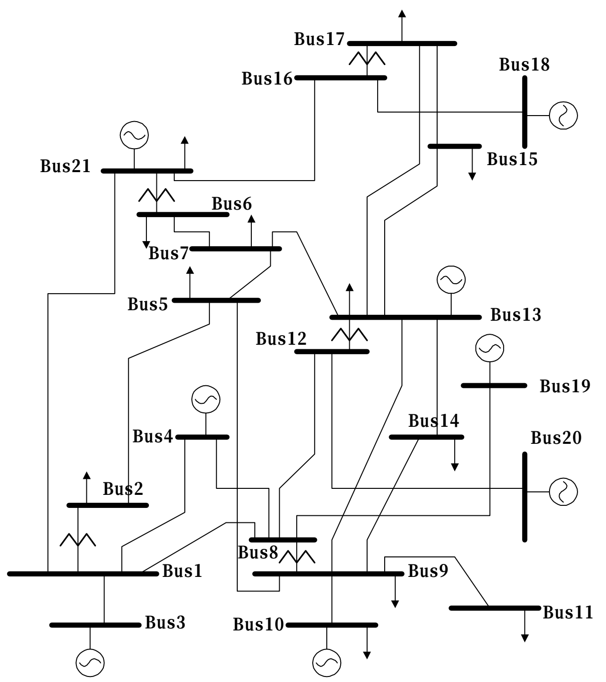

Figure 1 – 21 buses test system for case studies *[MW]*

The proposed method was applied to the 21 buses test system as Figure 1. Table 2 shows input data of test system for case studies. In Table 2, GN, TF, TL and LD present generator, transformer, transmission and load. Also, SB and EB are starting bus and ending bus respectively. 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 decision maker. Z_c and Z_r are the aspiration level of cost and reserve rate respectively. W_c and W_r means 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 2. It is obtained that the result of the fuzzy case F0 with sufficient budget for construction is same plan with the crisp case. The supply and delivery reserve rates and satisfaction level of the composite power system of the cases are shown in Table 4.

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 branc-hes	Trans .Cost [M$]
Crisp C1	–	–	–	–	**$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**
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**

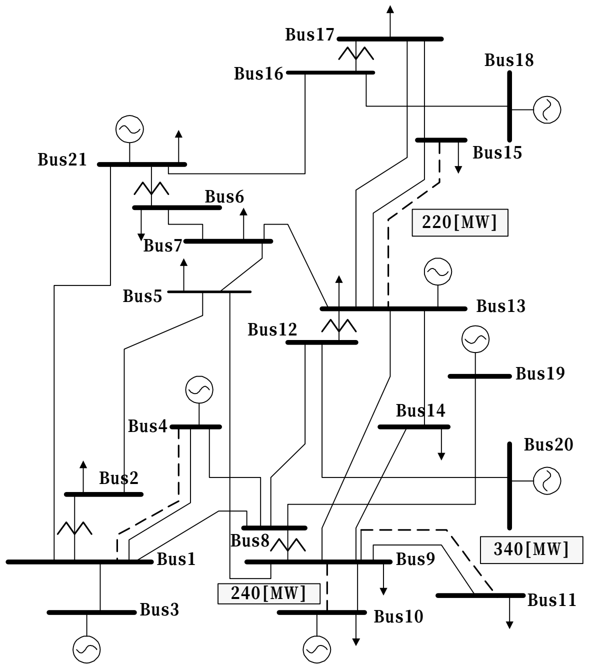

Figure 2 – The configuration of the transmission system expansion planning of the crisp case

Table 4 – The supply and delivery reserve rates and satisfaction level 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, Figure 3 and Figure 4 show the shape of membership functions pattern for cost and the supply and delivery reserve rate respectively. For example, the configuration of the transmission system expansion planning of the Case F1 is shown in Figure 5. In this Figure, the dotted transmission lines mean the configuration of the transmission system expansion planning obtained by the proposed fuzzy integer programming.

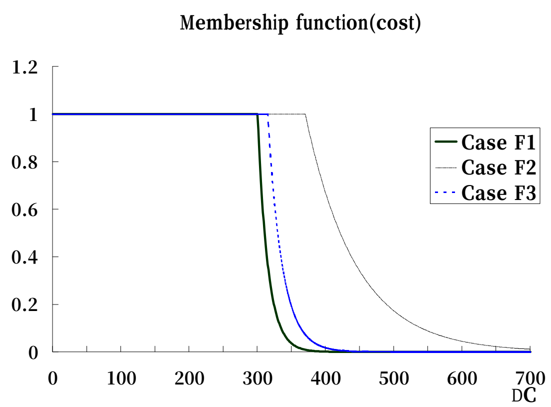

Figure 3 – Membership function of construction cost

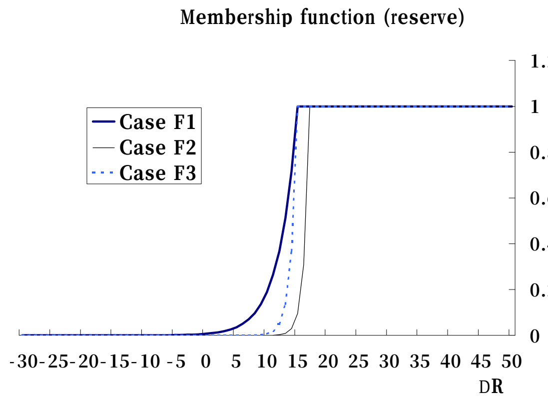

Figure 4 – Membership function of supply and delivery reserve rate

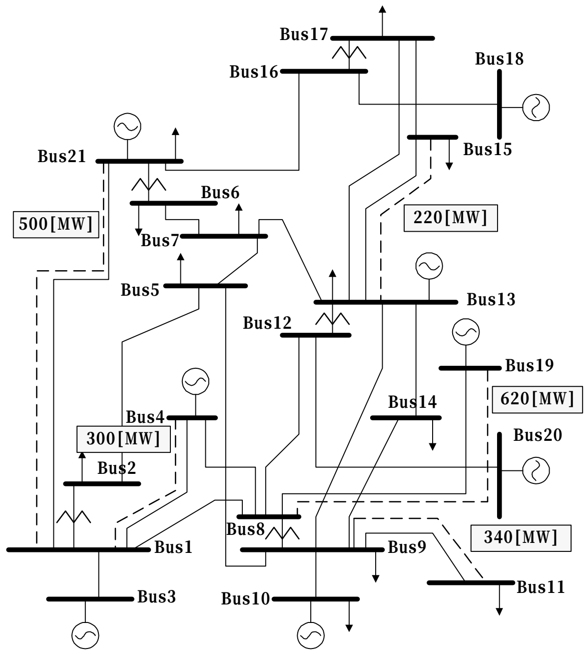

Figure 5 – The configuration of the transmission system expansion planning of the case F1

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 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 of transmission lines [MW]
SRR: supply reserve rate [%]
DRR: delivery reserve rate [%]

VI. 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 reserve rate(reliability) using fuzzy integer programming. The composite power system expansion planning problem with the uncertainties of power system has been formulated. The 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 proceed the stepwise cost characteristics analysis. A optimal plan of some draft plans/scenarios candidated can be selected by the method. The practicability and effectiveness of the proposed method have been demonstrated by simulation results of the model system.

VII. Acknowledgments

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IX. Biographies

Hongsik Kim was born in Chinhae, Korea in 1973. Obtained B.Sc. and M.Sc. degrees from Gyeongsang National University in 1998 and 2000 respectively. His research interest includes Generator Maintenance Scheduling using Fuzzy Theory and Reliability Evaluation of Power Systems. He is now working forward a Ph.D. degrees at Gyeongsang National University.

Jaeseok Choi was born at Kyeongju, Korea in 1958. Obtained B.Sc., M.Sc. and Ph.D. degrees from Korea University in 1981, 1984 and 1990 respectively. His research interest includes Expansion Planning, Probabilistic Production Cost Simulation, Reliability Evaluation Outage Cost Assessment and Fuzzy Applications, of Power Systems. He has been a Post-Doctor at University of Saskatchewan in Canada on 1996. Since 1991, he has been a faculty of Gyeongsang National University where is now a Professor.

Seungpil Moon was born at Sacheon, Korea in 1969. Obtained B.Sc. and M.Sc. degrees from Gyeongsang National University in 1996 and 1998 respectively. His research interest includes Probabilistic Production Cost Simulation, Reliability Evaluation and Outage Cost Assessment of Power Systems. He is now working forward a Ph.D. degrees at Gyeongsang National University. And he is a short term requested researcher in Korea Electric Power Research Institute (KEPRI).

Jinboo Choo received the B.Sc, M.Sc and Ph.D degrees from Seoul National University, Korea in 1977, 1987 and 1994 respectively. He has been with Korea Electric Power Co. since 1977. Presently, he is a chief researcher in Korea Electric Power Research Institute (KEPRI).

Donghoon Jeon received the B.Sc and the M.Sc degree from Hong-ik University, Korea in 1991 and 1993 respectively. His research interests are in stability analysis, reliability evaluation, economic operations and deregulation issues. Since 1994, he has been with Korea Electric Power Co.(KEPCO) and currently is a senior researcher in Korea Electric Power Research Institute (KEPRI).