A Study on Transmission System Expansion Planning on the Side of Highest Satisfaction Level of Decision Maker

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Abstract - This paper proposes a new method for choice of the best transmission system expansion plan on the side of highest satisfaction level of decision maker using fuzzy integer programming. The proposed method considers the permissibility and ambiguity of the investment budget (economics) for constructing the new transmission lines and the delivery marginal rate (reliability criteria) of the system by modeling the transmission expansion problem as a fuzzy integer programming one. It solves the optimal strategy (reasonable as well as flexible) using a fuzzy set theory-based on branch and bound method that utilizes a network flow approach and the maximum flow-minimum cut set theorem. Under no or only a very small database for the evaluation of reliability indices, the proposed technique provides the decision maker with a valuable and practical tool to solve the transmission expansion problem considering problem uncertainties. Test results on the 63-bus test system show that the proposed method is practical and efficiently applicable to transmission expansion planning.

Keywords: Flexibility and ambiguity, fuzzy branch and bound method, fuzzy integer programming, satisfaction level of decision maker, transmission system expansion planning.

1. Introduction

Transmission expansion planning addresses the problem of broadening and strengthening an existing transmission network to serve the growing electricity market in an optimal way subject to a set of economic and technical constraints. The problem revolves around how to minimize cost subject to a reliability level constraint. Various techniques including branch and bound, sensitivity analysis, Benders decomposition, simulated annealing, genetic algorithms, tabu search algorithms, and GRASP were all used in this paper to study the problem.

In a recently deregulated environment, electric utilities are expected to be winners of competitions. This environment makes it more important to assess and construct reasonable reliability criteria at load points. In such an environment, reliability of delivery of the marginal power rate of a transmission system becomes a more important parameter in transmission planning. In addition, in competitive electricity markets there exists more ambiguity of investment cost/budget and higher uncertainty of the delivery marginal power rate of the transmission system because of the profit maximization of the system owner being the major focus. Furthermore, the system planners and owners are asked how the reliability and economic parameters should be evaluated more reasonably in grid planning, although the planning problem includes numerous uncertainties such as construction cost/budget, reliability criteria, load forecasting and system characteristics, etc. It is a challenging task to develop an expansion plan that considers all the items in an effective and practical manner. When a very small or even non-existent database is available to evaluate component reliability indices and investment budget for constructing new equipment, it becomes difficult to use general statistical methods to solve the problem. Under such circumstances, an approach that is based on fuzzy set theory becomes attractive and useful to accomplish the task. Experience and knowledge of experts and decision makers can be very helpful in dealing with subjective uncertainty and ambiguity in planning problems. Such experience can be reflected in the membership functions of fuzzy objective functions and constraints. In addition, fuzzy set theory can conveniently handle multi-objective optimization problems. Accordingly, a fuzzy optimal decision policy can be conveniently formulated to

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maximize the satisfaction level of a decision maker.

In this paper, a new approach to transmission system expansion planning is proposed. It uses a fuzzy set theory to model the uncertainties and ambiguities associated with construction costs and delivery power marginal rate through appropriate membership functions. A fuzzy branch and bound algorithm includes the network flow theory. A maximum flow-minimum cut set theorem is proposed to obtain the optimal solution with highest satisfaction level of the decision maker. The effectiveness of the proposed approach algorithm is demonstrated by testing it on a 63-bus test system. The following are the assumptions used:

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

2. The Fuzzy Transmission Expansion Planning Problem

Considering the ambiguity and uncertainty of investment budget and reliability criterion, transmission expansion planning can be formulated as a Fuzzy Integer Programming (FIP) problem as follows (see Appendix A.2 for details)

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

where C is the total construction cost of new equipment.

Because the future investment budget cannot be certificated, the fuzzy goal function considering the decision maker's aspiration level for the construction cost Z^*_C, can be expressed by Eq. (2)

$$C^T \lesssim Z^*_C \qquad (2)$$

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 Fm (or the maximum flow of the network) in Table A.1 of Appendix A 3. Therefore, a no shortage power supply constraint can be expressed by Eq. (3)

$$P_c(X,\overline{X}) \geq L \qquad (s \in X,\ t \in \overline{X}) \qquad (3)$$

The demand constraint can be formulated by Eq. (4)

$$\sum_{(x,y)\in(X_k,\overline{X}_k)} [P^{(0)}_{(x,y)} + \sum_{i=1}^{m(x,y)} P^{(i)}_{(x,y)} U^i_{(x,y)}] \geq L \qquad (4)$$

The fuzzy constraint corresponding to the power delivery capacity of the transmission system can be expressed by Eq. (5)

$$\sum (P_{(x,y)} - L) \times 100 / L \gtrsim z^*_R \qquad (5)$$

where,

z^*_R : the decision maker's aspiration level of the delivery power marginal rate.

$P_c(X,\overline{X})$: the capacity of minimum cut-set of subsets, X and $\overline{X}$ including sources s and terminals t (=Fm)

N : the set of all nodes.

X : a subset of N including source and excluding terminal.

$\overline{X}$: a subset of N-X.

$$C^{(i)}_{(x,y)} = \sum_{j=1}^{i} \Delta C^{(j)}_{(x,y)} \qquad (6)$$

$$P^{(i)}_{(x,y)} = \sum_{j=1}^{i} \Delta P^{(j)}_{(x,y)} \qquad (7)$$

$$\sum_{i=1}^{m(x,y)} U^i_{(x,y)} = 1 \qquad (8)$$

$$U^i_{(x,y)} = \begin{cases} 1, P_{(x,y)} = P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \\ 0, P_{(x,y)} \neq P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \end{cases} \qquad (9)$$

$$P_{(x,y)} = P^{(0)}_{(x,y)} + \sum_{i=1}^{m(x,y)} P^{(i)}_{(x,y)} U^{(i)}_{(x,y)} \qquad (10)$$

L: total demand

$P(x,y)$: power of transmission line or generator between node x and node y

$\Delta C^{(j)}_{(x,y)}$: construction costs of *j-th* parallel element of branches between node x and node y

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

2.1 The Equivalent Crisp Integer Programming Problem and the Proposed Branch and Bound-Based Method

$$\left.\begin{array}{ll} maximize & \lambda \\ Sub. to & \lambda \le \mu_C\{P_{(x,y)}\} \\ & \lambda \le \mu_R\{P_{(x,y)}\} \\ & \lambda \ge 0 \end{array}\right\} \quad (11)$$

where,
λ: represents the satisfaction level of the decision maker
$\mu_C(\cdot)$: membership function of the set for construction costs.
$\mu_R(\cdot)$: membership function of the set for supply reserve rate.

The branch and bound algorithm has merits in the case of complex optimization problems with many constraints. A fuzzy branch and bound algorithm, which includes the network flow theory and the maximum flow-minimum cut set theorem, is proposed to obtain the optimal solution with the highest satisfaction level considering membership functions that reflect uncertainties and ambiguities associated with construction costs and the delivery power marginal rate.

2.2 The Membership Functions

In this paper, it is assumed that the threshold values of membership functions are determined from the results of simulating a conventional planning problem with crisp membership functions.

The membership function of fuzzy construction costs is

$$\mu_C\{P_{(x,y)}\} = \begin{cases} 1 & : \Delta C(\cdot) \le 0 \\ e^{-W_C \, \Delta C\{P(x,y)\}} & : \Delta C(\cdot) \rangle 0 \end{cases} \quad (12)$$

where,
$\mu_C(\cdot)$: membership function of fuzzy set for construction costs.
$\Delta C(\cdot) = \{C(P_{(x,y)}) - C_{asp}\} / C_{asp}$
$C(P_{(x,y)})$: construction costs at $P_{(x,y)}$
C_{asp} : aspiration level for construction costs ($= Z_C^*$)
Wc: a weighting factor associated with the membership function of the construction costs.

The membership function of the fuzzy supply reserve rate of HLII is expressed as follows

$$\mu_R\{P_{(x,y)}\} = \begin{cases} 1 & : \Delta R(\cdot) \ge 0 \\ e^{Wr \, \Delta R\{P_{(x,y)}\}} & : \Delta R(\cdot) < 0 \end{cases} \quad (13)$$

where,
$\mu_R(\cdot)$: membership function of fuzzy sets for supply reserve rate
$\Delta R(\cdot) = \{DMR(P_{(x,y)}) - R_{asp}\} / R_{asp}$
$DMR(P_{(x,y)})$: delivery marginal rate at $P_{(x,y)}$
Rasp: aspiration level for delivery marginal rate of composite power system (HLII) ($= z_R^*$).
Wr: weighting factor of the membership function for the supply reserve rate of HLII.

3. Solution Algorithm

The objective in the conventional crisp branch and bound method is to minimize the total construction costs subject to a specified reliability level and delivery power reserve rate. The proposed fuzzy branch and bound-based method maximizes the satisfaction level λ of the decision maker and produces the optimal solution considering both the construction costs and the delivery power marginal rate.

The solution algorithm for the proposed approach follows and the accompanying flow chart is shown in Fig. 1.

Step 1. Check the need for transmission expansion for the system and its possibility using the candidate lines.

Step 2. Set $j=1$ (initial system), $j_{opt}=0$, $jmax=0$, $\lambda_{opt}=0$ and $ENNOD_j=0$. $ENNOD_j$ is 1 means that the *j-th* system is the end node.

Step 3. If $ENNOD_j=1$, the *j-th* system is the end node in the solution graph used to obtain the optimal solution and there would be no need to consider any of the other graphs following this system. Proceed to Step 15.

Step 4. Calculate the minimum cut-set using the maximum flow method for the *j-th* system (*j-th* solution in the solution graph).

Step 5. Select the *i-th* branch/line of the candidate branches/ lines set (S_j) involved in the minimum cut-set and add to the *j-th* system. In what follows, the new system is named the *ji-th* system.

Step 6. If the *ji-th* system is already considered in the solution graph, proceed to Step 14.

Step 7. Calculate the total cost $C^T_{ji} = C^T_j + C(P^{(i)}_{(x,y)})$ for the *ji-th* system and evaluate the cost membership grade μ_{Cji}.

Step 8. Calculate the minimum cut-set capacity $P_{Cji}(X, \overline{X})$ using the maximum flow/minimum cut-set theorem and evaluate the delivery marginal rate (reliability) membership grade μ_{Rji}.

Step 9. Calculate λ_{ji} = minimum$\{\mu_{Cji}, \mu_{Rji}\}$.

Step 10. If $\mu_{Cji} < \lambda_{opt}$ (the current system (*ji-th*)) with a cost of C^T_{ji} is optimal and the lambdas of the following systems will be lower than the current optimal solution (λ_{opt}). Proceed to Step 14.

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

Step 12. If $\lambda_{ji} > \lambda_{opt}$, set $\lambda_{opt} = \lambda_{ji}$, $j_{opt} = jmax$, and proceed to Step 14.

Step 13. If $\mu_{Cji} < \mu_{Rji}$, set $\lambda_{jmax} = \lambda_{ji}$, $ENNOD_{jmax} = 1$, and proceed to Step 15.

Step 14. Add this *j-th*max(*ji-th*) solution to the solution graph.

Step 15. If all the candidate branches/lines in set S_j have been considered, proceed to Step 16. Otherwise set $i = i + 1$ and proceed to Step 5.

Step 16. If $j = jmax$, continue. Otherwise set $j = j + 1$ and proceed to Step 4.

Step 17. For $j = jmax$, the solution graph has been constructed fully and the optimal solution with λ_{opt} being the highest satisfaction level of the decision maker is obtained at Step 12.

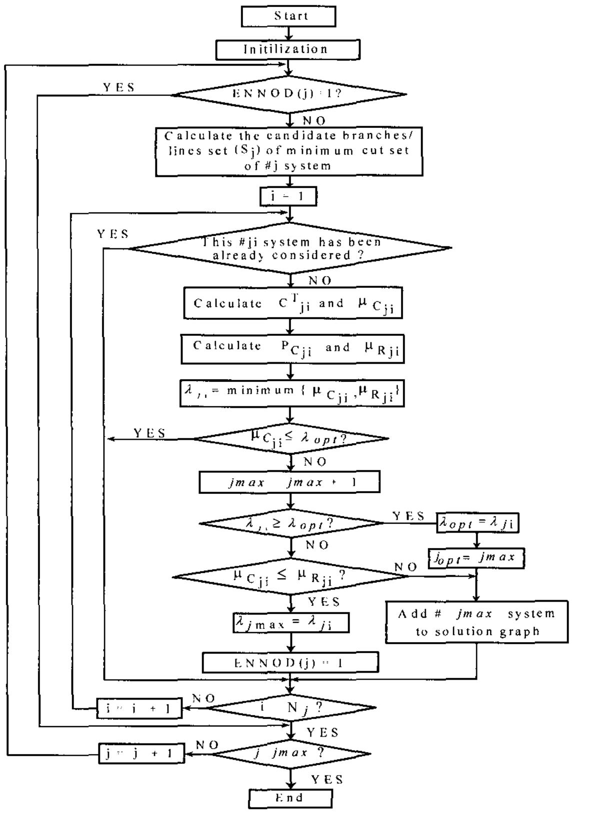

Fig. 1 Flow chart

4. Case Studies

The proposed method was tested on the 63-bus test system shown in Fig. 2. Considering a forecasted future system load, the crisp case C1 (minimization of construction cost) and six fuzzy test cases of maximizing the satisfaction level of the decision maker (F0, F1, F2, F3, F4 and F5) were studied. The crisp case is simply a conventional cost minimization problem subject to minimum cut-set capacity. Tables 1 and 2 display the parameters of system load points and the installed status and forecast of generation capacity, respectively. Table 3 shows the system data with GN, TF, TL and LD representing generators, transformers, transmission lines and loads, respectively. SB and EB are start and end buses, respectively. P(0) and C(0) are the capacity and cost of constructing transmission lines or generators. P(i) and C(i), for i=1,...,4 are, respectively, the capacity and cost of the candidate lines.

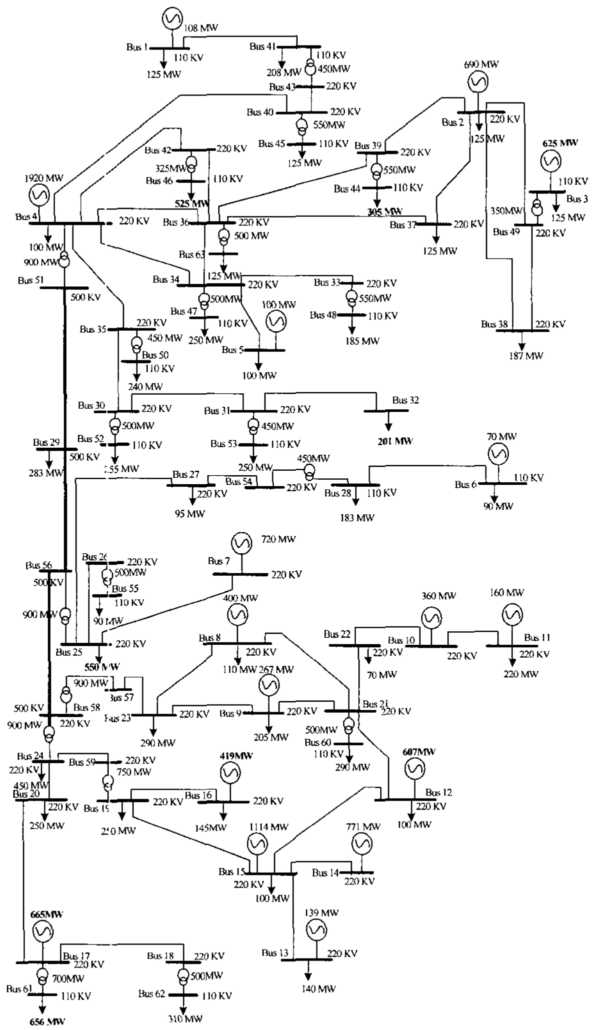

Fig. 2 Configuration of 63-bus test system

Table 1 Load demand at status and load forecasted

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

Table 2 Generation capacity installed, capacity expansion

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

Table 3 System Capacity and Cost Data

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

NL	SB	EB	ID	P(0)	P(1)	P(2)	P3)	P(4)	C(0)	C(1)	C(2)	C(3)	C(4)
1	0	1	GN	108	0	0	0	0	0	0	0	0	0
2	0	2	GN	690	0	0	0	0	0	0	0	0	0
:	:	:	:	:	:	:	:	:	:	:	:	:	:
20	40	45	TF	550	450	450	450	0	0	550	550	550	0
21	42	46	TF	325	325	325	325	0	0	450	450	450	0
:	:	:	:	:	:	:	:	:	:	:	:	:	:
39	1	41	TL	550	185	185	185	0	0	45	45	45	0
40	43	40	TL	585	185	185	185	0	0	45	45	45	0
:	:	:	:	:	:	:	:	:	:	:	:	:	:
123	41	64	LD	208	0	0	0	0	0	0	0	0	0
124	46	64	LD	525	0	0	0	0	0	0	0	0	0

(#0 and #64 signify source and terminal nodes, respectively)

Discussion of results

Prior to the fuzzy case studies, the crisp case C1 for the strict conventional optimization problem with total cost *minimization subject to minimum* cut-set capacity was studied in order to refer to more reasonable membership functions for fuzzy cases. The crisp optimal solution has been obtained at optimal minimum cost, 1290M$ and at DMR (delivery marginal rate) 8.075%, with the branch number of the solution graph at 13711. However, a violated solution with very small violation for the given constraint, DMR, can never be permitted for the feasible solution on crisp optimal problems.

Other fuzzy cases have been studied for obtaining more flexible solutions. The establishment of membership functions is very important in order to obtain more reasonable solutions using the proposed fuzzy branch and bound method. Table 4 and Table 5 show the input data of the assumed membership functions based on results of the crisp optimal solution for the cost/budget and the delivery marginal rate for six fuzzy case studies. The membership functions based on the good D/B of expert experiences instead of results of the crisp case study may provide a more reasonable solution for grid expansion planning.

For considering fuzzy environments in this planning problem, it was assumed that there are three levels of ambiguity, which are very sufficient (*VS*), sufficient (*S*) and not sufficient (*NS*) for budget guaranteed aspiration (Z_C) and also high (*H*), medium (*M*) and low (*L*) for reliability criteria aspiration (Z_R) of the grid requested by the owner. Furthermore, it was assumed that there are four levels of uncertainty, which are very secure (*VS*), secure (*S*), somewhat secure (*SS*) and not secure (*NS*) according to the certainty grade (W_C) of the budget guarantee, as well as very strict (*VS*), strict (*S*), somewhat strict (*SS*) and not strict (*NS*) according to the obligation grade (W_R) of the reliability criteria. In Table 5, the Z_C and Z_R are the aspiration level and the W_C and W_R signify the weighting factors of construction costs and the delivery marginal rate of the reliability criterion of membership functions, Eq. (12) and Eq. (13), respectively. Configurations of the membership functions are presented in Fig. 3 and Fig. 4.

Table 4 The ambiguity and uncertainty of budget guarantee and the ambiguity and obligation of reliability criteria.

Cases	Ambiguity and Uncertainty of Budget guarantee	Ambiguity and Obligation of Reliability criteria
Fuzzy Case F0	Sufficient & Very Secure	Medium & Very Strict
Fuzzy Case F1	Not Sufficient & Not Secure	High & Medium Strict
Fuzzy Case F2	Sufficient & Not Secure	High & Strict
Fuzzy Case F3	Not Sufficient & Secure	Medium & Very Strict
Fuzzy Case F4	Very Sufficient & Very Secure	Low & Very Strict
Fuzzy Case F5	Not Sufficient & Very Secure	High & Very Strict

Table 5 Conditions of the crisp and Fuzzy cases for case studies

Cases	Z_c (M$)	W_c	Z_r (%)	W_r
Fuzzy Case F0	1300 (S)	10 (VS)	8 (M)	5 (VS)
Fuzzy Case F1	1200 (NS)	2 (NS)	10 (H)	4 (SS)
Fuzzy Case F2	1300 (S)	1 (NS)	10 (H)	3 (S)
Fuzzy Case F3	1200 (NS)	5 (S)	8 (M)	5 (VS)
Fuzzy Case F4	1500 (VS)	10 (VS)	5 (L)	5 (VS)
Fuzzy Case F5	1200 (NS)	10 (VS)	10 (H)	5 (VS)

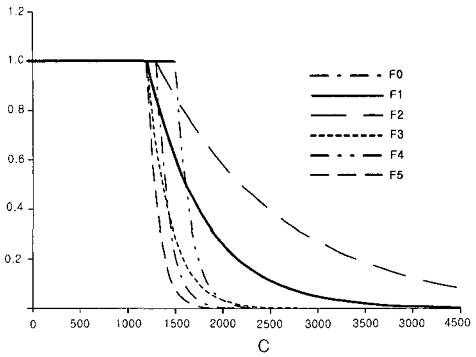

Fig. 3 Membership function of the construction cost/budget

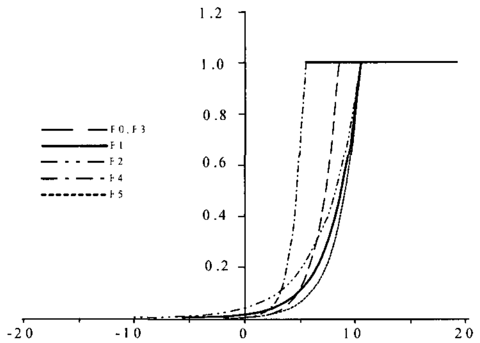

Fig. 4 Membership function of the delivery marginal rate.

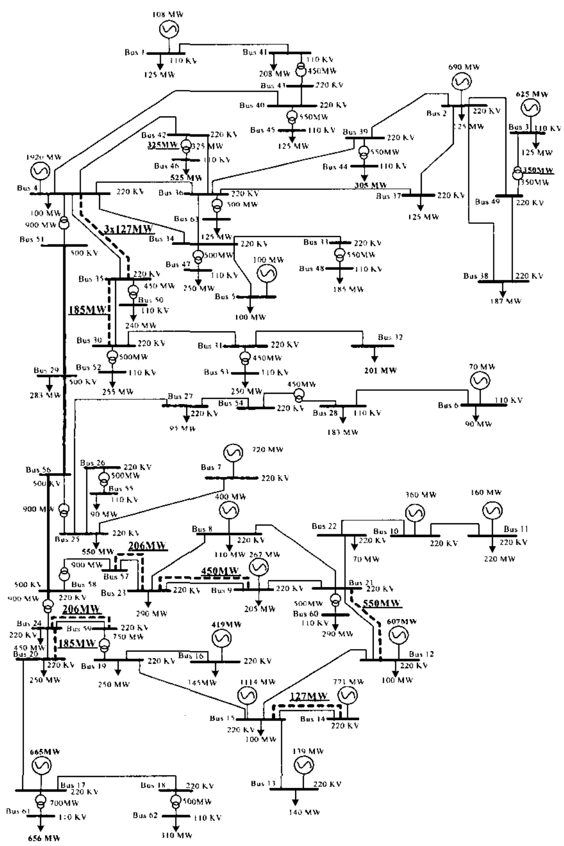

Fig. 5 The configuration of the transmission system expansion planning of the fuzzy case F1 (Fuzzy Base Case)

The result configuration of the transmission system expansion planning of the fuzzy case F1 for the fuzzy base case study is shown in Fig. 5.

Table 6 indicates the results of a crisp case with minimization of construction costs and six fuzzy cases with maximization of the satisfaction level of the decision maker. It is found that the result of the fuzzy case F0 with sufficient budget for constructing provides the same solution as the crisp case C1.

Table 6 Results of the crisp case with total cost minimization and fuzzy cases with the maximization of the satisfaction level of decision maker

Cases	Solution	Total Branches	Total Cost (M$)	DMR (%)
Crisp C1	$TF_{42-46}^1, TF_{59-19}^1, T_{4-35}^1$ $T_{4-35}^2, T_{4-35}^3, T_{35-30}^1, T_{24-20}^1$ $T_{24-59}^1, T_{57-23}^1, T_{9-23}^1, T_{12-21}^1$ T_{15-19}^1	**13711**	**1290**	**8.075**
Case F0	$TF_{42-46}^1, TF_{59-19}^1, T_{4-35}^1$ $T_{4-35}^2, T_{4-35}^3, T_{35-30}^1, T_{24-20}^1$ $T_{24-59}^1, T_{57-23}^1, T_{9-23}^1, T_{12-21}^1$ T_{15-19}^1	**11497**	**1290**	**8.075**
Case F1	$TF_{42-46}^1, TF_{3-49}^1, T_{4-35}^1$ $T_{4-35}^2, T_{4-35}^3, T_{35-30}^1, T_{24-20}^1$ $T_{24-59}^1, T_{57-23}^1, T_{9-23}^1, T_{12-21}^1$ T_{14-15}^1	**34824**	**1435**	**8.324**
Case F2	$TF_{42-46}^1, TF_{3-49}^1, TF_{59-19}^1$ $T_{4-35}^1, T_{4-35}^2, T_{4-35}^3, T_{35-30}^1$ $T_{24-20}^1, T_{24-59}^1, T_{12-21}^1, T_{14-15}^1$ T_{15-19}^1	**79893**	**1720**	**8.324**
Case F3	$TF_{42-46}^1, TF_{59-19}^1, T_{4-35}^1$ $T_{4-35}^2, T_{4-35}^3, T_{35-30}^1, T_{24-20}^1$ $T_{24-59}^1, T_{57-23}^1, T_{9-23}^1, T_{12-21}^1$ T_{15-19}^1	**13711**	**1290**	**8.075**
Case F4	$TF_{42-46}^1, TF_{3-49}^1, T_{4-35}^1$ $T_{4-35}^2, T_{4-35}^3, T_{35-30}^1, T_{24-20}^1$ $T_{24-59}^1, T_{57-23}^1, T_{9-23}^1, T_{12-21}^1$	**7628**	**1395**	**8.075**
Case F5	$TF_{42-46}^1, TF_{59-19}^1, T_{4-35}^1$ $T_{4-35}^2, T_{4-35}^3, T_{35-30}^1, T_{24-20}^1$ $T_{24-59}^1, T_{57-23}^1, T_{9-23}^1, T_{12-21}^1$ T_{15-19}^1	**16091**	**1290**	**8.075**

The delivery marginal rates and satisfaction level of the power systems of the cases are indicated in Table 7, which shows that the delivery marginal rates are somewhat different respectively since the capacity constraints of transmission lines are considered, while supply reserve rates are identical for the all cases since the rates are calculated without considering the transmission system.

Table 7 The delivery power marginal rates and satisfaction levels of the power system for case studies

Cases	Supply reserve rate [%]	Delivery marginal rate [%]	Satisfaction level
Case F0	**8.324**	**8.075**	**1**
Case F1	**8.324**	**8.324**	**0.512**
Case F2	**8.324**	**8.324**	**0.605**
Case F3	**8.324**	**8.075**	**0.687**
Case F4	**8.324**	**8.075**	**1**
Case F5	**8.324**	**8.075**	**0.382**

5. Conclusions

This paper addresses the problem of transmission expansion planning when a very small database or no database at all exists for the evaluations of reliability and economics. It presents a new and practical approach that should serve as a useful guide for the decision maker when selecting a reasonable expansion plan. The proposed method determines the optimal transmission expansion plan in terms of highest satisfaction level of the decision maker considering uncertainties associated with the construction costs/budget (economics) and the delivery power marginal rate (reliability). It models the problem as a fuzzy integer programming problem by considering uncertainties through fuzzy modelling. A proposed fuzzy branch and bound algorithm, which includes the network flow method, and the maximum flow-minimum cut set theorem is proposed to solve the problem.

Testing of the proposed method on the 63-bus test system including various sensitivity analyses indicates that the proposed method is efficiently applicable to the practical expansion planning of transmission systems.

Appendix

A.1 Definition [17]

The fuzzy decision set D resulting from q fuzzy goal sets $G_1,\ldots,Cq$ and p fuzzy constraint sets $C_1,\ldots,Cp$ results from their intersection.

$$D = \left(\bigcap_{i=1}^{q} G_i\right) \cap \left(\bigcap_{j=1}^{p} C_j\right) \qquad (A1)$$

Its membership function μ_D resulting from fuzzy goals and constraints is defined by

$$\mu_{D(x)} = \min_{i=1\sim p} \left[\min \mu_{Gi}, \min_{j=1\sim q} \mu_{Cj}\right] \qquad (A2)$$

The fuzzy mathematical programming problem consists of determining the maximum of the fuzzy decision D

$$\mu_{D(x^*)} = \max \mu_{D(x)} \qquad (A3)$$

where x* is the optimal decision solution.

The vector (A3) can be rewritten as follows:

$$\mu_{D(x1^*,x2^*,\ldots,xN^*)} = \max_{x1\ldots xN} \mu_{D(x1,x2,\ldots,xN)} \qquad (A4)$$

A.2 Fuzzy Integer Programming (FIP) [25]

Multi objective transmission systems expansion planning can be formulated as an ordinary integer problem with only 0 or 1 as follows

$$\begin{aligned} & maximize(minimize)\ \mathbf{F(x)} \\ & s.t.\quad \mathbf{Ax} \le \mathbf{b} \\ & \mathbf{x} = \{0, 1\} \end{aligned} \qquad (A5)$$

where x: decision vector

F: coefficient matrix of the objective function(q x n)

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

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

p: number of constraints

Considering the fuzzy characteristics of its variables, the problem can be formulated as a Fuzzy Inter Programming (FIP) problem as follows [17] [20]

$$\begin{aligned} & \mathbf{F(x)} \lessapprox \mathbf{Z_0} \text{ (fuzzy objective functions: q)} \\ & \mathbf{Ax} \lessapprox \mathbf{b} \text{ (fuzzy constraints: p)} \\ & \mathbf{x} = \{0, 1\} \text{ (0,1 constraints: n)} \end{aligned} \qquad (A6)$$

The fuzzy mathematical programming problem consists of finding the maximum point of the membership functions. The fuzzy optimal decision policy maximizes the satisfaction level of the decision maker. Using the A.1 Definition I for fuzzy optimal decision policy, the optimal solution x* for (A6) can be obtained by (A7) [17] [20]

$$\begin{aligned} & \max_{X\ge 0}[\min\{\min_{i=1,\ldots,q} \mu_i(\mathbf{F(x)}), \min_{i=1,\ldots,p} \mu_i(\mathbf{Ax})\}] \\ & = \max_{x\ge 0}[\min_{i=1,\ldots,p+q} \mu_i(\mathbf{B(x)})] \end{aligned} \qquad (A7)$$

where, x* is the optimal decision solution.

$\mu_i(\cdot)$: the membership function of the i^{th} fuzzy inequality constraints

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

Introducing a parameter, λ (satisfaction level of the decision maker), problem (A7) can be expressed as a conventional optimization programming as follows [17] [20]

$$\left.\begin{array}{ll} \text{maximize} & \lambda \\ s.t. & \lambda \leq \mu_i(\mathbf{B}(\mathbf{x})) \\ & \mathbf{x} = \{0,1\} \\ & \lambda \geq 0 \end{array}\right\} \quad \text{(A8)}$$

The optimal solution of the problem can be obtained with an optimization algorithm. The arbitrary shape of the membership functions is available for fuzzy integer programming because the fuzzy integer programming is originally a non-linear programming.

A.3 Network Modelling of Power System

The generators, substations, and load points have limited capacities. It is difficult to check the shortage power supply of the system because these elements are presented as nodes in a real system model. Network modelling of the system makes it convenient to check a shortage of power supply because the network elements mentioned above are presented as branches with a capacity limitation [26, 27]. Aspects of a shortage of power supply according to a bottleneck are as given in Table A1.

Table A1 Various aspects of power supply Bottleneck

$F_m = L \leq G$	No shortage of supply
$F_m = G < L$	Shortage of power generation
$F_m < L \leq G$	Shortage of transmission delivery capacity
$F_m < G < L$	Shortages of power generation and transmission delivery capacity

Where,

Fm: maximum flow of the network

G: total power generation

L: total system load

A.4 Delivery Marginal Rate (*DMR*)

The hierarchical level II (HLII) of the power system has considered the generation and transmission system. The delivery marginal rate of the power system can be expressed by Eq. (A.2)

$$DMR = \frac{DMP}{Lp} 100\% \quad \text{(A.9)}$$

Where,

L_p: Peak load

DMR: Delivery marginal rate

DMP: Delivery marginal power

Minimum Cut-set Power (*MCP*) or Bottleneck

$$DMP = MCP - L_p$$

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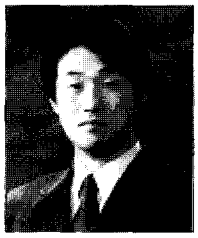

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