Network Planning in Unbundled Power Systems

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***Abstract*—In this paper, a new approach for network planning in unbundled power systems is presented. The approach takes into account the desires of demand customers, power producers, system operator, network owner(s), and regulator in network planning. Competition, reliability, flexibility of operation, transmission expansion cost, and environmental impacts are used as planning criteria. In order to consider the importance degrees of stakeholders and planning criteria in network planning, first importance degrees of stakeholders and planning criteria are determined by a presented new method. Then, importance degrees of stakeholders and planning criteria are aggregated with appropriateness degrees of expansion plans to compute a fuzzy index for measuring the goodness of expansion plans. The final plan is selected using the presented fuzzy risk assessment method. The approach is applied to an eight-bus test system.**

***Index Terms*—Analytic hierarchy process, fuzzy decision making, market-based transmission expansion planning, power system stakeholders, probabilistic locational marginal price (LMP), scenario technique, stakeholders' desires.**

I. INTRODUCTION

RESTRUCTURING and deregulation have unbundled the roles of network stakeholders [1]–[3]. Unbundling the roles has brought new challenges for stakeholders. Stakeholders have different desires and expectations from operation and expansion of the system. Therefore, new incentives and disincentives have emerged regarding transmission expansion decisions. Moreover unbundling the roles within stakeholders has changed the objectives of network planning and increased the uncertainties [4], [5]. Hence, transmission investors have been faced with great risk in deregulated environments. Because of these new objectives and uncertainties, new approaches are required for network expansion planning in unbundled power systems.

A. Transmission Planning Objectives

In general, the main objective of network planning in unbundled power systems is to provide a nondiscriminatory competitive environment for all stakeholders while maintaining power system reliability. Specifically, the objective of transmission planning is providing for the desires of stakeholders. The desires of stakeholders in transmission expansion are [2]–[9] as follows:

- encouraging and facilitating competition among electric market participants;
- providing nondiscriminatory access to cheap generation for all consumers;
- alleviating transmission congestion;
- minimizing the risk of investments;
- minimizing the costs of investment and operation;
- increasing the reliability of the network;
- increasing the flexibility of system operation;
- reducing the network charges;
- minimizing the environmental impacts.

The above desires have different degrees of importance for different stakeholders. On the other hand, stakeholders have different degrees of importance in network expansion decisions. These must be considered in network planning [1]–[3].

B. Power System Uncertainties and Vagueness

Uncertainties can be classified in two categories: random and nonrandom uncertainties. Random uncertainties are a deviation of those parameters, which are repeatable and have a known probability distribution. Hence, their statistics can be derived from the past observations. Uncertainty in load is in this category. Nonrandom uncertainties are evolution of parameters that are not repeatable, and hence, their statistics cannot be derived from the past observations. Uncertainty in generation expansion is in this category. Besides the uncertainties, there are vague data in network planning. Vague data are the data that cannot be clearly expressed. Since methods of modeling random uncertainties, nonrandom uncertainties, and vagueness are different, power system uncertainties and vagueness must be identified and classified clearly before planning. Sources of random uncertainties in unbundled power systems are [2]–[4], [6], [10], [11] as follows:

- load;
- generation costs and consequently bid of generators;
- power and bid of independent power producers (IPPs);
- wheeling transactions;
- availability of generators, lines, and other system facilities.

Sources of nonrandom uncertainties are [3], [4], [6], [11]–[16] as follows:

- generation expansion/closure;
- load expansion/closure;
- installation/closure of other transmission facilities;
- replacement of transmission facilities;
- transmission expansion costs;
- market rules.

Manuscript received June 28, 2004; revised November 17, 2005. Paper no. TPWRS-00347-2004.

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Digital Object Identifier 10.1109/TPWRS.2006.873016

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There is vagueness in the following data [2], [3], [6]:

- importance degrees of stakeholders in decision making;
- importance degrees of planning criteria from the viewpoint of different stakeholders;
- occurrence degrees of possible future scenarios.

Probabilistic methods [2], [3], [6], [10], [11], scenario technique [3], [4], [6], [11]–[16], and fuzzy decision making [2], [3], [6] are used to take into account random uncertainties, nonrandom uncertainties, and vagueness, respectively.

II. MODEL OVERVIEW

First strategic scenarios are identified to model the nonrandom uncertainties. In each scenario, probability distribution function (PDF) of locational marginal price (LMP) for each bus is computed using probabilistic optimal power flow. Some expansion candidates are suggested based on PDFs of LMPs. Each of the candidates is added to the network, and PDFs of LMPs are computed again for each scenario. Appropriateness of expansion plans versus different planning criteria are computed based on PDFs of LMPs. Importance degrees of planning criteria and stakeholders are determined using analytic hierarchy process. Appropriateness degrees of expansion plans, importance degrees of planning criteria, and importance degrees of stakeholders in network planning are aggregated to compute a fuzzy appropriateness index for measuring the goodness of expansion plans. The final plan is selected using the presented fuzzy risk assessment method. The planning procedure consists of the following stages:

1) identifying the set of possible strategic scenarios;
2) suggesting candidates for transmission expansion based on PDFs of LMPs;
3) computing appropriateness degrees of expansion plans versus different criteria in each scenario;
4) determining the importance degrees of stakeholders and planning criteria;
5) aggregating appropriateness degrees of expansion plans with importance degrees of stakeholders and planning criteria to compute the fuzzy appropriateness index for measuring the goodness of expansion plans;
6) selecting the final plan using fuzzy risk assessment;
7) computing the capacity of selected expansion plan.

This paper is organized as follows. Identifying the set of possible strategic scenarios is discussed in Section III. A probabilistic market-based method for suggesting expansion plans is presented in Section IV. A fuzzy appropriateness index for measuring the goodness of expansion plans is defined in Section V. In Section VI, a method for fuzzy risk assessment is presented. Capacity of selected line is discussed in Section VII. The method is applied to an eight-bus test system in Section VIII. The Conclusion in Section IX closes the paper.

III. IDENTIFYING THE SET OF STRATEGIC SCENARIOS

A scenario (future) is a set of outcomes or realizations of all uncertainties. To model the nonrandom uncertainties, all possible strategic scenarios and their occurrence degrees must be identified. Since in unbundled power systems generation expansion planning is not coordinated with network expansion planning, the main nonrandom uncertainty is related to expansion or closure of generation. Consequently, the main strategic scenarios are related to expansion or closure of generation.

IV. SUGGESTING EXPANSION PLAN CANDIDATES

In transmission planning, the set of possible expansion plans is very large since between each two buses a new transmission line can be constructed. There are $n(n-1)/2$ candidates for expansion of an n bus network. Most of these candidates do not satisfy the constraints of planning and must be eliminated. In order to determine the effective expansion candidates, first PDFs of LMPs are computed for different scenarios using Monte Carlo simulation [2], [3], [6], [10], [11]. Note that the presented approach is a midterm static approach and PDFs of LMPs are computed for the peak load of end year of planning horizon. A high mean of LMP at a bus indicates no access to cheap generation, and a low mean of LMP indicates access to excess cheap generation and no access to enough load. Hence, constructing a new line between two buses with low and high mean of LMP will allow the dispatch of the excess cheap generation. Consequently, energy flows from the low LMP bus to the high LMP bus due to price potential difference. Therefore, between each two buses that have average LMP difference greater than a specified value (SV), a new line is suggested as expansion candidate. The set of candidates is equal to union of candidates of all scenarios.

V. MEASURING THE GOODNESS OF EXPANSION PLANS

To measure the goodness of expansion plans, each of them, with the highest possible capacity, is introduced to the network, and PDFs of LMPs are computed for each scenario. Now we need an appropriateness index to measure the goodness of each expansion plan. This appropriateness index must take into account importance degrees of stakeholders in decision making, importance degrees of planning criteria from the viewpoint of different stakeholders, and appropriateness degrees of expansion plans versus different planning criteria.

A. Importance Degrees of Stakeholders and Planning Criteria

The stakeholders who have interests in transmission expansion planning and exert driving force for expansion are demand customers, power producers, system operator, network owner(s), and regulator [1]–[3]. Stakeholders' desires (planning criteria) are competition, reliability, flexibility of operation, transmission expansion cost, and environmental impacts [1]–[3]. It is very difficult and may be impassible to assign crisp values to importance degrees of stakeholders and planning criteria. In this paper, importance degrees of stakeholders and planning criteria are modeled by fuzzy numbers. In order to assign a fuzzy number to each importance degree, a survey was done. Two questionnaires were designed. In the first questionnaire respondents were asked to answer the following questions.

How important is decision of stakeholder S_i relative to decision of stakeholder S_j in decision making on network planning? Please choose one of the following options:

OL☐ VL☐ SL☐ ML☐ E☐ MM☐ SM☐ VM☐ OM☐

where $S_1 = demand\ customers$, $S_2 = power\ producers$, $S_3 = system\ operator$, $S_4 = network\ owner(s)$, $i = 1, \dots, 5$, and $j = i + 1, \dots, 5$. OL, VL, SL, ML, E, MM, SM, VM, and OM are abbreviations of Overwhelmingly Less important, Very strongly Less important, Strongly Less important, Moderately Less important, Equally important, Moderately More important, Strongly More important, Very strongly More important, and Overwhelmingly More important, respectively. In the second questionnaire, we ask respondents to answer the following questions.

How important is planning criterion C_i relative to planning criterion C_j? Please choose one of the following options:

OL☐ VL☐ SL☐ ML☐ E☐ MM☐ SM☐ VM☐ OM☐

where $C_1 = competition$, $C_2 = reliability$, $C_3 = flexibility\ of\ operation$, $C_4 = transmission\ expansion\ cost$, $C_5 = environmental\ impacts$, $i = 1, \dots, 5$, and $j = i + 1, \dots, 5$. The first questionnaire was sent to some network planning consultant, professors, and Ph.D. students who are involved in network expansion planning. The second questionnaire was sent to some demand customers, power producers, transmission owners, regional system operators, and regulator. Questionnaire 2 was also sent to some planning consultant, professors, and Ph.D. students. They are asked to answer the questionnaire from the viewpoint of different stakeholders separately. Analytic hierarchy process [17], [18] is used to determine the importance degrees of stakeholders in decision making and importance degrees of planning criteria from the viewpoint of different stakeholders.

Suppose m demand customers answer questionnaire 2. The procedure of assigning fuzzy numbers to importance degrees of planning criteria from the viewpoint of demand customers is as follows.

1) Computing Importance Degrees of Planning Criteria for Each Answer:

a) Computing Pairwise Comparison Matrix for Answer p: Answer p includes I^p_{ij} for $i = 1, \dots, 5$, and $j = i + 1, \dots, 5$, where I^p_{ij} is the importance degree of planning criterion C_i relative to planning criterion C_j from the viewpoint of demand customer p. Values 9^{-1}, 7^{-1}, 5^{-1}, 3^{-1}, 1, 3, 5, 7, and 9 are assigned to OL, VL, SL, ML, E, MM, SM, VM, and OM, respectively [17], [18]. Pairwise comparison matrix is computed for answer p. Pairwise comparison matrix is given by

$$A^p = \left[I^p_{ij}\right] \quad i = 1, \dots, 5, \quad j = 1, \dots, 5. \tag{1}$$

I^p_{ij} is equal to I^p_i / I^p_j, where I^p_i is the importance degree of planning criterion i from the viewpoint of demand customer p. Pairwise comparison matrix has consistency relation, i.e.,

$$I^p_{ij} = I^p_{ik} \cdot I^p_{kj}. \tag{2}$$

If pairwise comparison matrix is computed using all I^p_{ij} given by a respondent, the consistency relation may be violated. Pairwise comparison matrix can be computed by four independent elements of I^p_{ij}. To keep the consistency relation, four independent elements of I^p_{ij} are identified using Hasse diagram. [17]. Pairwise comparison matrix is computed using the independent elements of answer p.

b) Computing the Eigenvector of Nonzero Eigenvalue of A_p: Through multiplying pairwise comparison matrix A^p by vector of importance degrees I^p, we obtain the following equation:

$$A^p I^p = \begin{bmatrix} \frac{I^p_1}{I^p_1} & \frac{I^p_1}{I^p_2} & \cdots & \frac{I^p_1}{I^p_5} \\ \frac{I^p_2}{I^p_1} & \frac{I^p_2}{I^p_2} & \cdots & \frac{I^p_2}{I^p_5} \\ \vdots & & & \\ \frac{I^p_5}{I^p_1} & \frac{I^p_5}{I^p_2} & \cdots & \frac{I^p_5}{I^p_5} \end{bmatrix} \begin{bmatrix} I^p_1 \\ I^p_2 \\ \vdots \\ I^p_5 \end{bmatrix} = 5 \begin{bmatrix} I^p_1 \\ I^p_2 \\ \vdots \\ I^p_5 \end{bmatrix}. \tag{3}$$

Rank of matrix A is one. Therefore, it has only one nonzero eigenvalue. It is easy to show that the nonzero eigenvalue of A is equal to 5. Equation (3) shows that vector I^p is the eigenvector of nonzero eigenvalue of matrix A^p. Therefore, elements of normalized I^p are importance degrees of planning criteria from the view point of demand customer p.

2) Eliminating Bad Data: After computing the importance degrees of planning criteria for each answer, mean and standard deviation of each planning criterion is computed over different answers. Suppose μ_i and σ_i are mean and standard deviation of I^p_i over $p = 1, \dots, m$. If some values of I^p_i for $p = 1, \dots, m$ are located out of $[\mu_i - 3\sigma_i \quad \mu_i + 3\sigma_i]$, then the related answer is considered as bad data and is eliminated.

3) Assigning a Fuzzy Number to Each Planning Criterion: Consider I^p_i for $p = 1, \dots, m$ and $i = 1, \dots, 5$. Triangular fuzzy number $f(I_i) = \langle \min_p\{I^p_i\}, \mu_i, \max_p\{I^p_i\} \rangle$ is assigned to criterion I_i, where μ_i is mean of I_i after eliminating bad data. This fuzzy number covers all values of I^p_i for $p = 1, \dots, m$ and $f(\mu_i) = 1$. There are five planning criteria. Sum of I^p_i for $i = 1, \dots, 5$ is equal to 1. In order to limit the vagueness in importance degrees of planning criteria, it is assumed that the accepted range for I^p_i is $[\mu_i - 1/5 \quad \mu_i + 1/5]$. Therefore, the assigned triangular fuzzy number is corrected as follows:

$$f(I_i) = \left\langle \max\left\{ \min_p \{I^p_i\}, \mu_i - \frac{1}{5} \right\}, \right. \\ \left. \mu_i, \min\left\{ \max_p \{I^p_i\}, \mu_i + \frac{1}{5} \right\} \right\rangle.$$

Fig. 1(a) shows the assigned fuzzy numbers to importance degrees of planning criteria from the viewpoint of demand customers. The same algorithm is used to compute the importance degrees of planning criteria from the viewpoint of other stakeholders and importance degrees of stakeholders in decision making on network planning. Fig. 1 shows the importance degrees of planning criteria from the viewpoint of different stakeholders. Fig. 2 shows the importance degrees of stakeholders in decision making on network planning.

B. Market-Based Criteria

The following criteria are used to measure the appropriateness degrees of expansion plans versus different stakeholders' desires.

Competition: In a stable perfect competitive market, all producers offer their products at the same price, and

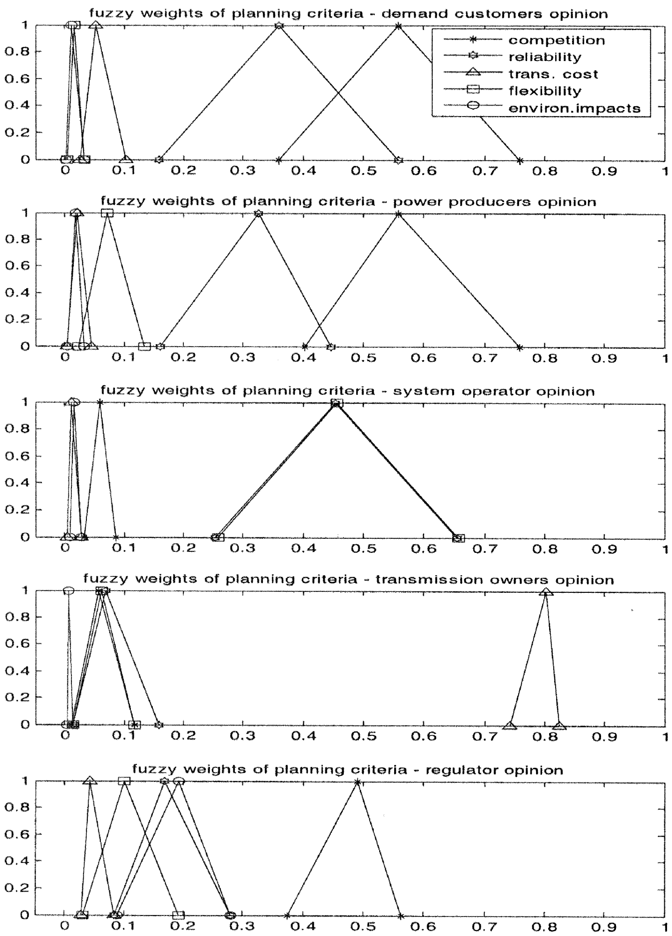

Fig. 1. Importance degrees of planning criteria.

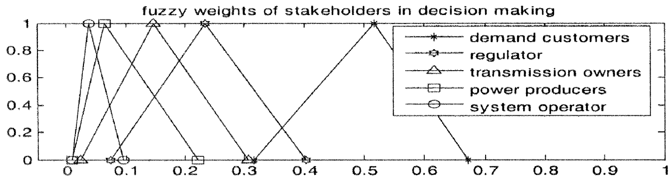

Fig. 2. Importance degrees of stakeholders in network planning.

consumers have no limitation to buy from any producer. Therefore, to have a competitive electric market, LMPs must be made equal and congestion must be alleviated. As more (less) transmission lines are congested, i.e., as constraints for dispatching the cheapest undispatched generation increase (decrease), LMP differences among buses and consequently congestion cost increases (decreases) and vice versa. Therefore, congestion cost is a proper criterion for measuring price discrimination and transmission constraints and consequently competition. To model random uncertainties, average congestion cost is used to measure the competitiveness degree of an electric market [3], [10], [11].

Reliability: Average load curtailment cost is used to measure the reliability of the network.

Flexibility: Average load curtailment cost can also be used to measure the flexibility of network operation. If expansion planning reduces the number of congested lines, flexibility of network operation increases. Therefore, number of congested lines can be used as a criterion for measuring the flexibility of network operation. Here, number of lines with average power greater than 0.9 of their limits multiplied by average load curtailment cost is used to measure the flexibility of operation.

Transmission expansion cost: Annual investment cost plus annual reduction in operation cost after planning is used to measure transmission expansion cost.

Environmental impacts: Cost of compensating the environmental impacts is used to measure the environmental impacts of expansion plans.

Suppose C_{ki}^{l} is the value of criterion i for plan k in scenario l. C_{ki}^{l} for $i=1,\ldots,5$ represents the value of criterion that is used to measure competition $(i=1)$, reliability $(i=2)$, operation flexibility $(i=3)$, transmission expansion cost $(i=4)$, and environmental impacts $(i=5)$. Smaller values of all these criteria indicate better conditions. Hence, inverse of above criteria are used to measure the appropriateness degree of expansion plans versus above planning criteria

$$\mathcal{A}_{ki}^{l} = \frac{1}{C_{ki}^{l}}. \tag{4}$$

The appropriateness degrees of expansion plans must be comparable versus different planning criteria. Therefore, $\mathcal{A}_{ki}^{l}$ is normalized on its maximum value over different scenarios and expansion plans

$$\mathcal{N}_{ki}^{l} = \frac{\mathcal{A}_{ki}^{l}}{\max\limits_{k,l}\left(\mathcal{A}_{ki}^{l}\right)} \tag{5}$$

where $\mathcal{N}_{ki}^{l}$ is the normalized appropriateness degree of plan k versus planning criterion i in scenario l.

C. Fuzzy Appropriateness Index

Now an appropriateness index must be defined for measuring the goodness of expansion plans. This index must represent the degree of appropriateness of expansion plans versus combination of all above planning criteria considering importance degree of stakeholders and planning criteria.

Let fuzzy number W_j represent the importance degree of stakeholder j in decision making and fuzzy number V_{ij} represent the importance degree of criterion i from the viewpoint of stakeholder j. The importance degree of criterion i is equal to the weighted mean of V_{ij} i.e.,

$$U_i = \frac{1}{N_{st}}\left[(W_1 \otimes V_{i1}) \oplus (W_2 \otimes V_{i2}) \oplus \cdots \oplus (W_{N_{st}} \otimes V_{iN_{st}})\right] \quad \text{for } i = 1,\ldots,N_{pc} \tag{6}$$

where N_{st} and N_{pc} are the number of stakeholder groups and planning criteria. Operators $\oplus$ and $\otimes$ are fuzzy addition and multiplication. Fuzzy arithmetic operations are defined using

α-cuts of fuzzy intervals [19]. U_i is a fuzzy number and represents the importance degree of criterion i from the viewpoint of transmission planners.

Fuzzy appropriateness index of plan k in scenario l versus combination of all planning criteria is equal to weighted mean of $\mathcal{N}_{ki}^l$, i.e.,

$$\mathcal{F}_k^l = \frac{1}{N_{pc}}\left[\left(U_1\otimes\mathcal{N}_{k1}^l\right)\oplus\left(U_2\otimes\mathcal{N}_{k2}^l\right)\oplus\cdots\oplus\left(U_{N_{pc}}\otimes\mathcal{N}_{kN_{pc}}^l\right)\right]$$
$$\text{for } k=1,\ldots,N_p,\ \text{and } l=1,\ldots,N_s \quad (7)$$

where N_p and N_s are the number of expansion plans and scenarios. $\mathcal{F}_k^l$ is a fuzzy number and represents the appropriateness degree of plan k in scenario l versus the combination of all planning criteria.

VI. FUZZY RISK ASSESSMENT

If there is only one scenario, there is only one $\boldsymbol{\mathcal{F}}_k^l$ for each plan. In this case, the plan that has the maximum $\boldsymbol{\mathcal{F}}_k^l$ is selected as the optimal plan. In multi-scenario cases, there are N_s fuzzy appropriateness indexes ($\boldsymbol{\mathcal{F}}_k^l$) for each plan. Criteria minimax regret, expected cost, Laplace, Von Neumann-Morgenstern, Hurwicz, robustness, and β-robustness are used to select the final plan in multi-scenario cases. However, as discussed in [6] and [13], each criterion has a shortcoming. Expected cost and Laplace criteria are not valid since the scenarios are not repeatable. Minimax regret and β-robustness criteria are used for very important decisions, where surviving under an unlikely but catastrophic scenario is needed. In addition, these criteria are relative [6], [13]. Von Neumann-Morgenstern and Hurwicz criteria are extremely pessimistic or extremely optimistic. Robustness criterion is very crisp and hence is not logical always. To overcome the shortcomings of these criteria, new criteria are defined and fuzzy multi-criteria decision making is used for selecting the final plan.

Definition: Plan k is robust of order m in scenario l if its regret in scenario l is in the range of $[(m-1)\zeta\ m\zeta)$, where ζ is a percentage of maximum regret over all plans and scenarios, e.g., 2% or 5% of maximum regret. The value of ζ depends on the variations of regrets.

Definition: Degree of robustness of order m of plan k is equal to number of scenarios in which plan k is robust of order m.

Although minimax regret and expected cost have shortcomings, they are important factors in selection of the final plan. Since $\mathcal{F}_k^l$ is a fuzzy number, regret is a fuzzy number and defined as below.

Definition: Fuzzy regret of plan k in scenario l is defined as difference between the fuzzy appropriateness index of plan k in scenario l and fuzzy appropriateness index of optimal plan of scenario l multiplied by the occurrence degree of scenario l

$$R_k^l = Y^l \otimes \left(F_{op}^l \ominus F_k^l\right) \quad (8)$$

where Y^l is the occurrence degree of scenario l, and F_{op}^l is the appropriateness index of optimal plan of scenario l. Operator $\ominus$ is the fuzzy subtraction and is defined using α-cuts of fuzzy intervals [19]. Optimal plan of scenario l is the plan that has the maximum fuzzy appropriateness index. To find the plan that has the maximum fuzzy appropriateness index, fuzzy appropriateness indexes must be ranked. Several methods have been presented for ranking fuzzy numbers. Here, we use convex combination of left and right integral value [20]–[22], centroid indexes [23], and extended centroid index [23] for ranking fuzzy numbers.

TABLE I
IMPORTANCE DEGREES OF DECISION CRITERIA

Criterion	MR	AR	R1	R2	R3	R4	R5
Imp. Degree	H	H	VH	H	M	L	VL

* MR=Max regret, AV=Average regret, Ri=Degree of robustness of order i

TABLE II
TRIANGULAR FUZZY NUMBERS CORRESPONDING TO LINGUISTIC VARIABLES

VL	L	M	H	VH
(0,0,0.25)	(0,0.25,0.5)	(0.25,0.5,0.75)	(0.5,0.75,1)	(0.75,1,1)

In this paper, maximum regret, average regret, degree of robustness of order one, and degree of robustness of order five are used to select the final plan. These decision criteria do not have the same degree of importance. To represent the importance weights of the decision criteria, the following linguistic variables are used:

$$\mathrm{Z} = \{\mathrm{VL}, \mathrm{L}, \mathrm{M}, \mathrm{H}, \mathrm{VH}\}$$

where VL, L, M, H, and VH are abbreviations of very low, low, medium, high, and very high, respectively. Table I shows the importance weights of decision criteria. A triangular fuzzy number is assigned to each member of above set. Table II shows the triangular fuzzy numbers.

Suppose M_{ki} for $i=1,\ldots,7$ is the criterion that is used to measure maximum regret ($i=1$), average regret ($i=2$), degree of robustness of order 1 ($i=3$), ..., and degree of robustness of order 5 ($i=7$) of plan k. Smaller maximum regret and average regret indicate better situation. Therefore, inverse of these criteria are used to measure the appropriateness degrees of expansion plans versus maximum and average regret. Greater degree of robustness of order m for $m=1,\ldots,5$ indicate better situation. Therefore, these criteria are used to measure the appropriateness degrees of expansion plans versus degree of robustness of order m. Suppose A_{ki} is the appropriateness degree of plan k versus decision criteria i; then

$$A_{ki} = \frac{1}{M_{ki}} \quad \text{for } i=1,2 \quad (9)$$
$$A_{ki} = M_{ki} \quad \text{for } i=3,\ldots,7. \quad (10)$$

The appropriateness degrees of expansion plans must be comparable versus different decision criteria. Therefore, A_{ki} is normalized on its maximum value over all expansion plans

$$N_{ki} = \frac{A_{ki}}{\max\limits_{k}(A_{ki})} \quad (11)$$

where N_{ki} is the normalized appropriateness degree of plan k versus decision criterion i.

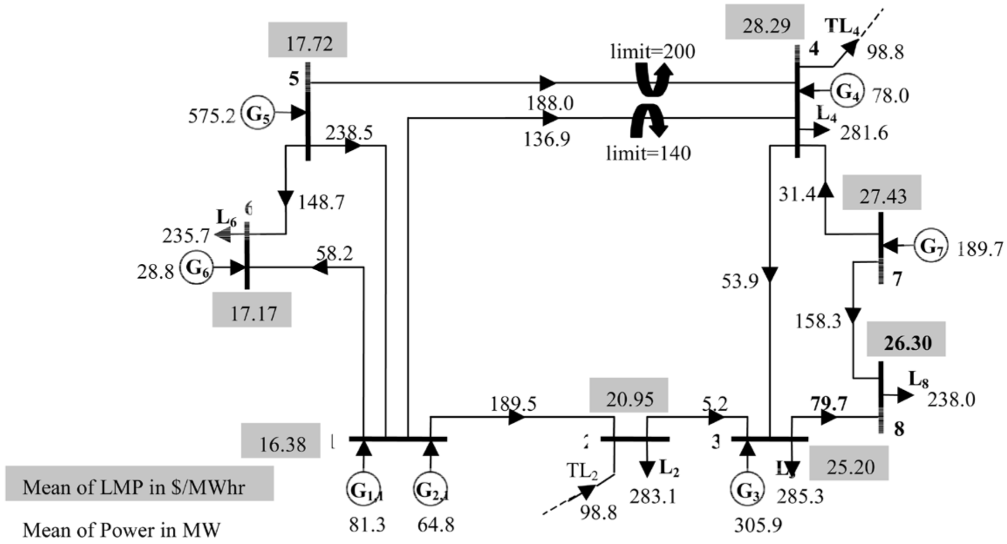

Fig. 3. Single-line diagram of an eight-bus system.

Let $Z_i \in Z$ be the importance weight of decision criterion i. Fuzzy appropriateness index of plan k versus combination of all decision criteria is equal to weighted mean of N_{ki}, i.e.,

$$F_k = \frac{1}{N_{dc}} \left[(Z_1 \otimes N_{k1}) \oplus (Z_2 \otimes N_{k2}) \oplus \cdots \oplus (Z_{N_{dc}} \otimes N_{kN_{dc}}) \right] \tag{12}$$

where F_k is the fuzzy appropriateness index of plan k and represents the appropriateness degrees of plan k versus combination of all decision criteria. N_{dc} is the number of decision criteria. The expansion plan that has the greatest fuzzy appropriateness index is selected as the final plan.

VII. DETERMINING THE CAPACITY OF SELECTED PLAN

The capacity of the selected transmission line is determined using the PDFs of power of selected transmission line in different scenarios. The capacity is determined so that the probability of violating the line limit is less than 1% in each scenario during the peak load of planning horizon.

VIII. CASE STUDY

The presented approach is applied to the eight-bus test system, which is shown in Fig. 3. Characteristics of generators, transmission lines, and loads for the peak load of planning horizon are given in Tables III–V. Mean of generation power, mean of load, mean of power of lines, and mean of LMPs for the peak load of planning horizon are shown on Fig. 3. The generator of bus 4 may be retired. If the generator of bus 4 is retired, either a new generator or a new IPP may be installed in this bus. Characteristics of the new generator and IPP are given in the last two rows of Table III. The planning stages are as follows.

A. Identifying the Set of Possible Strategic Scenarios

The following scenarios are defined to cover above non-random uncertainties.

Scenario 1: Base case (existing network)
Scenario 2: Base case minus Gen. 4
Scenario 3: Base case minus Gen. 4 plus new Gen.
Scenario 4: Base case minus Gen. 4 plus new IPP

It is assumed that the occurrence degrees of above scenarios are the same.

TABLE III
DATA OF GENERATORS

Bus No.	Type	Min	Max (MW)	PDF of Bid ($/MWhr)	Unavailability
1	Gen.	0	110	N~(14, 2.5)	0.02
1	IPP	0	N~ (100, 20)	N~(15, 1.8)	0.02
3	Gen.	0	520	N~(25, 1.5)	0.02
4	Gen.	0	250	N~(30, 2)	0.02
5	Gen.	0	600	N~(10, 3)	0.02
6	Gen.	0	400	N~(20, 2.1)	0.02
7	Gen.	0	150	N~(25, 2)	0.02
8	IPP	0	N~(75, 15)	N~(20, 2)	0.02

TABLE IV
DATA OF LOADS

Bus No	Min	PDF of load (MW)	Bid ($/MWhr)	Unavailability
2	0	N~(100, 25)	32	0.05
3	0	N~(200, 30)	42	0.05
4	0	N~(150, 20)	35	0.05
6	0	N~(150, 25)	30	0.05
8	0	N~(200, 50)	32	0.05

TABLE V
DATA OF TIE-LINES

Bus No	PDF of Power (MW)	Unavailability
2	N~(100, 10)	0.05
4	equal to power of tie-line of bus 2	0.05

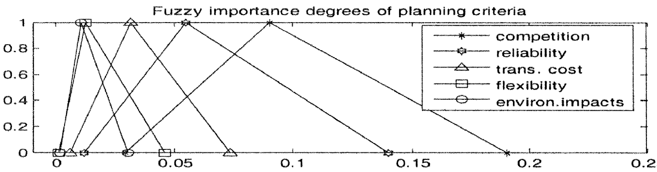

Fig. 4. Importance degrees of planning criteria.

TABLE VI
APPROPRIATENESS DEGREES OF EXPANSION PLANS VERSUS PLANNING CRITERIA IN DIFFERENT SCENARIOS

	Competition				Reliability				Flexibility of Operation				Net. Cha.	Env. Imp.
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1-S4	S1-S4
Do nothing	0.28	0.25	0.30	0.27	0.51	0.13	0.38	0.27	0.30	0.07	0.22	0.16	1.0	1.0
Line 1-3	0.38	0.33	0.62	0.37	0.65	0.11	0.61	0.33	0.25	0.06	0.23	0.13	0.60	0.70
Line 1-4	0.42	0.41	0.54	0.48	0.62	0.39	0.70	0.61	0.24	0.15	0.20	0.18	0.75	0.50
Line 1-7	0.41	0.39	0.42	0.40	0.67	0.23	0.64	0.45	0.39	0.13	0.25	0.26	0.80	0.55
Line 1-8	0.42	0.38	0.70	0.42	0.79	0.24	1.0	0.61	0.31	0.14	0.39	0.24	0.72	0.65
Line 5-4	0.56	0.54	0.63	0.62	0.56	0.47	0.69	0.57	0.22	0.18	0.41	0.33	0.79	0.72
Line 5-7	0.46	0.42	0.62	0.46	0.66	0.21	0.68	0.48	0.39	0.12	0.27	0.19	0.69	0.68
Line 5-8	0.47	0.41	1.0	0.58	0.78	0.15	0.85	0.56	0.45	0.09	1.0	0.33	0.70	0.57
Line 5-3	0.42	0.35	0.80	0.43	0.59	0.08	0.56	0.28	0.35	0.04	0.66	0.33	0.65	0.70
Line 6-3	0.32	0.26	0.49	0.31	0.45	0.04	0.33	0.14	0.26	0.02	0.19	0.08	0.75	0.50
Line 6-4	0.30	0.27	0.45	0.41	0.60	0.35	0.61	0.52	0.23	0.20	0.23	0.20	0.77	0.55
Line 6-7	0.30	0.26	0.33	0.30	0.50	0.11	0.42	0.26	0.29	0.06	0.16	0.15	0.68	0.63
Line 6-8	0.36	0.30	0.65	0.37	0.57	0.08	0.52	0.29	0.33	0.05	0.20	0.17	0.72	0.68

TABLE VII
FUZZY APPROPRIATENESS INDEX ($\mathcal{F}_k^l$) OF EXPANSION PLANS IN DIFFERENT SCENARIOS. OPTIMAL PLANS ARE MARKED

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Do noth.	(0.0038, 0.0173, 0.0447)	(0.0024, 0.0112, 0.0297)	(0.0035, 0.0158, 0.0409)	(0.0030, 0.0138, 0.0360)
Line 1-3	(0.0045, 0.0188, 0.0465)	(0.0027, 0.0107, 0.0267)	(0.0058, 0.0225, 0.0542)	(0.0035, 0.0143, 0.0353)
Line 1-4	(0.0046, 0.0190, 0.0472)	(0.0039, 0.0158, 0.0392)	(0.0055, 0.0218, 0.0533)	(0.0049, 0.0196, 0.0483)
Line 1-7	(0.0049, 0.0205, 0.0510)	(0.0034, 0.0137, 0.0341)	(0.0047, 0.0196, 0.0488)	(0.0041, 0.0171, 0.0426)
Line 1-8	(0.0052, 0.0216, 0.0537)	(0.0034, 0.0137, 0.0341)	(0.0074, 0.0295, 0.0714)	(0.0046, 0.0191, 0.0475)
Line 5-4	(0.0053, 0.0212, 0.0520)	**(0.0050, 0.0198, 0.0485)**	(0.0063, 0.0253, 0.0616)	**(0.0058, 0.0233, 0.0565)**
Line 5-7	(0.0052, 0.0214, 0.0526)	(0.0036, 0.0141, 0.0347)	(0.0060, 0.0237, 0.0575)	(0.0045, 0.0182, 0.0448)
Line 5-8	**(0.0056, 0.0231, 0.0568)**	(0.0032, 0.0128, 0.0315)	**(0.0094, 0.0367, 0.0866)**	(0.0055, 0.0219, 0.0530)
Line 5-3	(0.0047, 0.0197, 0.0485)	(0.0027, 0.0108, 0.0268)	(0.0072, 0.0281, 0.0665)	(0.0040, 0.0163, 0.0398)
Line 6-3	(0.0037, 0.0155, 0.0390)	(0.0020, 0.0084, 0.0216)	(0.0043, 0.0168, 0.0411)	(0.0027, 0.0109, 0.0275)
Line 6-4	(0.0039, 0.0167, 0.0424)	(0.0031, 0.0133, 0.0339)	(0.0048, 0.0196, 0.0484)	(0.0043, 0.0176, 0.0438)
Line 6-7	(0.0037, 0.0159, 0.0400)	(0.0023, 0.0096, 0.0244)	(0.0035, 0.0148, 0.0372)	(0.0029, 0.0124, 0.0312)
Line 6-8	(0.0043, 0.0183, 0.0457)	(0.0024, 0.0100, 0.0254)	(0.0057, 0.0223, 0.0537)	(0.0035, 0.0144, 0.0358)

B. Suggesting Candidates for Transmission Expansion

PDFs of LMPs are computed for the peak load of planning horizon of the existing network for above scenarios. If between each two buses that have average LMP difference greater than \$8 a transmission line is suggested as expansion candidate, 12 candidates will result. The set of transmission candidates is as follows:

$$\begin{aligned}&\{\text{do nothing, line }1-3,\text{ line }1-4,\text{ line }1-7,\text{ line }1-8,\\&\text{line }5-3,\text{ line }5-4,\text{ line }5-7,\text{ line }5-8,\text{ line }6-3,\\&\text{line }6-4,\text{ line }6-7,\text{ line }6-8\}.\end{aligned}$$

C. Computing Fuzzy Appropriateness Index

Importance degrees of planning criteria (U_i) are computed by aggregating importance degrees of stakeholders in decision making (see Fig. 2) and importance degrees of planning criteria from viewpoint of different stakeholders (see Fig. 1) using (6). Fig. 4 shows the importance degrees of planning criteria. Appropriateness degrees of expansion plans versus planning criteria are computed for each scenario. Table VI shows the normalized appropriateness degrees of expansion plans versus planning criteria in different scenarios (N_{ki}^l). Fuzzy appropriateness index ($\mathcal{F}_k^l$) for measuring the goodness of expansion plans versus combination of all planning criteria is computed for each plan in each scenario by aggregating importance degrees of planning criteria (see Fig. 4) and appropriateness degrees of expansion plans (see Table VI) using (7).Table VII shows the fuzzy appropriateness index of expansion plans in different scenarios. In this table, the optimal plan of each scenario was marked. Each marked fuzzy number is the greatest fuzzy number in related column. Line 5-8 is the optimal plan of scenarios 1 and 3, and line 5-4 is the optimal plan of scenarios 2 and 4. All the ranking methods select the same optimal plan.

D. Fuzzy Risk Assessment

Fuzzy regret of each plan in each scenario is computed by considering occurrence degrees of future scenarios using (8). Table VIII shows the fuzzy regret of expansion plans in different scenarios. Fuzzy risk assessment is applied to Table VIII for selecting the final plan. Maximum regret, average regret, and degree of robustness of order one to five are computed for each plan. Maximum regret, average regret, and degree of robustness of order one to five are given in columns 2-8 of Table IX. Convex combination of right and left integral values with $\alpha = 0.5$ is used for assigning a crisp value to fuzzy regrets. Fuzzy appropriateness index (F_k) is computed by aggregating importance degrees of decision criteria (see Table I) and appropriateness degrees of expansion plans versus decision criteria (columns 2–8

TABLE VIII
FUZZY REGRETS OF EXPANSION PLANS IN DIFFERENT SCENARIOS

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Do noth.	(0.0105, 0.0436, 0.1009)	(0.0155, 0.0467, 0.0979)	(0.0128, 0.0519, 0.1249)	(0.0136, 0.0468, 0.1032)
Line 1-3	(0.0100, 0.0428, 0.1004)	(0.0164, 0.0470, 0.0977)	(0.0091, 0.0484, 0.1232)	(0.0138, 0.0465, 0.1028)
Line 1-4	(0.0098, 0.0426, 0.1003)	(0.0127, 0.0442, 0.0968)	(0.0093, 0.0488, 0.1234)	(0.0101, 0.0436, 0.1017)
Line 1-7	(0.0087, 0.0419, 0.1001)	(0.0142, 0.0454, 0.0972)	(0.0106, 0.0499, 0.1240)	(0.0117, 0.0450, 0.1023)
Line 1-8	(0.0080, 0.0413, 0.0998)	(0.0142, 0.0454, 0.0972)	(0.0043, 0.0447, 0.1219)	(0.0103, 0.0439, 0.1019)
Line 5-4	(0.0085, 0.0415, 0.0997)	(0.0099, 0.0420, 0.0959)	(0.0070, 0.0469, 0.1228)	(0.0077, 0.0417, 0.1010)
Line 5-7	(0.0083, 0.0414, 0.0998)	(0.0140, 0.0451, 0.0970)	(0.0081, 0.0478, 0.1230)	(0.0111, 0.0444, 0.1020)
Line 5-8	(0.0071, 0.0405, 0.0995)	(0.0149, 0.0459, 0.0973)	(0, 0.0409, 0.1204)	(0.0087, 0.0424, 0.1012)
Line 5-3	(0.0094, 0.0423, 0.1002)	(0.0163, 0.0470, 0.0977)	(0.0056, 0.0455, 0.1221)	(0.0125, 0.0454, 0.1024)
Line 6-3	(0.0120, 0.0445, 0.1010)	(0.0179, 0.0483, 0.0983)	(0.0127, 0.0514, 0.1244)	(0.0161, 0.0483, 0.1035)
Line 6-4	(0.0111, 0.0439, 0.1009)	(0.0142, 0.0456, 0.0974)	(0.0107, 0.0500, 0.1240)	(0.0114, 0.0447, 0.1022)
Line 6-7	(0.0117, 0.0443, 0.1010)	(0.0170, 0.0476, 0.0981)	(0.0138, 0.0525, 0.1249)	(0.0150, 0.0475, 0.1033)
Line 6-8	(0.0102, 0.0430, 0.1005)	(0.0167, 0.0474, 0.0979)	(0.0092, 0.0485, 0.1232)	(0.0137, 0.0465, 0.1028)

TABLE IX
VALUES OF DECISION CRITERIA, FUZZY APPROPRIATENESS INDEX (F_k), AND RANKED F_k

	MR	AR	DR1	DR2	DR 3	DR4	DR5	Fuzzy appropriateness index	IV-0.5
Do nothing	0.8442	0.9197	0.3333	0.3333	0.5	0	1	(0.2034, 0.3080, 0.4365)	0.3140
Line 1-3	0.8904	0.9357	0.3333	0.6667	0	1	0	(0.2138, 0.3504, 0.4752)	0.3474
Line 1-4	0.8856	0.9586	0.6667	0.3333	0	1	0	(0.2270, 0.3643, 0.4777)	0.3583
Line 1-7	0.87	0.9465	0.3333	0.6667	0	0	1	(0.2131, 0.3137, 0.4381)	0.3196
Line 1-8	0.946	0.9758	0.3333	0.6667	0.5	0	0	(0.2385, 0.3607, 0.4710)	0.3577
Line 5-4	0.9122	0.9898	1	0	0	1	0	(0.2430, 0.3824, 0.4860)	0.3734
Line 5-7	0.8999	0.9608	0.3333	0.6667	0	1	0	(0.2162, 0.3541, 0.4801)	0.3511
Line 5-8	1	1	0.6667	0.6667	0	0	0	(0.2619, 0.3810, 0.4762)	**0.3750**
Line 5-3	0.9329	0.9539	0.3333	0.6667	0.5	0	0	(0.2360, 0.3569, 0.4660)	0.3539
Line 6-3	0.8502	0.9055	0	0.3333	1	0	1	(0.1849, 0.2952, 0.4413)	0.3042
Line 6-4	0.8696	0.9387	0	1	0	0	1	(0.2006, 0.3009, 0.4369)	0.3098
Line 6-7	0.8369	0.9077	0	0.3333	1	0	0	(0.1841, 0.2941, 0.4040)	0.2941
Line 6-8	0.8888	0.9331	0.3333	0.6667	0	1	0	(0.2135, 0.3500, 0.4746)	0.3470

* MR=Max regret, AV=Average regret, DR*i*=Degree of robustness of order *i*, IV-0.5= convex combination of right and left integral value with α=0.5

of Table IX). Column 9 of Table IX shows the fuzzy appropriateness indexes. Convex combination of right and left integral values of fuzzy appropriateness indexes with $\alpha = 0.5$ are shown in column 10 of Table IX. Line 5-8 has the maximum fuzzy appropriateness index and is selected as the final plan.

If right integral value, left integral value, convex combination of right and left integral values with $\alpha = 0.5$, or distance of extended centroid point from zero is used for ranking fuzzy appropriateness indexes, line 5-8 is selected as the final plan. If x of centroid point or distance of centroid point from zero is used for ranking fuzzy appropriateness indexes, line 1-8 is selected as the final plan.

E. Computing the Capacity of Selected Expansion Plan

Capacity of line 5-8 and line 1-8 must be greater than 424 and 374 MW, respectively, in order to ensure that the probability of violating their limits is less than 1% in all scenarios during the peak load of planning horizon.

IX. CONCLUSION

In this paper, a new market-based approach for network expansion planning in unbundled power systems was presented. In order to consider random uncertainties, nonrandom uncertainties, and vagueness, the approach is a combination of probabilistic optimal power flow, scenario technique, and fuzzy decision making. To measure the goodness of expansion plans, a fuzzy appropriateness index is defined. The fuzzy appropriateness index takes into account importance degrees of stakeholders in decision making, importance degrees of planning criteria from the viewpoint of different stakeholders, and appropriateness degrees of expansion plans versus planning criteria. Importance degrees of stakeholders and planning criteria are determined using analytic hierarchy process. The final plan is selected using the presented fuzzy risk assessment method.

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