468 Journal of Electrical Engineering & Technology Vol. 7, No. 4, pp. 468~479, 2012
http://dx.doi.org/10.5370/JEET.2012.7.4.468

Market-Based Transmission Expansion Planning Under Uncertainty in Bids by Fuzzy Assessment

Gholam-Reza Kamyab†, Mahmood Fotuhi-Firuzabad* and Masoud Rashidinejad**

Abstract – In this paper, by a simple example it is shown that existing market-based criteria alone cannot completely and correctly evaluate the transmission network expansion from market view. However criteria congestion cost (CC) and social welfare (SW) together are able to correctly evaluate transmission network from market view and so they are adopted for the market-based transmission expansion planning. To simply indicate the limits of CC and SW social welfare percentage (SWP) and congestion cost percentage (CCP) are defined. To consider uncertainty in bids of market producers and consumers, and also indeterminacy in the acceptable boundaries of the SWP and CCP and their priorities, fuzzy assessment approach is used. In this approach, appropriate fuzzy sets and a fuzzy rule base are provided to evaluate the acceptability of an expansion plan. Then, the least-investment cost plan, which is acceptable in all probable scenarios, is searched. The proposed method is applied to an 8-bus system.

Keywords: Transmission expansion planning, Restructured power systems

1. Introduction

There are several objectives for transmission expansion planning (TEP) in restructured power systems. The most important of which, are: encouraging and facilitating competition among electric market participants, and minimizing the investment cost of expansion plan. On the other hand, deregulation has increased uncertainties in TEP. The main and effective uncertainties are the uncertainty in bids of power producers and consumers (generators and loads) and the uncertainty in power demands of consumers in the future. Because of long list of objectives and uncertainties, TEP in restructured power systems is turned to a complex problem. Therefore, new approaches are needed to deal with the problem.

In recent years, a number of researches have been done in the field of the TEP in restructured power systems [1] and [2]. Some of the items that have been regarded in these researches are:

- Introducing some criteria or methods for providing competition environment [3-8].
- Introducing methods to simultaneously satisfy multiple criteria such as competition, reliability, investment cost, operational cost and congestion cost [9-15].
- Presenting methods for accounting uncertainties in TEP [3, 9, 13, 16, 17.
- Coordination of generation and transmission expansion planning [16, 18]
- Multistage transmission expansion planning [5, 19].
- Applying meta-heuristic optimization methods such as genetic algorithm [10, 14], expert system (ES) [19], fuzzy-set theory [9, 10], Pareto-based solution technique [20], Simulated Annealing [21] and LP-Based Particle Swarm Optimization [22] to solve TEP.
- Applying mathematical optimization approaches such as Benders decomposition [19, 23], “branch and bound” algorithm [24, 25]; and mixed-integer linear programming [13, 17] to solve TEP.
- Long-term TEP [13, 26].

In this paper, first, two new criteria, i.e. the social welfare percentage (SWP) and the congestion cost percentage (CCP), are defined for TEP in restructured power systems. Then, by a simple example, it is shown that existing market-based criteria alone cannot fully and truly evaluate the transmission network expansion from market view. Therefore the criteria SWP and CCP together are proposed for the full and true evaluation of the market-based transmission expansion planning. Next fuzzy sets are used to define linguistic values for the bids of market participants (producers and consumers) to sell and buy power, SWP, CCP and for the occurrence possibility of each scenario of the bids. After that, a fuzzy rule base is defined to evaluate the acceptability of an expansion plan. Then the least-investment-cost expansion plan which of course has to satisfy the acceptability measures in all probable scenarios is searched. The results of implying the proposed method to a typical 8-bus power system are illustrated.

The paper is organized as follows. In section 2, the

† Corresponding Author: Science and Research Branch, Islamic Azad University (IAU), Tehran, Iran. (kamyabgolamreza@yahoo.com)
* Dept. of Electrical Engineering, Sharif University of Technology, Tehran, Iran. (fotuhi@sharif.edu)
** Shahid Bahonar University of Kerman, Kerman, Iran. (mrashidi@mail.uk.ac.ir)
Received: May 14, 2011; Accepted: March 1, 2012

social welfare percentage and the congestion cost percentage are defined. In section 3, the drawbacks of the already presented market-based criteria are shown by a simple example which is followed by a new proposal for the full and true evaluation of the market-based TEP. Section 4, contains the definition of the transmission expansion planning problem together with the method by which the problem is solved. The fuzzy evaluation of a transmission expansion plan is expressed in section 5, and in section 6, the acceptability conditions of the plan is stated. Section 7 is where the results of applying the proposed method to a test power system are presented; and finally, conclusions of the paper are provided.

2. Comparison of Market-based Criteria

Since transmission network in restructured power systems has an effective role in maintaining competition environment, market-based criterion for TEP is needed to measure how competitive an electric market is and how much a specific expansion plan improves competition. By now, several market-based criteria such as total congestion cost of the transmission network [3, 8, 27], standard deviation of the mean of the LMPs [3, 27] and Lerner index [6, 7] have been presented to evaluate transmission network from the viewpoint of market.

In this section by a straightforward example the weaknesses of the following four criteria have been indicated: The total congestion cost of the transmission network (CC), Standard deviation of the LMPs (σ), Lerner index (LI), and maximum social welfare (SW). Appendix A contains the definitions for these criteria.

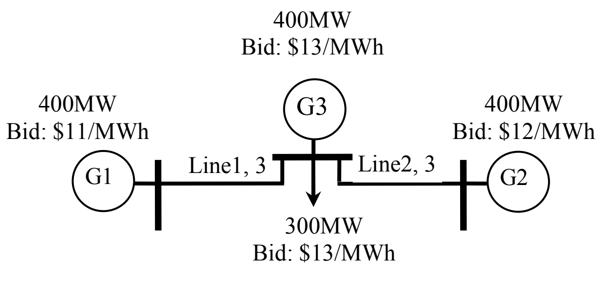

Fig. 1. The 3-bus example power system

Let us consider the 3-bus simple power system shown in Fig. 1. In this system, maximum capacity limits of the generators G1, G2 and G3 are 400 MW and the bids of the generators are assumed 11, 12 and 13 $/MWh respectively. The maximum demand of the only load of the system, which is connected to bus 3, is equal to 300 MW and its bid is 13 $/MWh. There are two transmission lines in the transmission network of the system. The capacity of each line is 100 MW.

In order to indicate the weaknesses of the criteria, seven expansion cases for the transmission network of the simple system can be considered. Table 1 shows the seven cases. The transmission network in case 1 is the original (existing) network without any expansion. In cases 2 to 7, a number (one, two or three) of new 100MW-capacity circuits is/are added to the original network. The numbers of the new added circuits are shown in the second and third columns of the Table 1. In these columns $N_{i,j}$ is the number of the new circuits that have been added to the line connected between buses i and j. The values of the capacity of lines, total congestion cost (CC), maximum social welfare (SW), Lerner index (LI) and standard deviation (σ) for the seven cases are given in Table 1. The calculation details of the values are presented in appendix A. Now by referring to Table 1, the comparison is stated at the following points:

(a) In case 7, all of the buses have the same LMP (see Table 3 in appendix A), so from market view the network is ideal. Referring to Table 1, it can be observed that all the criteria of CC, SW, LI and σ in case 7 have their ideal values too. Therefore all the criteria can truly indicate the ideal improvement of the transmission network.

(b) In cases 2 and 3, one new circuit is added to the original network (case 1), so the networks of case 2 and 3 with respect to case 1 have been improved, while CC in cases 2 and 3 with respect to case 1 has been degraded (increased). Essentially, because the congestion cost of a line is the product of the transmitted power of the line and the LMP difference of the end buses of the line, as long as the LMP difference has not been decreased, by increasing the transmitted power of the line, the congestion cost will be increased. Therefore, in all cases, the congestion cost (CC) alone cannot appropriately indicate the improvement of the transmission network. It can only be a just indication factor for the ideal improvement.

(c) The transmission network in case 4 has an additional circuit with respect to the transmission network in case 3. Consequently it causes a reduction in the LMP of bus 3, from 13 $/MWh in case 3 to 12 $/MWh in case 4; moreover it highly decreases the congestion cost in case 4 with respect to case 3. Therefore the network in case 4 has been improved with respect to case 3. But it is observed that the maximum social welfare (SW) in case 4 with respect to case 3, in spite of the expectation, has been remained constant. The same trend is valid for cases 5 and 6. On the other hand, the value of SW in case 6 is at its maximum value and so it is expected that the network in case 6 is in its ideal form, but it is observed that in case 6, 50% of SW includes congestion cost. Consequently, the case whose network is ideal is not 6. However with a precise assessment, it can be indicated that the case 7 is ideal. Therefore, in all the cases, the criterion of "maximum social welfare (SW)" alone cannot indicate the improvement of the transmission network and achieving to the ideal network appropriately.

Table 1. The values of market based criteria for the different expansion cases of the transmission network of the 3-bus power system

Case No.	$N_{1,3}$	$N_{2,3}$	$L_{1,3}$ Cap.	$L_{2,3}$ Cap.	CC	SW	LI	σ
1	0	0	100	100	300	300	0.083	1
2	0	1	100	200	400	400	0.083	1
3	1	0	200	100	500	500	0.083	1
4	1	1	200	200	200	500	0.057	0.577
5	0	2	100	300	100	400	0.057	0.577
6	2	0	300	100	300	600	0.057	0.577
7	3	0	400	100	0	600	0	0

(d) Each one of the transmission networks in cases 2 and 3 has one additional circuit with respect to the transmission network in case 1. It has led to increase the maximum social welfare (SW) and improve the network of the system. But in spite of our expectation, standard deviation (σ) and Lerner index (LI) in these three cases have remained unchanged and they do not reveal any improvement. Furthermore, despite having different expansion forms of the network in cases 4, 5 and 6, Standard deviation (σ) and Lerner index (LI) have unfavorably remained constant in these cases. Only in ideal case 7, these two criteria achieve their ideal values, i.e. zero. Therefore, in all cases, none of the Standard deviation and Lerner index alone can indicate the improvement of the transmission network appropriately. They can truly indicate only the ideal case in the transmission network expansion. Essentially, because these two criteria are obtained from LMPs, they will not change unless there is/are some alteration(s) in the LMPs.

(e) By improving the transmission network in cases 1 to 7, in Table 1, it can be seen that the congestion cost (CC) is decreased and the social welfare (SW) is increased until they reach their ideal values (zero and 600 respectively) in ideal case 7. So the CC and SW together can indicate the transmission network improvement appropriately. In other words, if an expansion plan has smaller CC and simultaneously higher SW, it will be more desirable. To come to the point, the criteria CC and SW together can appropriately and truly evaluate transmission network from market view and so they are proposed for the market-based transmission expansion planning. Furthermore by specifying or limiting the values of the CC and SW criteria, transmission planner can determine to what extent the transmission expansion plan will provide competition in the corresponding market.

3. Definitions of the SWP and CCP

In the previous section it was shown that the criteria of CC and SW together can appropriately and truly evaluate transmission network from market view and so they are proposed for the market-based transmission expansion planning. In this section two criteria which have shown CC and SW as percentages are defined. By these percentages the limits of CC and SW can be simply indicated. So Eqs. (1) and (2) indicate the formal definitions for "social welfare percentage" and "congestion cost percentage" respectively:

$$SWP = \frac{SW^{Rl}}{SW^{Id}} \quad (1)$$

$$CCP = \frac{CC^{Rl}}{SW^{Rl}} \quad (2)$$

where SWP is the social welfare percentage; SW^{Rl} and SW^{Id} are the maximum social welfare for the under study and an ideal transmission networks respectively. CCP is the congestion cost percentage. CC^{Rl} is the congestion cost for the under study transmission network. The ideal transmission network is a network which has no capacity limitations and thus it does not cause congestion. Therefore in the ideal transmission network, all of the buses have the same LMPs, congestion cost is zero and the maximum social welfare (SW^{Id}) has its highest value. In the ideal case, SW^{Rl} reaches to the SW^{Id} and consequently the maximum value of the SWP is 1. Because the congestion cost (CC^{Rl}) is a component of the maximum social welfare (SW^{Rl}), the maximum value of the congestion cost is equal to the maximum social welfare. Thus the minimum and maximum values of the congestion cost percentage (CCP) are zero and 1 respectively.

For the calculation of CCP and SWP, the LMPs of the buses and generation power of the generators and load powers are needed. The LMPs and the powers can be calculated using appendix A in [28].

4. Transmission Planning Procedure

First some terms which will be used in the procedure need to be defined as follows:

- Expansion plan: In this paper it is assumed that a transmission line is made up of one or more parallel and similar circuits. In a transmission network, there are some existing or new transmission lines to which one or more circuits can be added. A transmission expansion plan is a combination of these new circuits that can be offered to expand the transmission network. Different expansion plans can be suggested. The purpose of this paper is to find the optimum expansion plan under conditions of new candidate lines given.

- Uncertainties in bid: In this paper, it is assumed that the exact amounts of the bid of each generator to sell power (C_G) and the bid of each consumer to buy power (C_D) are not specified, but the maximum and minimum of these bids are assumed to be specified. In other words, it is assumed that the bid of each generator (producer) to sell power up to its maximum available capacity may be changed within a specified interval ($C_{G\min} \le C_G \le C_{G\max}$). Furthermore, the bid of each consumer (load) to buy power up to its maximum demand may be changed within a specified interval ($C_{D\min} \le C_D \le C_{D\max}$). In the next section, a fuzzy membership function is defined for each one of the uncertainties.
- Scenario: Each one of the uncertainties (the bids of generators and consumers) may have various values. Each combination of these possible value-per-uncertainty units is called a scenario. In each scenario, the values of the generation and load powers are determined according to market rules.
- Acceptable expansion plan: In this study, an expansion plan is evaluated by an appropriateness index. If the appropriateness index of an expansion plan in all possible uncertainty scenarios has an acceptable value, the plan will be an acceptable one. The appropriateness index and its range of acceptable values are defined in the next section.
- Optimal expansion plan: Among the various acceptable expansion plans, the least-investment-cost acceptable plan is defined as optimal expansion plan. In fact, the TEP problem is to find the optimal expansion plan.

Now the mathematical formulation of our TEP problem is introduced as follows:

$$\underset{P}{Minimize} \qquad Inv(p) \tag{3}$$

Subject to:

$$APP(p) = A \tag{4}$$

where p is one of the candidate expansion plans whose investment cost (*Inv(p)*) must be minimized. *APP(p)* is the appropriateness index of the plan p which must be acceptable (*A*). The appropriateness (*APP*) is the fuzzy output of a fuzzy rule base which is based on three fuzzy variables including *PS* (the occurrence possibility of an uncertainty scenario), *SWP* and *CCP*. *APP* has two linguistic expressions, acceptable (*A*) and unacceptable (*U*). The definitions of the fuzzy variables (*PS*, *SW* and *CCP*), the fuzzy output (*APP*) and the method to determine *APP* and its range of acceptable values are stated in the next sections.

The planning procedure is carried out in the following steps:

Step 1. All of the probable expansion plans in ascending order of their investment cost are sorted.

Step 2. Through the sorted plans, the first (least-investment cost) plan for evaluation is selected which is called "current plan".

Step 3. By using the simulated annealing (SA) algorithm, the current plan in fuzzy space over different scenarios is evaluated to obtain the minimum value of the appropriateness for all possible scenarios. See appendix B for detail of simulated annealing algorithm.

Step 4. Based on the minimum value of the appropriateness index, the current plan is marked as acceptable or unacceptable.

Step 5. In case the current plan was an unacceptable one, the next plan from the list of the sorted plans would be selected as a new current plan and there would be a loop back to step 3. But if the current plan was acceptable, the current plan would be introduced as the final optimal expansion plan.

Fig. 2 shows the flowchart of the planning procedure.

It has to be mentioned that because of the infinity of the number of scenarios it is impossible to evaluate the whole set. This is reason the SA algorithm is utilized to determine the minimum value of the appropriateness index. Advantageously, the SA algorithm enables us to obtain the minimum value of the appropriateness index by evaluating a small number of scenarios. Furthermore, since we have appropriateness index for a distinct scenario per iteration in the SA algorithm in step 3, the unacceptability of the current plan can be generally identified in a few initial iterations. Therefore the further evaluation of the expansion plans will be terminated very quickly.

5. Fuzzy Evaluation of a Transmission Expansion Plan

As mentioned above, the proposed transmission planning procedure will find the most low-cost expansion plan which is also acceptable from view point of the maximum social welfare percentage (SWP) and the congestion cost percentage (CCP) in different scenarios of bid producers and consumers. Bids values of producers and consumers usually are not exactly identified in the future but there is a vague knowledge of them. In addition, the boundaries of the acceptable and unacceptable values of the criteria, SWP and CCP, are not accurately known. The priorities of these criteria are not accurately determined. But the boundaries and priorities of these criteria can be stated with vague linguistic expressions. For example, the social welfare percentage (SWP) is more desirable to be high while the congestion cost percentage (CCP) is needed to be low for more likely bids (bids with the higher occurrence possibility); or as another example, the medium values of the SWP and CCP may be acceptable for less likely bids (bids with the less occurrence possibility).

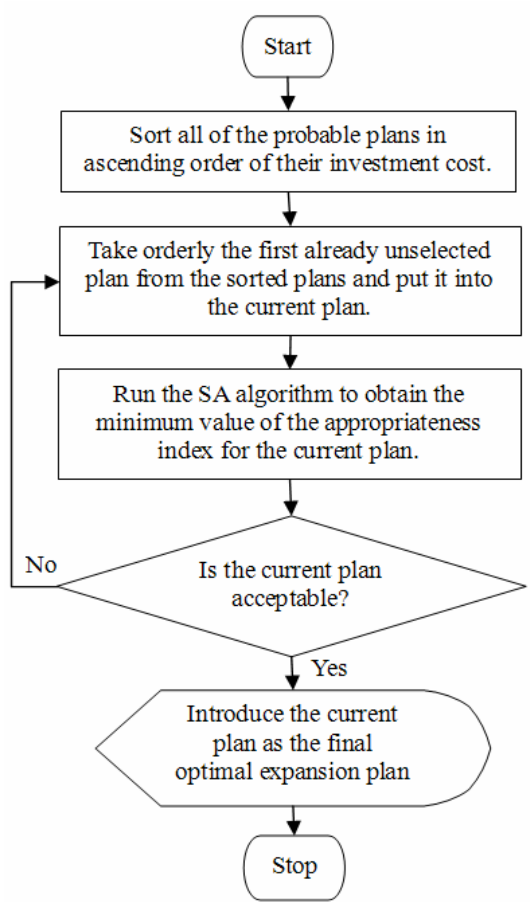

Fig. 2. The flowchart of the proposed planning procedure.

Because fuzzy sets are a suitable framework to model vague information and criteria, as well as decision-making with these vague information and criteria, in this study, the expansion plans are evaluated using the Fuzzy decision-making method. The method has three phases including fuzzification, fuzzy reasoning and defuzzification which will be expressed separately below.

5.1 Fuzzification

First, each uncertainty (bids of the producers and consumers) is considered as a fuzzy variable; so a fuzzy set with the trapezoidal membership function for each of the variables is defined. For instance, Fig. 3 shows the trapezoidal membership function for the uncertainty C which is the bid of a participant (producer or consumer) to the electricity market. The figure shows the linguistic description: "the bid of the fuzzy variable C is in the interval $[c_1, c_4]$, but its occurrence in the interval $[c_2, c_3]$ is likely". In brief, the function $\mu_C(x)$ indicates that at what degree the fuzzy variable C gets the real value of variable x.

We define the linguistic variables of *SWP* and *CCP* for the criteria, the maximum social welfare percentage (SWP) and the congestion cost percentage (CCP), respectively; where each of which, has three corresponding linguistic expressions (fuzzy sets). The linguistic expressions are low (*L*), medium (*M*) and high (*H*) that indicate the amounts of low, medium and high SWP or CCP. The membership functions of the low (*L*), medium (*M*) and high (*H*) are defined according to Fig. 4. The four parameters a_1, a_2, a_3 and a_4 in the figure shall be determined by the hands of experts.

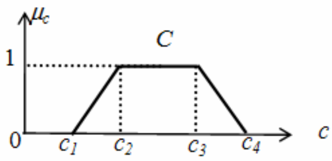

Fig. 3. Typical membership function of an input variable.

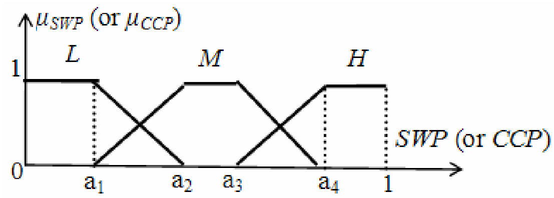

Fig. 4. The membership functions of the Low, Medium and High for the variables *SWP* and *CCP*.

To enter the effect of the membership functions of the uncertainties (bids of the producers and consumers) another fuzzy variable is defined which is called the occurrence possibility of an uncertainty scenario, briefly possibility of scenario (PS). The PS value is obtained by the Eq. (5).

$$PS = \min\{\mu_{Cg1}, \cdots, \mu_{CgNg}, \mu_{Cd1}, \cdots, \mu_{CdNd}\} \quad (5)$$

where μ_{Cgi} is the value of the bid membership function of producer (generator) *i*; μ_{Cdj} is the value of the bid membership function of consumer *j*; *Ng* is the number of generators and *Nd* is the number of consumers.

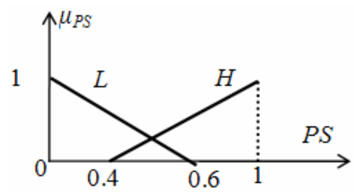

Fig. 5. The membership functions Low and High for the occurrence possibility of an uncertainty scenario (*PS*).

The fuzzy variable of *PS* is defined as Fig. 5. It has two linguistic expressions called low (*L*) and high (*H*). The membership functions of the linguistic expressions defined in this figure determine that the occurrence possibility of an uncertainty scenario is high or low. Thus the decision could be different in the scenarios with the low occurrence possibility with respect to the scenarios with the high occurrence possibility.

Now to perform the fuzzification for a specific expansion plan in a specific uncertainty scenario, for example scenario *s*, the following steps are to be done:

Step 1. Considering the values of the uncertainties in scenario *s* and their membership functions that were defined in Fig. 3, the values of membership μ_{Cgi} and μ_{Cdj} for all uncertainty variables are to be defined.

Step 2. Using Eq. (5), the value of the occurrence possibility of scenario *s* (i.e. *PS*) is to be obtained.

Step 3. Using the function indicated in Fig. 5, the value of the membership function μ_{PS} for the value of *PS* obtained in previous step is to be determined.

Step 4. Considering the uncertainty values in scenario *s* and implementing the OPF of appendix A in [28], the values of social welfare percentage (*SWP*) and the congestion cost percentage (*CCP*) is to be calculated.

Step 5. Using the membership function definitions in Fig. 4, the values of the membership functions of the fuzzy sets Low (*L*), medium (*M*) and high (*H*) for the fuzzy variables of *SWP* and *CCP* for the under study expansion plan are to be determined.

Thus the values of the all membership functions will be obtained.

5.2 Fuzzy reasoning

First the appropriateness of an expansion plan (*APP*) is considered as a fuzzy output; for which, two linguistic expressions, acceptable (*A*) and unacceptable (*U*), are defined. Fig. 6 shows the membership functions of the linguistic expressions for the output variable.

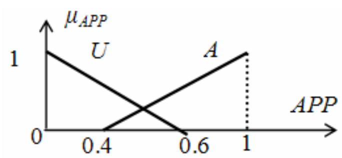

Fig. 6. The membership functions Acceptable and Unacceptable for the output variable (Appropria- teness).

Now for fuzzy reasoning, the fuzzy rule base according to the Mamdany model is being introduced. The three criteria PS, SWP and CCP for the fuzzy decision-making and determining the fuzzy output will be used; the criterion PS has two linguistic values and each one of the criteria of SWP and CCP has three linguistic values. Therefore the linguistic values form 18 different combinations. Then a rule base with the 18 fuzzy rules is being defined as follows:

Rule 1: If <*PS* is *H*> and <*SWP* is *H*> and <*CCP* is *L*> Then <*APP*=*A*>

Rule 2: If <*PS* is *L*> and <*SWP* is *H*> and <*CCP* is *L*> Then <*APP*=*A*>

Rule 3: If <*PS* is *L*> and <*SWP* is *H*> and <*CCP* is *M*> Then <*APP*=*A*>

Rule 4: If <*PS* is *L*> and <*SWP* is *M*> and <*CCP* is *L*> Then <*APP*=*A*>

Rule 5: If <*PS* is *L*> and <*SWP* is *M*> and <*CCP* is *M*> Then <*APP*=*A*>

Rule 6-18: Otherwise Then <APP=*U*>

Only in 5 rules of the above fuzzy rule base, the fuzzy output (the appropriateness of the expansion plan) has acceptable (*A*) value and in the 13 residual rules, the fuzzy output has unacceptable (*U*) value. In rules 1 and 2 where *SWP* is high and *CCP* is low, the expansion plan provides the best competitiveness condition; therefore the expansion plan will be accepted regardless of whether the occurrence possibility of the corresponding uncertainty scenario (*PS*) is high or low. In rules 3 to 5, because the occurrence possibility of the corresponding uncertainty scenario is low, the medium values for the *SWP* and *CCP* have been accepted and consequently the appropriateness of the expansion plan is acceptable for the scenario.

After fuzzification and determining the values of fuzzy input variables for the under study expansion plan, fuzzy inference is performed using the above rule base and according to the Mamdani model. In this fuzzy inference, if two or more rules have nonzero values, the union of them will be considered in accordance with the Mamdani model.

5.3 Defuzzification

The appropriateness value obtained from fuzzy inference is one of the linguistic values (*A* or *U*) or their union. But the evaluation index, which is needed to evaluate an expansion plan by the SA algorithm, should be a crisp or non-fuzzy value. Therefore, the crisp value of the appropriateness (*APP*) is computed using one of the existing defuzzification methods. Here the "Center of Gravity" method is used for the defuzzification. Thus the crisp value of the appropriateness (*APP*) of an expansion plan, which is a number between zero and one, is obtained as the evaluation index. If the index value is higher than 0.5, the expansion plan for the under study scenario will be recognized as an acceptable plan; while if it is less than 0.5, the expansion plan for the scenario will be recognized as an unacceptable one.

6. Determining the Acceptability of Expansion Plans

As noted earlier, in this study each expansion plan in each scenario is evaluated by the appropriateness index. If the appropriateness index value of an expansion plan in all probable uncertainty scenarios is in appropriateness acceptable range (greater than 0.5), the plan will be introduced as an acceptable plan. But there are unlimited numbers of scenarios, so it is not possible to calculate the appropriateness index in all of the scenarios. Hence, first it is tried to obtain the lowest value of the appropriateness index. It is clear that if the lowest value is greater than 0.5, the appropriateness index value of the plan in all probable uncertainty scenarios is greater than 0.5 and thus the plan will be acceptable. Therefore the simulated annealing (SA) algorithm is used to search the lowest value of the appropriateness index. Summary of the SA algorithm can be seen in Appendix B. Applying the SA algorithm only a small number of the scenarios are need to be evaluated to obtain the lowest value of the appropriateness index. The algorithm usually will not be trapped at the local optimal points of the problem and it can potentially obtain the global optimum. To apply the SA algorithm for determining the lowest value of the appropriateness index, the following points are mentioned:

(a) To execute the SA algorithm, scenarios must be coded first. Here, each uncertainty scenario is coded by an *ns* dimensional vector of decimal numbers (say vector *X*), where *ns* is the number of the uncertainties. Each element of vector *X* depends on one of the uncertainties (a bid) and can vary in the corresponding uncertainty interval. Each value of the vector *X* indicates a distinct numerical combination of all uncertainties, and therefore it shows a scenario of uncertainties.

(b) To execute the SA algorithm, the evaluation function (performance index) must be also determined. Therefore, to determine the lowest value of the appropriateness index, the value of the appropriateness index of the under-evaluation transmission network at scenario *X* is defined as the evaluation function of the scenario *X*. The simulated annealing algorithm searches the minimum value of the evaluation function.

(c) According to the SA algorithm, in each iteration of the algorithm a new solution is generated to evaluate. The generated new solution must be in the neighborhood of the solution of the previous iteration. Here to generate the new solution around the previous solution *X*, N_c elements of vector *X* are changed where N_c is a random number up to 50% of the elements of vector *X*. The amount of changing each element is also a random number which is up to 10% of the interval of the element.

(d) In each iteration of the simulated annealing algorithm, if the value obtained for the appropriateness index (evaluation function) is less than 0.5, the simulated annealing algorithm will be stopped and the related expansion plan will be introduced as an unacceptable plan. Usually most of the unacceptable expansion plans will be determined in a few initial iterations; so further evaluation of the expansion plans is terminated very quickly.

7. Case Study

The proposed method in this paper is applied to a sample 8-bus power system [9, 27, 28]. Fig. 7 shows the single-line diagram of the system. It has to be mentioned that lines 1 to 11 are the lines of the original system and lines 12 to 23 are the new lines which may be constructed. In Fig. 7, the existing lines are depicted by solid lines and the new lines are illustrated by dashed lines. The characteristics of the generators, loads, the original and new lines of this system are given in appendix C.

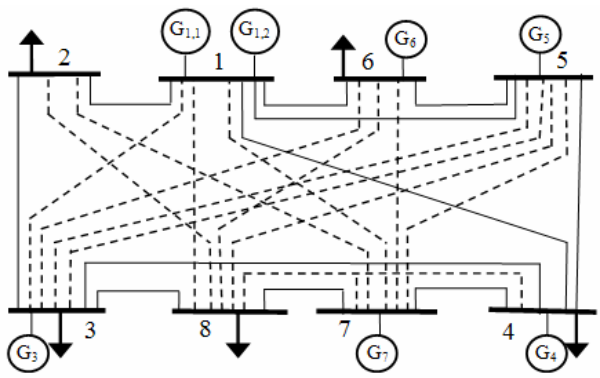

Fig. 7. The diagram of the 8-bus system.

To consider possible expansion plans, it is assumed that it is possible to add up to three new circuits to the original network so that each new circuit is similar to one of the existing or new lines. Thus 2600 expansion plans are obtained; which were sorted in ascending order of their investment cost. Thereafter each plan is evaluated in its turn from view point of satisfying market-based criteria.

Now, the optimum expansion plan will be searched within the following three cases.

Case 1: In this case, the membership function of each uncertainty (bid of a producer or consumer) has been selected so that each uncertainty will change up to ±10 percent of its predicted value. Fig. 8(a) shows the membership function of each uncertainty for this case. Although the membership function of the *SWP* and the *CCP* have been selected so that strict conditions will be prepared to support competition in the market. Figs. 9(a) and 10(a) show the membership functions of the *SWP* and the *CCP* respectively.

Case 2: In this case, the membership function of each uncertainty has been selected like case 1, but the *SWP* and the *CCP* have been considered less strict compared to case 1. Fig. 8(a) shows the membership function of each uncertainty and Figs. 9(b) and 10(b) show the membership functions of the *SWP* and the *CCP* respectively for this case.

Case 3: In this case, the membership function of each uncertainty has been selected so that each uncertainty will change up to ±20 percent of its predicted value. Fig. 8(b)

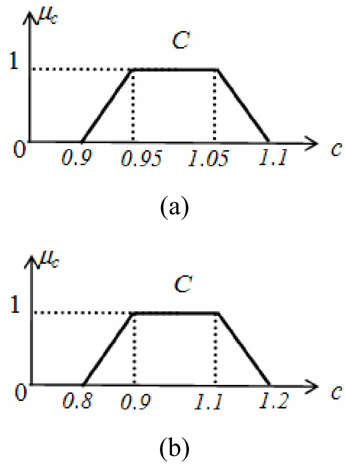

Fig. 8. The membership function of each uncertainty (bid of each producer or consumer): (a) for cases 1 and 2; (b) for case 3.

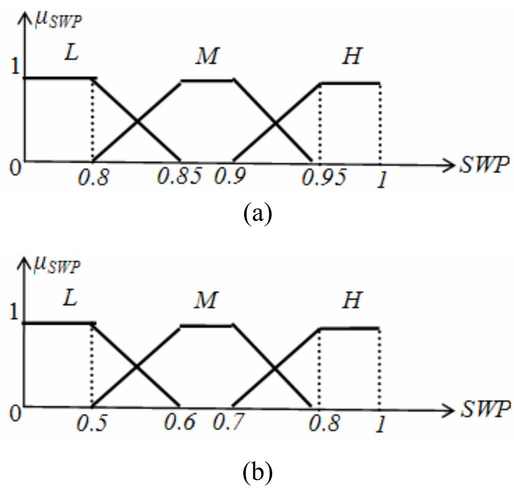

Fig. 9. The membership functions of the Low, Medium and High for variable *SWP*: (a) for case 1; (b) for cases 2 and 3.

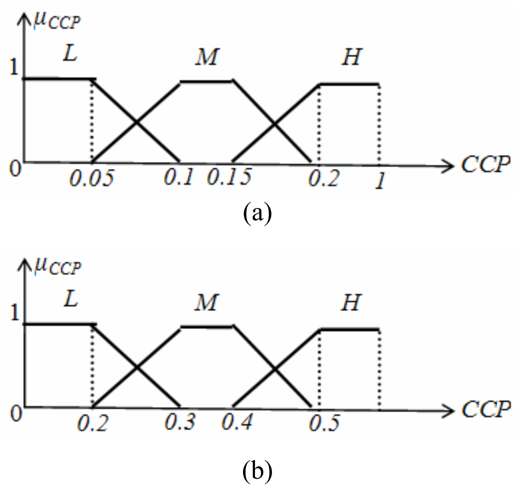

Fig. 10. The membership functions of the Low, Medium and High for variable *CCP*: (a) for case 1; (b) for cases 2 and 3.

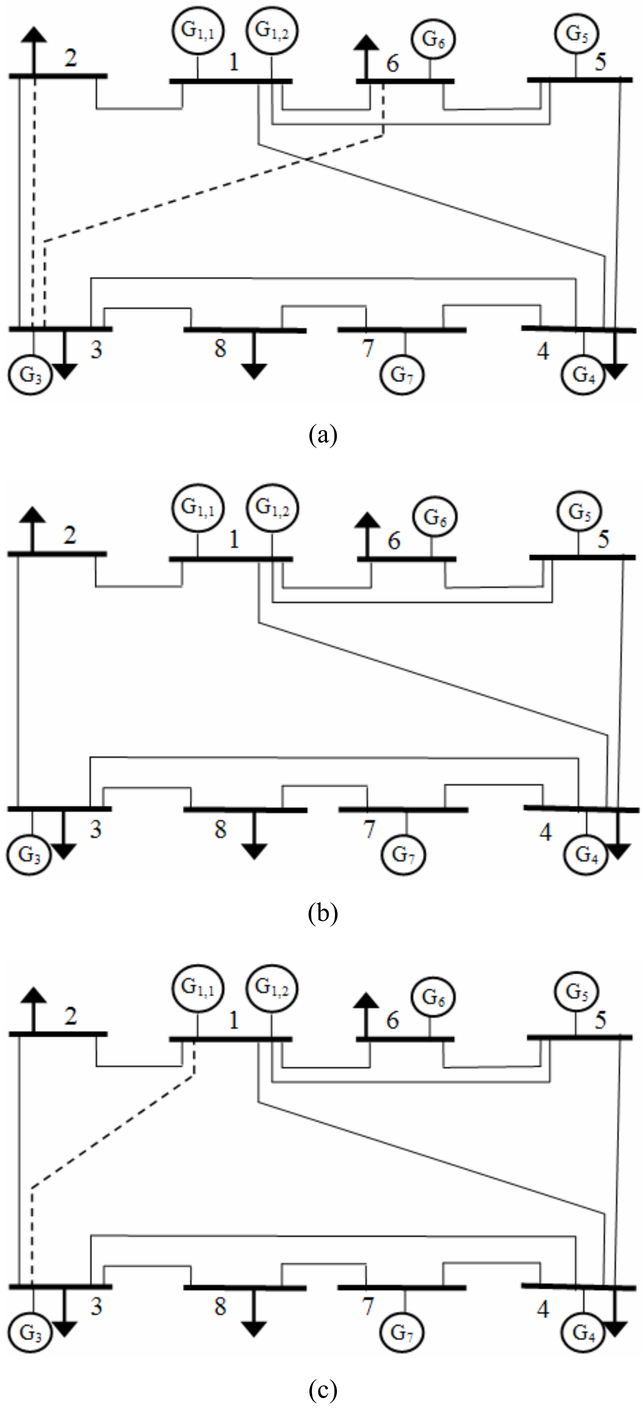

Fig. 11. The diagram of the obtained optimum expansion plans for (a) case 1, (b) case 2 and (b) case 3.

shows the membership function of each uncertainty for this case. But the membership functions of the SWP and the CCP have been considered like case 2 (less strict). Figs. 9(b) and 10(b) show the membership functions of the *SWP* and the *CCP* respectively.

The obtained optimum expansion plans in the three cases are given in Table 2 and shown in Fig. 11. The results in Table 2 show that the optimal expansion plan in case 1, where the strict conditions are considered, has two new circuits on lines 4 (between buses 2 and 3) and 21 (between buses 6 and 3) with investment cost 0.32 per unit; But in case 2, where the less strict conditions are considered, the optimal expansion plan has no new circuits (the original network) and its investment cost has been reduced to zero. Although the competitiveness conditions in case 3 are still less strict as the ones in case 2, but because the interval of the uncertainty changes has grown, the optimal expansion plan in case 2 includes just one circuit on line 12 (between buses 1 and 3) which led to an increase in the investment cost of the optimal plan with respect to case 2, raising it up to 0.15 per unit. Thus the investment cost of optimal plan has been increased by increasing the interval of the uncertainty changes or by increasing the limits of acceptable competitiveness.

The last row of table 2 shows the order number of the optimum plan among the list of the sorted plans. Note that the number of studied plans is quite low in all the three cases.

Table 2. The parameters and optimum expansion plan for three cases of the network of the 8-bus power system

Case	1	2	3
Optimum Plan	$N_{2,3}$=1& $N_{6,3}$=1	Original Network	$N_{1,3}$=1
Investment Cost of Optimum Plan	0.32	0	0.15
Investment Plan Order Number	52	1	5

8. Conclusions

In this paper, first it was shown that none of the criteria: the total congestion cost of the transmission network (CC), Standard deviation of the LMPs (σ), Lerner index (LI), and maximum social welfare (SW), alone is able to completely and truly evaluate the transmission network expansion, from market view. But CC and SW criteria together can appropriately and truly evaluate transmission network from market view and so they are proposed for the market-based transmission expansion planning. To simply indicate the limits of CC and SW, the social welfare percentage (SWP) and congestion cost percentage (CCP) were defined. Then by defining fuzzy sets for the bids of market participants, SWP, CCP and the occurrence possibility of each scenario of the bids and by defining a fuzzy rule base, we could successfully evaluate the acceptability of each expansion plan. So the least-investment-cost expansion plan, which is acceptable in all probable scenarios, was searched and introduced as optimal plan. The results of applying the proposed method to a typical 8-bus and 23-line power system were illustrated.

Appendix

A. details of the market-based criteria calculation for the 3-bus example system

According to the reference [3], Definitions of σ and CC are as flows:

$$\sigma = \sqrt{\frac{1}{Nb-1}\sum_{i=1}^{Nb}(LMP_i - LMP_{av})^2} \tag{6}$$

$$CC = \sum_{k=1}^{Nl}(LMP_{k1} - LMP_{k2})P_{k2,k1} \tag{7}$$

Where σ is the standard deviation of the LMPs of the buses; LMP_i is the locational marginal price of bus i; LMP_{av} is the average of the LMPs of all buses and Nb is the number of the buses of the network. CC is the total congestion cost of all lines; indexes $k1$ and $k2$ are the numbers of the end buses of line k. $P_{k2,\,k1}$ is the transmitted power of line k from bus $k2$ to bus $k1$; and Nl is the total number of lines of the network.

According to the definition of [6], the Lerner index is defined by Eq. (8):

$$LI = \frac{LMP_{av} - LMP_{uncong}}{LMP_{av}} \tag{8}$$

where LI is the Lerner index; LMP_{av} is the average of the locational marginal prices of all buses and LMP_{uncong} is the LMPs of all buses while there is no congestion or in other words while the capacity of the lines are unlimited.

SWP is obtained by Eq. (1) after solving the optimal power flow stated in appendix A of [28] and calculating the generation and load powers.

The values of the bids of generators (C_{G1}, C_{G2}, and C_{G3}) and the bid of the load (C_{D3}) are:

$$C_{G1} = 11 \quad C_{G2} = 12 \quad C_{G3} = 13 \quad C_{D3} = 13$$

Table 3. The values of the powers and LMPs for the seven expansion cases of the network of the 3-bus system

Case	P_{G1}	P_{G2}	P_{G3}	LMP_1	LMP_2	LMP_3	LMP_{av}	$P_{line1,3}$	$P_{line2,3}$
1	100	100	100	11	12	13	12	100	100
2	100	200	0	11	12	13	12	100	200
3	200	100	0	11	12	13	12	200	100
4	200	100	0	11	12	12	11.667	200	100
5	100	200	0	11	12	12	11.667	100	200
6	300	0	0	11	12	12	11.667	300	0
7	300	0	0	11	11	11	11	300	0

Table 3 gives the values of generation powers of generators (P_{G1}, P_{G2} and P_{G3}), locational marginal prices of the buses (LMP_1, LMP_2 and LMP_3), the average of the locational marginal prices of all buses (LMP_{av}) and the transmitted power of the lines ($P_{line1,3}$ and $P_{line2,3}$) in each case of the seven discussed cases of the 3-bus simple example in section 2. Essentially, these values are calculated by solving the optimal power flow stated in appendix A of [28] but for this simple example these values can be determined evidently. The LMP of each bus can be evidently determined by this definition that it equals the cost of supplying next MW of load at that bus.

The load value of bus 3 (P_{D3}) is 300 MW at all the seven cases.

In the ideal network where the capacity of lines are assumed unlimited, there is no congestion cost and LMPs of all buses are the same. In this case, the generation powers of the generators, the load power and the LMPs of the buses are as follows:

$$LMP_1^{Id} = LMP_2^{Id} = LMP_3^{Id} = LMP_{uncong} = 11$$

$$P_{G1}^{Id} = 300 \quad P_{G2}^{Id} = P_{G3}^{Id} = 0 \quad P_{D3}^{Id} = 300$$

Now by aforementioned data, σ, *LI* and *SWP* for the seven cases can be calculated. The results are given in table 1.

B. Simulated annealing algorithm

The simulated annealing algorithm is summarized below [21]:

Step 1. Select an initial solution x_0 in the solution space X and set the iteration counter *ITC* at zero.

Step 2. Evaluate x_0 computing the evaluation function f(x_0).

Step 3. Assign x_0 to x_{opt} and $f(x_0)$ to $f(x_{opt})$. The index opt denotes the best solution identified so far.

Step 4. Sample a new solution in neighborhood of the current solution at iteration *ITC*, and compute the evaluation function $f(x_{ITC})$.

Step 5. Testing

a) If $f(x) \le f(x_{ITC})$ then assign *x* to x_{ITC}.

b) If $f(x) \le f(x_{opt})$, then assign *x* to x_{opt} and $f(x)$ to $f(x_{opt})$.

c) Else, get a random number *rp* in *[0, 1]* and compute the probability of accepting worse solutions at iteration *ITC* by (9):

$$rp(ITC) = \exp\left(\frac{f(x_{ITC}) - f(x)}{T}\right) \quad (9)$$

where: *T* is the control parameter that is called system temperature in analogy with the original application of annealing.

d) if $rp \le rp(ITC)$, assign *x* to x_{ITC+1}.

Step 6. End if a stopping rule is reached; otherwise, let *ITC= ITC+1* and go back to step 4.

Along the algorithm, the temperature (*T*) is lowered in a slow pace. Usually, the temperature evolves by levels, meaning that each one is used during a fixed number of iterations. After that, the temperature is lowered by a coefficient α, which is inferior but usually close to 1.0.

C. Characteristics of the typical 8-bus power system

The characteristics of the transmission lines, generators, and loads of the 8-bus system are given in tables 4, 5 and 6. It has to be mentioned that lines 1 to 11 are the lines of the original system and lines 12 to 23 are the new lines which may be constructed. The investment cost of each circuit is considered proportional to its capacity. The base for the powers is 1000 MW.

Table 4. Line specifications of the 8-bus power system

Line Num.	From bus	To Bus	Reactance (P.U.)	Capacity (MW)	Investment Cost (P.U.)
1	1	2	0.030	280	0.28
2	1	4	0.030	140	0.14
3	1	5	0.0065	380	0.38
4	2	3	0.010	120	0.12
5	3	4	0.030	230	0.23
6	4	5	0.030	200	0.20
7	5	6	0.020	300	0.30
8	6	1	0.025	250	0.25
9	7	4	0.015	250	0.25
10	7	8	0.022	340	0.34
11	8	3	0.018	240	0.24
12	1	3	0.013	150	0.15
13	1	7	0.0135	160	0.16
14	1	8	0.014	160	0.16
15	2	7	0.010	120	0.12
16	2	8	0.018	200	0.20
17	4	8	0.030	200	0.20
18	5	3	0.015	150	0.15
19	5	7	0.030	350	0.35
20	5	8	0.025	280	0.28
21	6	3	0.018	200	0.20
22	6	7	0.020	230	0.23
23	6	8	0.017	190	0.19

Table 5. Generator specifications of the 8-bus power system

Gen. Num.	Bus Num.	Min. Gen. (MW)	Max. Gen. (MW)	Bid ($/MWh)
1,1	1	0	110	14
1,2	1	0	100	15
3	3	0	520	25
4	4	0	250	30
5	5	0	600	10
6	6	0	400	20
7	7	0	200	20

Table 6. Load specifications of the 8-bus power system

Bus Num.	Min. Dem. (MW)	Max. Dem. (MW)	Bid ($/MWh)
2	0	300	30
3	0	300	32
4	0	300	35
6	0	250	28
8	0	250	35

References

[1] M.O. Buygi, H. M. Shanechi, G. Balzer, M. Shahidehpour, "Transmission Planning Approaches in Restructured Power Systems", in 2003 IEEE Power Tech Conference Proceedings, Bologna, Italy, June 2003; Vol. 2.

[2] F.F. Wu, F.L. Zheng, F.S. Wen, "Transmission investment and expansion planning in a restructured electricity market", Energy, Vol. 31, Issues 6-7, pp. 954-966, 2006.

[3] M.O. Buygi, G. Balzer, H.M. Shanechi, M. Shahidehpour, "Market-based transmission expansion planning", IEEE Transactions on Power Systems, Vol. 19, Issue 4, pp. 2060-2067, Nov. 2004.

[4] R. Fang, D.J. Hill, "A new strategy for transmission expansion in competitive electricity markets", IEEE Trans. Power Syst., Vol. 18, Issue 1, pp. 374-380, 2003.

[5] R. Fu, P. Wei, Y. Sun, G. Tang, "A new congestion monitoring index constrained multistage transmission expansion planning under market environment", Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT 2008), Nanjuing, 6-9 April 2008; 978-983.

[6] P. Wei, R. Fu, Y.P. Lu, Q.L. Wang, L. Wang, Y. Li and G.Q. Tang, "Congestion-based model for transmission expansion planning", 2006 IEEE Power Engineering Society General Meeting, Montreal, Que., 2006.

[7] R. Fu, P. Wei, G. Jiang, X. Zhou, Q. Wan, G. Tang. "New market power driven multistage transmission expansion strategy in power markets", 2006 IEEE Power Engineering Society General Meeting, Montreal, Que., 2006.

[8] M. Lu, Z. Lu, Z.Y. Dong, T.K. Saha, "A Novel approach to evaluate congestion for composite power system planning in a competitive electricity market", 2006 IEEE Power Engineering Society General Meeting, Montreal, Que., 2006.

[9] M.O. Buygi, M. Shahidehpour, H.M. Shanechi, G. Balzer, "Market Based Transmission Planning Under Uncertainties", in Int. Conf. on Probabilistic Methods to Power Systems, Iowa State University, Iowa, Sept 2004, pp. 563-568.

[10] M.O. Buygi, G. Balzer, H.M. Shanechi, Shahidehpour M., "Market Based Transmission Expansion Planning: Fuzzy Risk Assessment", Proc. of IEEE Int. Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004), Hong Kong, April 2004, pp. 427-432.

[11] M.O. Buygi, G. Balzer, H.M. Shanechi, Shahidehpour M., "Market Based Transmission Expansion Planning: Stakeholders' Desires", Proc. of IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004), Hong Kong, April 2004, pp. 433-438.

[12] L.P. Garces, A.J. Conejo, R. Garcia-Bertrand, R. Romero, "A Bilevel Approach to Transmission Expansion Planning Within a Market Environment", IEEE Transactions on Power Systems, Vol. 24, Issue 3, pp. 1513-1522, Aug. 2009.

[13] S. De la Torre, A.J. Conejo, J. Contreras, "Transmission Expansion Planning in Electricity Markets", IEEE Transactions on Power Systems, Vol. 23, Issue 1, pp. 238-248, Feb. 2008.

[14] P. Maghouli, S.H. Hosseini, M.O. Buygi, M. Shahidehpour, "A Multi-Objective Framework for Transmission Expansion Planning in Deregulated Environments", IEEE Trans. on Power Systems, Vol. 24, Issue 2, pp. 1051-1061, May 2009.

[15] G.R. Kamyab, M. Fotuhi-Firuzabad, and M. Rashidinejad, "Transmission Expansion Planning In Restructured Power systems Considering Investment Cost and n-1 Reliability", J. of Applied Sciences, Vol. 8, Issue 23, pp. 1-9, 2008.

[16] J. H. Roh, M. Shahidehpour, L. Wu, "Market-Based Generation and Transmission Planning With Uncertainties", IEEE Transaction on Power Systems, Vol. 24, Issue 3, pp. 1587-1598, Aug. 2009.

[17] J. H. Zhao, Z. Y. Dong, P. Lindsay, K. P. Wong, "Flexible Transmission Expansion Planning With Uncertainties in an Electricity Market", IEEE Transactions on Power Systems, Vol. 24, Issue 1, pp. 479-488, Feb. 2009.

[18] J. H. Roh, M. Shahidehpour, Y. Fu, "Market-Based Coordination of Transmission and Generation Capacity Planning", IEEE Transactions on Power Systems, Vol. 22, Issue 4, pp. 1406-1419, Nov. 2007.

[19] M.S. Kandil, S.M. EL-Debeiky, N.E. Hasanien, "A Hybrid Mathematical and Rule-Based System for Transmission Network Planning in a Deregulated Environment", in Proceeding of Power Engineering Society Summer Meeting, July 2001; Vol.3, pp. 1451-1456.

[20] A. Orths, A. Schmitt, Z.A. Styczynski, J. Verstege, "Multi-criteria optimization methods for planning and operation of electrical energy systems", Electrical Engineering, 83, pp. 251-258, 2001.

[21] A.S.D. Braga, J.T. and Saraiva, "A multiyear dynamic approach for transmission expansion planning and long-term marginal costs computation", IEEE Trans. on Power Systems, Vol. 20, Issue 3, pp. 1631-1639, 2005.

[22] D. Kavitha, and K.S. Swarup, "Transmission Expansion Planning using LP-Based Particle Swarm Optimization", in Power India Conference, IEEE, April 2006.

[23] G.B. Shrestha, and P.A.J. Fonseka, "Congestion-driven transmission expansion in competitive power markets", IEEE Trans. on Power Systems, Vol. 19,

Issue 3, pp. 1658-1665, 2004.
[24] J. Choi, A.A. El-Keib, and T. Tran, "A fuzzy branch and bound-based transmission system expansion planning for the highest satisfaction level of the decision maker". IEEE Transactions on Power Systems, Vol. 20, Issue 1, pp. 476-484, 2005.
[25] J. Choi, T. Tran, A.A. El-Keib, R. Thomas, HyungSeon, Oh., and Billinton, R., "A method for transmission system expansion planning considering probabilistic reliability criteria". IEEE Transactions on Power Systems, Vol. 20, issue 3, pp. 1606-1615, 2005.
[26] S.R. Dahman, D.J. Morrow, K. Tynes, J.D. Weber, "Advanced Sensitivity Analysis for Long-Range Transmission Expansion Planning". Hawaii Imitational Conference on System Sciences, Proc. of the 41st Annual, Jan. 2008, pp. 166-166.
[27] M. Oloomi-Buygi, "Transmission Expansion planning in Deregulated Power Systems", PH.D. Thesis, TU Darmstadt, 2004.
[28] G.R. Kamyab, M. Fotuhi-Firuzabad, and M. Rashidi-Nejad, "Market Based Criteria for Transmission Expansion planning", in 2010 IEEE Int. Conf. on Power and Energy (PECON 2010), Kuala Lumpur, Malaysia, Nov 29-Dec.1 2010, pp. 846-851.

Gholam-Reza Kamyab He received his B.S. degree in electrical engineering from the Ferdowsi University of the Mashhad, Iran, in 1994 and M.S. degree in electrical engineering from the Tarbiat-Moderas University of the Tehran, Iran, in 1997. He is now a PhD. Student at the Department of Electrical Engineering, Islamic Azad University Science and Research Branch, Tehran, Iran; and he is now with Islamic Azad University Gonabad Branch. His research interest is power system planning.

Mahmood Fotuhi-Firuzabad He (IEEE Senior Member, 99) Obtained B.Sc. and M.Sc. Degrees in Electrical Engineering from Sharif University of Technology and Tehran University in 1986 and 1989 respectively and M.Sc. and Ph.D. Degrees in Electrical Engineering from the University of Saskatchewan, Canada, in 1993 and 1997 respectively. Dr. Fotuhi-Firuzabad worked as a postdoctoral fellow in the Department of Electrical Engineering, University of Saskatchewan from Jan. 1998 to Sept. 2000 and from Sept. 2001 to Sept. 2002 where he conducted research in the area of power system reliability. He worked as an assistant professor in the same department from Sept. 2000 to Sept. 2001. Presently he is a full professor and Head of the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran. Dr. Fotuhi-Firuzabad is a member of center of excellence in power system control and management in the same department.

Masoud. Rashidinejad He received his B.S. degree in Electrical Engineering and. M.S. degree in Systems Engineering Isfahan University of Technology, Iran. He received his PhD in Electrical Eng. from Brunel University, London, UK, 2000. He is currently associated professor at Electrical Eng. Dept., Shahid Bahonar University of Kerman, Kerman, Iran. His area of interests is power system optimization, Distribution networks, electricity restructuring and energy management.