FUZZY CONGESTION-DRIVEN AND SENSITIVITY ANALYSIS BASED HEURISTIC TRANSMISSION EXPANSION PLANNING METHOD

Min XIE   **Jinfu CHEN**   **Xianzhong DUAN**

The School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, Hubei, China, 430074

Email: xiemin_hust@163.com

ABSTRACT

Transmission expansion planning provides an essential measure for long-term congestion management. Congestion-driven planning method becomes one of the new challenges under deregulated environment. With POOL transaction pattern being the basic investigation background, the fuzzy congestion management models for bilateral auction market mode and single-buyer market mode are set up first in this paper. The soft constraints of line power flow limits, and market participants' bidding curve coefficients considering possible strategic bidding, are all described in form of fuzzy membership functions. Second, based on the maximum membership rule and maximum entropy principle, the fuzzy optimal congestion management problem is solved. New sensitivity indexes to select to-be-built or to-be-upgraded lines are defined for the two market modes respectively. They describe the compromise between congestion relieving impact and investments, and make the problem of transmission network planning solved fast, simple and heuristic. Test results illustrates that the fuzzy congestion-driven and sensitivity analysis based heuristic transmission network planning method for POOL transaction pattern presented by this paper is robust and practical under the deregulated environment.

Keywords: Congestion managemen, Heuristic transmission expansion planning, Electricity markets, Fuzzy set theory, Maximum entropy principle.

1. INTRODUCTION

With power system deregulation underway, transmission network will be used in ways different from originally planned or historically used. New transmission bottle neck will be created. Congestion becomes one of the outstanding problems for transmission planning and operation [1]. How to relieve transmission congestion effectively and economically is a hot topic in the field of electricity markets [2]. Generally speaking, there are short-term and long-term congestion relieving problems. Short-term congestion problem mainly relates to transmission short-term operation, while network planning provides an essential measure to relieve

long-term congestion and maintain system reliability [3]. This paper deals with the long-term congestion problem, and integrated it into transmission network planning, as is called congestion-driven transmission expansion planning.

As the concept of congestion-driven transmission network planning is proposed by [4], the research in this field is underway. The long-term transmission expansion problem in [4] is decoupled into the master problem of investment and the operational problem which gives network congestion level as the driving signal for the need of network expansion. The congestion cost and congestion revenue are used to describe the network congestion level, and Benders decomposition method is used to solve this planning problem. But the operational problem of congestion management does not consider any uncertainties and how to decide the acceptable congestion level is still under disputed. Ref. [5] uses heuristic algorithm, and presents the Average Total Congestion Cost as sensitivity index to describe the effect of network upgrade on congestion relieving, while the investment of network upgrade is not considered. Ref. [6] uses fuzzy numbers to describe price fluctuation, load growth and line investment uncertainties. But heavy computation is needed in the process of solving by transforming single-objective optimization problem into multi-objective one.

From the above, there are still some deficiencies to overcome in the existing achievement of the research on congestion-driven transmission expansion planning. With POOL transaction pattern being the basic investigation background, the fuzzy congestion management models for bilateral auction market mode and single-buyer market mode are set up first in this paper. The soft constraints of line power flow limits, and market participants' bidding curve coefficients considering possible strategic bidding, are all described in form of fuzzy membership functions. Second, based on the maximum membership rule and maximum entropy principle, the fuzzy optimal congestion management problem is solved. New sensitivity indexes to select to-be-built or to-be-upgraded lines are defined for the two transaction modes respectively. They describe the compromise between congestion cost and investments, and make the problem of transmission network planning solved fast, simple and heuristic. Test

results illustrates that the fuzzy congestion-driven and sensitivity analysis based heuristic transmission network planning method for POOL transaction pattern presented by this paper is robustic and practical under the deregulated environment.

2. FUZZY OPTIMAL CONGESTION MANAGEMENT MODEL AND SOLVING METHOD

In the POOL transaction pattern, generation companies (maybe also customers) provide pricing curves and take part in bidding. ISO (Independent System Operator) determines the dispatching result to meet the demand requirement and relieve transmission congestion. Generally speaking, there are two kinds of market modes in POOL pattern: bilateral auction market mode and single-buyer market mode. And each market mode corresponds to a certain congestion management model.

2.1 FUZZY OPTIMAL COGESTION MANAGEMENT MODEL

2.1.1 BILATERAL AUCTION MARKET MODE

In this market mode, generation companies and customers both take part in bidding. With the objective of maximum social benefits (that is to say, getting as much load benefits as possible by costing as little generation cost as possible), the accurate model of congestion management can be described with DC (Direct Current) based OPF (Optimal Power Flow) model, which is given as following:

a. Objective function

$$\min\{TC - TB\}$$

where, $TC = \sum_{i=1}^{N_g} C_i(x_{gi})$,

$$TB = \sum_{j-1}^{N_d} B_j(x_{dj})$$,

b. Units generation restraints

$$\underline{PG} \le X_g \le \overline{PG}$$

c. Power flow limits in lines

$$-\overline{PL} \le PL \le \overline{PL}$$

Min XIE, Jinfu CHEN, Xianzhong DUAN

d. Load power restrains

$$\underline{D} \le X_d \le \overline{D}$$

e. System power balance restraints

$$\sum_{i=1}^{N_g} x_{gi} = \sum_{j=1}^{N_d} x_{dj}$$

Where, TC is the total generation cost of the whole system; TB is the total load benefit of the whole system ; x_{gi}、x_{dj} stands for the active power of unit i and load j respectively ; $C_i(x_{gi})$ denotes the bidding cost function of unit i , and $B_j(x_{dj})$ is the bidding benefit function of load j . They are both described in quadratic forms, and C_2, C_1, B_2, B_1 are the corresponding constant coefficients. With X_g being unit active power vector, and X_d being load power vector, then

$$TC = X_g^{\ T} \cdot C_2 \cdot X_g + C_1^{\ T} \cdot X_g$$
$$TB = X_d^{\ T} \cdot B_2 \cdot X_d + B_1^{\ T} \cdot X_d \tag{1}$$

Moreover , N_g denotes the number of system units, N_d the number of customers and N_l the number of lines ; PL and $\overline{PL}$ are line power flow vector and its limits vector ; $\overline{PG}$ and $\underline{PG}$ are the unit output limits vectors ; $\underline{D}$ and $\overline{D}$ are load power limits vectors.

Based on DC power flow method, and with $X = \begin{bmatrix} X_g^{\ T} & X_d^{\ T} \end{bmatrix}^T$ being controls vector, the congestion model presented in formula a-e can be transferred into the following:

$$\min \left\{ X^T \cdot A_2 \cdot X^T + A_1^T \cdot X \right\}$$
$$\underline{X} \le X \le \overline{X} \tag{2}$$
$$s.t. \quad -\overline{PL} \le W \cdot X \le \overline{PL}$$
$$\begin{bmatrix} \delta_g & -\delta_d \end{bmatrix} \cdot X = 0$$

Where $A_2 = \begin{bmatrix} C_2^T & -B_2^T \end{bmatrix}^T$, $A_1 = \begin{bmatrix} C_1^T & -B_1^T \end{bmatrix}^T$, $\underline{X} = \begin{bmatrix} \underline{PG}^T & \underline{D}^T \end{bmatrix}^T$, $\overline{X} = \begin{bmatrix} \overline{PG}^T & \overline{D}^T \end{bmatrix}^T$,

$$W = BL \cdot E^T \cdot Y^{-1} \cdot \begin{bmatrix} \varepsilon_g & 0 \\ 0 & -\varepsilon_d \end{bmatrix} ,\ \varepsilon_g \text{ is the}$$

identity matrix of $N_g \times N_g$; ε_d is also an identity matrix but of $N_d \times N_d$; $\delta_g = (1,1,...1)_{1 \times N_g}$, $\delta_d = (1,1,...1)_{1 \times N_d}$; BL denotes the diagonal matrix of branch admittances; E denotes network conjunction matrix ; and Y is the imaginary part of bus admittance matrix。

In real power system, it's acceptable that line power flow can overstep its limits slightly. And market participants (generation companies and customers) may take strategic bidding to maximize their own benefits. That is to say, line power flow limits and market participants' bidding curves (formulated in (1)) both have fuzzy characteristics. Then triangle fuzzy membership function (illustrated in Fig.1(a)) are used here to describe the line power flow limits and market participants bidding curve coefficients C_2, C_1, B_2, B_1. Based on Equ. (2) and using $\overline{\mu_l}$、μ_{C2}、μ_{C1}、μ_{B2}、μ_{B1} to stand for corresponding fuzzy membership functions, the fuzzy optimal congestion management model for bilateral auction market can be formulated as following:

$$\min \left\{ X^T \cdot (\mu_{A_2} A_2) \cdot X^T + (\mu_{A_1} A_1) \cdot X \right\} \le f_{exp}$$
$$\underline{X} \le X \le \overline{X} \tag{3}$$
$$s.t. \quad -\text{diag}(\overline{\mu_l}) \cdot \overline{PL} \le W \cdot X \le \text{diag}(\overline{\mu_l}) \cdot \overline{PL}$$
$$\begin{bmatrix} \delta_g & -\delta_d \end{bmatrix} \cdot X = 0$$

where

$$(\mu_{A_2} A_2) = \left[\left(\text{diag}(\mu_{C_2})C_2 \right)^T \quad -\left(\text{diag}(\mu_{B_2})B_2 \right)^T \right]^T,$$
$$(\mu_{A_1} A_1) = \left[\left(\text{diag}(\mu_{C_1})C_1 \right)^T \quad -\left(\text{diag}(\mu_{B_1})B_1 \right)^T \right]^T$$

$\text{diag}()$ denotes diagonal matrix ; f_{exp} is the expected value of objective function , which can be determined by tentative calculation.

Also using fuzzy membership function (illustrated in Fig.1 (b)) to describe the fuzzy feature of the objective value, then fuzzy

Min XIE, Jinfu CHEN, Xianzhong DUAN

membership function μ_f can be formulated as Equ. (4).

$$\mu_f = \begin{cases} 1 & f \le f_{exp} \\ (\dfrac{f_{exp}+df-f}{df})^k & f_{exp} \le f \le f_{exp}+df \\ 0 & f > f_{exp}+df \end{cases} \quad (4)$$

Where, $k > 0$, $df > 0$。

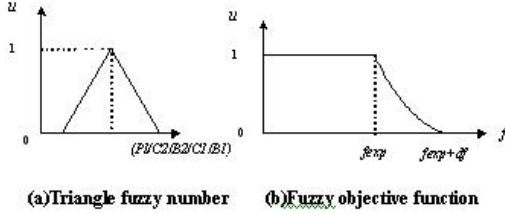(a)Triangle fuzzy number   (b)Fuzzy objective function

Figure 1. Fuzzy membership curves

2.1.2 SINGLE-BUYER MARKET MODE

In this market mode, only generation companies take part in bidding, and it can be regarded as a special case of bilateral auction market mode. The objective of optimal congestion management is to minimize generation costs. Similar to the model of Equ. (3), the fuzzy congestion management model can be formulated as following:

$$\min\{X_g^T \cdot (\text{diag}(\mu_{C_2}) \cdot C_2) \cdot X_g + (\text{diag}(\mu_{C_1}) \cdot C_1) \cdot X_g\} \le f_{exp}$$
$$\underline{PG} \le X_g \le \overline{PG} \qquad (5)$$
$$s.t. \quad (\mu Z_2) \le W \cdot X_g \le (\mu Z_1)$$
$$\delta_g \cdot X_g = \delta_d \cdot D$$

Where

$(\mu Z_1) = \text{diag}(\overline{\mu_l}) \cdot \overline{PL} + BL \cdot E^T \cdot B^{-1} \cdot D$ and

$(\mu Z_2) = -\text{diag}(\overline{\mu_l}) \cdot \overline{PL} + BL \cdot E^T \cdot B^{-1} \cdot D$

D is the load vector which is constant; and the unit active power vector X_g is controls variable.

2.2 SOLVING METHOD BASED ON MAXIMUM ENTROPY PRINCIPLE

By integrating the fuzzy objective and fuzzy constraints, fuzzy decision-making can be regarded as their intersection. Then the fuzzy decision-making membership function $\mu(X)$ is formulated as:

$$\mu(X)=\mu_f(X) \wedge \overline{\mu_l}(X) \wedge \mu_{C_2}(X) \wedge \mu_{C_1}(X) \wedge \mu_{B_2}(X) \wedge \mu_{B_1}(X)$$

where $\mu_{C_2}(X)=\mu_{C_{21}}(X) \wedge ... \wedge \mu_{C_{2N_g}}(X)$, and the expression of $\overline{\mu_l}$、μ_{C1}、μ_{B2}、μ_{B1} are similar with μ_{C_2}.

Based on the maximum membership function principle, and using the optimization idea of [7] for reference, the fuzzy optimal congestion management model (described in Equ.(3)) of bilateral auction market mode is transformed into the following form:

$$\max \mu(X) = \bigvee_X \left[\mu_f \wedge \overline{\mu_l} \wedge \mu_{C_2} \wedge \mu_{C_1} \wedge \mu_{B_2} \wedge \mu_{B_1} \right]$$
$$= \max_X \left\{ \min_X \left[\mu_f, \overline{\mu_l}, \mu_{C_2}, \mu_{C_1}, \mu_{B_2}, \mu_{B_1} \right] \right\}$$
$$\triangleq \min_X \left\{ \max_X \left[-\mu_f, -\overline{\mu_l}, -\mu_{C_2}, -\mu_{C_1}, -\mu_{B_2}, -\mu_{B_1} \right] \right\}$$
$$s.t. \quad \underline{X} \le X \le \overline{X}$$
$$-\overline{PL} \le W \cdot X \le \overline{PL}$$
$$\left[\delta_g \quad -\delta_d \right] \cdot X = 0$$

$$(6)$$

Similarly, the fuzzy congestion management model (presented as Equ.(6)) of single-buyer market mode can be transformed into the form of Equ. (7).

$$\min_X \left\{ \max_X \left[-\mu_f, -\overline{\mu_l}, -\mu_{C_2}, -\mu_{C_1}, -\mu_{B_2}, -\mu_{B_1} \right] \right\}$$
$$s.t. \quad \underline{PG} \le X_g \le \overline{PG}$$
$$Z_2 \le W \cdot X_g \le Z_1$$
$$\delta_g \cdot X_g = \delta_d \cdot D$$

$$(7)$$

Obviously, Equ.(6) and Equ.(7) are non-differential minimax optimization problems., which are always transformed into constrained nonlinear optimization problems, and its solving procedure is laborious. However, maximum Entropy principle introduced by [8] provides a very simple and fast method to solve this kind of non-differential minimax optimization problems.

2.2.1 MAXIMUM ENTROPY PRINCIPLE

The non-differential optimization problem is described as

$$\min_X \left\{ \max_{1 \le i \le m} \left[f_i(x) \right] \right\}$$
$$s.t. \quad g_j(x) \le 0 \qquad 1 \le j \le m_l$$

$$(8)$$

Min XIE, Jinfu CHEN, Xianzhong DUAN

Use $\varphi(x)$ as the maximum entropy function, and

$$\varphi(x) = \frac{1}{p}\ln\left(\sum_{i=1}^{m} e^{pf_i(x)}\right) + \frac{\alpha}{q}\ln\left(1 + \sum_{j=1}^{m_l} e^{qg_j(x)}\right)$$

Then, the non-differential optimization problem of Equ. (8) can be transformed into the following non-constrained optimization problem:

$$\min_X \varphi(x) = \min_X\left(\frac{1}{p}\ln\left(\sum_{i=1}^{m} e^{pf_i(x)}\right) + \frac{\alpha}{q}\ln\left(1 + \sum_{j=1}^{m_l} e^{qg_j(x)}\right)\right)$$

Where, p, q, α are constants and when $p, q \to \infty$, the above model can get the optimal results with enough precision. In this paper, $p = 1000, q = 1000, \alpha = 10$.

2.2.2 MAXIMUM ENTROPY FUNCTION OF FUZZY OPTIMAL CONGESTION MANAGEMENT MODELS
a. Bilateral Auction Market

$$\varphi(x) = \frac{1}{p}\ln\left(e^{\mu_f(X)} + \sum_{i}^{N_l} e^{\overline{\mu}_{l,i}(x)} + \sum_{j=1}^{N_g}(e^{\mu_{C_2,j}(x)} + e^{\mu_{C_1,j}(x)}) + \sum_{k=1}^{N_d}(e^{\mu_{B_2,k}(x)} + e^{\mu_{B_1,k}(x)})\right)$$
$$+ \frac{\alpha}{q}\ln\left(1 + \sum_{l=1}^{N_g+N_d}\left(e^{q(\underline{x}_l - x_l)} + e^{q(\overline{x}_l - x_l)}\right) + \sum_{l=1}^{N_l}\left(e^{q(\sum_{m=1}^{N_g+N_d} w_{lm}x_m - \overline{PL_l})} + e^{q(\sum_{m=1}^{N_g+N_d} -\overline{PL_l} - w_{lm}x_m)}\right)\right)$$

(9)

b. Single-Buyer Market

$$\varphi(x) = \frac{1}{p}\ln\left(e^{\mu_f(X)} + \sum_{i}^{N_l} e^{\overline{\mu}_{l,i}(x)} + \sum_{j=1}^{N_d}(e^{\mu_{C_2,j}(x)} + e^{\mu_{C_1,j}(x)})\right) + \frac{\alpha}{q}\ln\left(1 + \sum_{l=1}^{N_g}\left(e^{q(\underline{PG}_l - x_l)} + e^{q(\overline{PG}_l - x_l)}\right) + \sum_{l=1}^{N_l} e^{q\left(\sum_{m=1}^{N_l} w_{lm}x_m - (\mu Z)_l\right)}\right)(10)$$

3. HEURISTIC TRANSMISSION EXPANSION PLANNING MODEL AND SOLVING METHOD

Integrating the above congestion management models into transmission expansion planning process, the planning model becomes even more complex. Sensitivity analysis based heuristic method provides an efficient solving method. The congestion relieving impact of the expanded lines can be measured as the total social benefits increase (bilateral auction market mode) or the total generation costs reduction (single-buyer market mode) after upgrading the line to the network. Then, by sensitivity analysis of expansion investment to transmission congestion relieving impact, we get the right order of adding new lines or upgrading lines to expand transmission network.

3.1 NEW SENSITIVITY INDEXES

Here we define new sensitivity indexes to heuristic transmission expansion planning under POOL transaction pattern.
a. bilateral auction market mode

$$Index_l = \frac{(TC_l - TB_l) - (TC_l^0 - TB_l^0)}{INV_l}$$ (11)

b. single-buyer market mode

$$Index_l = \frac{TC_l - TC_l^0}{INV_l}$$ (12)

In the above Equ.(11)and Equ.(12), the subscript of l stands for indexes of line l; the superscript of 0 stands for the corresponding index of network without the line upgrade . For example, TC_l^0 is the total generation costs without building or upgrading of line l; TC_l is the total

generation costs after building or upgrading line l. The value of TC and TB can be computed by solving the congestion management model presented in Section 2. INV_l is the investment of line l, and $Index_l$ denotes the sensitivity index of line l under certain operation condition.

From Equ.(11) and Equ.(12), we can see that these two equations are common in nature. The numerators of the indexes describe the congestion relieving effect of the upgrade line. With the investment being the denominator, the defined sensitivity index presents that how much per unit of investment can relieve network congestion. Therefore, the line with greater sensitivity should be upgraded or built earlier.

3.2 THE FLOW CHART OF PLANNING
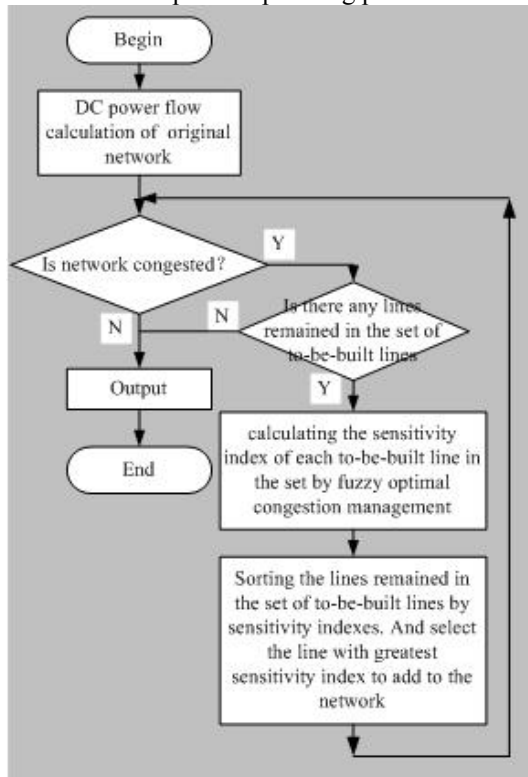Fig. 2 gives the flow chart of the heuristic transmission expansion planning procedure.

Figure 2. Flow chart for fuzzy congestion-driven heuristic transmission planning process

4. NUMERICAL EXAMPLES
The modified IEEE 14-node system (illustrated in Fig. 3) is used to test the fuzzy congestion-driven heuristic transmission expansion planning method. Planning results are given first. Then,

the fuzzy optimal congestion management is carried out on the planning target network.
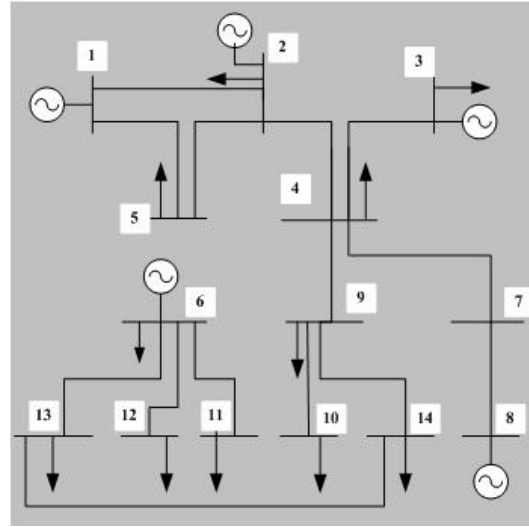

Figure 3. The modified IEEE 14-node transmission network

The to-be-built (or to-be-upgraded) lines data are listed in Tab. 1. And it's assumed that the maximum power flow in all lines (including existing ones and the to-be-upgraded ones) are limited to 40MW.

4.1 PLANNING RESULTS
Based on the fuzzy models of Equ. (6) and (7), and sensitivity indexes of Equ. (11) and (12), the lines needed to add to the original transmission network to relieve congestion are listed in Tab. 2. Add the lines in Tab. 2 to the original transmission network, we'll get the target transmission network of each market mode.

From the results in Tab. 2, some discussions are as follows:
1. Given the same original data, different market modes lead to different planning results.
2. The bilateral auction market mode can be considered as a case with elastic load, since customers can adjust their demand by attending bidding process. While single-buyer market mode only permits generation companies attending bidding, so it can be regarded as the case with inelastic load. From the planning results of bilateral auction market mode, the first one to add to the

network is line 4-5 which provides linkage between two demand centers. The second to add is line 2-3 which joins a generation source and a demand center. And line 5-6 is the last one to add to the network, which links two generation sources. The sequence to add these new lines to expand networks materializes the effect of load elasticity on transmission congestion relieving [9]. That is, in bilateral auction market mode, to maximize total social benefits, the self-adjustment of demand centers is preferential by first adding linkage between demand centers, and introducing cheapest generation power to demand centers is in the second place, until transmission congestion is relieved. While in single-buyer market mode with inelastic load, introducing cheapest generation power is the only preferential means to relieve transmission congestion. This is the case with the planning results of single-buyer market mode. Fig. 5 illustrates generation costs curves of source 2、3、6 which is associated with to-be-upgraded lines. The cheapest power is generated by source 2, and then source 6. Generation source 3 produces the most expansion power among these three ones. So, after perfectly utilizing load elasticity, and to achieve as great social benefit or to cost as little generation costs as possible, the line linking the cheapest generation source 2 is preferential. That is the case in Tab. 2.

3. From the above discussion, the fuzzy congestion-driven and sensitivity analysis based heuristic transmission expansion planning method presented in this paper is effective under the deregulated environment.

Table 1. Data for the to-be-built (or to-be-upgraded) lines

from	to	R	X	Bc	Investment
2	3	0.04699	0.19797	0.04380	200
4	5	0.01335	0.04211	0.01280	150
5	6	0.0	0.23490	0.0	130
7	9	0.0	0.1100	0.0	120
10	11	0.08205	0.19207	0.0	180
12	13	0.22092	0.19988	0.0	200

Note: R, X, Bc are ratios with the base value of 100 MVA; The unit of Investment is million dollars.

Table 2. Transmission planning results on modified IEEE 14-node system

Bilateral Auction Market Mode		
from	to	sensitivity
4	5	52.3875
2	3	3.3066
5	6	1.2738
Single-Buyer Market Mode		
From	to	sensitivity
2	3	2.2043

- – – – is the planning result of bilateral auction market mode
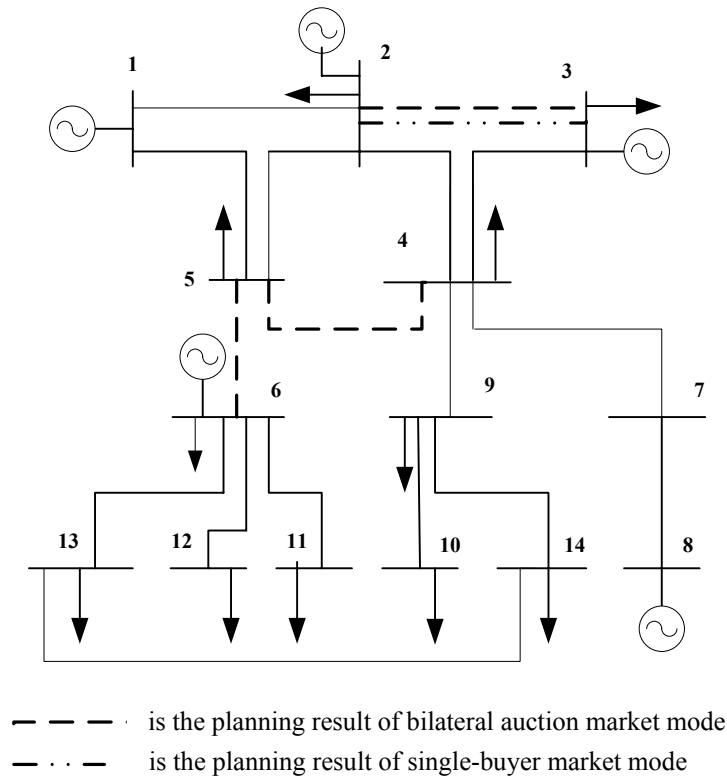- – · · – is the planning result of single-buyer market mode

Figure 4. The planning target transmission networks
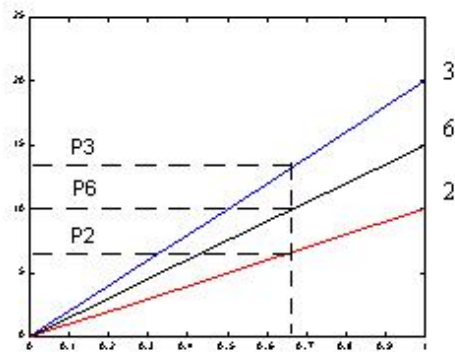
Figure 5. Generation cost curves of No. 2, No.3, No. 6 generators

4.2 FUZZY OPTIMAL CONGESTION DISPATCHING RESULTS ON THE TARGET TRANSMISSION NETWORK

Since the bilateral auction market mode can best represent the features of POOL transaction pattern, for simplicity, we'll only test the corresponding fuzzy optimal congestion management model of bilateral auction market mode. In order to confirm the efficiency of the fuzzy optimal congestion management model and its maximum entropy principle based solving method, we'll compare the calculation results of the following two conditions:

① Using quadratic programming method to solve the accurate optimal congestion dispatching model of Equ. (2). The calculation results are listed in Tab. 3.

② Using the maximum entropy principle based method proposed by this paper to solve the fuzzy optimal congestion dispatching model of Equ. (6). The calculation results are listed in Tab. 4.

Comparing the results in Tab. 3 and Tab. 4, there is very small difference between them, and the optimal objective value of Tab. 4 is a little advantageous over that of Tab. 3. Therefore, the maximum entropy principle based method to solve the fuzzy optimal congestion dispatching model of Equ.(6) is effective and robust to apply to the deregulated environment.

Min XIE, Jinfu CHEN, Xianzhong DUAN

Table 3. Accurate congestion dispatching results by quadratic programming method

Gen	bus		1	2	3	6	8			
	power		77.2587	90.6559	37.1083	10.1272	5.0000			
Demand	bus		2	3	4	5	6	9		
	power		18.445	80.070	40.630	6.460	9.520	25.0750		
	bus		10	11	12	13	14			
	power		7.6500	2.975	5.185	11.475	12.665			
	line	Power Flow			line	Power Flow			line	Power Flow
Line Power Flow	1->2	-40.00			4->5	31.2871			6->13	-26.1840
	1->5	-38.0710			4->7	5.0000			7->8	5.0000
	2->3	-40.0000			4->9	-33.0191			9->10	7.6500
	2->4	-40.0000			5->6	-33.7368			9->14	2.0440
	2->5	-33.0798			6->11	-2.9750			13->14	-14.7090
	3->4	2.7680			6->12	-5.1850				
Objective Value (monetary units)			-8449.3							

Table 4. *Fuzzy congestion dispatching results by maximum entropy method*

Gen	bus		1	2	3	6	8			
	power		76.9769	90.6059	37.2699	10.1389	5.3775			
Demand	bus		2	3	4	5	6	9		
	power		18.8045	80.2179	40.8715	6.7677	9.8178	25.334		
	bus		10	11	12	13	14			
	power		7.9090	3.2728	5.4828	11.7660	12.9378			
	line	Power Flow			line	Power Flow			line	Power Flow
Line Power Flow	1->2	-39.9594			4->5	30.6763			6->13	-26.1623
	1->5	-38.1712			4->7	5.3775			7->8	5.3775
	2->3	-39.8605			4->9	-32.8307			9->10	-7.9090
	2->4	-39.9899			5->6	-34.5970			9->14	1.4585
	2->5	-33.2166			6->11	-3.2728			13->14	-14.3963
	3->4	2.6302			6->12	-5.4828				
Objective Value (monetary units)			-8685.0							

5. CONCLUSION

(1) The heuristic transmission expansion planning method gives detailed consideration on fuzzy optimal congestion management procedure. With the basic investigation background of POOL transaction pattern, the fuzzy optimal congestion management models for bilateral auction market mode and single-buyer market mode are set up respectively. The soft constraints of line power flow limits, and market participants' strategic bidding are all described in form of fuzzy membership functions. Based on the maximum entropy principle, the fuzzy optimal congestion management problem is transformed into non-constrained optimization problem, which can be simply and quickly solved. All in all, this fuzzy optimal congestion management model and its solving method proposed by this paper have much advantage in computation speed and optimization results over traditional mathematical optimization method.

(2) The new sensitivity indexes to select to-be-built or to-be-upgraded lines are defined for bilateral auction market mode and single-buyer market mode respectively in this paper. They describe the compromise between congestion relieving degree and expansion investments, and make the problem of transmission network planning solved fast, simple and heuristic. Test result also shows that these new sensitivity

Min XIE, Jinfu CHEN, Xianzhong DUAN

indexes can not only describe the impact of load elasticity on congestion relieving, but also the market economy requirements.

REFERENCES

[1] C. Cagigas, M. Madriga**.**, "Centralized vs. Competitive Transmission Expansion Planning: the Need for New Tools", *IEEE Power Engineering Society General Meeting*, Vol: 2, pp. 1012-1017, July 2003 .

[2] Xu Lin, Yu Yixin, Liu Huaidong, Lu Fang, Zhang Yun, Huang Yaogui, "Double-Sided Transmission Congestion Management and Quasi-Aumann-Shapley Pricing", *Proceedings of the CSEE*, Vol: 22, No: 10, pp. 56-60, 2002.

[3] E. F. Sanchez-Ubeda, J. Peco, P. Raymont., T. Gomez, S. Banales, A. L. Hernandez, " Application of data mining techniques to identify structural congestion problems under uncertainty", *IEEE Power Tech Proceedings*, Porto, Vol: 1, pp. 6-11, Sept. 2001.

[4] G. B. Shrestha, P. A. J. Fonseka, " Congestion-Driven Transmission Expansion in Competitive Power Markets", *IEEE Trans. on Power Systems*, Vol: 19, No: 3, pp. 1-8, Aug. 2004.

[5] K. Y. Lee, S. Manuspiya, Choi Myeonsong, Myongchul Shin, "Network Congestion Assessment for Short-term Transmission Planning under Deregulated Environment", *IEEE Power Engineering Society Winter Meeting*, Columbus, Ohio USA, Vol: 3, pp. 1266-1271, Jan. 2001.

[6] Sun Hongbo, Xu Guoyu, Qin Yihong, Zhao Youxin, "the Fuzzy Stochastic Optimization Model for Power Network Planning", *Power System Technology*, Vol: 25, No: 5, pp. 4-7, 1996.

[7] Yang Hongming, Duan Xianzhong, "Bilateral Transmission Curtailment Model Based on Fuzzy Theory", *Automation of Electric Power systems*, Vol: 26, No: 20, pp. 24-28, 2002.

[8] Li Xingsi, "An Effective Solving Method for a Class of Nondifferential Optimization Problems", *Science in China (Series A)*, Vol: 24, No: 4, pp. 371-377, 1994.

[9] He hui, Xu zheng, Huang Ying, "The Role of Load in Transmission Congestion Management", *Automation of Electric Power systems*, Vol: 27, No: 17, pp. 11-14, 2003.