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A STUDY OF TRANSACTION CURTAILMENT MODEL BASED ON FUZZY SET THEORY

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ABSTRACT

Transaction curtailment has become the chief method of relieving congestion to maintain system security and reliability. In the NERC curtailment model, all parameters are definite. However in practice, the power transfer distribution factors (PTDFs) are inaccurate and the limits to line flows are soft. In view of the fuzzy characteristics of the curtailment problem, the fuzzy curtailment set is defined first. Based on this curtailment set, the fuzzy constraints and objective are described and the fuzzy optimization curtailment model is presented. Second, using the maximum entropy method, this fuzzy optimization problem is solved as an unconstrained optimization one whose calculating procedure is both fast and simple. Finally, test results show that the fuzzy curtailment set can reduce the impact of the computational errors of the PTDFs on the transaction curtailment while the fuzzy optimization model will lead to less curtailment than does the crisp optimization model when slight violation of the operational limits is allowed.

Keywords: *bilateral transaction; transaction curtailment; fuzzy optimization; maximum entropy*

1. INTRODUCTION

Transmission congestion is an operating condition where there is no sufficient network transfer capacity to simultaneously deliver all traded transactions owing to network constraints. In actual power system operation, transmission congestion should be avoided to ensure system security and reliability. When congestion is caused in transmission, it should be relieved with definite measures.

For the currently used bilateral model, there are mainly two congestion relieving methods, transaction redispatch and transaction curtailment [1,2]. Transaction redispatch can be accomplished by adopting the incremental and decremental bids submitted by traders or by counter-flow transactions that create a counter-flow over a constrained line [3]. When abundant redispatch resources are available, this method can help relieve congestion to achieve maximum utilization of the system transfer capacity. But, if there is a shortage of redispatch resources, or when no redispatch resources are available during an unexpected fault with the transmission network, it will be necessary to adopt the method of transaction curtailment to relieve congestion. Although this method will affect the economic

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efficiency of market operation, it is the last defense line of congestion prevention.

The key to the study of transaction curtailment lies in which curtailment model should be adopted to realize minimum and fair transaction curtailment. Recently, the North American Electric Reliability Council (NERC) has formulated the transmission loading relief (TLR) method to curtail the bilateral transactions when they threaten the security of the system [4]. The objective of this model is to minimize the squared sum of the transactions' curtailment weighted by the inverse transaction. The curtailed amount of transaction is proportional to their impact on the congested lines to achieve relatively fair curtailment [5]. To prevent curtailing too many transactions in too small an amount, the NERC has made a 5% PTDF rule, that is, transactions with 5% or greater PTDF on the congested line are entitled to curtailment [6].
In the NERC's curtailment model, all the parameters are definite. The curtailment set formed by 5% PTDF rule is a two-valued crisp set, and the limits to line flows are hard constraints. However, in real world curtailment problems, the PTDFs are inaccurate themselves since they are calculated according to the DC power flow. In addition, the limits to line flows are soft constraints. The NERCs curtailment model cannot describe these fuzzy phenomena and so no minimum and rational transaction curtailment can be ensured.

As mentioned previously, an actual curtailment problem has many fuzzy characteristics. Therefore, the fuzzy set theory can be applied to this problem to help define a fuzzy curtailment set and describe the degree in which a transaction belongs to this set by the membership function. Secondly, the fuzzy constraints on line flows and the fuzzy objective are introduced, with the fuzzy optimization model for bilateral transaction proposed. Thirdly, this fuzzy optimization problem is solved as an unconstrained nonlinear optimization problem using the maximum entropy method. This solving procedure is simpler and faster than that with the conventional method based on the constrained nonlinear optimization problem. Finally, three types of case study are provided on the IEEE 14-node system to test the fuzzy curtailment model proposed. A comparison each is made between the fuzzy curtailment set and the NERC's crisp curtailment set, the fuzzy optimization model and the crisp optimization model, and the maximum entropy solving method and the conventional solving method.

2. THE NERC CURTAILMENT MODEL

The solving procedure for transaction curtailment consists mainly of two steps, defining the curtailment set in which transactions should be curtailed and minimizing the curtailed amount of transactions in the curtailment set to satisfy the security constraints of the system.

2.1 The NERC's Curtailment Set

The NERC's curtailment set is formed by 5% PIDF rule, that is, it is composed of transactions that have 5% or greater PTDFs on the congested lines. The degree to which a transaction belongs to this set is described by the following membership function:

$$\mu_i = \begin{cases} 0 & PTDF^i < 5\% \\ 1 & PTDF^i \geq 5\% \end{cases} \quad (i = 1,2,\cdots,m) \qquad (1)$$

where

$$PTDF^i = \max\{PTDF_{i1}, PTDF_{i2} \cdots, PTDF_{iL}\}$$

$PTDF_{li}$ is the power transmission distribution factor on line l for transaction i and reflects the incremental power flows on line l to one unit increase in transaction i

L is the total number of congested lines
m is the total number of bilateral transactions

The curve of the membership function μ_i is shown in Fig.1.

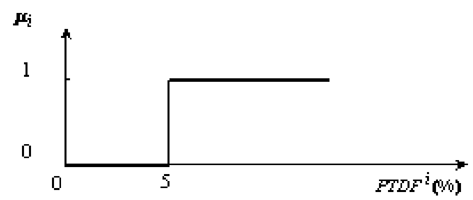

Fig.1 Membership function for NERC curtailment set

Figure 1 shows that μ_i is only equal to 1 or 0. If $\mu_i = 1$ transaction belongs to the NERC curtailment set, then it will need to be curtailed whereas if $\mu_i = 0$ transaction does not belong to the set, then it will not need to be curtailed.

2.2 The NERC's Optimization Model

The NERC's optimization model is developed to minimize the squared sum of the curtailed amount of the transactions in the curtailment set. Based on DC power flow, it can be mathematically formulated as:

(1) Objective function

$$\min f(\Delta T) = \frac{1}{\mu_1 T_1}\Delta T_1^2 + \frac{1}{\mu_2 T_2}\Delta T_2^2 + \cdots + \frac{1}{\mu_m T_m}\Delta T_m^2$$

$$\Delta T = (\Delta T_1, \Delta T_2, \cdots, \Delta T_m)$$

(2) Line power flow constraints

$$P_l(\Delta T) = PTDF_{l1}(T_1 - \Delta T_1) + \cdots + PTDF_{lm}(T_m - \Delta T_m) \le P_{l\max} \quad (l = 1,2,\cdots,L)$$

(3) Transaction curtailment power constraints

$$0 \le \Delta T_i \le T_i \qquad (i = 1,\cdots,m)$$

where

T_i is the scheduled power of transaction i

ΔT_i is the curtailed power of transaction i

P_l is the power flow on line l

$P_{l\max}$ is the power flow normal limit on line l

In an objective function, when a transaction does not need to be curtailed, $\mu_i = 0$. To prevent numerical overflow, μ_i can be taken as a very small value.

A bilateral transaction is an active power contract that is directly made between a generating plant and a consumer. For network injection, it can be modeled as a positive injection of active power at the source node and a negative injection of the same amount of active power at the sink node. In a DC power flow model that does not take the power loss into account, the power balance constraints are spontaneously satisfied and so not listed above.

$PTDF_{li}$ is the effect on the congested line l of raising one unit generation in the source node and lowering one unit load in the sink node to simulate transaction i. Based on DC power flow, it can be found that:

$$PTDF_{li} = \frac{b_{rx} - b_{ry} - b_{sx} + b_{sy}}{X_{rs}}$$

where: r, s are the terminal nodes of line l, x, y are the source and sink nodes of transaction i, X_{rs} is the reactance of line l, $b_{rx}, b_{ry}, b_{sx}, b_{sy}$ are the $rx-, ry-, sx-$ and $sy-th$ terms of the inverse of the bus admittance matrix B.

3. THE FUZZY CURTAILMENT MODEL

3.1 The Fuzzy Curtailment Set

As shown in Fig.1, the NERC's curtailment set is a conventional crisp set based on definite and accurate principles. The membership degree of transaction is only 0 (does not belong) or 1 (belongs). However, in actual curtailment problems, there are inaccurate characteristics, such as the computational errors of the PTDFs, the issue of the cutoff value 5%. Therefore, it is inappropriate to describe the curtailment set by the crisp set with definite extension so that rational curtailment is not guaranteed.

To model the PTDFs fuzzy characteristics mentioned above, the fuzzy set can be introduced to form the curtailment set with fuzzy extension, and then the membership function for this fuzzy curtailment set is defined as:

$$\mu_i = \begin{cases} 0 & PTDF^i < a_1\% \\ \dfrac{PTDF^i - a_1\%}{a_2\% - a_1\%} & a_1\% \le PTDF^i < a_2\% \\ 1 & PTDF^i \ge a_2\% \end{cases} \quad (i = 1,2,\cdots,m) \qquad (2)$$

The curve of the membership function μ_i is shown in Fig.2.

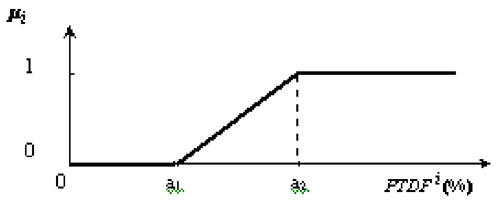

Fig.2 Membership function for fuzzy curtailment set

Figure 2 shows that if a transaction has more than $a_2\%$ PTDFs and $\mu_i = 1$, then the transaction absolutely belongs to the curtailment set while if a transaction has less than $a_1\%$ PTDFs and $\mu_i = 0$, then the transaction definitely does not belong to this set. If the PTDF value is in the interval $[a_1\%, a_2\%]$ and $0 \le \mu_i \le 1$, which shows that the transaction ambiguously belongs to this set, the greater the value PTDF is, the greater the degree of belonging of the transaction will be. As the fuzzy factors are modeled by the fuzzy extension of the curtailment set in its formation, it reduces the impact of the computational errors of the PTDFs and the variation of the cutoff value on transaction curtailment to achieve more rational curtailment.

In the membership function μ_i, the values a_1 and a_2 can be determined by consultation between the system operator and market participants in the real world power market. In this paper, they are taken as 5 and 10, respectively.

3.2. The Fuzzy Optimization Model

The line power flow constraints are soft since slight violation of the normal line limits is allowable. The curtailment optimization problem can be appropriately stated as enforcing the hard constraints exactly while reducing the curtailed amount and satisfying the soft constraints as much as possible. As the concept of "as much as possible" is fuzzy in nature, the curtailment optimization problem with fuzzy constraints and objective function can be written as:

$$\min f(\Delta T) = \frac{1}{\mu_1 T_1}\Delta T_1^2 + \frac{1}{\mu_2 T_2}\Delta T_2^2 + \cdots + \frac{1}{\mu_m T_m}\Delta T_m^2 \,\tilde{\le}\, f'$$

$$s.t.\ P_l(\Delta T) = PTDF_{l1}(T_1 - \Delta T_1) + \cdots + PTDF_{lm}(T_m - \Delta T_m) \,\tilde{\le}\, P_{l\max} \quad (l = 1,2,\cdots,L)$$

$$0 \le \Delta T_i \le T_i \qquad (i = 1,\cdots,m)$$

where: "$\tilde{\le}$" is the notation for the fuzzy relation, the objective being to minimize $f(\Delta T)$ so that it will not exceed the desired value f' "too much". The solution should also satisfy the line flow constraints as much as possible while not violating the limit $P_{l\max}$ "too much".

In an objective function, if the membership function $\mu_i = 1$, the transaction's weight is still the inverse transaction amount; if $0 < \mu_i < 1$, the transaction's weight increases in proportion to the value μ_i, showing that the relative importance of its curtailment decreases and that it is curtailed relatively less. If $\mu_i = 0$, then the curtailed amount of the transaction equals 0. In the actual calculating procedure, μ_i can be taken as a very small value to prevent numerical overflow.

The membership function μ_{Ll} for the fuzzy constraint can be given by:

$$\mu_{Ll} = \begin{cases} 0, & P_l > P_{l\max} + d_{Ll} \\ \left(\dfrac{P_{l\max} + d_{Ll} - P_l}{d_{Ll}}\right)^k, & P_{l\max} < P_l \le P_{l\max} + d_{Ll} \\ 1, & P_l \le P_{l\max} \end{cases}$$

$$(l = 1,2,\cdots,L)$$

where k is a positive constant which controls the reducing rate of the membership function, the parameter $P_{l\max}$ represents the desired lowest limit that should be enforced and $(P_{l\max} + d_{Ll})$ is the highest acceptable value.

The curve of the membership function μ_{Ll} is shown as:

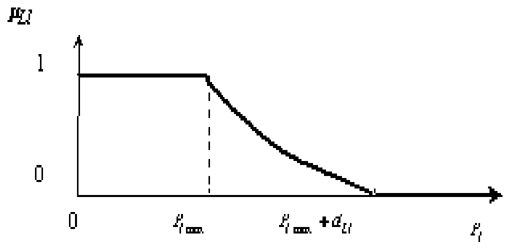

Fig.3 Membership function for line flow constraints

Similarly, the membership function μ_f for the fuzzy objective is expressed as:

$$\mu_f = \begin{cases} 0, & f > f' + d_f \\ \left(\dfrac{f' + d_f - f}{d_f} \right)^k, & f' < f \le f' + d_f \\ 1, & f \le f' \end{cases}$$

The curve of the membership function μ_f is shown in Fig.4.

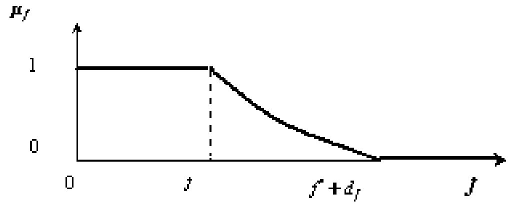

Fig.4 Membership function for objective function

where $(f' + d_f)$ is the highest acceptable objective value, which can be set to represent the current non-optimized operating state. And the parameter f' is the desired lowest objective value and can be determined by 2~3 trials (for this procedure see example 5.2 in section 5). The degree of satisfaction decreases as the objective value increases from f' to $(f' + d_f)$.

4. SOLVING METHOD BASED ON MAXIMUM ENTROPY

The solution for the fuzzy optimization problem consists in minimizing a fuzzy objective while satisfying the fuzzy constraints. By integrating the fuzzy objective and fuzzy constraints, fuzzy decision-making can be regarded as their intersection. Then the membership function $\mu_D(\Delta T)$ for fuzzy decision-making is:

$$\mu_D(\Delta T) = \mu_f(\Delta T) \wedge \mu_{p1}(\Delta T) \wedge \cdots \wedge \mu_{pL}(\Delta T) \tag{3}$$

By using the maximum membership function principle, that is, by maximizing all the membership functions of the fuzzy objective and fuzzy constraints, we shall be able to describe the fuzzy transaction curtailment problem as follows:

$$\begin{aligned} \max_{\Delta T} \mu_D(\Delta T) &= \vee_{\Delta T} \left[\mu_f(\Delta T) \wedge \mu_{L1}(\Delta T) \wedge \cdots \wedge \mu_{LL}(\Delta T) \right] \\ &= \max_{\Delta T} \min \{ \mu_f(\Delta T), \mu_{L1}(\Delta T), \cdots, \mu_{LL}(\Delta T) \} \end{aligned} \tag{4}$$

$$s.t. \quad 0 \le \Delta T_i \le T_i \quad (i = 1, \cdots, m) \tag{5}$$

4.1. Conventional Solving Method

The fuzzy curtailment problem stated in Eqs. (4)-(5) is a non-differentiable minimax optimization one. With the conventional method, this problem is transformed into a constrained nonlinear optimization problem.

$$\begin{aligned} & \max \lambda \\ s.t. \quad & \mu_f(\Delta T) \ge \lambda \\ & \mu_{Ll}(\Delta T) \ge \lambda \\ & (l = 1, 2, \cdots, L) \\ & 0 \le \Delta T_i \le T_i \\ & (i = 1, \cdots, m) \\ & 0 \le \lambda \le 1 \end{aligned}$$

Then the original problem becomes the differentiable optimization problem, but many inequality constrains have to be handled in calculation. To deal with the difficulty involved in handling the inequality constraints, the maximum entropy is introduced.

4.2. The Maximum Entropy Method for the Minimax Problem

For a non-differentiable minimax problem:

$$\min_x f(x) = \max_{1 \le i \le m} f_i(x)$$

$$s.t. \; g_j(x) \le 0 \qquad 1 \le j \le m_1$$

By using the precise penalty function, the minimax problem is rewritten as follows.

$$\min_x \psi(x) = f(x) + \alpha \max[0, g_1(x), \cdots, g_{m1}(x)] \quad (6)$$

where: α is a penalty factor.

The maximum entropy principle is introduced by Ref. [7] and a maximum entropy function is deduced to replace the non-differentiable maximum function. Then the objective function $f(x)$ becomes:

$$f(x) = \max_{1\le i\le m} f_i(x) = \frac{1}{p}\ln\left(\sum_{i=1}^{m} e^{pf_i(x)}\right) \quad (p \to +\infty) (7)$$

Similarly, the penalty term can also be aggregated into a maximum entropy function, that is:

$$\max[0, g_1(x), \cdots, g_{m1}(x)] = \frac{1}{q}\ln\left(1 + \sum_{j=1}^{m_1} e^{qg_j(x)}\right)$$

$$(q \to +\infty) \quad (8)$$

Substituting (7) and (8) into (6), we find the minimax problem equivalent to:

$$\min_x \psi(x) = \frac{1}{p}\ln\left(\sum_{i=1}^{m} e^{pf_i(x)}\right) + \frac{\alpha}{q}\ln\left(1 + \sum_{j=1}^{m_1} e^{qg_j(x)}\right) \quad (9)$$

Strictly speaking, function $\psi(x)$ is a precise penalty function when p, q approach infinity. In actual calculation, the optimal solution can be obtained as long as p, q are big enough.

By solving (9) directly using the unconstrained optimization algorithm, the optimal solution to the minimax problem can be obtained. The advantages of this algorithm are simple programming, quick convergence and steady numerical value [7.8].

4.3. The Maximum Entropy Solving Method

In order to apply the maximum entropy method to the fuzzy optimization problem Eqs. (4)~(5), the following transformation has to be performed:

$$\max_{\Delta T} \min\{\mu_f(\Delta T), \mu_{L1}(\Delta T), \cdots, \mu_{LL}(\Delta T)\}$$
$$\to \min_{\Delta T}[-\min\{\mu_f(\Delta T), \mu_{L1}(\Delta T), \cdots, \mu_{LL}(\Delta T)\}]$$
$$\to \min_{\Delta T}[1 - \min\{\mu_f(\Delta T), \mu_{L1}(\Delta T), \cdots, \mu_{LL}(\Delta T)\}]$$
$$\to \min_{\Delta T}[\max\{\{1 - \mu_f(\Delta T), 1 - \mu_{p1}(\Delta T), \cdots, 1 - \mu_{pL}(\Delta T)\}]$$
$$\to \min_{\Delta T} \max\{-\mu_f(\Delta T), -\mu_{L1}(\Delta T), \cdots, -\mu_{LL}(\Delta T)\}$$
$$(10)$$

By using the maximum entropy method for the minimax problem, (10) becomes:

$$\min_{\Delta T} \max\{-\mu_f(\Delta T), -\mu_{L1}(\Delta T), \cdots, -\mu_{LL}(\Delta T)\}$$
$$= \min_{\Delta T} \frac{1}{p}\ln\left(e^{-p\mu_f(\Delta T)} + \sum_{l=1}^{L} e^{-p\mu_{Pl}(\Delta T)}\right) \quad (11)$$

And the constraint terms $0 \le \Delta T_i \le T_i \ (i = 1, \cdots, m)$ can also be aggregated into a surrogate constraint:

$$\frac{1}{q}\ln\left(\sum_{i=1}^{m}\left(e^{q(\Delta T_i - T_i)} + e^{-q\Delta T_i}\right)\right) \quad (12)$$

By using the precise penalty function to integrate the objective equation (11) with constraint equation (12), the fuzzy optimization becomes:

$$\min_{\Delta T} \frac{1}{p}\ln\left(e^{-p\mu_f(\Delta T)} + \sum_{l=1}^{L} e^{-p\mu_{Pl}(\Delta T)}\right)$$
$$+ \frac{\alpha}{q}\ln\left(1 + \sum_{i=1}^{m}\left(e^{q(\Delta T_i - T_i)} + e^{-q\Delta T_i}\right)\right) \quad (13)$$

In the calculating procedure, p, q are taken as 10^3 and α as 10. By solving the unconstrained problem Eq. (13), the optimal curtailed amount of transactions is determined.

5. NUMERICAL EXAMPLES

Three types of example are provided on the IEEE 14-node system to test the fuzzy curtailment model.

In order to show the curtailment of transactions that have about 5% PTDFs, the following modifications to the IEEE 14-node system parameters are made: line 4-5 is disconnected; the reactance of line 2-5 is 0.5. For simplification, DC power flow is used.

Ten transactions are considered in the system. The scheduled power of transactions and the PTDFs on lines 6-13 and 5-6 are given in Table 1. The ten transactions will cause $93.42MW$ and

$236.21MW$ power flows on lines 6-13 and 5-6, respectively.

5.1. A Comparison between Fuzzy Curtailment Set and Crisp Curtailment Set

Suppose the flow limits to lines 6-13 and 5-6 are $50MW$ and $250MW$ and the transactions cause line 6-13 to overload. To relieve the congestion (overloaded line), transactions should be curtailed in the curtailment set formed with the NERC's 5% PTDF rule and the fuzzy set theory, respectively. The calculation results are shown in Table 2 (In the optimization model, the objective and line flow constraints are crisp).

Table 1 shows that the PTDF value on line 6-13 for transaction 2 is 6.19%, which is 1.19% higher than the NERC's cutoff value 5%. If the 1.19% is due to the computational errors, then the curtailed amount of transaction 2 will cause $8.00MW$ errors using the NERC's curtailment model.

With the fuzzy curtailment set proposed, the curtailed amount of transaction 2 is $1.94MW$. This shows that even though the PTDF value has 1.19% computational errors, the impact of the errors is very small on the transaction curtailment.

5.2. A Comparison between Fuzzy Optimization Model and Crisp Optimization Model

If the power flow limits to lines 6-13 and 5-6 are $50MW$ and $150MW$, then the two lines are congested. To relieve the congestion, transactions are curtailed using the fuzzy optimization model for the three cases. The curtailment results are shown in Table 3. After transactions are curtailed, the power flows on lines 6-13 and 5-6 are given in Table 4 (In the optimization model, $k = 1.0$ □ $d_{L1} = 10$, $d_{L2} = 40$).

Case A shows if the desired objective value is set high, the fuzzy constraints and fuzzy objective function can be strictly satisfied. Then the degree of membership for decision-making will be equal to 1.0. Hence the fuzzy optimization model is equivalent to the crisp optimization model, and the curtailment results from the fuzzy model in this case are exactly the same as those from the crisp model.

Compared with case A, case B has the desired objective value decreased by 25 and the total curtailment from this fuzzy model is reduced by $8.72MW$, or 5.4%. Furthermore, after transactions are curtailed, the power flows on lines 6-13 and 5-6 are $51.11MW$ and $154.42MW$, slightly higher than their normal limits $50MW$ and $150MW$. If these overloads can be accepted, the savings of $8.72MW$ in the curtailment would bring about significant economical benefits under congestion conditions. Compared with case B, case C has less total curtailment, but the line flows on line 5-6 are 108% their normal flow limits. And the degree of membership is 0.70, or 0.19 lower than that of case B, which means that it is less desirable to use these curtailment results.

It can be seen from Tables 3 and 4 that if the desired objective value is low, then the fuzzy optimization will suggest a solution, which can have less curtailment but more violations of line flow constraints. Judging by the trade-off between curtailment and violations, the results of case B are the best of the three as mentioned above.

5.3. A Comparison between the Maximum Entropy Method and the Conventional Method

In view of the three cases mentioned above, Table 5 lists the computing time and degree of membership for decision-making by using the conventional constrained method and the unconstrained maximum entropy method, respectively. The two solving methods are both implemented with Matlab 5.3 software, and their initial conditions are the same. Table 5 shows that for all three cases, the maximum entropy method has the same optimal results as the conventional method. In addition, the computing time is shorter, which means it is feasible and effective for solving the fuzzy optimization problem with the maximum entropy method.

Table I. Scheduled transactions

Trans.	Source Node	Sink Node	Scheduled Power (MW)	PTDF on Line 6-13 (%)	PTDF on Line 5-6 (%)
1	1	3	100	3.98	12.86
2	2	4	100	6.19	20.01
3	1	5	50	-2.48	-8.01
4	1	6	10	-9.83	68.23
5	2	9	10	12.76	41.25
6	1	10	100	8.09	43.92
7	1	11	50	-0.38	56.94
8	1	12	100	29.47	66.10
9	1	13	50	60.17	64.43
10	1	14	50	33.49	51.39

Table II. Degree of transaction membership to curtailment set and curtailed amount of transactions

Trans.	Scheduled Power (MW)	NERC's Curtailment Model		Fuzzy Curtailmen Model	
		Degree of Membership	Curtailed Amount (MW)	Degree of Membership	Curtailed Amount (MW)
1	100	0	0.0	0.0	0.0
2	100	1	8.00	0.238	1.94
3	50	0	0.0	0.0	0.0
4	10	0	0.0	0.0	0.0
5	10	1	1.65	1.0	1.68
6	100	1	10.45	0.618	6.57
7	50	0	0.0	0.0	0.0
8	100	1	38.09	1.0	38.71
9	50	1	38.88	1.0	39.52
10	50	1	21.64	1.0	22.00

Table III. Results of transaction curtailment

Trans.	Case A $f' = 80$ $d_f = 10$	Case B $f' = 55$ $d_f = 35$	Case C $f' = 35$ $d_f = 55$
1	8.00	7.54	6.80
2	12.43	11.72	10.58
3	0.0	0.0	0.0
4	2.34	1.89	0.96
5	2.56	2.29	2.28
6	23.90	22.09	19.20
7	12.17	9.66	6.04
8	46.59	44.68	41.52
9	32.36	32.16	31.70
10	21.35	20.65	19.34
$\sum \Delta T$	161.70	152.98	138.42
f	63.83	58.87	51.42
μ_D	1.0	0.89	0.70

Table IV. Line power flows after curtailment

Line		Case A	Case B	Case C
6-13	Power Flows (MW)	50	51.11	52.99
	Overload (%)	0	2.22	5.98
5-6	Power flows (MW)	150	154.42	161.95
	Overload (%)	0	2.95	7.97

Table V. Comparison between the maximum entropy method and the conventional method

Method		Case A	Case B	Case C
Maximum Entropy Method	μ_D	1.0	0.89	0.70
	Computational Time (s)	0.17	0.47	0.60
Conventional Method	μ_D	1.0	0.89	0.70
	Computational Time (s)	0.24	1.13	1.30

6. CONCLUSION

A novel fuzzy curtailment model for bilateral transaction is presented by introducing the fuzzy set theory. With this model, a fuzzy optimization curtailment model with fuzzy objective and constraints is proposed with the fuzzy characteristics of the PTDFs and line flow limits taken into account and the fuzzy curtailment set defined. Then the maximum entropy method is used to transform the fuzzy optimization problem into an unconstrained optimization problem, thus simplifying programming and quickening convergence. Test results show that the fuzzy curtailment model can reduce the impact of the PTDFs computational errors on transaction curtailment and lead to less curtailment than does the crisp model when small violations of the operational limits are allowable.

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