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Calculation of Available Transmission Capability Based on Monte Carlo Simulation

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Abstract -- With the further development of power markets, large amount of electric power wheeling and frequent transmission transaction is emerging, accurately determining Available Transmission Capability (ATC) and broadcasting the ATC information in time are very important to prevent and relieve transmission congestion effectively. In practical power markets, there are large amount of uncertainties involved in Transmission Reliability Margin (TRM) and Capacity Benefit Margin (CBM) of ATC. Considering calculation accuracy and time, a novel approach is proposed to calculate ATC based on Monte Carlo simulation and sensitivity analysis considering large amount of uncertainties impacting the value of ATC. The steady state constraints and voltage stability and transient stability constraints are taken into account. The iterative solution based on PSASP by China EPRI is developed. IEEE 14-bus test system is used to verify the presented approach. The results show that the model and algorithm is correct and effective. The research achievements are undergoing to transfer to the application in certain provincial power system in China, and some new problems are suggested in the end of paper.

Index Terms **-- Available Transmission Capability (ATC), Transmission Reliability Margin (TRM), Capacity Benefit Margin (CBM), Monte Carlo Simulation, Sensitivity Analysis**

I. INTRODUCTION

NORTH America Electric Reliability Council (NERC) defines Available Transmission Capability (ATC) as a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. ATC is an indication of the expected transfer capability remaining on the transmission network. It is available transfer capability that could be scheduled to the designated path under the conditions considered in calculating ATC values. ATC is a market signal that refers to the capability of a system to transport or deliver energy above that of already subscribed transmission uses. The creation and formation of Regional Transmission Organizations (RTO), initially called for by Federal Energy Regulatory Commission (FERC) order No.2000 and further enhanced by its 2003 White Paper Wholesale Power Market Platform", are expected to bring increased efficiency of power market through improved grid management and increased customer access to competitive power supplies. The ATC value is required to be posted on Open Access Same-time Information System (OASIS) by FERC's order 889, 2000 and White Paper to make competition reasonable and effective. The ATC value between two points is given as

$$ATC = TTC - TRM - CBM - ETC \quad (1)$$

where TTC is Total Transfer Capability, TRM is Transmission Reliability Margin, CBM is Capacity Benefit Margin, and ETC is Existing Transmission Commitment including retail customer services between the same two points.

ATC computations should consider limits imposed on the system components such as thermal, voltage, and stability limits. In addition, uncertainties in load forecasts and simultaneous transfers should be taken into account. For these reasons, uncertainties should be quantified properly to increase the efficient use and the security of the system and to provide necessary information for system operation and planning. Uncertainties are expressed by two margins, TRM and CBM, during ATC calculations. Factors such as transmission line and generating unit outages may dramatically affect ATC if they are not taken into consideration.

NERC defines TRM as "the amount of transfer capability necessary to provide a reasonable level of assurance that the interconnected transmission network will be secure." TRM accounts for the inherent uncertainty in system conditions, its associated effects on ATC calculation, and the need for operating flexibility to ensure reliable system operation as system conditions change.

There are several calculating TRM approaches:

Take a fixed percentage of TTC (say 4%) as TRM. This approach is relative conservative and not accurate.

Monte Carlo statistical approach, which is based on the repeated computation of TTC using variations in the base data, gives the difference between the maximum and the minimum. This kind of computation is very time consuming with the system expansion.

Sensitivity analysis approach is realized by calculating several gradient values to take uncertainties into consideration.
NERC defines CBM as "the amount of firm transfer capability preserved for Load Service Entities (LSEs) on the host transmission system where their load is located, to enable the access to generation from interconnected systems to meet generation reliability requirements." Preservation of CBM for a LSE allows that entity to reduce its installed generating capacity below what may otherwise have been necessary without interconnections to meet its generation reliability requirements. The transmission capacity preserved as CBM is intended to be used by LSE only in times of emergency generation deficiencies. A LSE would get the benefit from CBM by sharing installed capacity reserves with other parties elsewhere in the interconnected network.

ATC is calculated hourly, daily or monthly based on market requirements. Certain factors should be taken into account in ATC calculations such as the list of contingencies that would represent most sever disturbances, accuracy of load forecast and distribution, unit commitment, system topology and configuration, and maintenance scheduling. System control devices such as voltage regulators and reactive power control devices also have a direct impact on ATC values.

The literature of ATC calculation can be divided into two categories: deterministic methods and probabilistic methods. Repeated power flow (REP) in [2], continuation power flow (CPF) in [3], and optimal power flow (OPF) in [4] and [5] are based on power flow computation. For these methods, the steady state constraints can be easily considered but dynamic stability constraints are difficult to be taken into account, and the computation time is longer. Sensitivity analysis in [6] can provide results with shorter computation time. References [7] and [8] adopt AI methods to deal with uncertainties of power systems with a shorter computer time, but with the system expansion, the validity and effect of the algorithm is still to be verified. These methods all belong to deterministic methods. The probabilistic methods include: stochastic programming in [9] and enumeration method in [10] which consider uncertainties, but the computation time will increase rapidly when the size of system increases. Bootstrap procedure in [12] computes the distribution of ATC value that reflects the recent market activities, while it is hard to deal with uncertainties. Monte Carlo simulation in [11] can process uncertainties of power systems within a shorter computation time.

Considering calculation accuracy and time, a novel method is proposed in this paper to calculate ATC based on Monte Carlo simulation and sensitivity analysis considering large amount of uncertainties, which have large impacts on the value of ATC. The steady state constraints and voltage stability and transient stability constraints are taken into account. The iterative solution based on PSASP by China EPRI is developed. IEEE 14-bus test system is used to verify the presented approach. The results show that both model and algorithm are correct and effective.

The paper is organized as follows. In Section II the Monte Carlo based probabilistic approach dealing uncertainties in ATC calculation is introduced. The mathematical model of ATC computation and Sensitivity analysis approach are described in

Section III. The numerical examples are given and discussed in Section IV. Last are conclusions in Section V.

II . MONTE CARLO BASED PROBABILISTIC APPROACH FOR

ATC CALCULATION

Using Monte Carlo simulation and sensitivity analysis to calculate ATC has three parts: i) construct the operation states of power systems using Monte Carlo simulation; ii) assess the states by power flow calculation; iii) calculate the value of ATC by repetitive linear iteration based on sensitivity analysis.

Monte Carlo simulation is a computer simulation method based on the probabilistic theory and the statistic technique. It can easily deal with the uncertainties. Its computation time nearly does not increase with power systems' scale and complexity. It is very suitable for sampling for the system with large scale. In this paper we sample the operation states according to the system element's probabilistic distribution using Monte Carlo simulation as follows:

For generators and transmission lines, two operation states: operation or fault, are supposed while the corresponding probability distribution is two-point distribution.

For transformers, besides two states of operation and fault, there exist other states, such as transformer tapping in different positions. When sampling the states of transformers, two steps are needed, firstly according to two-point distribution to randomly create a state, and then select a tapping position. The corresponding probability distribution of transformer tapping can be given based on actual operation data.

For loads, we think that every bus load is a random variable fluctuating around the forecast value, and can be modeled by normal distribution $N(\mu, \sigma^2)$, where μ is the vector of the forecasted load, and σ, which is estimated by the system running experiment, is variance vector.

After getting the current operation state, the repeated linear iteration based on sensitivity analysis is used to calculate ATC, which utilizes a tangent vector at an initial solution of power flow equations to predict the next operating point that is closer to the right solution, then improve the precision by the repeat linear iteration. In this paper, the derived sensitivity formula describes the relation between the injection power, the line power flow and bus voltage by the first partial derivative matrix.

A load factor λ is added to represent the increase of generator output and load demand. That can be presented as
follows: $P_{Li}=P_{Li}^{0}+\lambda K_{pli}$, $Q_{Li}=Q_{Li}^{0}+\lambda K_{qli}$, $P_{Gi}=P_{Gi}^{0}+\lambda K_{pgi}$, where K is the multiplier to designate the rate of load or power
change. If the node is fixed, then K is constant. Then the power flow equation is changed from $\boldsymbol{F(\delta, V)=0}$ to $\boldsymbol{F(\delta, V, \lambda)=0}$, and the changes of λ correspond to the change of the operating pattern of power systems.
Using the first-order sensitivity of bus voltage, line power and generator active power with respect to λ to describe the interaction of the system parameters. That is to say: Using ∂V/∂λ the sensitivity of bus voltage to λ, ∂Sij/∂λ the sensitivity of line power to λ and ∂PG/∂λ the sensitivity of generator active power to λ to describe the interaction of the system parameters. When the system parameters changed, the load factor λ can be decided by the first order sensitivity. Then the updating ATC value can be obtained.

The sensitivity analysis can calculate ATC sententiously, quickly and exactly, and enhance precision by the repeated linear iteration.

In ATC calculation, the thermal constraints, voltage constraints, generator capacity constraints, load demand, and power flow balance constraints are taken into account. It is desired that the method calculating ATC should be easy, fast and efficient. The security margin concept, instead of direct stability analysis, is adopted in this paper. Stability constrains here are divided into voltage stability and transient stability. Checking these margins after completing power flow calculation is as an alternative of complicated stability computation. The mathematical model and detailed ATC calculation processes are described in Section

III. ATC COMPUTATION MODEL

ATC Computation Model

The objective of ATC calculation is point by certain percentage (say 1%) step by step to repeat computing power flow until 15% increase of load, and making sure it is convergence of every power flow and satisfied all constraints, which indicates the present operation state at least with 15% voltage stability margin.

B. Computation Processes

The ATC computation processes based on Monte Carlo and sensitivity analysis are listed as follows.
Construct the initial state by sampling in terms of the probabilistic distribution of each equipment.
Compute power flow of the initial state, and evaluate the corresponding operation state. If all constraints are satisfied, then go on to Step 3, or return to Step 1.
Repeatedly increase load power in the sink and generators' output in the source, and compute relevant sensitivity factors as following:
a. Compute the sensitivities of the constraints with respect
to the load factor λ, including ∂V/∂λ, ∂Sij/∂λ, ∂PG/∂λ, expressed by (4) to (8).

$$\text{Max } J = \sum_{d\ R} P_{Ld} \qquad (2)$$

a) Solving $\frac{\partial V}{\partial \lambda}$

The constraints include:

$$P_i - V_i \sum_{j=1}^{N} V_j (G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) = 0$$

$$Q_i - V_i \sum_{j=1}^{N} V_j (G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) = 0$$

$$V_i^{min} \le V_i \le V_i^{max} \quad i \quad N$$

$$S_l^{min} \le S_l \le S_l^{max} \quad l \quad N_L \qquad (3)$$

$$P_{Gk}^{min} \le P_{Gk} \le P_{Gk}^{max} \quad k \quad N_G$$

$$Q_{Gk}^{min} \le Q_{Gk} \le Q_{Gk}^{max} \quad k \quad N_G$$

$$-45^\circ \le \delta_i \le 45^\circ \quad i \in N$$

Where R is the set of load in sink, P_{Ld} refers to the load linked to bus d; N is the number of nodes, and N_L the number of branches, N_G the number of generators; V_i^{min} and V_i^{max} are the Lower and upper voltage limits of bus i, respectively; S_l^{min} and S_l^{max} are the thermal stability constraints of branch l; P_{Gk}^{min}, P_{Gk}^{max}, and Q_{Gk}^{min}, Q_{Gk}^{max} are the output limits of generator k.

Δi is the phase angle of voltage of bus i. This paper adopts the lemma "the absolute values of phase angles of all buses voltages are less than 45°" as the simplified criterion to verify transient stability in [6]. After every power flow calculation, checking the absolute value of phase angle of each bus voltage to see whether within 45°, if it is, then the system is regarded as transient stability.

For voltage stability assessment, an experiential criterion: more than 15 percentage margin far from voltage collapse, is taken instead of computing the voltage collapse point under each state, which is realized by increasing load in the sink From power flow equations $F(\delta, v, \lambda) = 0$, we can get

$$\begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} & \frac{\partial P}{\partial \lambda} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \lambda} \end{bmatrix} \begin{bmatrix} d\delta \\ dv \\ d\lambda \end{bmatrix} = 0 \quad (4)$$

Then

$$\begin{bmatrix} \frac{\partial \delta}{\partial \lambda} \\ \frac{\partial V}{\partial \lambda} \end{bmatrix} = -\begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial P}{\partial \lambda} \\ \frac{\partial Q}{\partial \lambda} \end{bmatrix} \quad (5)$$

where $\begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix}$ is the Jaccbian matrix; $\begin{bmatrix} \frac{\partial P}{\partial \lambda} \\ \frac{\partial Q}{\partial \lambda} \end{bmatrix}$ is a column Vector. Amongst all elements, except those K_{Pi} or K_{Qi} related to the sink and the source are not zero elements, the remainder is zero.

b) Solving $\frac{\partial S_{ij}}{\partial \lambda}$

From the branch power flow equation

$$\tilde{S}_{ij} = V_i \left[\overline{V_i \left(j \frac{B_c}{2} \right)}^{*} + (\overline{V_i}^{*} - \overline{V_j}^{*}) \overline{y_{ij}}^{*} \right],$$

we can get

$$P_{ij} = V_i^2 g_{ij} - V_i V_j (g_{ij} \cos \delta_{ij} + b_{ij} \sin \delta_{ij})$$

$$Q_{ij} = -V_i^2 \left(\frac{B_c}{2} + b_{ij} \right) - V_i V_j (g_{ij} \sin \delta_{ij} - b_{ij} \cos \delta_{ij})$$

$$S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \quad (6)$$

Then

$$\frac{\partial S_{ij}}{\partial \lambda} = \frac{\partial S_{ij}}{\partial V_i} \frac{\partial V_i}{\partial \lambda} + \frac{\partial S_{ij}}{\partial V_j} \frac{\partial V_j}{\partial \lambda} + \frac{\partial S_{ij}}{\partial \delta_i} \frac{\partial \delta_i}{\partial \lambda} + \frac{\partial S_{ij}}{\partial \delta_j} \frac{\partial \delta_j}{\partial \lambda} \quad (7)$$

where

$$\frac{\partial S_{ij}}{\partial V_i} = \frac{1}{S_{ij}} \left(P_{ij} \frac{\partial P_{ij}}{\partial V_i} + Q_{ij} \frac{\partial Q_{ij}}{\partial V_i} \right)$$

$$\frac{\partial S_{ij}}{\partial V_j} = \frac{1}{S_{ij}} \left(P_{ij} \frac{\partial P_{ij}}{\partial V_j} + Q_{ij} \frac{\partial Q_{ij}}{\partial V_j} \right)$$

$$\frac{\partial S_{ij}}{\partial \delta_i} = \frac{1}{S_{ij}} \left(P_{ij} \frac{\partial P_{ij}}{\partial \delta_i} + Q_{ij} \frac{\partial Q_{ij}}{\partial \delta_i} \right)$$

$$\frac{\partial S_{ij}}{\partial \delta_j} = \frac{1}{S_{ij}} \left(P_{ij} \frac{\partial P_{ij}}{\partial \delta_j} + Q_{ij} \frac{\partial Q_{ij}}{\partial \delta_j} \right)$$

where P_{ij} and Q_{ij} are real power and reactive power flowed in branch ij; y_{ij}, g_{ij} and b_{ij} are parameters of line ij; B_c is susceptance of line-to-ground.

c) Solving $\frac{\partial P_G}{\partial \lambda}$

$$\frac{\partial P_G}{\partial \lambda} = K_{Pg} \quad (8)$$

where K_{Pg} is the change factor of generator's real power. ***b.*** Compute $\Delta\lambda$ by (9), (10) and (11).

$$\Delta\lambda_{Vi} = \frac{V_{\lim,i} - V_i^0}{\partial V_i / \partial \lambda} \quad (9)$$

$$\Delta\lambda_G = \frac{P_{G,\lim} - P_G^0}{\partial P_G / \partial \lambda} \quad (10)$$

$$\Delta\lambda_S = \begin{cases} \dfrac{S_{\lim,i,j} - S_{ij}^0}{\partial S_{ij} / \partial \lambda} & \partial S_{ij} / \partial \lambda > 0 \\ \dfrac{-S_{\lim,i,j} - S_{ij}^0}{\partial S_{ij} / \partial \lambda} & \partial S_{ij} / \partial \lambda < 0 \end{cases} \quad (11)$$

Where when $\partial V_i/\partial \lambda > 0$, $V_{\lim,i}$ is the upper limit; when $\partial V_i/\partial \lambda < 0$, $V_{\lim,i}$ is the lower limit; V_i^0 is the initial magnitude of V_i; $\partial V_i/\partial \lambda$ is the sensitivity of V_i with respect to λ; $S_{\lim,ij}$ is the thermal limit of branch ij; $\partial S_{ij}/\partial \lambda$ is the sensitivity of power in branch ij with respect to λ; $P_{G,\lim}$ is the maximum output of generators in the source point; P_G^0 is the initial output of all generators in the source point; $\partial P_G/\partial \lambda$ is the sensitivity of P_G with respect to λ.

c. Find the minimum increment of $\Delta\lambda$.

$$\Delta\lambda = \min\{\Delta\lambda_V, \Delta\lambda_S, \Delta\lambda_G\} \tag{12}$$

d. Modify λ.

$$\lambda^{(n+1)} = \lambda^{(n)} + \Delta\lambda \tag{13}$$

After n times of iteration, if $\Delta\lambda$ is less than the preset error ε, then to stop iterative computation, and the last λ is the

Maximum value under the specified condition.

e. Update load and power generation by (14).

$$\begin{aligned} P_{Li} &= P_{Li}^0 + \lambda K_{pli} \\ Q_{Li} &= Q_{Li}^0 + \lambda K_{qli} \\ P_{Gi} &= P_{Gi}^0 + \lambda K_{Pgi} \end{aligned} \tag{14}$$

where P_{Li} and Q_{Li} are real and reactive load power of bus i, K_{pli} and K_{qli} are the multipliers to designate the rate of load change, K_{Pgi} is the multiplier to designate the rate of power change, P_{Gi} is active power generation, and superscript 0 is the initial state.

(4) Compute power flow of the updated state, if power flow is convergent normally, then evaluate the corresponding operation state. If all constraints are satisfied, then return to Step 3, or go to Step 5.

(5) The ATC computation is terminated if any of the constraints is not satisfied. The value of ATC can be calculated by the recent power flow results as follows.

$$\text{ATC} = \sum_{d \in R} P_{Ld} \tag{15}$$

IV. NUMERICAL TESTS

The iterative solution based on PSASP/UPI [14] by China EPRI is developed. IEEE 14-bus test system is used to verify the presented approach. The single line diagram and parameters of the test system can be found in [15]. Bus 2 is supposed as the source bus, bus 12, 13 and 14 are selected as the sink buses, then ATC is defined as: ATC=P_{12}+P_{13}+P_{14}. This paper will verify the approach from the flowing three aspects:

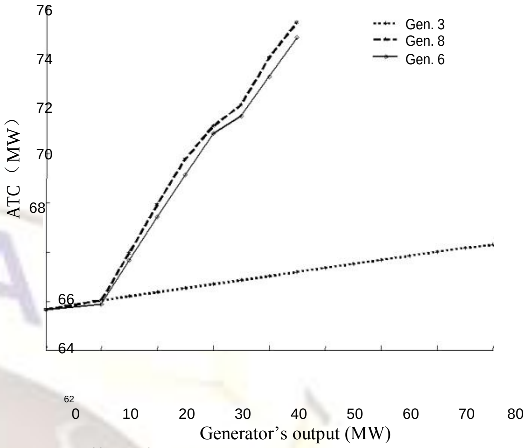

Fig. 1. The effect of the generation on ATC

(1) The influence of active power change of one generator on ATC value. In the test system, there are 5 generators: bus 1 is set as the slack bus; bus 2 is the source bus, so consider the influences of bus 3, 6, 8 separately. The constraints of the generator’s active power are: G3 (15MW, 80MW), G6 (10MW, 45MW) and G8 (10MW, 40MW). Select 5MW as the incremental active power, then active power change of each generator is used to study the influences on the value of ATC with the results shown in Fig.1. Analyzing Fig.1 we can conclude: the active power increase of non-source generator has the influence on the value of ATC; and different electrical distance of non-source generator has different influence. In the tests generators 6 and 8 are near the source, their influences to ATC are more evident than generator 3 that is far from the source bus. It also suggests active power generation and unit commitment have obvious influences on the value of ATC.

(2) The influence of load change on ATC. Select 0.02 per unit as the step, increase the load of each node from 80% to 120% of the forecast value, then we can get the relation curve of load change with ATC shown in Fig.2. From Fig.2 we can conclude: when the load increases, the value of ATC will decrease. It refers to the accuracy of load forecast is

important in ATC calculation.

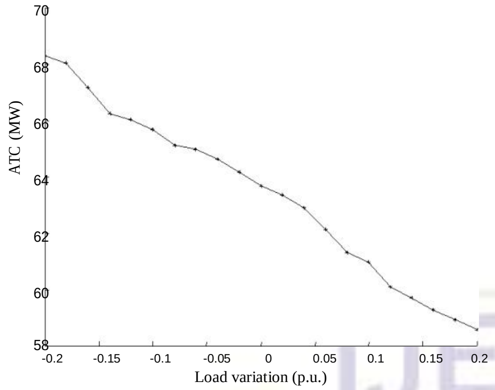

Fig. 2. The influence of load changing on ATC

(3) The influence of different uncertainties on ATC. Suppose the actual load value changes within ±2% of forecasting value, the fault probability of the generators is supposed at 0.02, the fault rate of the lines is 0.01, and the fault rate of the transformers is 0.02. Assume transformers' tapping have 5 levels, the probability distribution of each level is: 100% 0.5, 102.5% 0.15, 97.5% 0.15, 105% 0.10, and 95% 0.10, respectively. Using Monte Carlo sampling in terms of the probabilistic distribution of each equipment to construct a series of system states, and then use sensitivity analysis to get corresponding ATC values, and select the minimum as the final result. The examples are shown in Table I.

In Table I, Case 1 is the IEEE standard state, there is no load change no fault; Case 2 only has load change; Case 3 have load and transformers' tapping adjustment simultaneously; Case 4 have load change and one line fault; Case 5 has load change and one non-source generator fault.

TABLE I
ATC CALCULATION RESULTS

Case	ATC/MW
1	63.662
2	61.357
3	65.373
4	58.937
5	57.204

Analyzing Table I, we can conclude that uncertainties play an important role in ATC calculation. For example, load change and transformer tapping adjustment make the value of ATC great change; the fault of line, transformer and generator will decrease the value of ATC. Load change randomly all the time, the fault of components and transformer tapping can be viewed as specific probability distribution. The ATC calculation should consider not only the influences of single uncertainty, but also the ones of these uncertainties' combination. For example, multi-fault and multi-uncertainty impact the value of ATC at the same time. After sampling and calculation, we can get a series of results representing different states, selecting the minimum one as the finial ATC value. Compare to deterministic methods, the presented approach in this paper can give the value of ATC more accurate. For this test, we select the result of Case 5 as the finial result. If we take out CBM (5%), the finial ATC is 57.204·95%=47.3438MW.

We are undergoing to transfer the research achievements to the application in certain provincial power system in China.

V. CONCLUSIONS AND NEXT WORK

According to the ATC definition of North America Electric Reliability Council (NERC), this paper mainly studies two margins of ATC: TRM and CBM. Considering calculation accuracy and time, a novel method is proposed to calculate ATC based on Monte Carlo simulation and sensitivity analysis considering large amount of uncertainties involved in TRM and CBM, which have large impacts on the value of ATC. The steady state constraints and voltage stability and transient stability constraints are taken into account. The iterative solution based on PSASP by China EPRI is developed. IEEE 14-bus test system is used to verify the presented approach. The results show that the model and algorithm is correct and effective. Compare to the deterministic methods, the proposed approach gives the value of ATC more accurate. When we transfer the theoretical achievements to practical applications, we found some work needed further study.

1. The proposed approach in this paper, like most of other methods, is mainly suitable for theoretically calculating ATC at a time point. But in practical power markets, load and trading scheme are continuously change, so it is necessary for ATC computation approach to consider load demand and relevant bidding strategies continuous variation. The states, stochastically produced in terms of probability distribution introduced above, should be related to current system operation, and when simulating continuous ATC calculation, it should be additionally considered the transfer probability from the current state to next one. Unit commitment and maintenance scheduling even bidding strategies should be taken into account.

2. Existing Transmission Commitment (ETC) should be considered more detailed in continuous ATC calculation. Because in power

markets, ATC is an important signal to all participants, and the decision and evaluation about the risk of different trading is also worth of consideration.

How to improve ATC is an attractive issue. FACTS device is a good choice, and it can not only improve the value of ATC, but also improve the stability of the system. But how to decide the optimal installation position of the FACTS device and how to coordinate multiple FACTS devices are still need further research.

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VII. BIOGRAPHIES

Yajing Gao was born in Hebei Province, China, on Dec 31, 1980. She received the B.S. degree in Electrical Engineering, from North China Electric Power University (NCEPU) in 2002. Now she is pursuing the Ph. D. degree at NCEPU. Her research interest is electricity markets.

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