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## TRM Quantification Considering Market and System Uncertainties

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### ABSTRACT

*Available Transfer Capability (ATC) is a measure of the transfer capability remaining in the physical transmission network for the future commercial activity. There are three main components to calculate ATC, TTC, CBM, and TRM. Among these three components, this paper describes quantification method for TRM considering system and market uncertainties. To calculate TRM, uncertainties of power system and market, such as generation output, bus voltages, line outages, and cancellation of power delivery contracts are considered as complex random variables (CRV) in the PLF process. One distinguishing feature of the proposed method is that TRM can be computed as a function of a specified probability margin, which offers operational flexibility to system operator. Suggested TRM quantification method based on PLF analysis verified using 7 bus RBTS. The result shows that proposed method can take into account various system uncertainties in TRM quantification.*

### 1. INTRODUCTION

Successful implementation of electric power deregulation requires efficient methods for calculating available transfer capability of power systems. In the operation of bilateral markets, Available Transfer Capability (ATC) is used to allocate reservations of transmission rights, and in the pooled markets, transfer capability combined with bid information can be used to help allocate financial transmission rights or transmission congestion contracts. ATC values are the key to competitive electricity markets as indices that determine whether proposed particular transactions of electric power between participants could be approved or not.

By the NERC definition [1], ATC determination involves several parameters, namely, Total Transfer Capability (TTC), Transmission Reliability Margin (TRM) and Capacity Benefit Margin (CBM). Among these three parameters, TRM is the reserved capacity to account for the uncertainties of network conditions as well as calculation error. And it is desirable to properly quantify the uncertainty in the ATC calculation as a safety margin so that the power system will remain secure despite the uncertainties such as generator/transmission line outages, load deviation and line impedance changes [2-4].

There are many approaches to quantify TTC and TRM, and most of the approaches are based on deterministic methods such as Continuous Power Flow (CPF) and Power Transfer Distribution Factor (PTDF) [5, 6]. However, these conventional deterministic methods show only snap shots of certain condition of network, and it is impractical to calculate every possible combination of bus loads and generator outages. Therefore, there is no room for system operators to adjust TRM to reflect system uncertainties, such as bad weather conditions and load forecasting error.

To address these shortcomings of deterministic methods, this paper suggests a probabilistic approach to quantify TRM using Probabilistic Load Flow (PLF) [7, 8] based on the method of moments

[9, 10]. The suggested method can take into account network uncertainties such as generation outage, bus voltages, load deviation, line outage, contract cancellation while TRM calculation, and TRM value can be quantified using the suggested method according to the desired probabilistic margin based on probability density function (PDF) of interconnection transmission line.

In the case study, RBTS with 7 buses is used for comparing results of conventional deterministic method and suggested PLF method. Results show that suggested PLF method can offer the range of line flow and bus voltage variation at the limiting element, and operational flexibility to determine TRM value reflecting the system uncertainties.

## 2. ATC AND PARAMETERS

ATC is determined as a function of increases in power transfers between different systems through prescribed interfaces, and ATC determination involves several parameters, TTC, CBM and TRM.

The definitions of these three parameters are given as follows:

- (1) The TTC is the largest flow through the selected interface, which causes no thermal overloads, voltage limit violations, voltage collapse and/or any other system security problems such as transient stability.
- (2) The TRM is the reserved capability that accounts for uncertainties related to the transmission system conditions, contingencies, and parameter values. The TRM is the amount of transmission capability required to ensure that the interconnected network is secure under a reasonable range of uncertainties in system conditions.
- (3) The CBM is the amount of transmission transfer capability reserved by Load Serving Entities (LSE) to ensure access to generation from interconnected systems. CBM is reserved to meet the generation reliability requirements of LSE.

Among these parameters, TRM and CBM are the factors that account for the uncertainty and reliability in the power system, and the TTC and ATC can be expressed as:

$$TTC = \text{Min}\{ \text{Thermal}, \text{Voltage}, \text{Stability}, \text{Limits} \} \quad (1)$$

$$ATC = TTC - TRM - ETC - CBM \quad (2)$$

TRM accounts for the inherent uncertainty in system conditions such as generation/line forced outage and the need for operating flexibility to ensure reliable system operation as system condition changes, and several approaches to the computation of TRM have been proposed. The first approach is based on repeated computation of TTC using variations in the base case data considering system uncertainties. The second approach is a single repeat computation of the TTC using limitations reduced by a fixed percentage. The third is simply to reduce the TTC by a fixed percentage.

The first one is a Monte Carlo statistical approach that can provide an accurate ATC value but needs plenty of computational effort and time. The second and the third approaches are the conventional deterministic methods, which are simple and easy to apply in complex large power systems but normally result in a lower ATC value.

## 3. PROBABILISTIC APPROACH TO TRM CALCULATION

The load flow study performs the steady-state simulation of a power system. Conventional methods of load flow analysis depend on specific values for loads, generation inputs, and network

conditions, and any variation of them will require a new power flow solution.

In the operational or planning point of view, especially in a complex market situation, it is desirable to assess bus voltages and line flows for a range of load generation and market conditions. However, it is impractical to carry out standard deterministic load flow computations for every possible or probable combination of bus loads, generating unit outages, and contract cancellation because an extremely large computational burden is expected.

A practical way to overcome these difficulties of standard load flow analysis is to select a limited number of variations of loads and assume that output of each generating unit is equal to the expected value, and this method is used in conventional CPF method to calculate TRM. However, the results obtained using this method are based on partial information of probable states of network and market condition, and therefore, are inaccurate.

To take into account uncertainties of the network and market, this paper suggests probabilistic approach using PLF, which is based on the method of moments to quantify TRM value with the desired probabilistic margin.

The PLF method converts the load flow problem from deterministic to stochastic formulation, and the results obtained by stochastic approach define the range of variation of load flow analysis output quantities, i.e., active and reactive power, bus voltage and line flows along with associated probabilities.

In this paper, the variables of power flow analysis are considered as complex random and the power flow equations are solved in the moment domain. Method of moments is used to calculate complex random variables for convolution of various random variables. The Gram-Charlier expansion is used to approximate the probability density function of the most limiting line flow or bus voltage from the knowledge of moments and cumulants obtained through the PLF analysis.

### 3.1 CRV and its Moments and Cumulants

In this paper, generation output, line outage, and cancellation of power delivery contracts are considered as discrete complex random variables (CRV) to reflect the stochastic characteristics of the network and the market. As can be seen in Fig. 1, generator, line and contracts are modeled as a 2-states model.

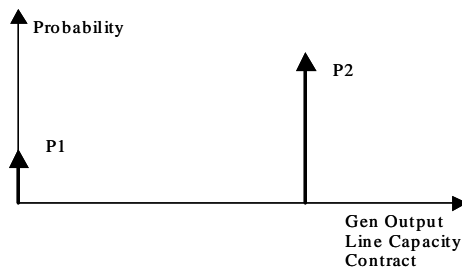


Fig. 1 Discrete PDF of Generator Line and contract

Referring to the PDF of CRV as shown in Fig. 1, the moments about origin of order  $t$  of the 2-state CRV  $Z$  are defined as:

$$m_t = E[Z^t] = \sum_{i=1}^2 Z_i^t P_i \quad (3)$$

where,  $E[.]$  = the expected value of RV,

$Z_i^t$  =  $t$ th power of  $i$ th value of CRV  $Z$ , and

$P_i$  = probability of  $i$  th value of CRV.

The corresponding cumulants are obtained using the relationship between moments and cumulants as given below:

The recurrence relationship between cumulants and moments are:

$$\begin{aligned} k_1 &= m_1 \\ k_i &= m_i - \sum_{r=1}^{i-1} \binom{i-1}{r} k_{j-r} m_r, \quad j \geq 2 \end{aligned} \quad (4)$$

or equivalently

$$\begin{aligned} m_1 &= k_1 \\ m_j &= k_j + \sum_{r=1}^{j-1} \binom{j-1}{r} k_{j-r} m_r, \quad j \geq 2 \end{aligned} \quad (5)$$

In PLF calculation, moments and cumulants are applied each in multiplication and addition operation.

### 3.2 The Concepts of PLF

The first step in the solution of the PLF is to find the net injected power at each bus except slack bus. The PDF of total available capacity at each bus may be obtained by convolving the individual PDFs of the units connected at the bus using the cumulants method.

After calculating net injected power at each bus, moments of Y-bus elements are to be calculated for voltage calculation. The moments of voltage are calculated by iteration method and, moments of voltage equation for the  $(n+1)^{th}$  iteration are given by:

$$m_t(V_{k(n+1)}^r) = (1/m_t Y_{kk}^{(r)}) m_t [S_k^* / (V_{k(n)}^{(r)})^* - \sum_{i=1}^{k-1} Y_{ki}^{(r)} V_{i(n+1)}^{(r)} - \sum_{i=k+1}^n Y_{ki}^{(r)} V_{i(n)}^{(r)}] \quad (6)$$

where,  $Y_{ki}$  = admittance between buses  $k$  and  $i$ , and  
 $V_{k(n)}$  = voltage at bus  $k$  for  $n$  th iteration.

The iterative process is continued till the change in magnitude of bus voltage is less than a certain specified tolerance for all bus voltages. After calculating the bus voltages, moments of line currents and line powers are obtained by solving the current equations in moment domain.

The Gram-Charlier expansion is selected to convert moments to PDF. Consider the PDF of a RV, expanded in terms of standardized RV and its corresponding normal PDF, as follows:

$$\begin{aligned} f(z) &= N(z) \\ f^{(i)}(z) &= (-1)^i H_i(z) f(z), \quad i = 0, \dots, r \end{aligned} \quad (7)$$

where,  $z$  =  $(x - \mu) / \sigma$ , and

$$H_r(x) = \sum_{i=0}^{\lfloor \frac{r}{2} \rfloor} A(r, i) x^{r-2i}$$

Using Gram-Charlier expansion mentioned above, PDF of line flow or bus voltage at the most limiting element by which TTC is limited, can be calculated.

### 3.3 TRM quantification using PLF

The process to quantify TRM using the proposed PLF begins with calculating base case TTC using CPF method. As a result of this CPF process, the most limiting element that limits the base case TTC can be found, and the PLF is solved based on the base case TTC condition that the most limiting element is at its full load.

The PLF analysis shows the PDF of line flows and bus voltages of tie lines and its relevant buses, and new reduced line flow or bus voltage limit for the tie lines can be calculated using the PDF of the elements, so that the probabilistic margin of the corresponding element can be obtained.

The new line flow or bus voltage limit can be calculated by integrating the PDF from the original limiting value until desired probabilistic margin (PM) is obtained. The Eq. (8) and Fig. 2 show this concept in detail.

$$PM = \frac{\int_{NewLimit}^{ExistingLimit} PDF( Lineflow or Bus Voltage )}{ExistingLimit} \quad (8)$$

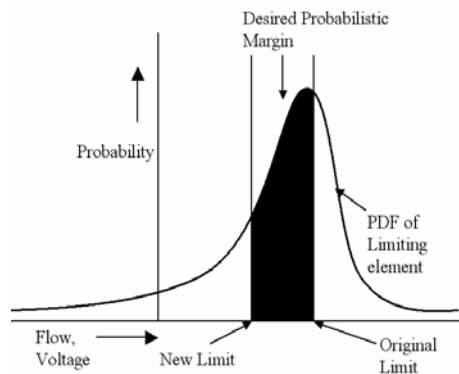


Fig. 2 New Flow and voltage Limit using PDF

As can be seen in Fig. 2, probabilistic margin is the margin for the line flow or bus voltage change of the tie line and connection point bus, which results from the uncertainties of the network and market. If the TTC is limited at the modified line flow or bus voltage limit, the system has probabilistic margin to remain secure after contingency, which could increase line flow or bus voltage at the tie lines and connection points. Using Eq. (8) and the iterative method, we can adjust new limit of the tie line elements, which is in accordance with the desired probability margin.

After adjusting the limits, new TTC is calculated by CPF. As a consequence, TRM is the difference of the base case TTC and new TTC reduced by new limit of the tie line.

Fig. 3 shows the flow chart of TRM quantification process using PLF. As can be seen in this flowchart, PLF is executed only once in the whole process, otherwise repeated power flow calculation should be executed for the several alternative cases to reflect the system uncertainties, which would bring the computational burden.

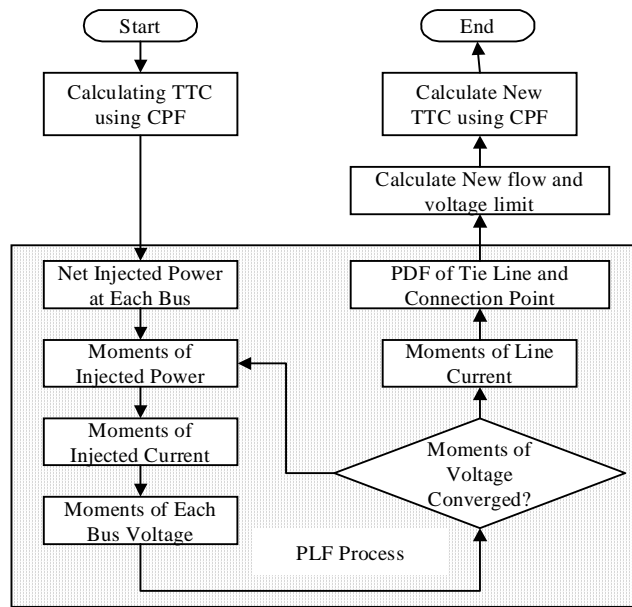


Fig. 3 Flow chart of TRM calculation using PLF

#### 4. CASE STUDIES

##### 4.1 Test System

The RBTS with 7 buses is used to demonstrate the suggested method to quantify TRM. The diagram of the RBTS 7 bus is shown in Fig. 4, and the system is divided into two areas, which are connected through 3 tie lines, and the tie line flow limit of this system is 120MW, and bus voltage range is  $\pm 0.2$  pu.

In this case study, Bus 7 is selected as the selling point (Injection), and the buying point is Bus 3(Extraction). Tie lines between the areas are line 2-5, 2-6, and 4-5. To consider the effect of other power transfer contracts on the TRM calculation, transactions from bus 6 to bus 2 with 20MW, and from bus 6 to bus 3 with 10MW are simulated. The cancellation probability of each transaction is set as 0.1.

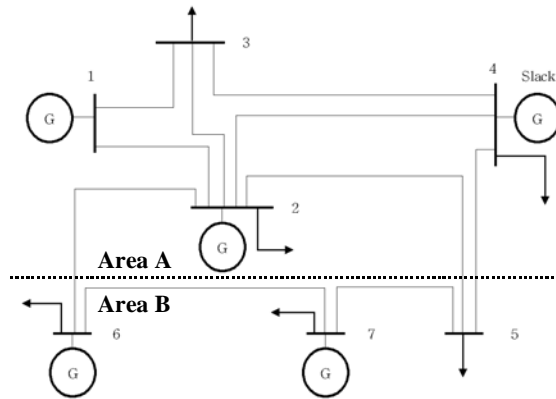


Fig. 4 RBTS 7 Bus System

#### 4.2 TTC, TRM and ATC calculation using CPF

First, conventional CPF method is applied to calculate TTC and TRM of the test system to compare results with proposed PLF method.

TRM is calculated by comparing the TTC results of several alternative cases such as rating reduction, line outage and line impedance variation. For the rating reduction case, the ratings of line flow and bus voltage are reduced by 3% of its base case rating. Line reactance is both increased and decreased by 10% from its original reactance for variation of line impedance case, and 3 tie-line outages are considered for the line outage case.

In Table 1, the results of TTC, TRM and ATC from Area B to Area A using conventional CPF method are listed. It can be seen that TTC of the base case is 81.3 MW and TRM is determined at the line outage case at the line 2-6 because minimum TTC is appeared at the rating reduction case among all the alternative cases. As a result, TRM and ATC are determined as 13.1MW and 68.2MW, respectively. It is noticeable that as a nature of the deterministic method, conventional CPF method shows one fixed value regardless of network conditions.

Table 1 TTC, ATC and TRM using Conventional CPF Method

	TTC[MW]	TRM[MW]	ATC[MW]
Base Case	81.3	13.1	68.2
Reactance : +10%	75.3		
Reactance : -10%	83.2		
Rating reduction	70.8		
Line 2-6 outage	68.2		
Line 2-5 outage	77.3		
Line 4-5 outage	78.6		

#### 4.3 TRM quantification using PLF

The first step to quantify TRM using PLF is to calculate base case TTC using conventional CPF. Next, PLF is solved with the initial data that reflects the base case TTC condition. As a result of PLF analysis, the PDFs of tie lines flow and connection points voltage are obtained. In this case study, PDF of 3 tie lines(line 2-5, 2-6, and 4-5) and 4 connection points(bus 2, 4, 5, and 6) are analyzed, and the Figs. 6, and 7 are show the line flow and bus voltage PDFs respectively.

As can be seen in Fig. 5, PDF of line 2-6 shows its peak value about 120MW, the line flow limit, and this PLF result is well accordance with the deterministic power flow calculation. Because base case TTC is reached its maximum value when line flow at line 2-6 hit its limit 120MW. In Fig. 6, bus 5 shows the worst value among the 4 connection points, but bus 4 has low curvature, and it means that small variation of system condition can cause large voltage deviation at bus 4.

To insure the system security after system fault or transaction cancellation, new line flow and voltage range limit should be calculated by Eq. 8, which reflects desired probabilistic margin. In this case study, new line flow limit at tie line 2-5 and 4-6 are not calculated because those line flow values are too low to be a constraint condition of TTC. The results of new line flow and voltage limits with 10% of probabilistic margin are shown in Table 2.

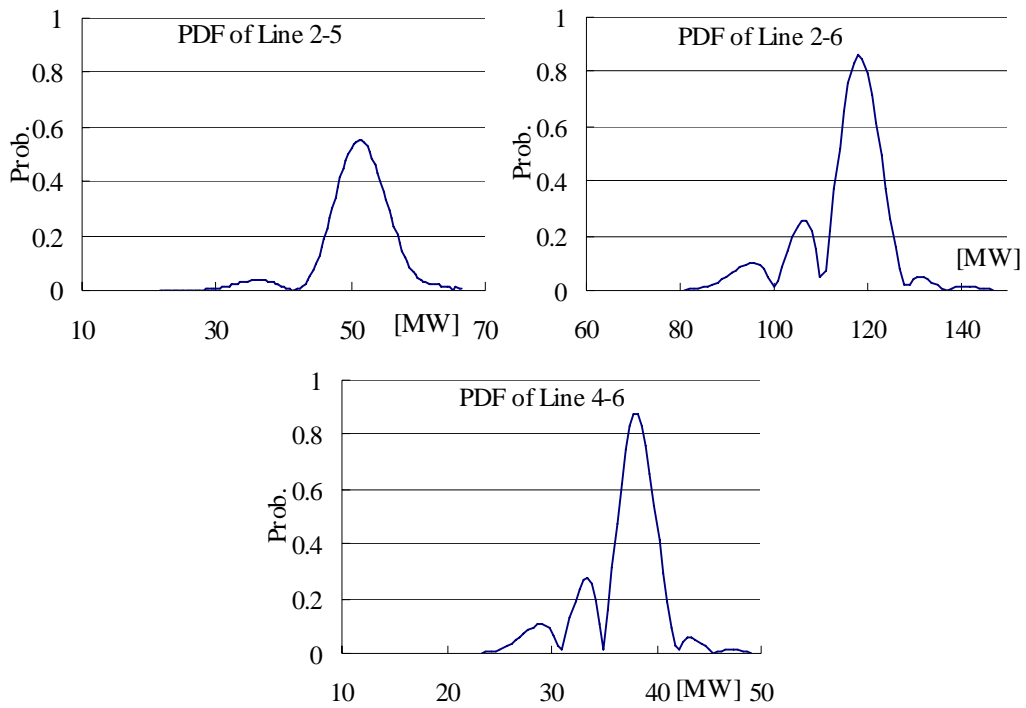


Fig. 5 PDF of 3 Tie Lines

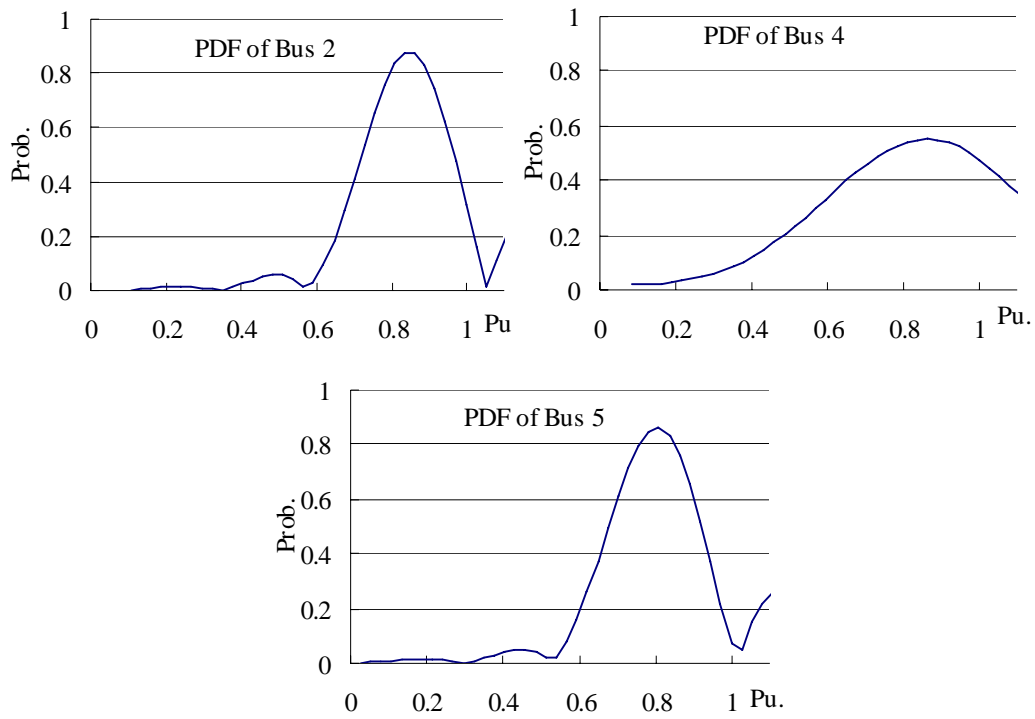


Fig. 6 PDF of 4 Connection Points



Table 2 New Flow and Voltage limit with 10% of Probabilistic Margin

Flow Limit of Line 2-6	116.5 [MW]
Low Voltage Limit	
Bus 2	0.835 [pu.]
Bus 4	0.892 [pu.]
Bus 5	0.863 [pu.]
Bus 6	0.852 [pu.]

The next step to quantify TRM is calculating TTC using CPF with modified line flow and voltage limits. The result is shown in Table 3. In this new TTC calculation, the low voltage at bus 4 limits TTC at 71.1MW.

Table 3 TRM using PLF method

Base case TTC	81.3 [MW]
TTC with New Limit	71.1 [MW]
TRM using PLF	10.2 [MW]

As can be seen in Table 3, TRM with the desired probabilistic margins can be calculated by the suggested PLF method, this characteristic can give operational flexibility to system operator and this is the main advantage of suggested TRM quantification method using PLF. Compared with the deterministic quantification method, PLF method can take into account various system and market uncertainties in one PLF analysis.

## 5. CONCLUSIONS

This paper has presented a new technique to estimate TRM with a stochastic procedure. According to the NERC definition, TRM is the reserved capacity to account for the inherent uncertainties related to the transmission system conditions, contingencies, and parameter values. The conventional method to quantify TRM is based on deterministic load flow method that carries out load flow analysis repeatedly for a limited number of variations of network and market conditions. However, the result of this deterministic method is just one fixed value of numerous possibilities of the future network and market conditions and therefore, does not reflect the stochastic characteristics of the transmission system.

To overcome these shortcomings, PLF method is proposed, and the uncertainties of network are considered in the quantification process by applying PLF with the method of moments.

The results of the case study show that suggested PLF method could assess the range of line flow and bus voltage variation by the system uncertainties, and modify new line flow and bus voltage limit according to the desired probabilistic margins, which give flexibility to quantify TRM. By using the suggested PLF method, TRM can be determined in accordance with weather, system load, and market transaction conditions by the system operator.

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