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Evaluation of Transfer Capability Considering Uncertainties of System Operating Condition and System Cascading Collapse

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Abstract**—**Over the past few decades, power system industry in many developing and developed countries has gone through a restructuring process of the industry where they are moving towards deregulated power industry. This situation will lead to competition among the generation and distribution companies to provide quality and efficient production of electric energy, which will reduce the price of electricity. Therefore it is important to obtain an accurate value of the available transfer capability (ATC) and transmission reliability margin (TRM) in order to ensure the effective power transfer between areas during the occurrence of uncertainties in the system. In this paper, the TRM and ATC is determined by taking into consideration the uncertainties of the system operating condition and system cascading collapse by applying the bootstrap technique. A case study of the IEEE RTS-79 is employed to verify the robustness of the technique proposed in the determination of TRM and ATC.

Keywords**—**Available transfer capability, bootstrap technique, cascading collapse, transmission reliability margin**.**

I. Introduction

With the movement towards the open transmission access, quantifying the transmission transfer capacity of an interconnected power system is becoming a very important issue of concern to both system planners and operators which has direct to the definition of available transfer capability (ATC). ATC is a measure of ability of the interconnected system to reliably and efficiently transfer electric power from one area to another area by means of transmission lines under specified system conditions [1]. Mathematically, ATC is defined as the total transfer capacity (TTC) minus the total amount of transmission reliability margin (TRM), existing transmission commitments and also the capacity benefit margin (CBM) [2]. By definition, TTC is the maximum quantity of power that can be transmitted in a system while meeting all the specific set of pre- and post- defined contingency system conditions. TRM is the maximum amount of transmission capacity essential to make sure that the transmission network is protected under a reasonable range of uncertainty in the system operating condition. CBM is the amount of transmission capability reserved by load serving entities to meet the generation reliability requirements [3].

There are various methods used to perform the analysis of power system reliability. Venkata et al. [4] applies the particle swarm optimization (PSO) to obtain the optimal location for Flexible Alternating Current Transmission System (FACTS) devices by estimating the feasible optimal setting for the FACTS in order to enhance power transfer capability of the system. A hybrid mutation particle swarm optimization (HMPSO) technique is used by Farahmand et al. [5] for improved estimation of ATC. Rodrigues et al. [6] uses the Monte Carlo method together with Sequential Simulation (MCMSS), to generate system uncertainties such as hourly load fluctuations and equipment availabilities. These uncertainties are used to assess the sequential variations in the determination of ATC. Zaini et al. [7] also takes into consideration system uncertainties such as system operating condition and transmission line outages in order to determine the TRM and also ATC. However, this research uses the bootstrap technique in order to estimate the TRM and ATC. In order to consider the uncertainties of power system operating conditions in the computation of ATC, various approaches have been proposed to assess the ATC. However, at present, not much work has been done in the assessment of TRM.

This paper presents a method to evaluate the TRM by taking into consideration specific uncertainties using bootstrap technique. Particularly, parametric bootstrap technique is applied in order to randomly generate the uncertainties of system parameters which are the hourly peak loads in a day and system cascading collapse. After that, the ATCs in a day are calculated based on the two uncertainties of the system parameters. The effectiveness of the proposed method in evaluating TRM and ATC is validated using the IEEE RTS-79. The advantage of using parametric bootstrap technique is that, large uncertainty of ATCs generated by bootstrap can produce accurate result of TRM and also it could give realistic information of uncertainty in the determination of TRM.

II. Evaluation of TRM Using Bootstrap Techniques Considering the Uncertainties of System Operating Condition

This section will explain on the accomplishment of the bootstrap technique that is used to determine the large

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uncertainty of ATCs. The used of parametric bootstrap technique is basically to produce random values of ATCs. The determination of ATCs is based on a certain percentage of bootstrap confidence interval. The results of the ATCs obtained is then be used to determine the TRM. The next sub sections will explain on the implementation of the proposed method.

A. Calculation of Transfer Capability Uncertainty Using Parametric Bootstrap Technique

This section discusses on the parametric bootstrap technique used to generate the large uncertainty of ATCs that will later be used to determine the value of TRM. The procedures to perform the parametric bootstrap method are as follows [8].

a) Take $ATC_1, ATC_2, ATC_3, \ldots, ATC_n$ as a sample of data points which they are the original variables of ATC in a specified day where *n* is a positive integer representing the total number of time intervals in a day. The first-order sensitivity approach is used to establish the inherent variables of ATC based on the original variables of the system operating condition. The first-order sensitivity is used because it provides fast computation of ATC [8] and is given by :

$$ATC_n = ATC^o + \frac{\partial ATC}{\partial x}(x_n - x^o) \quad (1)$$

where,
ATC^o is the base case value of ATC at a given case of power transfer;
$\frac{\partial ATC}{\partial x}$ is the change of ATC with respect to the change of the system operating condition for example, the load demand, also known as the first-order sensitivity.
x^o: Base case system operating condition;
x_n: Variables of system operating, such as the hourly peak load;
n: 1, 2, 3… *N*; where *N* is the total number of time intervals in a day.

Slightly increase the system parameter, *x* which is the system loading and hence perform the recursive AC power flow that will vary the value of power transfer. Followed by that, the sensitivity is calculated using (1).

b) Determine the parametric distribution using the normal cumulative distribution function (CDF) which is the best representative of parametric distribution that fits to the empirical distribution factor of the actual values [3].
c) Generate random number of *n* values to replace ATC_n with the non-parametric bootstrap sample, ATC_n^*. The outcome shows that the non-parametric bootstrap sample, ATC_n^* randomly replicates from the original sample, ATC_n.
d) Repeat step (c) in order to obtain $ATC_{n,b}^*$, where $\mathrm{b} = 1,2,3,\ldots,\mathrm{B}$ and *B* is the number of samples of non-parametric bootstrap samples.
e) Determine the parameters of the normal CDF which are the mean and variance of each non-parametric bootstrap sample. The mean and variance is given by (2) and (3) respectively.

$$\mu(ATC_b^*) = \frac{1}{N}\sum_{n=1}^{N} ATC_{n,b}^* \quad (2)$$

$$\sigma^2(ATC_b^*) = \frac{1}{N-1}\sum_{n=1}^{N}\left[ATC_{n,b}^* - \mu(ATC_b^*)\right]^2 \quad (3)$$

f) Apply (4) to obtain the parametric bootstrap samples with normal random variables and it represents the ATCs in a day with large uncertainty.

$$ATC_{n,b} = rand_n\left[\sqrt{\sigma^2(ATC_b^*)}\right] + \mu(ATC_b^*) \quad (4)$$

g) Arrange the parametric bootstrap samples, $\mathrm{ATC_{n,b}}$ by referring to the mean, $\mu(ATC_b^*)$ sorted in ascending order.
h) Select a parametric bootstrap sample based on the confidence interval of the mean bootstrap sample, $\mu(ATC_b^*)$. The preferred (1-α) x 100% bootstrap confidence interval of uncertainty is in the range of $ATC_{n,b=q1}$ and $ATC_{n,b=q2}$.

where,
q1= $\left(\frac{B\alpha}{2}\right)$
q2= *B* – *q1* + 1
B is the number of bootstrap sample
α is the degree of confidence
A parametric bootstrap samples, $ATC_{n,b}$ is then used in the determination of TRM.

Step (a) to step (e), (g) and also (h) is the method of non-parametric bootstrap. It can be used to determine the TRM. For the parametric bootstrap sample, $ATC_{n,b}$ that is obtained in step (g) are substituted by the non-parametric bootstrap samples, $ATC_{n,b}^*$ that has been obtained in step (d). Therefore, $ATC_{n,b=q1}$ in (h) represents the non-parametric bootstrap samples which have been selected based on a specified confidence interval of the non parametric bootstrap samples. It is then being used in the determination of TRM.

B. Determination of TRM Using Bootstrap Techniques

The following method is performed in order to obtain the TRM for each case of power transfer by using the bootstrap techniques.

a) Start the simulation from a solved base case AC power flow solutions.
b) Identify the bootstrap sample, *B*, and also the percentage of bootstrap confidence interval, α. Obtain the large uncertainty of ATCs that is estimated at a pre-defined percentage of bootstrap confidence interval by using procedure in previous section. The actual variables of transmission line impedances and hourly peak loads in a day are the factors considered in the determination of the ATCs by using the bootstrap techniques. $\mathrm{ATC_{n,b=q1}^{g}}$ is representing the bootstrap samples, $\mathrm{ATC_{n,b}}$ at different factors and it is approximated at a certain value of α.

where,
g= 1, 2, 3,…, G
G is the total number of factors considered in the analysis.

c) Establish the parametric or non-parametric bootstrap samples estimated at 0% of bootstrap confidence interval where it represents as the actual variables of ATC in a day.
d) For a certain power transfer, calculate TRM_n by using (5) where it represents the value of TRM at *n*th time interval.

$$TRM_n = \sqrt{\sum_{g=1}^{G}\left(ATC_{n,b=0\%}^{g} - ATC_{n,b=q1}^{g}\right)^2} \quad (5)$$

where,
$ATC_{n,b=0\%}^{g}$ is the value of ATC estimated at 0% bootstrap confidence interval and it is calculated using the first order sensitivity $\frac{\partial \text{ATC}}{\partial \text{x}}$.
$ATC_{n,b=q1}^{g}$ is the value of ATC estimated at various factors and it is also calculated using the first order sensitivity $\frac{\partial ATC}{\partial x}$.

First order sensitivity $\frac{\partial ATC}{\partial x}$ provides fast computation of ATC and it is based on the limiting point of system constraints [9]. For each *n*th time interval, the determination of TRM_n is performed by using the following procedure.

i. At each *n*th time interval, identify the value of $ATC_{n,b=0\%}^{g}$ where this procedure is performed on the chronological (sequential) of $ATC_{n,b=0\%}^{g}$. The chronological arrangement of $ATC_{n,b=0\%}^{g}$ is the same as the chronological arrangement of the actual ATCs.
ii. Identify the percentile of variability or the percentage of normal CDF for $ATC_{n,b=0\%}^{g}$ at each *n*th time interval where it is determine on the normal CDF of the $ATC_{n,b=0\%}^{g}$.
iii. Determine the numerical difference between $ATC_{n,b=q1}^{g}$ and $ATC_{n,b=0\%}^{g}$ at each percentile of variability for every factors of system operating condition, g.
iv. Repeat steps (i) – (iii) in order to determine the difference of ATCs for each g^{th} factor referring to the percentile obtained in step (ii). The factors considered in this study are the transmission line impedance and the hourly peak loads.
v. For a particular time interval represented by the percentile of variability, determine the variance for all the factors.
vi. Finally, the result in step (v) is applied to (5) in order to obtain the value of TRM at nth time interval.

e) Repeat procedure (b) – (d) to obtain the value of TRM at different case of power transfer.

III. Determination of TRM Considering the Uncertainties of Cascading Collapse

It is important for a power system operator to determine the uncertainty of cascading collapse due to its severe impact on a power system operation which would depreciate the amount of power transfer between areas. Therefore, the uncertainty of system cascading collapse should be considered in the assessment of TRM for effective selling and buying of electricity based on the information of ATC. This section will explain in detail on the procedure of TRM determination considering the uncertainties of system cascading collapse and chronological of hourly peak loads. The procedure of TRM by taking into account the uncertainty of system cascading collapse is summarized as follows:

(a) Increase the system loading condition, *l*, by 10% whilst retaining a constant power factor at all buses.
(b) Determine $\hat{P}_{C_i}$ for every initial line tripping event. The procedure to obtain $\hat{P}_{C_i}$ has been explained in detail in [9].
(c) Use (6) to calculate the risk of a system cascading collapse, R_c, at the current loading condition, *l*.

$$R_C = \frac{1}{I}\sum_{i=1}^{I}\hat{P}_{C_i} \quad (6)$$

where,
I is the total number of initial line tripping

(d) Repeat steps (a)–(c) to determine the risk of a system cascading collapse, R_c, for the next increment of system loading condition, *l*. This process is repeated until the system loading condition has been increased up to 240% from the base case. This is because, analytical hypothesis has proven that the risk of a cascading collapse, R_c, will start to increase exponentially from 150% until 240% of the system loading condition for the IEEE RTS-79 [10].
(e) Record the risk of a system cascading collapse for every increment of loading condition, R_{C_l}, obtained in step (d).
(f) Use (7) to calculate the ATC for every risk of a system cascading collapse obtained in step (e).

$$ATC_l = R_{C_l} \text{ x } ATC^o \quad (7)$$

(g) Sort the value of ATC_l in an ascending order and determine the TRM_{col} using (8).

$$TRM_{col} = D\sigma ATC_l \quad (8)$$

The value TRM_{col} obtained in (8) is the product of D with the standard deviation of ATC (σATC_{new}) where D is a constant that is used to increase the value of TRM as it is set to a higher percentage of normal percent PDF [11]. In a parametric bootstrap technique, the TRM_{col} obtained in (8) is combined with (5) at every *n*th time interval in order to evaluate the new TRM (TRM_n^{new}) that takes into account the uncertainties of system operating conditions and system cascading collapse. Therefore, the TRM_n^{new} selected at a certain percentage of confidence interval can be obtained by applying (9).

$$TRM_n^{new} = \sqrt{TRM_n^2 + TRM_{col}^2} \quad (9)$$

IV. Calculation of Available Transfer Capability

Generally, the procedure used to calculate ATC involves the determination of a base case power flow, network system response and maximum amount of power transfer so-called the total transfer capability (TTC). In this case study, the determination of ATC is performed by applying the repetitive

AC power flow solution under a particular set of system operating conditions. The procedure of ATC calculation is summarized as follows:

(a) Perform a base case ac power flow solution.
(b) Identify the areas of power transfer. The area-to-area transfer involves the participation of all generators in a specific selling area and all loads in a particular buying area.
(c) Increase the power transfer by referring to the additional amount of generation and load equally elevated at the selling area and buying area, respectively.
(d) Determine the maximum amount of power transfer or TTC once the MVA power flow limit or voltage magnitude limit is violated.
(e) Compute the value of ATC which is the TTC minus the base case power flow and TRM_n^{new}.

In step (e), the actual value of ATC is determine at every time interval of TRM_n^{new}. This is contrary to base case ATC, ATC_0 in which it is obtained by considering the base case system operating conditions and also without considering the TRM.

V. Results and Discussion

This section discusses on the results of TRM and ATC by taking into consideration the uncertainties of chronological hourly peak loads and system cascading collapse. The proposed technique is tested on the IEEE RTS-79 [12]. This system consists of 32 generating units with the total generation capacity is 3405MW, 20 load buses summing up to 2850MW total load and 38 transmission lines. The discussion of TRM and ATC in the following explanation will focus only on the transfer case from area 3 to area 2. The chronological hourly peak loads on 1st March 2002 is selected as a case study for the analysis of TRM and ATC for IEEE RTS-79. The sequential hourly peak loads on 1st March 2002 obtained from [7] is depicted in Fig. 1.

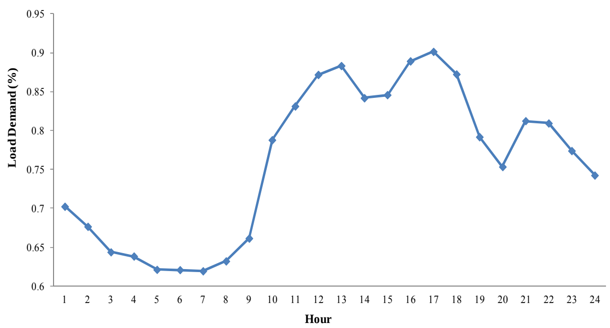

Fig. 1 Profile of hourly peak load for 1st March 2002

The sequential hourly peak loads are applied into the parametric bootstrap technique in order to produce numerous samples of ATCs with large uncertainty required for TRM determination. The bootstrap samples of ATCs are usually randomly generated through normal distribution referring to the sequential hourly peak loads. In order to ensure the accurateness of TRM estimation, 2000 parametric bootstrap samples of $ATC_{n,b}$ are determined in this case study. Equation (5) is used to calculate TRM_n for every time interval by considering the $ATC^g_{n,b=0\%}$ and $ATC^g_{n,b=95\%}$. Fig. 2 shows sequential variations of ATC at 0% and 95% of bootstrap confidence interval. For exemplar, the inherent ATC, $ATC^g_{n,b=0\%}$ of 206.78 MW is obtained at 20:00 hour. The 95% of bootstrap confidence interval that is selected to incorporate large uncertainty of hourly peak load resulting to $TRM_{n=20:00}$ of 19.72 MW. Therefore, at 20:00 hour, $ATC^g_{n,b=95\%}$ of 187.06 MW is obtained by subtracting the inherent value of ATC, $ATC^g_{n,b=0\%}$ = 206.78 MW with $TRM_{n=20:00}$ = 19.72 MW. For this reason, this shows that 187.06 MW is the utmost allowable amount of power that can be transferred from area 3 to area 2 despite of more uncertainty of hourly peak loads occurred at 95% of confidence interval.

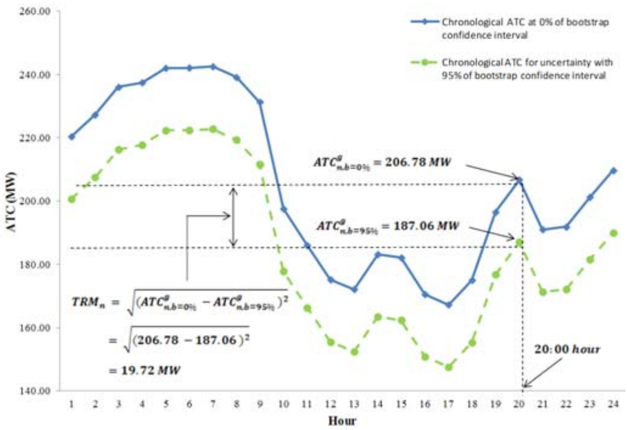

Fig. 2 TRM and ATC variations pertaining the uncertainty of hourly peak load

Fig. 3 shows sequential variations of ATC at 0% and 95% of bootstrap confidence interval. For exemplar, the inherent ATC, $ATC^g_{n,b=0\%}$ of 206.78 MW is obtained at 20:00 hour. The 95% of bootstrap confidence interval that is selected to incorporate large uncertainty of system cascading collapse yielding to $TRM_{col=20:00}$ of 18.99 MW. Therefore, at 20:00 hour, $ATC^g_{n,b=95\%}$ of 187.79 MW is obtained by deducting the actual value of ATC, $ATC^g_{n,b=0\%}$ = 206.78 MW with $TRM_{col=20:00}$ = 18.99 MW. Therefore, this shows that 187.79 MW is the maximum acceptable quantity of power that can be transferred from area 3 to area 2 regardless of large uncertainty of system cascading collapse occurred at 95% of confidence interval.

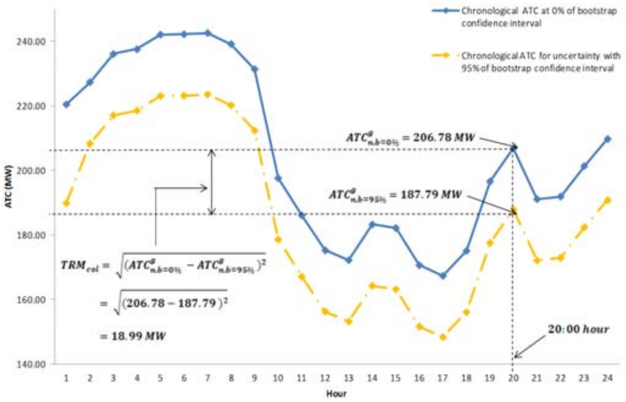

Fig. 3 TRM and ATC variations considering the uncertainty of system cascading collapse

Table I shows the results of TRM_n and TRM_{col} considering the uncertainties of hourly peak loads and system cascading collapse based on the transfer of power for different areas of IEEE RTS-79. It is observed that the TRM_n produced large amount of TRM for the power transfer of area 1 to 2, area 3 to 1 and area 3 to 2. However, TRM_{col} contributes large amount of TRM for the cases of power transfer for area 2 to 1, area 1 to 3 and area 2 to 3. This implies that both uncertainties of hourly peak load and system cascading collapse brings to a significant effect that yield to a large amount of TRM.

TABLE I
RESULTS OF TRM_n AND TRM_{col} FOR DIFFERENT TRANSFER CASES OF IEEE RTS-79

Area of Power Transfer	TRM_n (MW)	TRM_{col} (MW)
1 to 2	57.87	51.44
2 to 1	77.79	134.25
1 to 3	57.87	60.87
3 to 1	21.44	19.39
2 to 3	61.97	77.56
3 to 2	19.72	18.99

VI. CONCLUSION

In an electric power deregulation industry, the need for efficient and secure electricity is important in order to supply electricity to the whole nation. The importance of TRM is to make sure a safe and secure operation of the interconnected system due to the impact of huge uncertainty of the system operating condition. This paper has proven that the method used is applicable to provide accurate estimation of TRM and ATC by taking into consideration the uncertainties that could cause instability to the system. The TRM is calculated by considering the effect of system operating condition and cascading collapse. Results shows that the uncertainties occurred in a power system could reduce the amount of power transfer between areas. The bootstrap technique used in this paper is robust in providing realistic information which might occur in the future by producing new information with various level of uncertainty and at the same time, only requires a small number of inherent information. Therefore, it is important to determine accurate value of TRM and ATC by taking into consideration several uncertainties of system operating conditions.

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