Fast Determination of Simultaneous Available Transfer Capability (ATC)

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Abstract: This paper proposes a novel fast computational method to determine the simultaneous power available transfer capability (ATC) in a power system. This method consists of a fast estimation algorithm and a constrained power flow iteration. The ATC limiting factors considered in the method are: line thermal limits, bus voltage limits, and generator reactive power limits. When combined with the first line contingency considerations, this method will give the fastest ATC computing. The feature of this method is that it uses only one steady state power flow result for the fast estimation algorithm. Without further time consuming power flow iterations, it is the fastest estimation algorithm available. Based on the fast estimation, with a few more constrained power flow iterations, precise ATC value can be obtained. This method can be used to improve the speed of many available ATC programs. Especially, it may be used in addition to the widely used DC power flow program or simply replace it to provide additional voltage and var information, since DC power flow generally ignore voltage or var problems. This method can help the independent system operator (ISO) to determine the validity of the bidding results in an open access deregulated electricity market when timely ATC information is very important. It can also help the power market participants to place bids strategically when congestion happens.

Keywords: Interconnected power systems, Power system availability, Power system parameter estimate, Power system reliability, Power system security, Power transmission reliability, Simultaneous power transfer, Available transfer capability, ATC, ISO, Congestion, Deregulation.

I. INTRODUCTION

The deregulation of the US power market has imposed great impact on the US utility industry. At the beginning of the new environment, new technologies and computation methods are urgently needed to smooth out the transition from the regulated market to the new deregulated market. At the top of the list is a fast algorithm to calculate the available transfer capability (ATC) [1]. Without a fast calculation algorithm, the center computer of the independent system operator (ISO) can only perform calculation at present speed of about every 10 minutes, instead of any faster speed as the market would appreciate.

Since the need of a fast ATC calculation method appears only after the industry started deregulation recently, there are not many fast ATC calculation algorithms available today [3].

The ATC concept in this paper is as follows: from a base case, the load increases along a fixed direction, the generation also increases accordingly along a fixed direction considering contingencies. When a system-limiting factor is reached, the generation above the base case is called the available transfer capability (ATC). It is possible to have the loads in one area while the generation in another area provides power. This becomes an interarea ATC. The ATC concept is similar to NERC's incremental transfer capability [9,10]. The ATC is the minimum transfer under first line outage conditions, called the First Contingency Incremental Transfer Capability (FCITC).

The system-limiting factors that limit a power system's ATC are many. Among them are the line current limits, voltage magnitude limit, generator reactive power limit, and voltage collapse limit, etc.

The line current limit usually is a line's thermal limit. Too much current flow in a line may cause a line to droop or damage nearby connected equipments. DC power flow has been widely used to calculate thermal limit with great speed. But DC power flow can not deal with other limiting factors.

The bus voltage magnitudes also needs to be kept within reasonable limits. Voltage over-limit may cause damage to system equipments, and reduce the power quality to the customers. Low voltage sometimes is also an indication that the system is near a voltage collapse. Both high voltage and low voltage are regulated by system circuit breakers and pose limits to the power transfer.

Generators have reactive power output limits. After a limit is reached, a generator will not be able to regulate its bus voltage. It is degraded from a PV bus into a PQ bus. This may cause voltage collapse or system instability [2].

The voltage collapse is the upper physical limit that a power system can function properly. Beyond this point, no mathematical solution exists. This situation usually happens after a bus voltage has a significant drop or when a generator's var limit is reached. It is not considered here since the two factors that cause it has been considered.

Other system limits may include angular separation limit between two buses, etc. which are not considered here. But they can be considered as additional programs.

The ATC is calculated as the generation increment before any of these limits is reached. Usually ATC calculation also considers first line contingencies. This allows a power system to remain stable after most accidents.

This paper presents a new method to determine ATC taking considerations of the first line contingency condition. Precise solution can also be obtained at a little additional computational cost after the fast estimation algorithm. Compared to commonly used ATC calculation using continuation power flow [3], the presented method is far more efficient benefited by the estimation from sensitivity analysis.

II. THE FAST METHOD

The proposed fast method contains mainly two parts: the fast estimation algorithm and the constrained power flow equation that is based on the fast estimation results. The fast estimation algorithm also includes the modified power flow equation, the sensitivity analysis under both normal condition and first-line-outage conditions.

A. The power balance equation with direction information.

To estimate the available transfer capability (ATC), the generation direction and load direction have to be specified first, since different directions yield different results. The generation direction p_{gen} is defined from each additional generator output DP_G and load direction s_{load} from each additional load DS_L above the base case S^0.

$$p_{gen} = \frac{1}{\sum_{i=1}^{n} \Delta P_{G_i}} \begin{bmatrix} \Delta P_{G_1} \\ \vdots \\ \Delta P_{G_n} \end{bmatrix} \quad (1)$$

$$s_{load} = \frac{1}{\sum_{i=1}^{n} Real(\Delta S_{L_i})} \begin{bmatrix} \Delta S_{L_1} \\ \vdots \\ \Delta S_{L_n} \end{bmatrix} \quad (2)$$

The additional total generation above the base case is defined as $g \bullet p_{gen}$ where g is a scalar parameter, and the total additional load is defined as $R \bullet s_{load}$, where R is a scalar "slack" variable to balance g.

To including generation and load directions into consideration, the modified power balance equation has to have a special form. The modified power balance equation for an n bus system can be described in complex vector forms as:

$$S(l, m) = VI^* = V(YV)^* \quad (3)$$

$$S(l, m) - g \bullet p_{gen} - j\Delta Q_{gen} + \ell \bullet s_{load} - S^0 = 0 \quad (4)$$

where:

- l system state variables containing bus voltage magnitudes $|V|$ and angles q
- m controllable system parameter vector. (In this paper m is the line admittance, m is included in the Y matrix)
- p_{gen} unit generation direction vector
- g generation parameter (equals total generation above the base case, or, ATC of that direction)
- s_{load} unit load direction vector
- R slack variable needed for power balance
- DQ_{gen} generator reactive power output vector above base case
- S^0 Power injection into each bus at base case

The generator reactive powers in (1-4) are not specified since generators are treated as PV buses in a power flow equation and will be balanced after the power flow solution.

B. Estimation without contingencies

At just one steady state (x^0, g^0, m^0) that is also the base case (g=l=0), the modified power flow equation from (4) is:

$$F^0(x^0, g^0, m^0) = 0 \quad (5)$$

where x includes both l and R as variables, g is the parameter, m is system control parameter, and "^{0}" denotes base case. Assuming the control parameter m is fixed, then from (5)

$$F_x^0 dx + F_g^0 dg = 0 \quad (6)$$

or

$$\frac{dx^0}{dg} = -\left(F_x^0\right)^{-1} F_g^0 \quad (7)$$

Since voltage magnitudes and angles are used as variables in x during the modified power flow iteration and are obtained as the results, the line current magnitude calculated from those results will have to be taken from an absolute value of a complex equation or taken from a square root. To simplify the derivation, the square of the current magnitude is used. This will avoid taking absolute value of a complex equation or taking a square root of an equation. Thus great simplification can be made as will be shown in the following derivatives. The results will not be affected by the substitution. To apply to current amplitude, defining

$$II_i = \vec{I}_i \times \vec{I}_i^{\,*} = \left|\vec{I}_i\right|^2 \quad (i \;\forall\; lines) \quad (8)$$

Also considering the PQ bus voltage magnitude $|V_j|$, and generator reactive power output Q_k, the sensitivities of their magnitudes to generation increase are:

$$\begin{aligned} &\frac{dII_i^0}{dg} = \frac{\partial II_i^0}{\partial x}\frac{dx^0}{dg}; \quad \frac{d|I_i^0|}{dg} = \frac{1}{2|I_i^0|}\frac{dII_i^0}{dg} \;(i \;\forall\; lines) \\ &\frac{d|V_j^0|}{dg} = \frac{\partial |V_j^0|}{\partial x}\frac{dx^0}{dg} \quad (j \;\forall\; PQ\ buses) \\ &\frac{dQ_k^0}{dg} = \frac{\partial Q_k^0}{\partial x}\frac{dx^0}{dg} \quad (k \;\forall\; generators) \end{aligned} \quad (9)$$

Using linear estimation, the additional generation increment before each limit is reached can be expressed as:

$$\begin{aligned} &\Delta g_{|I_i|}^0 = \left(I_{limit}(i) - |I_i^0|\right) \Big/ \left(\frac{d|I_i^0|}{dg}\right) \quad (i \;\forall\; lines) \\ &\Delta g_{|V_j|}^0 = \left(V_{limit}(j) - |V_j^0|\right) \Big/ \left(\frac{d|V_j^0|}{dg}\right) \quad (j \;\forall\; PQ\ buses) \\ &\Delta g_{Q_k}^0 = \left(Q_{gen,limit}(k) - Q_k^0\right) \Big/ \left(\frac{dQ_k^0}{dg}\right) \quad (k \;\forall\; generators) \end{aligned} \quad (10)$$

The minimum of these Δg's is the system's available transfer capability (ATC) Δg^0

$$\Delta g^0 = \min\{\Delta g_{|I_i|}^0, \Delta g_{|V_j|}^0, \Delta g_{Q_k}^0\} \quad (11)$$

It also identifies the limiting factor as which line current, which bus voltage or which generator reactive power reaches its limit first.

C. Estimation under first line outages

C1. Estimate new state variables under line contingency

The above section only deals with one normal steady state without considering system contingencies. For security reasons, ATC should be considered under at least the first line outage situations. To estimate ATC under the first line outage situation, assuming still at state (x^0, g^0, m^0), from (5), assuming g is fixed at g^0, this leads to:

$$F_x^0 dx + F_m^0 dm_r = 0 \tag{12}$$

or

$$dx = -\left(F_x^0\right)^{-1} F_m^0 dm_r \tag{13}$$

where r represent the outage line, dm_r is the line admittance change which is

$$dm_r = 0 - m_r^0 \tag{14}$$

The new estimated state x can be obtained as

$$x^r = x^0 + dx = x^0 + \left(F_x^0\right)^{-1} F_m^0 m_r^0 \tag{15}$$

Noticing that here x^r is an estimated state only and not a precise solution after power flow iterations. The time of power flow iterations is saved. The possible error can be small and can be corrected as will be shown later. However, obtaining a precise solution from power flow equation instead of estimated solution can sometimes reduce the total computing time in certain cases as will be shown from the results, as it reduces the error of final estimation so that fewer constrained power flow iterations will be necessary.

From x^r, the new values of current $|I_i^r|$, PQ bus voltage magnitudes $|V_j^r|$, and generator reactive outputs Q_k^r can be easily calculated.

C2. Estimate new sensitivity under line contingency

At the line outage state x^r, the new sensitivities considering the first line contingencies can be obtained similar to (7).

$$\frac{dx^r}{dg} = -\left(F_x^r\right)^{-1} F_g^r \tag{16}$$

Since the above sensitivity is considered at x^r, $\left(F_x^r\right)^{-1}$ and F_g^r are both recalculated using the state x^r value. The admittance matrix Y^r needed for calculating $\left(F_x^r\right)^{-1}$ and F_g^r also need recalculation taking first line r outage situation where

$$m_r^r = 0 \tag{17}$$

The sensitivities can be obtained like in (9)

$$\frac{dII_i^r}{dg} = \frac{\partial II_i^r}{\partial x}\frac{dx^r}{dg}; \quad \frac{d\left|I_i^r\right|}{dg} = \frac{1}{2\left|I_i^r\right|}\frac{dII_i^r}{dg} \quad (i \,\forall\, lines\ except\ line\ r)$$
$$\frac{d\left|V_j^r\right|}{dg} = \frac{\partial\left|V_j^r\right|}{\partial x}\frac{dx^r}{dg} \quad (j \,\forall\, PQ\ buses)$$
$$\frac{dQ_k^r}{dg} = \frac{\partial Q_k^r}{\partial x}\frac{dx^r}{dg} \quad (k \,\forall\, generators) \tag{18}$$

C3. Estimate ATC under line contingency

For line r outage, its ATC Δg^r can be calculated as (9-10)

$$\Delta g^r_{|I_i|} = \left(I_{limit}(i) - \left|I_i^r\right|\right) \Big/ \left(\frac{d\left|I_i^r\right|}{dg}\right) \quad (i \,\forall\, lines\ except\ line\ r)$$
$$\Delta g^r_{|V_j|} = \left(V_{limit}(j) - \left|V_j^r\right|\right) \Big/ \left(\frac{d\left|V_j^r\right|}{dg}\right) \quad (j \,\forall\, PQ\ buses)$$
$$\Delta g^r_{Q_k} = \left(Q_{gen,limit}(k) - Q_k^r\right) \Big/ \left(\frac{dQ_k^r}{dg}\right) \quad (k \,\forall\, generators) \tag{19}$$

$$\Delta g^r = \min\{\Delta g^r_{|I_i|}, \Delta g^r_{|V_j|}, \Delta g^r_{Q_k}\} \tag{20}$$

After getting Dg^0 and Dg^r, the ATC $Dg*$ for the system under first line contingencies is

$$\Delta g^* = \min\{\Delta g^0, \Delta g^r\} \ (r \,\forall\, lines) \tag{21}$$

Note these calculations are all simple math manipulations without involving any power flow iterations.

D. Multi-line contingency consideration

If multi-line contingencies need to be considered, simple modification can be made by adding another m_s to m_r for line r and s contingency. Equation (15) will become

$$x^{r,s} = x^0 + \left(F_x^0\right)^{-1} F_m^0 m_r^0 + \left(F_x^0\right)^{-1} F_m^0 m_s^0 \tag{22}$$

And (16) will become

$$\frac{dx^{r,s}}{dg} = -\left(F_x^{r,s}\right)^{-1} F_g^{r,s} \tag{23}$$

where $Y^{r,s}$ will be used as necessary.

The results for multi-line contingency could be considered in addition to single line contingency with minimum added computation time.

E. Obtain the precise solution based on estimation

The fast estimation results can be double-checked and be used to obtain the precise solution, which will prevent large estimation errors from system nonlineraty. This can be done by solving the modified power flow equation along with the fast estimation results as the constraint. The result is a constrained power flow equation. The constrained power flow equation uses the combination of previous modified power flow equation and one more constraint equation [5].

For example, if the estimation result shows that line i's thermal limit is the ATC's limiting factor, then the constraint equation is:

$$C(x) = II_i(x) - II_{limit}(i) = 0 \tag{24}$$

If the ATC's limiting factor is a bus's voltage, then

$$C(x) = \left|V_j\right| - V_{limit}(j) = 0 \tag{25}$$

For a generator limit as the ATC's limiting factor

$$C(x) = Q_{gen,k}(x) - Q_{gen,limit}(k) = 0 \tag{26}$$

The constraint equation for voltage collapse is also available but is not considered in this article.

The constrained power flow equation will be the combined equations as

$$\begin{pmatrix} F(x,g,m) \\ C(x) \end{pmatrix} = 0 \tag{27}$$

Notice in the above equations, g is treated like a variable similar to x, while m is still a fixed control parameter. In the constrained power flow equation, the admittance matrix Y is taken under the appropriate line contingency as indicated by the fast estimation. The solved g will be the precise solution of $g^*=Dg^*$ (at base case $g=0$).

When the estimation results show that several different limiting factors give close ATC estimations, several constrained power flow equations might need to be solved in parallel for each limiting factor, so the precise ATC and its limiting factor can be identified. For the correctly identified ATC and its limiting factor, the solved constrained power flow equation will show no other limit violation. If a wrong limiting factor is estimated, the results from the constrained power flow equation will show another limiting factor is violated and another constrained power flow equation needs to be solved for the violated limiting factor to get a smaller g. This process will repeat until the correct limiting factor is identified.

The constrained power flow equation will take roughly the same time to solve as a standard power flow equation. However, it takes the most computation time of the whole algorithm. Therefore it can be omitted if only the estimation results are required for timely information.

F. The final check steps

Linear estimation is usually accurate on current prediction, while voltage estimation can be highly nonlinear. This can be shown in a well know PV curve (nose curve) where the whole curve looks like a parabolic curve. The common industry practise usually limits the voltage between 0.9 per unit and 1.1 per unit. So it can be safely assumed that the voltage behaves linear during the narrow limits, which is a small portion of the PV curve.

Due to the tough industry safety standard, to reduce the error in the rare case where voltage is highly nonlinear during the narrow limits, a nonlinear factor a can be added to equation (10) and (19) so that

$$\Delta g_{|V_j|}^{factored} = a \times \Delta g_{|V_j|}^{estimated} \tag{28}$$

The value of a can be experimentally set fixed between 0.8 to 1.0. Or a can be set as a function of $\Delta g_{|V_j|}^{estimated}$.

Another safe guard against the rarely highly nonlinear case is the final check. This can be done by solving a normal power flow at determined ATC limit under no contingency situation ($g^* = Dg^*$ above the base case) to get a precise solution (x^*, g^*, m^0). Then steps as in (12-15) can be repeated to check against all limits, or, just to obtain a precise solution under each contingency at g^*. For the corrected ATC determination, there is one and only one limit violation, which is the ATC limiting factor. This process will take the computation time of a standard power flow and some linear manipulations.

However, if precise solutions from constrained power flow equations are obtained at each contingency, the final check steps will not be necessary. Further more, if choosing to obtain the precise solution at each contingency, only those contingencies with small ATC needs to be solved from constrained power flow equations, and those with relative large ATC estimation can be neglected to save computing time.

G. The whole algorithm

The whole algorithm is illustrated in Fig.1. This algorithm is also very flexible. Precise solutions can be obtained at any of the estimation stages to improve estimation results. It can be a very rough estimation or a very precise solution depending on the computation time allowed. For example, no precise solution will be necessary for screening out obviously bad bids. For a market participant, a fast but less precise solution might be favorable for fast bidding decision making, which involves many different generation directions. For an ISO, a precise solution is always necessary to ensure its responsibility of keeping the system reliable.

III. SIMULATION RESULTS

The fast ATC determination method is tested on the IEEE 24 bus system [7] as shown in Fig. 2.

Due to the system limits, it is very difficult to find a base case that is reliable under *all* line contingencies, only the results for *credible* line contingencies are presented here. Other line contingencies causing immediate system limit violation are not considered. Those scenarios do exist in actual power systems. For example, single branch line outage (such as line from bus 7 to 8) is not a credible contingency and is not considered here because this kind of outage will definitely disconnect the rest of the system from the bulk system. And the removal of generation and/or load in the rest of system will cause change in the generation direction or the load direction. A continuation power flow similar to [3,4,6,8] is used to compare the results.

The method proposed is tested on unix SUN Ultrasparc machine in MATLAB codes. The results are shown in Table 1. The <u>first</u> column is the credible outaged line number. The <u>second</u> column shows the cpu time needed for pure estimation method. Since this method is not precise, errors may be large. It is recommend for rough screening only. The <u>third</u> column is also estimation, but it is based on precise line

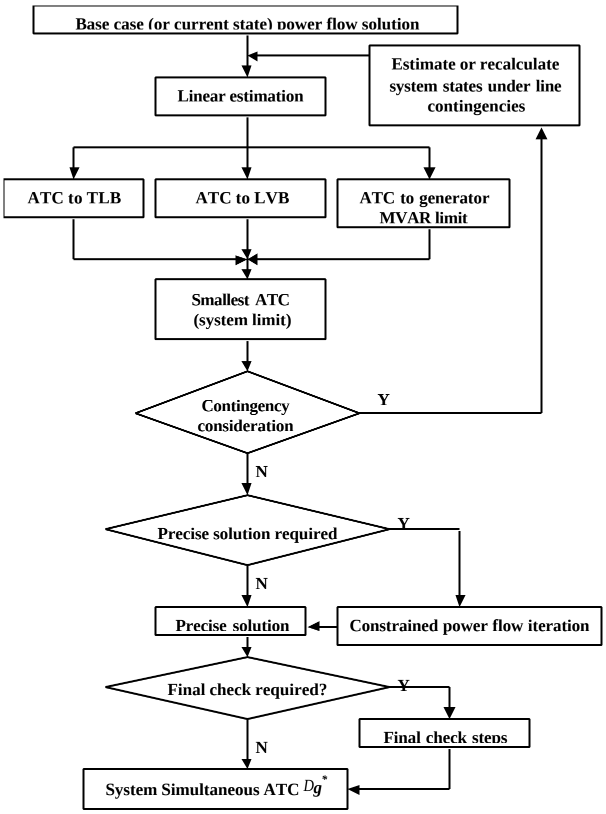

Figure.1: Illustration of the fast determination method.

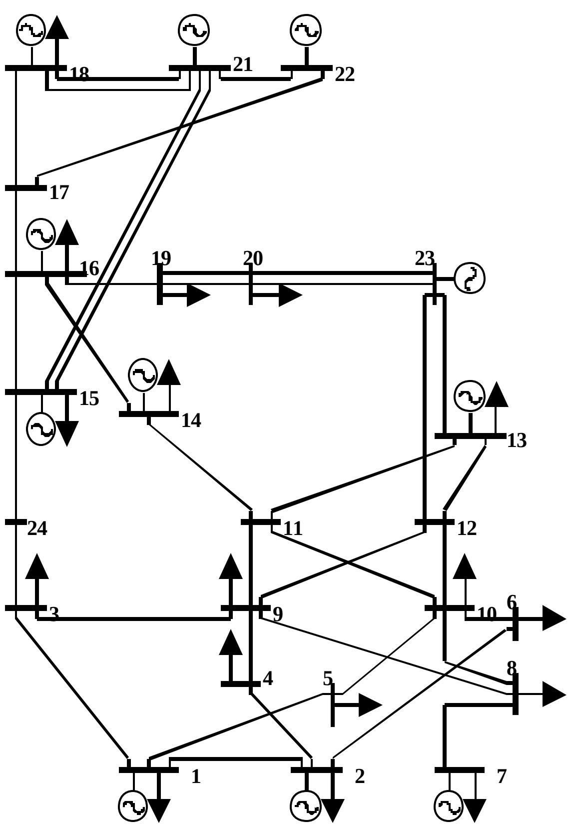

Figure 2: The IEEE 24 bus system.

Table 1: CPU time (sec) of different ATC calculation method compared (*: Normal case without contingency)

Line outage	Pure estimation	Estimation with precise solution x^r	Estimation with final precise solutions	Continuation power flow
*	0.03	0.03	0.10	11.55
1	0.05	0.09	0.16	11.69
2	0.05	0.08	0.16	7.36
3	0.05	0.09	0.16	10.21
4	0.04	0.10	0.18	1.52
5	0.05	0.08	0.15	8.72
6	0.05	0.09	0.16	10.48
8	0.06	0.08	0.22	12.33
9	0.05	0.08	0.17	11.74
12	0.06	0.10	0.16	11.33
13	0.05	0.09	0.16	11.98
18	0.06	0.08	0.15	5.07
19	0.04	0.09	0.17	6.58
20	0.05	0.09	0.16	9.83
21	0.06	0.09	0.16	6.75
22	0.05	0.08	0.14	8.38
23	0.05	0.11	0.18	4.37
24	0.07	0.10	0.19	3.88
25	0.05	0.10	0.16	4.04
26	0.05	0.09	0.15	4.08
27	0.06	0.12	0.18	17.59
28	0.05	0.08	0.16	2.70
29	0.04	0.11	0.17	6.06
30	0.05	0.08	0.15	7.56
31	0.06	0.09	0.16	11.34
32	0.05	0.09	0.16	11.81
33	0.05	0.11	0.19	11.82
34	0.05	0.09	0.16	13.67
35	0.05	0.09	0.17	13.67
36	0.06	0.10	0.24	13.67
37	0.06	0.10	0.24	13.67
38	0.05	0.09	0.17	9.27

outage state x^r. It can be seen that the overall time is mainly spent on obtaining x^r. But the error can be controlled within 13%. The forth column takes more time for the precise solution which is the same as the continuation power flow solution. It shows more time is required solving the constrained power flow, which might be used repeatedly when the estimation results give a wrong limiting factor. Results also show, for certain cases, obtaining a precise x^r is well worth the time since it reduces the error of identifying the right limiting factor using estimation. The fifth column is the time required for a standard continuation power flow, which takes the most of time. It is well known that a continuation power flow method uses a series of precise solutions to approach the right limiting factor, which involves solving many power flow equations.

The results showed that the method is fast yet flexible. For different precision requirements on the results, it ranges from hundreds time to about 50 times faster than a standard continuation power flow method.

IV. DISCUSSION

While the ATC calculations described in this paper conform to the "normal" procedure for determining the maximum capability of the system (including contingency effects), the actually computed numbers are a function of the dispatch pattern that underlies the ATC calculation. This dispatch pattern is pre-specified as part of the data. A change in the presumed generation dispatch pattern will have an effect on the available ATC. In particular, it is often possible to increase the available ATC by modifying the dispatch pattern of the system. Doing so generally results in higher costs. Thus, to a nontrivial degree, a pure separation of ATC determination from economic issues is impossible. Nevertheless, this paper stays with the more conventional view of ATC as a separable measure of system capability that is independent of economic considerations.

The paper works by using a distance to margin prediction formula that, for cases of line flow limits, rapidly determines the loadability limit of the system with respect to any limit without the need for a much slower continuation step. A key concept behind this paper is that it is possible to combine ATC determination with contingency analysis in a manner that is efficient. This is done by using the linearized formulas to establish the effect of contingencies on both the base case flows and the linearization formula itself. Previous attempts have dealt with contingencies as part of a "verify" step: increase the transfer, verify the adequacy to each contingency, and increase the transfer again. The new approach directly determines the size of the step that leads to a contingency limit. The method works exceedingly well for systems that reach a line flow limit. It is not expected to work particularly well to cases where the limit is due to voltage problems.

If generator MVAR limit is not considered as a factor for ATC limit, this method will not be accurate when a generator MVAR is reached. The PV bus will turn into a PQ bus. This changes the power flow equation and its Jacobian. The sensitivities from former Jacobian will be inaccurate. This difficulty happens with almost every linear estimation methods. To overcome this difficulty, another power flow solution should be solved at the point when the generator just reached the MVAR limit by treating the generator PV bus as a PQ bus.

The constrained power flow used in this paper is a kind of direct method [11]. Like all direct methods, if the initial condition is too far from the final solution, the direct method may not converge. If this happens, part of the continuation power flow method can be applied to get the initial condition closer to the final solution.

V. CONCLUSION

This paper presents a fast and direct ATC calculation method that is readily adapted to deregulated power market calculations. It is theoretically much faster than the widely used continuation power flow method

In a real power market, load forecast error always exists. The ATC computation method presented should give the market participants enough and quick information to make bidding decisions.

In a competitive dynamic power market, ATC depends on the generation pattern and loading pattern as determined by the bidding results. Yet market participants also need ATC information before bidding strategically. The fast ATC calculation method will make more efficient rounds of bidding for both market participants and ISO.

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VII. BIOGRAPHIES

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