Determination of Available Transfer Capability and Its Enhancement in Competitive Electrical Market

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Abstract—Available transfer capability in the transmission network has become essential quantity to be declared well in advance for its commercial use in a competitive electricity market. Its fast computation using DC load flow based approach is used worldwide for on line implementation. In this paper, ACPTDF based approach has been proposed for multi-transaction cases using power transfer sensitivity and Jacobian matrix. The method can be implemented for any number of transactions occurring simultaneously. The results have been determined for intact cases taking multi-transaction (simultaneous) as well as single transaction cases. This paper presents the application of the Static Var Compensator (SVC) to enhance the transfer capability of a power system incorporating the reactive power flows in ATC calculations. By redistributing the power flow, the ATC is improved. Studies on a sample IEEE 24-bus RTS power system model are presented to illustrate the effectiveness of SVC device to improve available transfer capacity as well as voltage profile.

Keywords: Available transfer capability, AC loads flow, AC power transfer distribution factors, SVC.

I. INTRODUCTION

Deregulated framework has been replacing the traditional vertically integrated structure of power supply system. This has fostered regulators to initiate reforms to restructure the electricity industry to achieve better service, reliable operation and competitive rates that can drive down the cost in power production. As a result, electric utilities are required to produce commercially viable Information of available transfer capability (ATC) so that the vital information can facilitate power marketers, sellers and buyers in planning, operation and reserving the transmission services. ATC is the additional amount of power that may flow across the interface, over and above the base case flows without jeopardizing the power system security. ATC can also become a useful indicator for the operator to indicate the amount by which the inter area power transfers can be increased without jeopardizing system security. Mathematically, ATC [2] is defined as the total transfer capability (TTC) less the transmission reliability margin (TRM), less the capacity benefit margin (CBM) and less the base case power transfer .

Mathematically, ATC is defined as,

$$ATC=TTC-TRM-\{ETC+CBM\}.$$

In deregulated electricity markets, ATC of a transmission system has emerged as a new measure. Under the U. S. Federal Energy Regulatory Commission (FERC) orders 888 and 889, which established open access nondiscriminatory transmission services policy and open access same, time information system (OASIS), ATC is required to be posted on OASIS to make competition reasonable and effective. Such information will help power marketers, sellers and buyers in reserving transmission services. ATC has to be continuously updated and posted following changes in the system conditions or scheduled power transfers between the areas. The results have been obtained for IEEE RTS 24 bus system [21]. FACTS technology has introduced a severe impact to the transmission system utilization with regards to those constraints. From the steady state power flow viewpoint, networks do not normally share power in proportion to their ratings, where in most situations, voltage profile cannot be smooth. Therefore, ATC values are always limited by heavily loaded buses with relatively low voltage. Theoretically FACTS devices can offer an effective and promising alternative to conventional methods of ATC enhancement. They will provide new control facilities, both in steady state power flow control and dynamic stability control controlling power flow in electric power systems without generation rescheduling or topological changes can improve the network performance considerably. In this paper, with suitable location, the effect of a SVC on the ATC enhancement are studied and demonstrated through case studies. It is to be shown that, installing SVC in the proper location will improve voltage profile as well as ATC.

II. BACKGROUND

A. Methodology for ATC Determination in Case of multi-transactions

Consider a bilateral transaction P_t between a seller bus r and buyer bus s. Line l connected between buses i and j carries the part of the transacted power ΔP_{ij} . For a change in real power, transaction among the above buyer and seller by ΔP_{rs} MW, if the change in transmission line quantity is $\Delta P_{ij,}$ AC power factors can be defined as,

$$ACPTDF_{ij,rs} = \frac{\Delta P_{ij}}{\Delta P_{rs}} \qquad (1)$$

For PTDF calculation [19] using AC load approach, the power flow sensitivity and Jacobian of power injection equations is required. The Jacobian can be calculated using N-R load flow based approach. The power flow equations in polar form can be represented as:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \qquad (2)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \qquad (3)$$

Where n be the total no. of buses Pi and Qi are the real and reactive power injected at any bus i

$|V_i|$, $|V_j|$ are the voltage magnitudes at bus respectively

δ_i and δ_j are the voltage angles at buses i and j

$|Y_{ij}|$,θ_{ij} are taken from Y_{bus}.

Using Taylor series expansion, the change in power flows at any bus *i* can be formulated in terms of Jacobian as:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} \qquad (4)$$

Where [J] = $\begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}$ and

$[J_1] = \frac{\partial P}{\partial \delta}$; $[J_2] = \frac{\partial P}{\partial |V|}$; $[J_3] = \frac{\partial Q}{\partial \delta}$; $[J_4] = \frac{\partial Q}{\partial |V|}$

The change in the angle and voltage magnitude can be determined as:

$$\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}^{-1}\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} \qquad (5)$$

Using N-R load flow analysis bus voltage magnitudes and angles can be evaluated. For calculation of ACPTDFs, Jacobian and power flow sensitivity can be calculated. The power flow sensitivity can be determined using the power flow equations for real power. The real power flow (P_{ij}) in a line-k, connected between buses i and j , can be written as:

$$P_{ij} = V_i V_j Y_{ij}\cos(\theta_{ij} + \delta_j - \delta_i) - V_i^2 Y_{ij}\cos\theta_{ij} \qquad (6)$$

Where, V_i and δ_i are the voltage magnitude and angle at bus-i. Y_{ij} and $\theta_{ij}$are magnitude and angles of ij^{th} elements of [Y_{bus}].

Using Taylor series expansion and ignoring higher order terms change in real power flows can be written as:

$$\Delta P_{ij} = \frac{\partial P_{ij}}{\partial \delta_i}\Delta\delta_j + \frac{\partial P_{ij}}{\partial \delta_j}\Delta\delta_j + \frac{\partial P_{ij}}{\partial V_i}\Delta V_i + \frac{\partial P_{ij}}{\partial V_j}\Delta V_j \qquad (7)$$

The sensitivity coefficients appearing in (6) can be obtained using the partial derivatives of real power flow (5) with respect to variables δ and V as:

$$\frac{\partial P_{ij}}{\partial \delta_i} = V_i V_j Y_{ij}\sin(\theta_{ij} + \delta_j - \delta_i) \qquad (8)$$

$$\frac{\partial P_{ij}}{\partial \delta_j} = -V_i V_j Y_{ij}\sin(\theta_{ij} + \delta_j - \delta_i) \qquad (9)$$

$$\frac{\partial P_{ij}}{\partial V_i} = V_j Y_{ij}\cos(\theta_{ij} + \delta_j - \delta_i) - 2V_i Y_{ij}\cos\theta_{ij} \qquad (10)$$

$$\frac{\partial P_{ij}}{\partial V_j} = V_i Y_{ij}\cos(\theta_{ij} + \delta_j - \delta_i) \qquad (11)$$

The sensitivity of power flow equation can be written in the compact matrix form as:

$$\Delta P_{ij} = \left[\frac{\partial P_{ij}}{\partial \delta_2}\ldots\ldots\frac{\partial P_{ij}}{\partial \delta_{22}}, \frac{\partial P_{ij}}{\partial \delta_{24}}\ \frac{\partial P_{ij}}{\partial V_{g+1}}, \ldots\ldots\frac{\partial P_{ij}}{\partial V_n}\right]\begin{bmatrix}\Delta\delta_2\\ \vdots\\ \Delta\delta_{22}\\ \Delta\delta_{24}\\ \Delta|V_{g+1}|\\ \vdots\\ \Delta|V_n|\end{bmatrix} \qquad (12)$$

Where $\left[\frac{\partial P_{ij}}{\partial \delta_2} \dots \dots \frac{\partial P_{ij}}{\partial \delta_{22}}, \frac{\partial P_{ij}}{\partial \delta_{24}}\ \frac{\partial P_{ij}}{\partial V_{g+1}}, \dots \dots \frac{\partial P_{ij}}{\partial V_n}\right]$ is line power flow sensitivity corresponding to angle and voltage magnitude.

For a single transaction case between seller bus r and buyer bus s, the change in power transactions can be substituted at position of bus m and bus n as:

$$\Delta P_r = +P_t$$
$$\Delta P_s = -P_t$$

$$\Delta P_{ij} = \left[\frac{\partial P_{ij}}{\partial \delta_2} \dots \dots \frac{\partial P_{ij}}{\partial \delta_{22}}, \frac{\partial P_{ij}}{\partial \delta_{24}}\ \frac{\partial P_{ij}}{\partial V_{g+1}}, \dots \dots \frac{\partial P_{ij}}{\partial V_n}\right] [\,J\,]^{-1} \begin{bmatrix} 0 \\ \vdots \\ +P_t \\ 0 \\ \vdots \\ -P_t \\ 0 \end{bmatrix}$$
$$= ACPTDF_t * P_t \qquad (13)$$

So, ACPTDFs for the transaction between seller bus m to buyer bus n can be represented as:

$$ACPTDF_{ij,rs} = \left[\frac{\partial P_{ij}}{\partial \delta_2} \dots \dots \frac{\partial P_{ij}}{\partial \delta_{24}}, \frac{\partial P_{ij}}{\partial V_{g+1}}, \dots \dots \frac{\partial P_{ij}}{\partial V_n}\right] [\,J\,]^{-1} \begin{bmatrix} 0 \\ \vdots \\ +1 \\ 0 \\ \vdots \\ \vdots \\ -1 \\ 0 \end{bmatrix} \qquad (14)$$

In a deregulated market environment number of transactions can occur simultaneously as more and more participants are involved in the trading of power. When ATC is determined for more than one transactions occurring simultaneously in a system, ATC in such a case is called as simultaneous or multi-transaction ATC. The procedure for simultaneous ATC is similar as discussed for single transactions case with a change in the power injection matrix. In the simultaneous ATC case, the power injection matrix can be modified based on the transactions occurring between many sellers and buyers as:

$$\Delta P = \begin{bmatrix} 0 \\ +P_t \\ \vdots \\ -P_t \\ 0 \\ +P_t \\ \vdots \\ -P_t \\ 0 \end{bmatrix} \qquad (15)$$

Depending on the number of transactions, the entry at the corresponding seller and buyer buses can be added in the power transaction column matrix. Once this is known, the change in flows can be determined as obtained. The ACPTDFs with simultaneous transactions can be calculated as:

$$ACPTDF_{ij,rs} = \left[\frac{\partial P_{ij}}{\partial \delta_2} \dots \dots \frac{\partial P_{ij}}{\partial \delta_{22}}, \frac{\partial P_{ij}}{\partial \delta_{24}}\right] [\,J\,]^{-1} \begin{bmatrix} 0 \\ +1 \\ \vdots \\ -1 \\ 0 \\ +1 \\ \vdots \\ -1 \\ 0 \end{bmatrix} \qquad (16)$$

B. ATC Determination for Intact System

ATC can be determined using the method explained in previous section. Real power flows in base case obtained from N-R approach and line limits as a given data are utilized for ATC determination.
Now P_{ij-rs}^{max} for any transaction seller bus r to buyer bus s:

$$P_{ij-rs}^{max} = \left\{ \begin{matrix} \frac{Limit_{ij}^{max} - P_{ij}}{ACPTDF_{ij,rs}} & ;\ ACPTDF > 0 \\ \infty(infinite) & ; ACPTDF = 0 \\ \frac{-Limit_{ij}^{max} - Pij_{max}}{ACPTDF_{ij,rs}} & ; ACPTDF < 0 \end{matrix} \right\}$$

(17)

Where P_{ij} is the real power flow through any line i-j. $Limit_{ij}^{max}$ is the thermal limit of any line i-j. $P_{ij,rs}^{max}$ is the maximum allowable transaction amount from bus r to bus s constrained by the line flow limit from bus i to bus j. For the given transaction, the ATC can be defined as:

$$ATC_{rs} = \min\{P_{ij,rs}^{max}\ \ \text{ij} \in N_l\ \} \qquad (18)$$

Where, N_l is the total number of lines in the system.

Algorithm

Following algorithm can be carried out for the determination of ATC of the network.

- Compute initial system conditions (base case) such as, bus voltage, bus angles power flows and current flows using Newton-Raphson Load Flow method.

- Apply the real power transaction between the seller bus m and buyer bus n.
- Obtain the change in real power flows by carrying out sensitivity analysis.
- Determine the PTDFs and calculate Available Transfer capability at base case condition.
- Finally evaluate ATC by subtracting ETC from TTC.

Updating the values of power flows after the transaction is applied and the substituting them in place of base power flow than ATC can be evaluated accurately.

III. MODELING OF SVC

The Shunt Compensator SVC is simply considered as a static capacitor/reactor with susceptance Bsvc [22]. Operation of SVC is controlled by the adjusting the selection of firing angle of GTOs (Gate turn off transistors) or thyristors to change the reactance of inductor. During operation SVC behaves like shunt variable susceptance. SVC can work in inductive or capacitive region.Fig.1 shows the equivalent circuit of the SVC that can be modeled as a shunt connected variable susceptance Bsvc at bus-i.

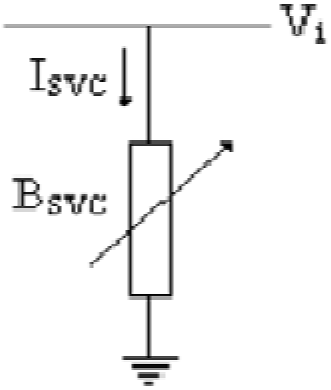

Fig.1. equivalent circuit of the SVC

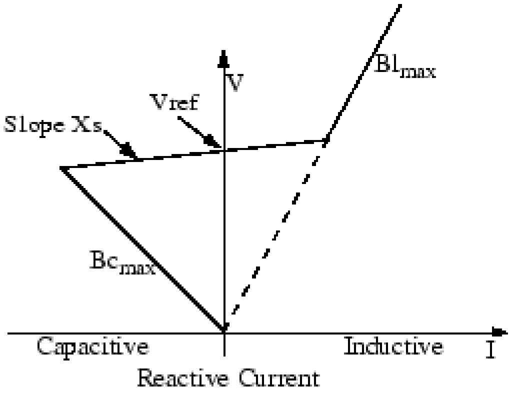

Fig 2: Characteristic of SVC

During operation SVC behaves like shunt variable susceptance. SVC can work in inductive or capacitive region both shown in Fig.2. The slope value depends on the desired voltage regulation, the desired sharing of reactive power production between various sources, and other needs of the system. The slope is typically 1-5%. At the capacitive limit, the SVC becomes a shunt capacitor. At the inductive limit, the SVC becomes a shunt reactor (the current or reactive power may also be limited). Connecting SVC on any bus i, reactive power is provided by SVC can be written as:

$$Q_{SVC} = -V_i^2 * B_{SVC} \qquad (19)$$

Where V_i is the voltage magnitude of the bus at which the SVC is connected.

IV Results and Discussion

Available transfer capability has been obtained for different transactions taken as single and simultaneous/multi-transactions for intact as wells as with line contingencies for IEEE 24 bus RTS. These transactions have been categorized as:

T1: transaction between seller bus 23 to buyer bus15
T2: transaction between seller bus 10 to buyer bus 3
T3: transaction between seller buses 23 and 10 to buyer bus 15 bus 3(simultaneous transactions).

ACPTDFs computed for N-R method for transactions T1 to T3 are shown in Fig.3.

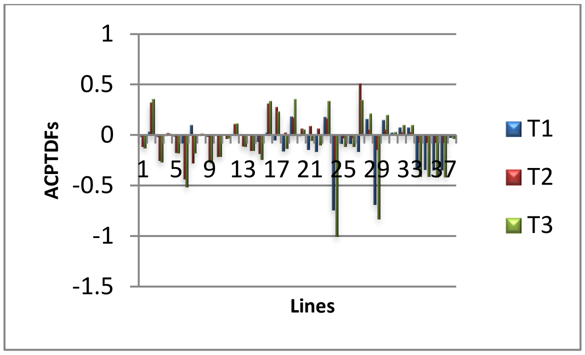

Fig.3. ACPTDFs with N-R Jacobian based approach

The results of ATC for different Transactions are given in Table 1 and Fig.4.

Table1. ATC for different Transactions

T1	T2	T3
7.5785	2.8342	2.7629

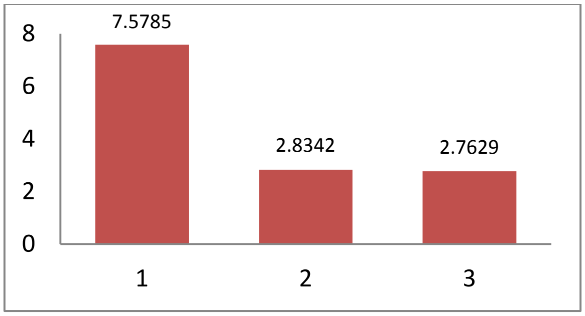

Fig.4. ATC for different Transactions

ACPTDFs computed for N-R method **with SVC** for transactions T1 to T3 are shown in Fig. 6.

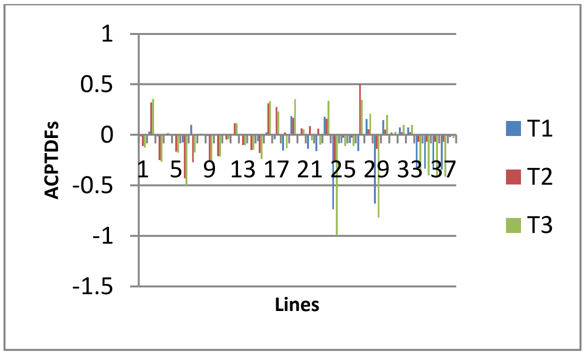

Fig.5. ACPTDFs with N-R Jacobian based approach

Now, the results of ATC with SVC for different Transactions are given in Table 2 and Fig 7.

Table2. ATC with SVC for different Transactions

T1	**T2**	**T3**
7.5797	2.8947	2.8845

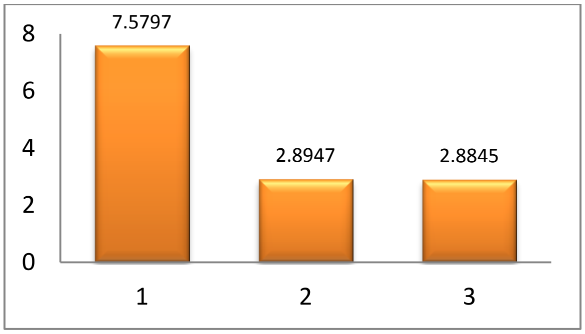

Fig.6. ATC with SVC for diifferent Transactions

Comparison of ATC with and without SVC

Comparing the results of ATC obtained without SVC, it is observed that ATC increases for all transaction cases with SVC. It is observed that ATC with SVC increases slightly for all transaction cases as compared to its base case. The comparison of ATC without and with SVC is shown in Table 3.

Table3. ATC with and without SVC for different Transactions

Transaction	ATC without SVC	ATC with SVC
T1	7.5785	7.5797
T2	2.8342	2.8947
T3	2.7629	2.8845

Fig.7. ATC with and without SVC

V Conclusions

In this paper, methodology for ATC determination has been proposed for simultaneous in deregulated electricity market based on AC power transfer distribution factors. Method based on Jacobian and power flow sensitivity calculations have been implemented for simultaneous for ATC determination under intact case. The ATC value serves as an important indicator of system performance. ATC reduces for multi-transaction cases with intact case. The results obtained with AC PTDF based method is more accurate compared to DC PTDF based approach as there are no assumptions involved with N-R based ACPTDF approach. The method with AC approach can be implemented online ATC calculations. One of the FACTS devices SVC is placed optimally based on sensitivity indices. The minimum amount of VAR support by SVC for network security is obtained and consequently the location of SVC is finalized based on MVAR required for congestion relief. From the results, it is shown that installing SVC as a FACTS device will improve voltage profile as well as resulting ATC enhancement.

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