ATC in Competitive Electricity Market Using TCSC

S. K. Gupta, Richa Bansal

Abstract—In a deregulated power system structure, power producers and customers share a common transmission network for wheeling power from the point of generation to the point of consumption. All parties in this open access environment may try to purchase the energy from the cheaper source for greater profit margins, which may lead to overloading and congestion of certain corridors of the transmission network. This may result in violation of line flow, voltage and stability limits and thereby undermine the system security. Utilities therefore need to determine adequately their available transfer capability (ATC) to ensure that system reliability is maintained while serving a wide range of bilateral and multilateral transactions. This paper presents power transfer distribution factor based on AC load flow for the determination and enhancement of ATC. The study has been carried out for IEEE 24 bus Reliability Test System.

Keywords—Available Transfer Capability, FACTS devices, Power Transfer Distribution Factors.

I. INTRODUCTION

A Transfer Capability (ATC) is a measure of remaining power transfer capability of the transmission network for further transactions [1]. Authors in [1] describe the assessment of ATC using AC power transfer distribution factors (ACPTDF) in combined economic emission dispatch (CEED) environment. The ACPTDFs are derived using sensitivity based approach for the system intact case and utilized to check the line flow limits during ATC determination. The ATC value serves as an important indicator of system performance. G. C. Ejebe et al. [2] presented a detailed formulation and implementation of a fast program for Available Transfer Capability (ATC) calculations based on the linear incremental power flow to account for the line flow thermal loading effects and presents reports on the features and implementation of a program for Available Transfer Capability calculations [3]. A novel formulation of the ATC problem has been adopted based on full AC power flow solution to incorporate the effects of reactive power flows, voltage limits and voltage collapse as well as the traditional line flow (thermal loading) effects. For proper system operations under the various transactions, ATC calculations must be reasonably accurate and fast enough. A. Kumar et al. [4] presented the development of a simple and non-iterative method to calculate Available Transfer Capability (ATC) for a transmission system using new set of distribution factors. The accuracy of these distribution factors have been established with respect to full Newton Rapson Load Flow results and ATC results have been obtained for bilateral and multilateral transactions. The authors in [5] presented the application of one type of Flexible AC Transmission System (FACTS) device, the Thyristor Controlled Series Compensator (TCSC) to improve the transfer capability of a power system incorporating the reactive power flows in ATC calculations. By redistributing the power flow, the ATC is improved. P. Venkatesh et al. [6] describes the evaluation of multi-area ATC using AC Power Transfer Distribution Factors (ACPTDF) and Participation Factors (PF) in Combined Economic Emission Dispatch (CEED) environment normal, line outages contingency. A method which incorporates two types of FACTS devices namely Thyristor Controlled Series Compensator (TCSC) and Static Var Compensator (SVC) to enhance ATC was presented in [7]. Ashwani Kumar et al. [8] proposed ACPTDF based approach for multi-transaction cases using power transfer sensitivity and Jacobian calculated with three different methods. The methods can be implemented for any number of transactions occurring simultaneously. The results have been determined for intact and line contingency cases taking multi-transaction/simultaneous as well as single transaction cases. NERC Report 1996 [9] provides an initial framework on ATC that will likely be expanded and modified as experience is gained in its use and as more is learned about how the competitive electric power market will function. Claudio A. Canizares and Alberto Berizzi et al. [10] concentrate on the effect of SVC and TCSC controllers on the ATC. The transmission capability was enhanced in most efficient way by FACTS devices. The impact of TCSC has also been considered for enhancement of ATC. The proposed method has been implemented on IEEE 24 bus RTS.

II. MATHEMATICAL FORMULATION

A. Power Transfer Distribution Factors (PTDFs)

Consider a bilateral transaction P_t between a seller bus r and buyer bus s. Line k carries the part of the transacted power and is connected between buses i and j. 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 ΔP_{ij}, AC power transfer distribution factors can be defined as,

$$ACPTDF_{ij-rs} = \frac{\Delta P_{ij}}{\Delta P_{rs}} \tag{1}$$

where r and s may vary from 1 to n (n is the total no. of buses). For PTDF calculation using AC load approach, the power flow sensitivity and Jacobian is required. The Jacobian can be calculated using N-R load flow based approach in polar

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form. 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 P_i and Q_i are the real and reactive power injected at bus i. $|V_i|$, $|V_j|$ are the voltage magnitudes at buses, respectively. δ_i and δ_j are the voltage angles at buses i and j. $|Y_{ij}|, \theta_{ij}$ are taken from Y_{bus}. Using N-R method, the change in power flows 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 angle and voltage and voltage magnitude can be determined as:

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

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:

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

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

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

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

$$\Delta P_{ij} = \left[\frac{\partial P_{ij}}{\partial \delta_2} \cdots \cdots \frac{\partial P_{ij}}{\partial \delta_{n-1}}, \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_{g+1}}, \cdots \cdots \frac{\partial P_{ij}}{\partial V_n}\right]\begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_{n-1} \\ \Delta\delta_n \\ \Delta|V_{g+1}| \\ \vdots \\ \Delta|V_n| \end{bmatrix} \qquad (8)$$

where $\left[\frac{\partial P_{ij}}{\partial \delta_2} \cdots \cdots \frac{\partial P_{ij}}{\partial \delta_{22}}, \frac{\partial P_{ij}}{\partial \delta_{24}} \frac{\partial P_{ij}}{\partial V_{g+1}}, \cdots \cdots \frac{\partial P_{ij}}{\partial V_n}\right]$ is line power flow sensitivity corresponding to angle and voltage magnitudes. g is the total no. of PV buses.

A transaction is defined by four parameters (t, i, j, P_t) where t is transaction number, r and s are the source and the sink buses and P_t is MWs transacted. Changes in injected power at all buses expect bus r &bus s are zero. Since change in the injected power at bus no. r and change in the injected power at

bus no. s are $+P_t$ and $-P_t$ respectively. Therefore, Put $\Delta P_r = +P_t$ and $\Delta P_s = -P_t$

$$ACPTDF_{ij-rs} = \left[\frac{\partial P_{ij}}{\partial \delta_2} \cdots \cdots \frac{\partial P_{ij}}{\partial \delta_{n-1}}, \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_{g+1}}, \cdots \cdots \frac{\partial P_{ij}}{\partial V_n}\right][J]^{-1}\begin{bmatrix} 0 \\ \vdots \\ +1 \\ 0 \\ \vdots \\ \vdots \\ -1 \\ 0 \end{bmatrix} \qquad (9)$$

Due to the installation of FACTS device there is a change in power flow as the reactance value gets changed. The new ACPTDFs with FACTS devices can be given as:

$$ACPTDF_{ij-rs} = \left[\frac{\partial P_{ij}}{\partial \delta_2} \cdots \cdots \frac{\partial P_{ij}}{\partial \delta_{n-1}}, \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_{g+1}}, \cdots \cdots \frac{\partial P_{ij}}{\partial V_n}\right]_{FACTS}[J]^{-1}{}_{FACTS}\begin{bmatrix} 0 \\ \vdots \\ +1 \\ 0 \\ \vdots \\ \vdots \\ -1 \\ 0 \end{bmatrix} \qquad (10)$$

B. Simultaneous/Multi-Lateral Transactions with FACTS Devices

The procedure for simultaneous ATC determination is similar as discussed for single transactions case described in above section with a change in the power injection matrix. In the simultaneous ATC case, the power injection matrix can be modified as:

$$\Delta P = [0 \ +P_t \ .. \ .. \ -P_t \ 0 \ +P_t \ ... \ -P_t \ ]^t \qquad (11)$$

Depending on the number of transactions, Let r^{th} bus selling the power to s^{th} bus and t^{th} bus selling the power to u^{th} bus by an amount of P_t each. Therefore, r, s, t and u position in the column matrix are +1,-1, +1,-1 respectively.

The ATC with simultaneous transactions can be calculated as:

$$ACPTDF_{ij-rs,tu} = \left[\frac{\partial P_{ij}}{\partial \delta_2} \cdots \cdots \frac{\partial P_{ij}}{\partial \delta_{n-1}}, \frac{\partial P_{ij}}{\partial \delta_n} \frac{\partial P_{ij}}{\partial V_{g+1}}, \cdots \cdots \frac{\partial P_{ij}}{\partial V_n}\right][J]^{-1}\begin{bmatrix} 0 \\ +1 \\ \vdots \\ -1 \\ 0 \\ +1 \\ \vdots \\ -1 \\ 0 \end{bmatrix} \qquad (12)$$

C. ATC Determination using ACPTDFs with TCSC

Now, P_{ij-rs}^{max} for any transaction seller bus r to buyer bus s:

$$P_{ij-rs}^{max} = \begin{cases} \frac{Limit_{ij}^{max} - P_{ij}}{ACPTDF_{ij-rs}} & ; \ ACPTDF > 0 \\ \infty (infinite) & ; \ ACPTDF = 0 \\ \frac{-Limit_{ij}^{max} - ij}{ACPTDF_{ij-rs}} & ; \ ACPTDF < 0 \end{cases} \qquad (13)$$

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

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allowable transaction amount from bus r to bus s constrained by the line flow limit from bus i to bus j.

For the all transactions, the ATC can be defined as:

$$ATC_{r,s} = \min \{P_{ij-r,s}^{max} \; ij \in N_l \} \qquad (14)$$

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

D. Optimal Location of TCSC

The sensitivity analysis criterion has been considered for the optimal placement of TCSC device in the transmission network. This method based on the sensitivity of total system reactive power loss (Q_L) with respect to the control parameter of TCSC. Placing TCSC between buses i and j the take net line series reactance X_{ij} becomes variable. The sensitivity index for ij^{th} line can be given as [11]

$$a_{ij} = \frac{\partial Q_L}{\partial X_{ij}} = [V_i^2 + V_j^2 - 2V_iV_j \cos (\delta_i - \delta_j)] \frac{R_{ij}^2 - X_{ij}^2}{(R_{ij}^2 + X_{ij}^2)^2} \qquad (15)$$

The TCSC should be installed in a line whose loss index a_{ij} value is most positive one.

III. SYSTEM STUDIES

The proposed approaches of ATC in competitive Electricity market using TCSC have been tested on IEEE 24 bus RTS for different transactions taken as single and simultaneous transactions. The IEEE 24 bus RTS consists of 13 load buses, 11 generators and 38 lines. These transactions have been taken as:

T1. transaction between seller bus 23 to buyer bus 15.
T2. transaction between seller bus 10 to buyer bus 3.
T3. transaction between seller buses 23 and 10 to buyer buses 15 and 3 (simultaneous transaction).
T4. transaction between seller buses 23, 10, and 21 to buyer buses 15, 3, 6 (multi-transaction).

The ACPTDFs for different transactions have been calculated without TCSC for ATC calculation and is shown in Fig. 1.
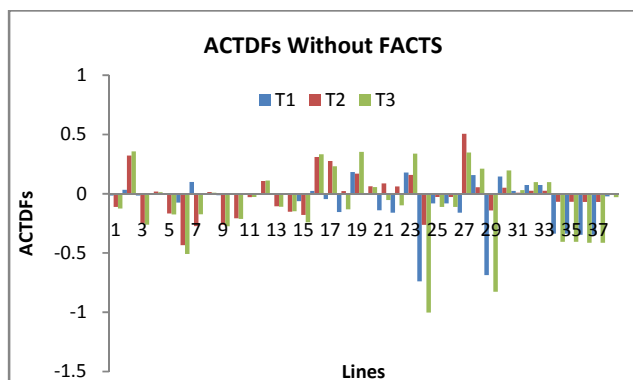

Fig. 1 ACTDFs without FACTS

The sensitivity index for the placement of TCSC of some of the few lines is shown in Table I. The most sensitive line which is having highest value of a_{ij} is written in bold style.

TABLE I
SENSITIVITY INDICES OF 24 BUS RTS

Line No.	i-j	a_{ij}
2	**1-3**	**-0.0733**
4	2-4	-0.2854
9	**5-10**	**-0.0027**
14	9-11	-2.8645
29	16-19	-2.9954
35	19-20	-0.3655

Table I indicates that Line no. 9th connected between buses 5 and 10 and Line no. 2nd connected between buses 1 and 3 are the best location for the placement of TCSC. The control parameter value of TCSC for Line no. 9th is taken as 80% of line reactance and for Line no. 2nd is taken as 50% of line reactance.

The changes in the ACTDFs for various transactions with the installation of TCSC are shown in Fig. 2.
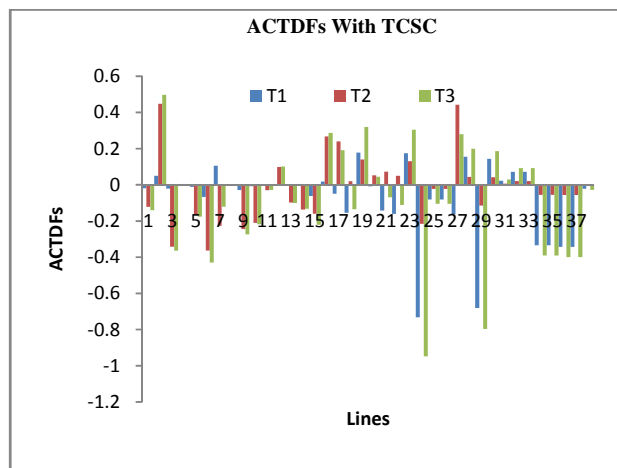

Fig. 2 ACTDFs with TCSC

Table II shows changes in ATC (p.u.) without TCSC [8] and with TCSC. It is observed that ATC (p.u.) is improved on employing TCSC in line no. 9th and 2nd.

TABLE II
CHANGES IN ATC(P.U.) WITHOUT TCSC AND WITH TCSC

Transactions	ATC without TCSC[8]	ATC with TCSC
T1	7.5785	7.646544
T2	2.8342	3.147793
T3	2.7629	3.067323

IV. CONCLUSION

This paper presented a method for the determination and enhancement of ATC using TCSC in competitive electricity market. In addition, reactive power loss reduction method is used to decide the optimal location of TCSC for controlling the power flow in the line. The ATC (p.u.) has been calculated without and with TCSC. From the above results it is concluded that the ATC (p.u.) is enhanced on application of TCSC [8].

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