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# IMPLEMENTATION of TCSC in CONGESTION MANAGEMENT

Naresh Kumar Yadav[1] and Arti saini[2]

Department of Electrical Engineering, at Deenbandhu Chhotu Ram University of Science and Technology,
Murthal (Sonepat) - Haryana[1]

Department of Electrical Engineering, at Apex Institute of Technology, Indri (Karnal) – Haryana[2]

**Abstract**- Competition is on rise in generation and distribution, which results huge transactions. Nonetheless, transmission lines are overloaded, since transmission system provides access of electricity having limited corridors. Consequently, the probability of congestion tends to be prominent. Congestion in transmission corridors not only causes collapse of that particular area but affects other area as well. Therefore, improvement of ATC of existing network by any means is essential. For this, various FACTS devices like UPFC, SSSC, TCSC, STATCOM, etc. may be used to improve the ATC of transmission lines. In this paper TCSC is employed in IEEE 5 bus system and IEEE 30 bus system to improve the ATC of transmission lines. In this paper ACPTDFs are used to evaluate the change in line flows. Due to the change in line flows the ATC of the transmission line also reflects changes. Both the real power and reactive power flows are considered in this paper.

**Keywords** – Available Transfer Capability (ATC), AC Power Transfer Distribution Factor (ACPTDF), Linear ATC, Reactive Power, Thyristor Controlled Switched Capacitor (TCSC).

## I. INTRODUCTION

In this competitive era, competition in Deregulated market is also mushrooming like a wild fire. Owing to it, vast implications have been compelled on generation and distribution industry. Congestion management is one of the technical challenges in Deregulated market and it arises when there is inadequate transfer capability to accommodate all the transactions [4]. The issue of transmission congestion is more prevalent in this market and it entails special handlings. In this ambiance, independent system operator has to relieve congestions so that system is retained in secured state and power flows within limits. Transfer computations would provide the system bottleneck. It is essential to assess the transfer computation and give a secured operation. Being responsible for controlling the transaction and over loading of lines beyond its limits, it becomes obligatory for system operator to calculate change in power flow by which we can be aware of the transmission loading. It does not allow transmission lines to violate the security constraints like thermal limits and MVA rating of line's steady state stability limit, transient stability limit and voltage limit [3]. According to North American Electric Reliability council (NERC) Available Transfer Capability (ATC) is a measure of transfer capability Which is remaining in physical transmission network for further commercial activity over and above already committed uses [1]. Federal Energy Regulatory Commission established open access same time information system (OASIS). Power market planner, buyer and sellers get assistance in reserving transmission services, when ATC is posted on OASIS [11]. The definition of ATC can be formulated as;

ATC=TTC – TRM - (ETC + CBM)

CBM is capacity benefit margin and TRM is transmission reliability margin [2]. TRM and CBM differ system to system therefore are not considered while calculating ATC. ATC studies often involve contingencies making this task for most real systems [10] [5]. The determination of ATC requires the continuation version of power flow, steady-state stability, voltage stability, and transient stability simulations [17]. ATC could be evaluated by various techniques like DC load flow, AC load flow, Continuation power flow, Optimal dispatch [9] [12]. In this paper ATC is calculated using AC load flow, which is sensitivity based analysis. To study ATC we commence with a base case system, which requires data specifications like generator bus, load bus and slack bus. By using Newton-Raphson load flow analysis we can calculate ATC voltages and angles of bus system. Transfer direction would be identified by participation factors of source and sink bus, which are known as seller bus and buyer bus, respectively. Two cases i.e. linear power flow and reactive power flow have been used to compute ATC using ACPTDF. Desired power flow of line could be attained by inserting FACTS devices in transmission lines, in order to facilitate ATC of congested line. They help to increase the transfer of congested link and such devices can help ISOs to regain control over the power flow. The devices such as Thyristor Controlled Series Capacitor (TCSC), Static VAR Compensator (SVC), and Unified Power Flow Controller (UPFC) have become more popular due to their efficiency in controlling the power flow. Installation of TCSC in transmission line will improve the change in power flow in line and hence ATC of that line is improved [8]. TCSC can be used in two way model, as a variable reactance model and as a firing angle model. This paper used firing angle model to improve its ATC. This paper is divided in to four sections.

## II LINEAR ATC

DC load flow based power transfer distribution factors are easy to calculate and gives swift estimate of ATC. DC load flow ignores voltage and reactive power effects [9]. ACPTDFs are a sensitivity based analysis and it can be calculated as [16];

$$\rho_{jk,i} = \frac{\partial P_{jk}}{\partial P_s} = -\frac{\partial P_{jk}}{\partial P_i} \qquad (1)$$

For system we assume there is a transfer from slack bus s to any bus I, due to transaction between buses and sensitivity factors are used to predict the change in line flow (line j-k) as;

$$\Delta P_{jk} = \rho_{jk,i}\Delta P_s = -\rho_{jk,i}\Delta P_{i\,\Delta}$$

(2)

In above equation $\Delta P_s = -\Delta P_i$ is the amount of power transfer from s to i and direction of power transfer can be given by participation factors. For calculation of ACPTDFs, jacobian and power flow has to be calculated and this can be determined using power flow equations as [9];

$$P_{jk} = V_j V_k Y_{jk} \cos(\theta_{jk} + \delta_k - \delta_j) - \left(V_j^2\, Y_{jk}\, \cos\theta_{jk}\right)$$

(3)

Change in line flow can be calculated as;

$$\Delta P_s^{jk} = \begin{cases} \dfrac{P_{jk}^{max} - P_{jk}^{\circ}}{\rho_{jk,i}}, & \rho_{jk,i} > 0 \\ \dfrac{-P_{jk}^{max} - P_{jk}^{\circ}}{\rho_{jk,i}}, & \rho_{jk,i} < 0 \end{cases}$$

(4)

$P_{jk}^{max}$ = positive line flow limit or MVA rating of line

$P_{jk}^{\circ}$ = base case real power flow

For a given transaction (bus s-i) linear ATC can be calculated as:

$$ATCL_{s\to i} = min\{\Delta P_s^{jk}\ : all\ lines\ jk\} \qquad (5)$$

As in the above section active power is used in determining ATC by using linear programming however, it could be analyzed by using reactive power flow in conjunction with active power which is going to be discussed in ensuing sections[6][14][16].

## III INCORPORATION OF REACTIVE POWER FLOW

### I LIMITING AND OPERATING CIRCLES

Thermal limit of the line and all the feasible operating points can be represented by circles with centers at the origin. These circles can be referred as the limiting circle and operating circle. $S_{jk}^{max}$ is referred to as radius of circle. It becomes mandatory to restrain complex power flow on the operating circle, but inside the limiting circle so that security constraint cannot be reached beyond limits.

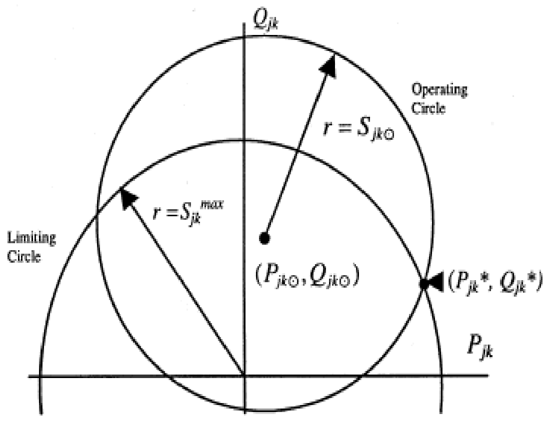

Fig.1: Limiting and operating circle

### II MAXIMUM COMPLEX POWER FLOW

In above Fig. there are two points, located at intersection of limiting circle and operating circle and complex power flow allow through transmission line corresponds to these point $(P_{jk}^*, Q_{jk}^*)$ [16]. This point of intersection relies on the thermal limit of line and system operating conditions. Consider the transmission line π model as shown in Fig. 2 below;

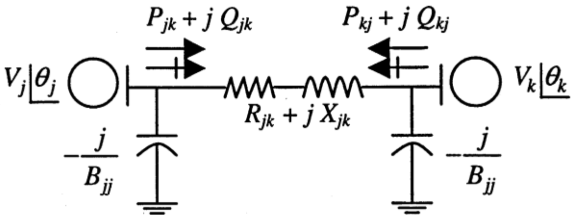

Fig: 2: Transmission line π model

Complex power flow from bus j (buyer) to bus k (seller) can be represented as;

$$S_{jk} = P_{jk} + jQ_{jk} = V_j^2 G_{jk} - V_j V_k Y_{jk} \cos(\delta_j - \delta_k + \theta_{jk}) + j(-V_j^2 B_{jj} - V_j^2 B_{jk} - V_j V_k Y_{jk} \sin(\delta_j - \delta_k + \theta_{jk}))$$

(6)

In above equation voltages and angles are respectively shown by $V_j, V_k$ and $\delta_j, \delta_k$ which are the state variables. Admittance can be calculated by;

$$G_{jk} + B_{jk} = \frac{1}{R_{jk} + jX_{jk}} \qquad (7)$$

During a transaction, it is essential to identify the relation between active power flow and reactive power. This can be done by separating the real and imaginary parts of equation (6) as;

$$P_{jk} = V_j^2 G_{jk} - V_j V_k Y_{jk} \cos(\delta_j - \delta_k + \theta_{jk})$$

$$Q_{jk} = V_j^2 B_{jj} - V_j^2 B_{jk} - V_j V_k Y_{jk} \sin(\delta_j - \delta_k + \theta_{jk})$$

(8)

Equation (8) shows active and reactive powers for j-k line and after rearranging, this equation can be written as;

$$P_{jk} - V_j^2 G_{jk} = -V_j V_k Y_{jk} \cos(\delta_j - \delta_k + \theta_{jk})$$

$$Q_{jk} + V_j^2 B_{jj} + V_j^2 B_{jk} = -V_j V_k Y_{jk} \sin(\delta_j - \delta_k + \theta_{jk})$$

(9)

Squaring and adding both sides

$$(P_{jk} - V_j^2 G_{jk})^2 + (Q_{jk} + V_j^2 B_{jj} + V_j^2 B_{jk})^2 = (V_j V_k Y_{jk})^2$$

(10)

If $V_j$ and $V_k$ remain constant during transfer (i.e. $\frac{\partial V_m}{\partial P_i} \cong 0$ , $\frac{\partial V_n}{\partial P_i} \cong 0$ which is an assumption ). Equation (10) represents a circle equation having center at;

$$(P_{jk\odot}, Q_{jk\odot}) = (V_j^2 G_{jk}, -V_j^2 B_{jj} - V_j^2 B_{jk})$$

(11)

and radius is equal to;

$$S_{jk\odot} = V_j V_k Y_{jk}$$

(12)

For calculating circle parameters put equation (11) and equation (12) into eqn. (10) and these parameters can be denoted by symbol (⊙). After calculation equation (13) can be shown as;

$$(P_{jk} - P_{jk\odot})^2 + (Q_{jk} - Q_{jk\odot})^2 = S_{jk\odot}^2$$

(13)

Complex flow at receiving end is different from sending end of transmission line, so at receiving end circle equation of complex power can be shown as;

$$(P_{kj} - P_{kj\odot})^2 + (Q_{kj} - Q_{kj\odot})^2 = S_{kj\odot}^2$$

(14)

In general $P_{jk\odot} \neq P_{kj\odot}$ and $Q_{jk\odot} \neq Q_{kj\odot}$. The radii of these circles though have the same value.

When transfer increases then power flow varies through the lines and all the feasible points lay on the operating circle. Power transfer is restricted to the limiting circle and maximum amount of transaction has to flow within the limiting circle such that $(S_{jk} \leq S_{jk}^{max})$ for all j-k lines.

## III ATC CALCULATION

For the calculation of active and reactive power Equation (15) must be solved [16].

$$(P_{jk} - P_{jk\odot})^2 + (Q_{jk} - Q_{jk\odot})^2 = S_{jk\odot}^2$$

$$P_{jk}^2 + Q_{jk}^2 = (S_{jk}^{max})^2$$

(15)

By expanding first one and subtracting the second one of equation (15), we can obtain;

$$Q_{jk} = \frac{1}{2Q_{jk\odot}}\left(-2P_{jk}P_{jk\odot} + \left(S_{jk}^{max}\right)^2 - M^2\right)$$

(16)

Where $M^2 = S_{jk\odot}^2 - P_{jk\odot}^2 - Q_{jk}^2$ substituting this value in above equation $P_{jk}^*$ can be obtained as;

$$\left(P_{jk\odot}^2 + Q_{jk\odot}{}^2\right)P_{jk}^{*\,2} - P_{jk\odot}\left((S_{jk}^{max})^2 - M^2\right)P_{jk}^{*} + \frac{1}{4}\left((S_{jk}^{max})^2 - M^2\right)^2 - Q_{jk\odot}^2\left(S_{jk}^{max}\right)^2 = 0$$

17)

By calculating the following constant coefficients we can calculate $P_{jk}^{*}$ as;

$$a = \left(P_{jk\odot}^2 + Q_{jk\odot}^2\right)$$

$$b = -P_{jk\odot}\left((S_{jk}^{max})^2 - M^2\right)$$

$$c = \frac{1}{4}\left((S_{jk}^{max})^2 - M^2\right)^2 - Q_{jk\odot}^2\left(S_{jk}^{max}\right)^2$$

(18)

$P_{jk}^{*}$ and $Q_{jk}{}^{*}$ can be calculated as;

$$P_{jk}^{*} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$Q_{jk}^{*} = \sqrt{\left(S_{jk}^{max}\right)^2 - P_{jk}^{*\,2}}$$

(19)

Reactive ATC can be computed by parameters $P_{jk}^{*}$ and $Q_{jk}^{*}$ and these terms could be evaluated by equations (18) and (19). For incorporating the effect of reactive power in linear ATC, this can be done by replacing $P_{jk}^{max}$ by $P_{jk}^{*}$ and this is the difference between linear ATC and reactive ATC.

Process for calculating linear ATC including effect of reactive power flows is as follows;

a) Calculate distribution factors using equation (1)

b) Using equation (18) and (19) calculate active power flow ($P_{jk}^{*}$) in j-k line

c) Replace $P_{jk}^{max}$ by $P_{jk}^{*}$ and compute the necessary transfer $\Delta P_s^{jk}$ to overload each line by using eqn. (4)

d) For computing reactive ATC obtain the minimum $\Delta P_s^{jk}$ from all lines

By using above step by step process we can calculate reactive ATC.

## IV TCSC MODELLING

Installing of FACTs device in electric utilities will maximize active power flow across existing transmission corridors [17]. These devices are capable of controlling the parameters such as voltage magnitudes and their angles, line impedances, active power and reactive power so the continuous variation of line impedance can be achieved by using TCSC and there by maintaining the active power flow in the transmission line at particular level [13]. TCSC is one of the best known FACTs controllers, and it has been in use for many years [7]. TCSC consists of parallel combination of capacitor and thyristor controlled reactor. In actual, TCSC system comprises a combination of many cascaded TCSC modules. In a network various parameters are considered for load flow analysis, which requires TCSC modeling. The two important modeling techniques are available for TCSC. Firstly, variable impedance model and secondly, firing angle control model. Variable impedance model uses the concept of series reactance model in which reactance is calculated using Newton -Raphson analysis. TCSC variable impedance model and firing angle techniques are interrelated to each other. This paper uses the firing angle model and equivalent model of TCSC is shown below in Fig. 3 as;

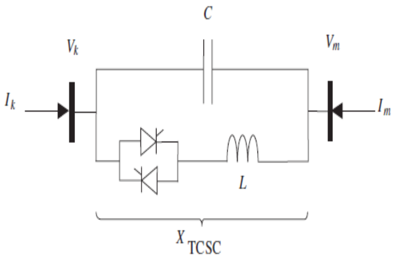

Fig. 3: Equivalent model of TCSC

TCSC basic module can be represented by three basic components: capacitor banks C, bypass inductor L and bidirectional thyristors.

The equivalent circuit of firing angle model can be represented by Fig. 3. It consists of anti-parallel connections of thyristors and combination of inductor and capacitors. This is a series connected device and which can be proved supportive in reducing net losses, provide voltage support, enhancing transient stability. As per operating principle of TCSC, it has ability to control active power flow in transmission line. In this model we could also use variable reactance method so as to manage firing angle. This makes engineering sense only in cases when all the modules making up the TCSC have identical design characteristics and are made to operate at equal firing angles. The fundamental frequency equivalent reactance $X_{TCSC(1)}$ of TCSC module is shown in Fig. 3. Impedance of TCSC can be represented as;

$$X_{TCSC(1)} = -X_C + C_1\{2(\pi - \alpha) + sin[2(\pi - \alpha)]\} - C_2\cos^2(\pi - \alpha)\{k\tan[k(\pi - \alpha)] - \tan(\pi - \alpha)\} \quad (20)$$

$X_{TCSC(i)}$, impedance of TCSC and it can be calculated using below equations;

$$C_1 = \frac{X_C + X_{LC}}{\pi}$$

$$C_2 = \frac{4X_{LC}^2}{X_L \pi}$$

$$X_{LC} = \frac{X_C X_L}{X_C - X_L}$$

$$k = \sqrt{\frac{X_C}{X_L}} \qquad (21)$$

$X_L = \omega L$ (reactance of inductor)

$X_C = 1/\omega C$ (reactance of capacitor bank)

**$\alpha$** = firing angle

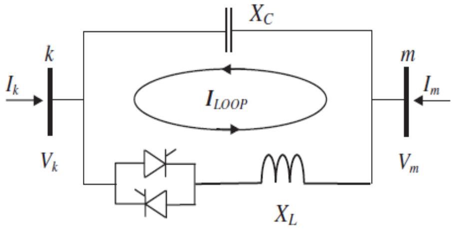

Fig. 4: Equivalent circuit of firing angle model

For variable impedance model, the susceptance values are given as follows;

For inductive mode of operation

$$B_{kk} = B_{mm} = \frac{1}{X_{TCSC}}$$

$$B_{km} = B_{mk} = -\frac{1}{X_{TCSC}}$$

For capacitive mode of operation

$$B_{kk} = B_{mm} = -\frac{1}{X_{TCSC}}$$

$$B_{km} = B_{mk} = \frac{1}{X_{TCSC}}$$

The inductance and capacitive reactance are taken to be 0.0068 and 15 ohm, respectively. TCSC operating range of firing angle is in between 90°- 180° and the capacitive and inductive region will depend on the firing angle. The maximum and minimum value of firing angle should be selected in such a way to avoid TCSC operating in high impedance region which results in high drop in this region.

The active and reactive power injections at bus 'k' and bus 'm' are given as;

$$P_k = V_k V_m B_{km} \sin(\theta_k - \theta_m)$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} \cos(\theta_k - \theta_m)$$

$$P_m = V_m V_k B_{km} \sin(\theta_m - \theta_k)$$

$$Q_m = -V_m^2 B_{mm} - V_m V_k B_{km} \cos(\theta_k - \theta_m)$$

(22)

After calculating active power and reactive power, set of power flow equations will be formed which is given by equation (23);

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km}^{\alpha TCSC} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial \alpha} \\ \frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_k} V_k & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial \alpha} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial \alpha} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_m}{\partial V_k} V_k & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial \alpha} \\ \frac{\partial P_{km}^{\alpha TCSC}}{\partial \theta_k} & \frac{\partial P_{km}^{\alpha TCSC}}{\partial \theta_m} & \frac{\partial P_{km}^{\alpha TCSC}}{\partial V_k} V_k & \frac{\partial P_{km}^{\alpha TCSC}}{\partial V_m} V_m & \frac{\partial p_{km}^{\alpha TCSC}}{\partial \alpha TCSC} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \Delta \theta_m \\ \frac{\Delta V_k}{V_k} \\ \frac{\Delta V_m}{V_m} \\ \Delta \alpha_{TCSC} \end{bmatrix} \qquad (23)$$

$$\Delta P_{km}^{\alpha TCSC} = P_{km}^{reg} - P_{km}^{\alpha TCSC,cal}$$

$\Delta P_{km}^{\alpha TCSC}$, is the active power mismatch for the firing angle model. Jacobian matrix is modified by inserting TCSC parameters and these parameters can be calculated as;

$$\frac{\partial P_k}{\partial \alpha} = P_k B_{TCSC} \frac{\partial X_{TCSC}}{\partial \alpha} \qquad (24)$$

$$\frac{\partial Q_k}{\partial \alpha} = Q_k B_{TCSC} \frac{\partial X_{TCSC}}{\partial \alpha} \qquad (25)$$

$$\frac{\partial B_{TCSC}}{\partial \alpha} = B_{TCSC}^2 \frac{\partial X_{TCSC}}{\partial \alpha}$$

(26)

$$\frac{\partial X_{TCSC}}{\partial \alpha} = -2C_1 [1 + \cos(2\alpha)] + C_2 \sin 2\alpha$$

$$\{\omega \tan[\omega(\pi - \alpha)]\} + C_2 \left\{\omega^2 \frac{\cos^2(\pi - \alpha)}{\cos^2[\omega(\pi - \alpha)]} - 1\right\}$$

(27)

$$\Delta\alpha_{TCSC} = \alpha_{TCSC}^{(i+1)} - \alpha_{TCSC}^{(i)}$$

(28)

After every iteration, jacobian matrix elements are updated according to equations (24), (25), (26) and (27) and firing angle would also updated according to equation (28). Equation (27) gives relation between reactance and firing angle, it means it is clear that reactance of TCSC is function of firing angle, and jacobian matrix is also firing angle dependent. In variable impedance model there is no firing angle effect [18].

## V. RESULTS AND DISCUSSION

### Case: 1 IEEE 5 bus test system

An IEEE 5 bus system is used to quantify the TCSC behavior in an interconnected system and network is modified using a single TCSC in it. In firing angle model of TCSC the firing angle is taken with lower limit as 90° and upper limit of 180°. TCSC inductive reactance and capacitive reactance are taken as 1.625e-3 and 9.375e-3. In the system under consideration TCSC is placed in between bus 3 & 4, which is randomly selected for a 5 bus test system. Fig. 5 as given below shows IEEE 5 bus system.

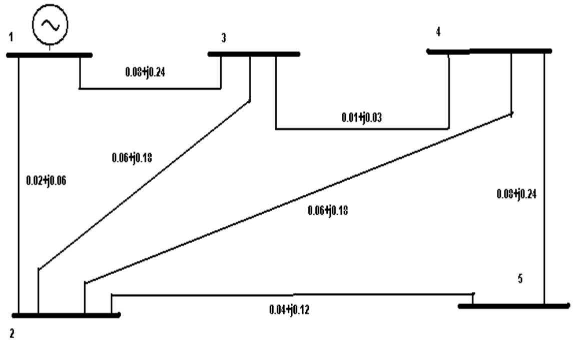

Fig. 5: IEEE 5 bus system

Calculated values of PTDFs for this system are shown in Table II and power flows for the cases of Linear and Reactive are also shown in the same table. Table III shows calculated values of power flows for linear and reactive methods which incorporate the effect of TCSC.

Table I: TCSC parameters

| Capacitive Reactance $X_c$ (ohm) | Inductive Reactance $X_c$ (ohm) | Initial Firing Angle (degree ) | Minimum Value of FA (degree) | Maximum Value of Firing angle (degree) |
|---|---|---|---|---|
| 1.625e-3 | 9.375e-3 | 100 | 90 | 180 |

Table II: Linear and Reactive power flows without TCSC in 5 Bus System

| Transfer Direction | Limiting Line | PTDF | $\Delta P_{ij}$ in p.u | $\Delta P_{ij}^*$ in p.u |
|---|---|---|---|---|
| 1-2 | 1-2 | -0.8777 | 1.9 | 1.7 |
| 1-3 | 1-3 | -0.5029 | 2.5 | 1.7 |
| 2-3 | 1-3 | -0.4883 | 3.2 | 2.2 |
| 2-4 | 2-4 | -0.6721 | 1.8 | 1.4 |
| 2-5 | 4-5 | -0.4471 | 4.71 | 4.70 |
| 3-4 | 3-4 | -0.9971 | 1.8 | 0.7 |
| 4-5 | 4-5 | -0.5529 | 1.92 | 1.90 |

Table III: Linear and Reactive power flow incorporating TCSC in the system

| Transfer Direction | Limiting Line | PTDF | $\Delta P_{ij}$ in p.u | $\Delta P_{ij}^*$ |
|---|---|---|---|---|
| 1-2 | 1-2 | 2.206 | 0.513 | 0.449 |
| 1-3 | 1-3 | -0.989 | 1.26 | 1.213 |
| 2-3 | 1-3 | 0.147 | 0.865 | 0.832 |
| 2-4 | 2-4 | 0.5093 | 1.550 | 1.544 |
| 2-5 | 4-5 | -0.088 | 0.691 | 0.690 |
| 3-4 | 3-4 | -4.05 | 0.808 | 0.344 |
| 4-5 | 4-5 | -1.065 | 0.978 | 0.976 |

Table IV: Linear and Reactive ATC with and without TCSC

| Transfer Direction | Linear ATC without TCSC | Reactive ATC without TCSC | Linear ATC with TCSC | Reactive ATC with TCSC |
|---|---|---|---|---|
| 1-2 | 1.8633 | 1.696 | 0.513 | 0.449 |
| 1-3 | 2.464 | 1.684 | 0.366 | 0.327 |
| 2-3 | 2.202 | 2.199 | 0.240 | 0.218 |
| 2-4 | 1.796 | 1.425 | 0.425 | 0.184 |
| 2-5 | 1.756 | 1.694 | 0.207 | 0.188 |
| 3-4 | 1.757 | 0.749 | 0.268 | 0.403 |
| 4-5 | 1.782 | 1.220 | 0.235 | 0.322 |

From tables II and table III it is clear that in case of incorporation of TCSC power flows are decreasing and Table IV shows that ATC values are improving with the inclusion of TCSC in the system. It signifies that with the less power flow in lines, transmission lines are less congested and ATC values are improved. When ATC values decrease means it is improving because ATC can be defined as TTC (Total Transmission Capacity) minus ETC (Existing Transmission Capacity). TTC is thermal limit of line which is unchanged, so by increasing the ETC we can improve ATC. In IEEE 5 bus system, TCSC is placed between bus 3 & 4 (i.e. line 3-4) which is randomly chosen, and TCSC initial firing angle is taken as 100°, which is updated after each iteration.

### Case II: IEEE 30 bus system

An IEEE 5 bus system is used to quantify the TCSC behavior in an interconnected system and network is modified using a single TCSC in it.

Table V: Power Flows for Linear and Reactive methods

| Transfer Direction | Limiting Line | $\Delta P_{ij}$ p.u Without TCSC | $\Delta P_{ij}^*$ Without TCSC | $\Delta P_{ij}$ p.u With TCSC | $\Delta P_{ij}^*$ With TCSC |
|---|---|---|---|---|---|
| 1-2 | 1-2 | 7.244 | 6.383 | 3.894 | 2.054 |
| 2-6 | 9-10 | 16.013 | 15.98 | 15.584 | 15.561 |
| 4-6 | 1-2 | 10.408 | 9.170 | 5.993 | 3.161 |
| 5-7 | 1-2 | 9.405 | 8.287 | 5.679 | 2.995 |
| 6-7 | 6-7 | 30.920 | 29.66 | 22.412 | 13.767 |
| 9-11 | 1-3 | 17.339 | 16.75 | 17.484 | 16.80 |
| 9-10 | 1-3 | 16.799 | 16.23 | 22.151 | 21.4 |
| 4-12 | 4-12 | 16.061 | 16.05 | 6.762 | 6.713 |
| 12-16 | 1-2 | 11.241 | 9.905 | 5.594 | 2.950 |
| 14-15 | 1-2 | 11.212 | 9.879 | 5.363 | 2.828 |
| 16-17 | 4-12 | 28.153 | 28.13 | 16.045 | 15.930 |
| 15-18 | 1-2 | 10.946 | 9.645 | 5.442 | 2.870 |
| 18-19 | 4-12 | 22.158 | 22.14 | 19.028 | 18.892 |
| 19-20 | 4-12 | 23.764 | 23.74 | 22.660 | 22.498 |
| 10-21 | 1-2 | 11.048 | 9.735 | 5.573 | 2.939 |
| 31-22 | 1-2 | 15.838 | 15.30 | 7.911 | 7.643 |
| 21-22 | 4-6 | 42.118 | 37.80 | 23.789 | 5.577 |
| 15-23 | 1-2 | 10.981 | 9.676 | 5.633 | 2.971 |
| 22-24 | 1-2 | 10.937 | 9.637 | 5.753 | 3.0344 |
| 23-24 | 4-6 | 45.592 | 40.91 | 25.953 | 6.084 |
| 24-25 | 1-2 | 11.002 | 9.695 | 5.626 | 2.96 |
| 25-26 | 4-6 | 36.122 | 32.45 | 28.382 | 6.64 |
| 28-27 | 1-2 | 11.149 | 9.824 | 5.746 | 3.030 |
| 27-29 | 4-6 | 34.823 | 31.28 | 30.975 | 7.262 |
| 29-30 | 3-4 | 29.376 | 26.04 | 24.694 | 21.892 |
| 8-28 | 9-10 | 23.312 | 23.27 | 21.628 | 21.595 |
| 6-28 | 3-4 | 33.180 | 29.41 | 12.920 | 11.454 |

Table VI: ATC Comparison for IEEE 30 Bus system

| Transfer Direction | Linear ATC Without TCSC | Reactive ATC Without TCSC | Linear ATC with TCSC | Reactive ATC with TCSC |
|---|---|---|---|---|
| 1-2 | 7.244 | 6.383 | 3.894 | 2.054 |
| 2-6 | 9.428 | 8.307 | 8.198 | 4.323 |
| 4-6 | 10.408 | 9.170 | 5.993 | 3.161 |
| 5-7 | 9.40 | 8.287 | 5.679 | 2.995 |
| 6-7 | 10.10 | 8.900 | 4.353 | 2.295 |
| 9-11 | 11.17 | 9.845 | 5.042 | 2.659 |
| 9-10 | 11.280 | 9.940 | 5.577 | 2.941 |
| 4-12 | 11.304 | 9.960 | 4.551 | 2.400 |
| 12-16 | 11.241 | 9.905 | 5.594 | 2.950 |
| 14-15 | 11.212 | 9.879 | 5.363 | 2.828 |
| 16-17 | 11.079 | 9.762 | 5.298 | 2.794 |
| 15-18 | 10.946 | 9.645 | 5.442 | 2.870 |
| 18-19 | 10.932 | 9.633 | 5.429 | 2.863 |
| 19-20 | 11.030 | 9.719 | 5.630 | 2.969 |
| 10-21 | 11.048 | 9.735 | 5.572 | 2.939 |
| 31-22 | 11.061 | 9.746 | 7.911 | 2.208 |
| 21-22 | 11.093 | 9.775 | 5.388 | 2.842 |
| 15-23 | 10.981 | 9.676 | 5.633 | 2.971 |
| 22-24 | 10.937 | 9.637 | 5.753 | 3.034 |
| 23-24 | 10.843 | 9.554 | 5.702 | 3.007 |
| 24-25 | 11.002 | 9.695 | 5.626 | 2.967 |
| 25-26 | 10.684 | 9.414 | 5.694 | 3.003 |
| 28-27 | 11.046 | 9.733 | 5.794 | 3.056 |
| 27-29 | 10.755 | 9.477 | 5.581 | 2.943 |
| 29-30 | 10.659 | 9.325 | 5.898 | 3.110 |
| 8-28 | 11.012 | 9.703 | 5.646 | 2.977 |
| 6-28 | 10.996 | 9.689 | 4.289 | 2.262 |

## VI CONCLUSION

A firing angle model of TCSC is presented in this paper for enhancing ATC. This model is implemented in MATLAB using Newton - Raphson load flow algorithm. In this paper TCSC model is validated for IEEE 5 & 30 bus system using ACPTDFs technique. In this work ACPTDFs technique is used to calculate the change in line flows for linear and reactive methods. Hence from the work done in the paper, it is inferred that there is remarkable enhancement in ATC values.

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## BIOGRAPHIES

**Naresh Kumar Yadav** obtained B. Tech. in Electrical Engineering from Maharshi Dayanand University, Rohtak (Haryana), India and M.Tech. in Electrical Engineering from National Institute of Technology, Kurukshetra, India, in 2000 and 2004, respectively. He worked with Imperial Malts Ltd., Gurgaon, India from 2000 to 2002. From 2004 to 2006 he worked with Apeejay College of Engineering, Sohna (Gurgaon), India. Since August-2006 he has been with Department of Electrical Engineering, Faculty of Engineering and Technology, Deen Bandhu Chhotu Ram University of Science & Technology, Murthal (Sonepat)-Haryana, India, where he is currently Assistant Professor. Recently, he has completed his Ph.D. research from Jamia Millia Islamia (A Central University), New Delhi-110025. His research interests include power system restructuring, FACTS applications to power system restructuring, Automatic Generation Control etc. Mr. Yadav is a life time member of Indian Society for Technical Education. He has participated in and presented many research papers at national and international conferences. He has published more than twenty research papers in national & international journals.

**Arti Saini** is a Masters student in Department of Electrical Engineering, Faculty of Engineering & Technology, D. C. R. University of Science & Technology, Murthal (Sonepat). Her research interests include power system restructuring and FACTS applications to power system restructuring.