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A Simple TCSC Based Power Flow Control Model in Electrical Power System

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***Abstract*—Load flow and stability are the most significant and fundamental aspects of power systems. Electrical power-flow problem is required for precise and real-time loading calculations at the demand and generation ends. In general, the load flow computation is dependent on the voltage, phase angle, real power and reactive power. This study describes the development of external control of simple thyristor control series capacitor (TCSC) as per the power flow requirement in the multi-bus system. The TCSCs is employed as power flow controller device in power system. Power flow analysis, which is used for the foundation of planning and operating power systems. The Newton Raphson's (NR) is fundamentally used for the Jacobian matrix for error computation iteratively to generate triggering pulses for TCSC control. FACTS devices like the TCSC are included to regulate a power network's performance under certain circumstances. The complete framework is developed on IEEE-5 bus system with simple TCSC and NR based external controller. The experimentation is done using MATLAB and it is found that 1.10337 MW of power can be saved with the proposed method.**

Keywords—TCSC, NR, Jacobian matrix, optimal power flow, load flow analysis, electrical power system.

I. INTRODUCTION

The utilization of electricity becomes mandatory for the whole world. For transmitting power through AC systems were implemented for easier transmission of power, high economizing, and better control compared to DC transmission systems [1]. Power produced through DC machines is costly; does not have neither DC transformer for stepping up voltage nor DC circuit breaker; which are the major restrictions for DC power transmission [2]. The electric power-flow problem, a part of power engineering, requires accurate and real-time calculation of loading at demand (receiving end) and generation (transmission end) levels [3]. Power flow analysis is very important in planning stages of new networks or addition to existing ones like adding new generator sites, meeting increase load demand and locating new transmission sites [4]. The main aim of the operations of the power system is to meet the demand with proper power supply: providing adequate reactive power compensation; maintaining voltage and frequency through AVR; and ensuring reliable power systems' operations [5]. One of the important jobs of the voltage regulator is to improve the power system stability of the electricity transmission. Improvement in the power system stability indicates an increase in the maximum power transfer capability for the existing power system network [5, 6]. The major factors affecting voltage stability of a power system are its generators reactive power limit, voltage actions [7, 8] control limits, characteristics of connected loads, reactive power compensation devices characteristics and their actions. The potential benefits of using Flexible AC Transmission system (FACTS) controllers for enhancing power system stability are well known [1-5, 10]. The use of these controllers gives grid planners and operators a greater flexibility regarding the type of control actions that can be taken at any given time. Thyristor Controlled Series Capacitors (TCSC), in particular, have been widely studied and reported in the technical literature, and have been shown and used in practice to significantly enhance system stability [11]. There some most usable power flow methods are: (i) Gauss–Seidel method (ii) Fast-decoupled-load-flow method (iii) Holomorphic embedding load flow method (iv) Backward-Forward Sweep (BFS) method. In this paper the Newton Raphson method is used to converge the load flow problem. This method begins with initial guesses of all unknown variables (voltage magnitude and angles at Load Buses and voltage angles at Generator Buses) [12]. Next, a Taylor Series is written, with the higher order terms ignored, for each of the power balance equations included in the system of equations. The load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting power channels. It determines the voltage of the buses [13]. The voltage level at the certain buses must be kept within the closed tolerances and system transmission loss minimizes [14]. The buses exist in the power system are:

(1) Slack Bus:

slack bus (or swing bus), defined as a Vδ bus, is used to balance the active power |P| and reactive power |Q| in a system while performing load flow studies.

(2) Generator Buses:

PV buses, we know Pi and |Vi | but not Qi or θ_i

(3) Load Buses:

PQ buses, we know Pi and Qi but not |Vi | or θ_i, including buses that have not either load or generation.

Let the $V_i\angle\delta_i and V_j\angle\delta_j$ are the voltages of two buses i and j with phase angle δ_i and δ_j respectively, as the power flows from i to j end. The line admittance between these two buses is Yij and existing phase angle is θ_{ij}. Power flow equations are to be written as:

$$P_k = \sum_{j=1}^{N} |V_i||V_j|\left(Y_{ij}\cos(\delta_i - \theta_{ij} - \delta_j)\right) \quad (1)$$

$$Q_k = \sum_{j=1}^{N} |V_i||V_j|\left(Y_{ij}\sin(\delta_i - \theta_{ij} - \delta_j)\right) \quad (2)$$

The Jacobian matrix is formed as:

$$\overbrace{M_J}^{(2N-1-N_G)\times(2N-1-N_G)} = \begin{bmatrix} \overbrace{M_J^{P\delta}}^{(N-1)\times(N-1)} & \overbrace{M_J^{PV}}^{(N-1)\times(N-N_G)} \\ \overbrace{M_J^{Q\delta}}^{(N-N_G)\times(N-1)} & \overbrace{M_J^{QV}}^{(N-N_G)\times(N-N_G)} \end{bmatrix} \quad (3)$$

Iteration wise there will be four equations. For the load flow problem, this equation is of the

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = M_J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_n \\ \Delta V_2 \\ \vdots \\ \Delta V_n \end{bmatrix} \text{ and } \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \vdots \\ \Delta Q_n \end{bmatrix}$$

Where, M_J is the Jacobian matrix

$$M_J = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_n} & |V_2|\frac{\partial P_2}{\partial |V_2|} & \cdots & |V_n|\frac{\partial P_2}{\partial |V_n|} \\ \vdots & M_{J11} & \vdots & \vdots & M_{J12} & \vdots \\ \frac{\partial P_n}{\partial \delta_2} & \cdots & \frac{\partial P_n}{\partial \delta_n} & |V_2|\frac{\partial P_n}{\partial |V_2|} & \cdots & |V_n|\frac{\partial P_n}{\partial |V_n|} \\ \frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_n} & |V_2|\frac{\partial Q_2}{\partial |V_2|} & \cdots & |V_n|\frac{\partial Q_2}{\partial |V_n|} \\ \vdots & M_{J21} & \vdots & \vdots & M_{J22} & \vdots \\ \frac{\partial Q_n}{\partial \delta_2} & \cdots & \frac{\partial Q_n}{\partial \delta_n} & |V_2|\frac{\partial Q_n}{\partial |V_2|} & \cdots & |V_n|\frac{\partial Q_n}{\partial |V_n|} \end{bmatrix}$$

II. LOAD FLOW ALGORITHM USING TCSC

(1) TCSC reactance updation:

The Newton Raphson method is used to find the optimal value of the function over given domain in iterative way [16]. Here x_i and x_{i+1} are the points that are computed from the given function, where the function having optimal value.

$$x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)} \quad (5)$$

In case of power flow there is computation of phase angle, voltage and power is prime [17]. In this way the change in real and reactive powers are computed from the computation of bus phase angle (δ) and bus voltage (V).

$$\delta^{(1)} = \delta^{(0)} + \Delta\delta^{(0)} \quad (6)$$

$$|V|^{(1)} = |V|^{(0)} + \Delta|V|^{(0)} \quad (7)$$

With the updation of real and reactive powers, the TCSC reactance changes to get optimal power flow in the multi-bus system as,

$$X_{TCSC}\ (X_{TCSC}^{i+1} = X_{TCSC}^{i} + \Delta X) \quad (8)$$

(2) Transmission line model:

Overhead transmission lines are modeled by their equivalent pi (π) model as shown in Fig. 1. The series impedance Z or its inverse which is the admittance Y depends on the short circuit current, Ish, whereas the admittance ($g_l + jb_l$) is a function of the no-load current I_o.

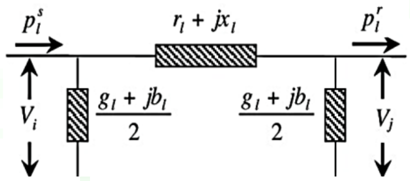

Fig. 1. Transmission line pi (π)model [1]

III.TCSC MODELLING

To divert power flow through the TCSC compensated line when a parallel path is overloaded, one would need to first sense that such a condition exists. Therefore, the current in the parallel tie line is measured [6-12, 18]. In case, the current magnitude in the parallel tie line is greater than the permissible value due to thermal limit, increase the power (or current) flow in the TCSC compensated line by increasing the TCSC capacitive reactance [19, 20, 21, 26]. Since the effective impedance of the TCSC compensated line is reduced, it will take on a larger share of the total power flow between the two areas [1, 2].

TCSC consists of three components: capacitor banks C, bypass inductor L and bidirectional thyristors T1 and T2.

The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations.According to the operating principle of the TCSC, it can control the active power flow for the line *l* (between bus- *i*and bus- *j* where the TCSC is installed) shown in Fig. 2.

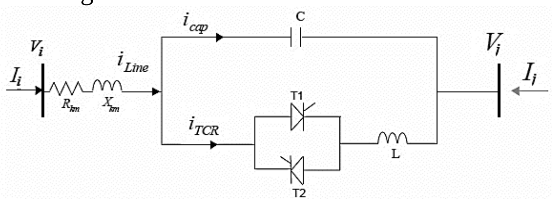

Fig. 2. TCSC model adjusted between two buses [8]

The real power P_{iinj}^{TCSC} and reactive power Q_{iinj}^{TCSC} injected at bus I can be expressed as:

$$P_{iinj}^{TCSC} = G_{ii}V_i^2 + (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij})V_iV_j \quad (9)$$

$$Q_{iinj}^{TCSC} = -B_{ii}V_i^2 + (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij})V_iV_j \quad (10)$$

Where,

$$G_{ij} = r_{ij}/(r_{ij}^2 + (X_{ij} - X_c)^2)$$

and

$$B_{ij} = (X_{ij} - X_c)/(r_{ij}^2 + (X_{ij} - X_c)^2)$$

TCSC works in-

1. *Blocking mode:* In this mode the TCSC performs like a fixed series capacitor.
2. *Bypass mode:* In this case the TCSC behaves like a parallel connection of the series capacitor and the inductor.

The rating of TCSC depends on the reactance of the transmission line where the TCSC is located.

$$X_{ij} = x_{line} + x_{tcsc} \quad (11)$$

$$x_{tcsc} = r_{tcsc} \cdot x_{line} \quad (12)$$

Where, x_{line} is the reactance of the transmission line and r_{tcsc} is the coefficient which represents the degree of compensation by TCSC. To avoid overcompensation, the working range of the TCSC is chosen between (-0.015 X line and 0.015 X line). By optimizing the reactance values between these ranges optimal settings of reactance values can be achieved [1, 4, 5, 8, 22, 23, 24, 27].

(1) Optimal power flow Inequality constraints

for the optimal power flow, the inequality constraint are the important assumptions to ensure the system stability in power systems.

Generators real and reactive power outputs:

$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, i = 1,\ldots,N_G$ and $Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, i = 1,\ldots,N_G$

Voltage magnitudes at each bus in the network

$V_i^{\min} \le V_i \le V_i^{\max}, i = 1,\ldots,N_L$

TCSC constraints: Reactance constraint of TCSC

$X_{TCSCi}^{\min} \le X_{TCSCi} \le X_{TCSCi}^{\max} i = 1,2,\ldots,n_{TCSC}$

Where, X_{TCSCi}= Reactance of TCSC at line

$X_{TCSCi}^{\min}$= Minimum reactance of TCSC at line

$X_{TCSCi}^{\max}$= Maximum reactance of TCSC at line *i*

N_{TCSC}= number of TCSC's

$$X_{tcsc} = \frac{X_c\left[\pi\left(k^2-1\right)^2 - k^2\left(k^2-1\right)(2\beta + \sin 2\beta) + 4k^2\cos^2\beta(k\tan k\beta - \tan\beta)\right]}{\pi\left(k^2-1\right)^2} \quad (13)$$

Where, $k = \sqrt{\frac{X_c}{X_L}}, \beta = \pi - \alpha$ X_C and X_L are reactances.

TCSC characteristics with respect to firing angle shown in Fig. 3.

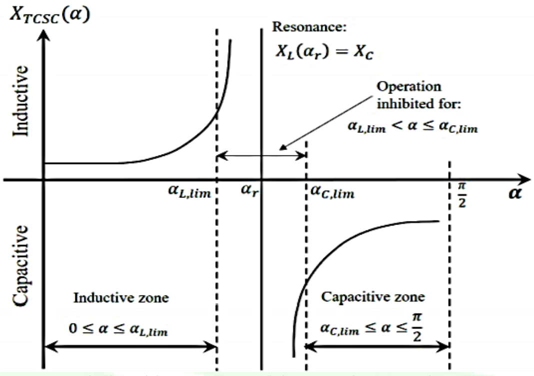

Fig. 3. Relationship Between Firing Angle (α) and X_{TCSC} [11]

Fig.4 shows a single line diagram of a 5-bus system with two generating units, seven lines. Per-unit transmission line series impedances and shunt susceptance are given in p.u. in Table1.

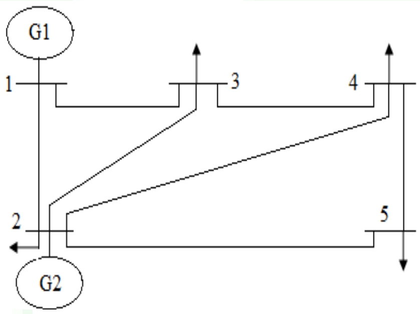

Fig. 4. Standard IEEE 5-bus system [1]

Real power generation, real and reactive power loads in p.u. are given in Table 2. With Bus 1is a slack bus, obtain a load flow solution by using Newton-Raphson method with tolerance of 0.002 p.u for the real and reactive bus powers.

Table-1Line Parameters

Bus code (From – to)	Impedance (R +jX)	Line Charging B/2
1 - 2	0.02+j0.06	0.0+j0.030
1 -3	0.08 + j 0.24	0.0 + j0.025
2-3	0.06 + j0.18	0.0 + j0.02
2-4	0.06 + j0.18	0.0 + j0.02
2-5	0.04 + j0.12	0.0 + j 0.015
3-4	0.01 + j0.03	0.0 + j0.010
4-5	0.08 + j0.24	0.0 + j0.025

Table-2 Bus Parameters

Bus No	Bus Voltages	Generation MW	Generation MVAR	Load MW	Load MVAR
1	1.06+j0.0	0	0	0	0

2	1.00+j0.0	40	30	20	10
3	1.00+j0.0	0	0	45	15
4	1.00+j0.0	0	0	40	5
5	1.00+j0.0	0	0	60	10

IV. RESULTS AND DISCUSSION

The proposed algorithm is implementation using MATLAB and analysed for its perfectness. The TCSC is implemented between bus 2 and bus 3, the 5-bus system stability improves because of the reactive power compensated by TCSC within the system. Step-by-step TCSC reactance updation according to requirement of line reactance for the optimal power flow. The effectiveness of the proposed method is clearly validated from the experimentation.

(1) Real power flow (MW) with TCSC and without TCSC

The buses active power stabilised with the TCSC implementation. Mismatch in the real power with the pupation of reactance in the line where the TCSC is implemented shown properly in Fig. 5 and Fig. 6 respectively.

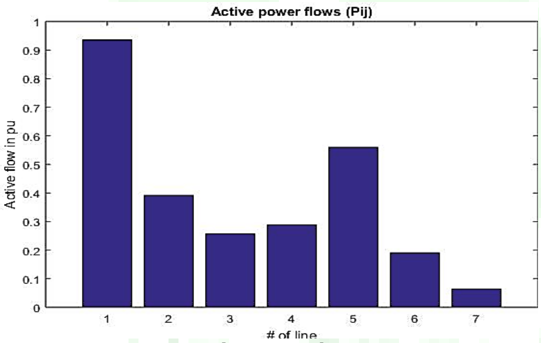

Figure 5 Real Power without TCSC

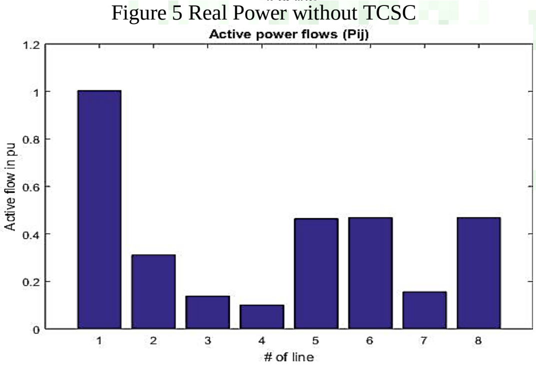

Figure 6. Real Power with TCSC

The reactive power mismatch is minimum with the TCSC implementation. TCSC works to modify the required effective reactance in the system to overcome the power mismatch problem and optimize the power flow.

(2) Reactive power (MVR) flow with TCSC and without TCSC

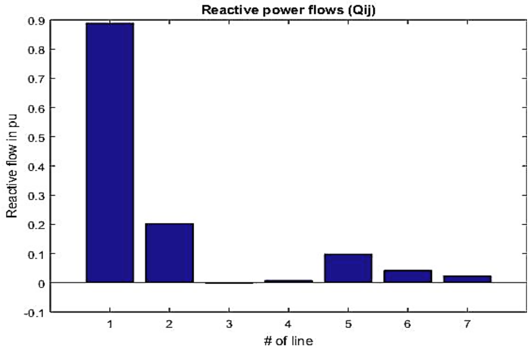

Fig. 7 Reactive Power without TCSC

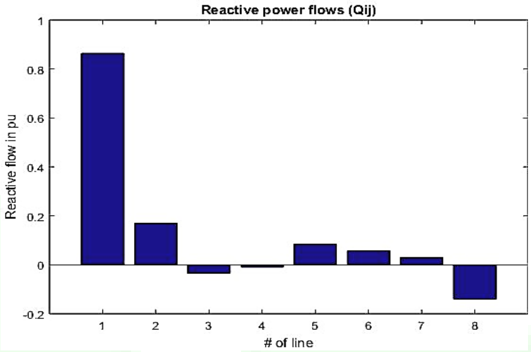

Fig. 8Reactive Power with TCSC

From Fig. 7 and Fig. 8 it is very clear and justified that the reactive power can be managed optimized by using FACTS controllers.

(3) Bus by bus load angle with TCSC and without TCSC

The load angle mismatch response is shown in the Fig. 9 andFig. 10 with and without respectively. The load angle stabilizes with the compensation of phase with the TSCS whenever it is required. More is the stability more is the power optimization.

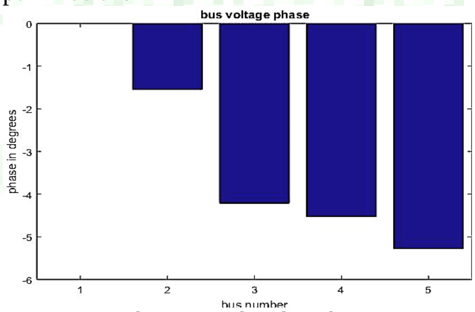

Fig. 9 Bus by Bus Load angle without TCSC

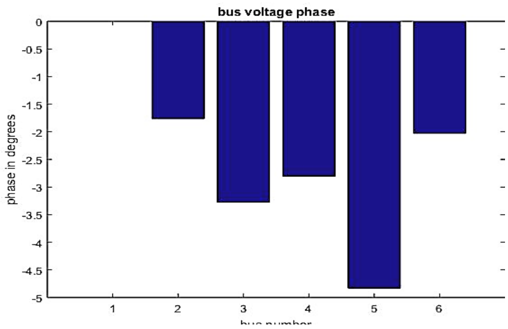

Fig. 10 Bus by Bus Load angle with TCSC

The bus voltages with and without TCSC are shown in Fig. 11 and Fig. 12.

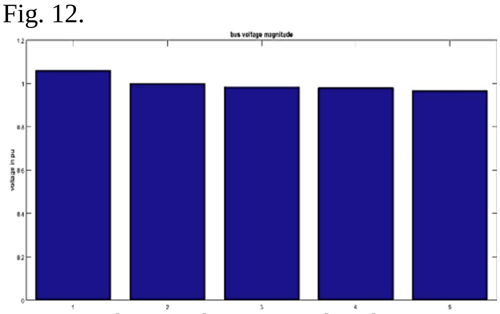

Fig.11 Bus by Bus voltage magnitude without TCSC

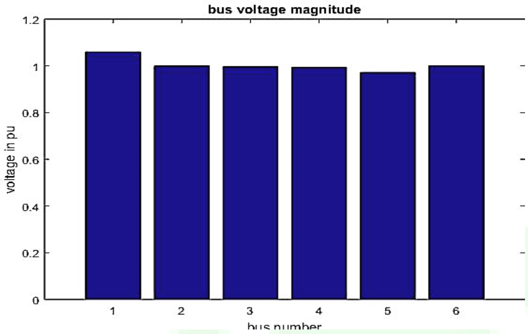

Fig.12 Bus by Bus voltage magnitude with TCSC

As the effective reactance changes the buses voltage also changes accordingly to ensure the system stability requirement.Total real power losses in the network without TCSC is 0.0672444 pu .i.e 6.7244 MW and real power losses in the network with TCSC is 0.0562107 pu .i.e 5.62107 MW, so it is very clear that there is total power saving in is of 1.10337 MW, this is shown graphically by the bar graph in Fig. 13.

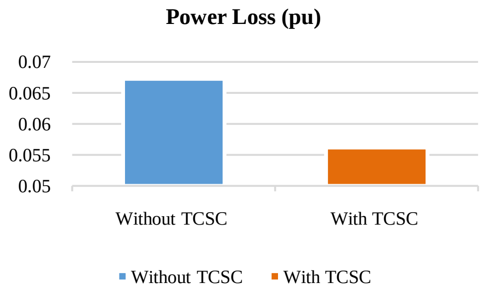

Figure 5.5 Power loss comparison bar chart

V. CONCLUSION AND FUTURE SCOPE

In this work the TCSC power flow model is introduced. The complete work is implemented in MATLAB, using optimization or convergence method (Newton-Raphson) for load flow, with this control method, it is possible to solve large power networks very reliably. The method with FACTS controller: TCSC retains Newton's quadratic convergence and the effectiveness is illustrated by some power flow solutions of the multi-bus systems. Power calculations in conventional manner indicates some suggestions related to the position of TCSC. The case studies for implementing the variable series impedance power flow model of TCSC is an effective and put evidence with respect to modelling and using TCSC to control power flows in multi bus systems. The experimental results show the effectiveness of the model and method used for voltage and power flow control.

This work can be further modified with the use of effective auxiliary control techniques, the response of TCSC could be modified. By using appropriate soft techniques for optimization like advanced PSO, advanced PSO with Newton Raphson the better results can be achieved. Modified Jacobian estimation-based power system modelling can be done for effective response.

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