Optimal Location of TCSC using Newton Raphson Method for Power Flow Analysis

Nikhil Kumar Nigam*, Ishta Garg
Department of Electronics Engineering, Delhi Technical Campus, Greater Noida (UP) India

Article Info

Article history:
Received 02 January 2017
Received in revised form 20February 2017
Accepted 28 February 2017
Available online 15 June 2017

Keywords

Thyristor controlled Series capacitor, FACTS devices, Newton Raphson method, Power Flow analysis etc.

Abstract

With the increase in development of power networks, the economical operation of power system has become a concern. The maximum capability of power systems can be exploited by means of FACTS devices. Currently, development of power electronics switches causes reduction in the cost of FACTS and therefore application of FACTS devices especially in distribution networks is more economical. But economic considerations limit the installation of FACTS controller in all of the buses or the lines. There are several methods for finding optimal locations of FACTS devices in power systems. In this paper power flow analysis using Newton Raphson method has been proposed to determine optimal location of Thyristor Controlled Series Compensator (TCSC) in a system. The paper concentrates on the development of the power flow software package using MATLAB and the steady-state modeling of the series FACTS devices TCSC. The configuration of a typical TCSC from a steady-state perspective is the fixed capacitor with a thyristor controlled reactor (TCR). The effect of TCSC on the network can be modeled as a controllable reactance inserted in the related transmission line. The TCSC modeling equations illustrate how the flexibility of the software environment in use allows the easy combination of different objective functions, different sets of variables and different formulations of functions. Case studies demonstrate the operating regions of the series FACTS devices and their effectiveness in increasing the MW power transferability of a particular network.

1. Introduction

In power engineering, the power-flow study, or load-flow study, is a numerical analysis of the flow of electric power in an interconnected system and focuses on various aspects of AC power parameters, such as voltages, voltage angles, real power and reactive power. It analyzes the power systems in normal steady-state operation.

The power flow problem is formulated as a set of non linear equations. Many calculation methods have been proposed to solve this problem. Among them, Newton-Raphson method and Fast-Decoupled method are two very successful methods.

In general, the decoupled power flow methods are only valid for weakly loaded network with large X/R ratio network [3, 10]. For systems conditions with large angles across lines (heavily loaded network) and with special control that strongly influence active and reactive power flows, Newton-Raphson method may be required. The Newton Raphson algorithm exhibits quadratic or near quadratic convergence characteristics, regardless of the size of the network and number of TCSC devices.

Therefore, when the AC power flow calculation is needed in systems with FACTS devices, Newton-Raphson method [5] is a preferred choice for achieving high accuracy.

TCSC is one of the generation facts controllers [4] which control the effective line reactance by connecting a variable reactance in series with the line. The variable reactance is obtained using FC – TCR combination with mechanically switched capacitor sections in series. The model presented in this paper is based on the concept of variable series compensator whose changing reactance adjusts itself in order to constraint the power flow across the branch to a specified value. TCSC can be used for damping power swings [6, 9].

In this paper, a power flow program using Matlab has been developed. The modeling equations are derived using different sets of variables and different formulations of functions. The effectiveness of this program has been demonstrated on five bus system. Issues include increased utilization of existing facilities such as secure system operation at higher power transfers across existing transmission lines which are limited by stability constraints.

***Corresponding Author,**
E-mail address er.nikhil2007@gmail.com

2. Problem Formulation for Power Flow Model of a Power System with TCSC

Before discussing the power flow solution of power system incorporating TCSC, we consider the system without TCSC, having a n-bus system and reference bus is numbered as 1. The active power and reactive VA at each bus are the functions of the magnitude of voltage and phase angle of voltage [1,10] (NR method) For ith bus

$$P_i = f_i(\delta, |V|) \quad \ldots\ldots\ldots..(1)$$

$$Q_i = f_2(\delta, |V|) \quad \ldots\ldots\ldots..(2)$$

When TCSC incorporated in the line from kth bus to mth for compensation of line and is increase the then the power flow in this branch is given by :-

$$P_{km} = |V_k|2|g_{km}| - |V_k|V_m|(g_{km}\cos\delta_{km} + b_{km}\sin\delta_{km}) \quad ..(3)$$

$$Q_{km} = -|V_k|2|b_{km}| - V_k|V_m|(g_{km}\sin\delta_{km} - b_{km}\cos\delta_{km}) \quad ..(4)$$

Where

$$Y_{km} = g_{km} + j\, b_{km} \quad \ldots\ldots\ldots..(5)$$

$$P = f_1(\delta, IVI, \alpha) \quad \ldots\ldots\ldots..(6)$$

$$Q = f_2(\delta, IVI, \alpha) \quad \ldots\ldots\ldots..(7)$$

$$P_{km} = f_3(\delta, IVI, \alpha) \quad \ldots\ldots\ldots..(8)$$

When the TCSC module is controlling the active power following from nodes k to m, at a specified value the set of linearized power flow equations.

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta P_{km} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} & \frac{\partial P}{\partial \alpha} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \alpha} \\ \frac{\partial P_{km}}{\partial \delta} & \frac{\partial P_{km}}{\partial V} & \frac{\partial P_{km}}{\partial \alpha} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \\ \Delta \alpha \end{bmatrix} \quad ..(9)$$

$$\Delta P_i^{(k)} = P_i^{sp} - P_i^{cal(k)} \quad \ldots\ldots..(10)$$

$$\Delta Q_i^{(k)} = Q_i^{sp} - Q_i^{cal(k)} \quad \ldots\ldots..(11)$$

$$\Delta P_{km}^{(k)} = P_{km}^{sp} - P_{km}^{cal(k)} \quad \ldots\ldots..(12)$$

$$Y_{km} = \frac{1}{R_{km} + j\, X_{km}} \quad \ldots\ldots..(13)$$

Where R_{km} is resistance of line km

X_{km} is reactance after inserting

In the proposed formulation the TCSC current, voltage and internal equivalent reactance TCSC has been formulated in following Section A and Section B discuss the detail formulation of Newton Raphson power flow incorporating TCSC.

2.1 Jacobian Modeling for TCSC Connected Bus

Section A -- **X_{TCSC} formulation**

The TCSC power flow model from node k to node m

$S_{km} = V_k\ I^*_{km} = V_k\ Y^*_{km}\ (V_k^* - V_m^*)$ ……….(14)

TCSC in line km

$X_{km} = X_{km}$ line + X_{TCSC} ……….(15) $X_{TCSC} = -j X_C X_L(\alpha) / (X_L(\alpha) - X_C)$ ……….(16)

$X_L(\alpha)$ [4] $= \pi X_L / (\pi - 2\alpha - \sin\alpha)$ $\quad X_L \le X_L(\alpha) \le \infty$ ……….(17)

$X_L = \omega L$ & α is delay angle measured from crest of capacitor voltage.

Differentiating Y_{km} with respect to firing angle α

$$\left|\frac{\partial Y_{km}}{\partial\alpha}\right| = \left|\frac{\partial}{\partial\alpha}\frac{1}{R_{km} + j X_{km}}\right| \quad ……….(18)$$

$$\frac{\partial g_{km}}{\partial\alpha} = \frac{2\pi\ R_{km} X_{km}\ X_c^2\ X_L(\alpha)\ (2 + \cos\alpha)}{\{(X_L(\alpha) - X_c)(\pi - 2\alpha - \sin\alpha)(R_{km}^2 + X_{km}^2)\}^2} \quad \text{and ...... (19)}$$

$$\frac{\partial b_{km}}{\partial\alpha} = \frac{\pi\ (R_{km}^2 - X_{km}^2)\ X_c^2\ X_L(\alpha)\ (2+\cos\alpha)}{\{(X_L(\alpha) - X_c)(\pi - 2\alpha - \sin\alpha)(R_{km}^2 + X_{km}^2)\}^2} \quad .....(20)$$

2.2 Section - B TCSC Power Flow Model

The TCSC power equations at node K are

$$S_K = V_K I_K^* = V_K \sum_{i=1}^{n} Y_{Ki}^*\ V_i^* \quad ……….(21)$$

$$= V_K \sum_{\substack{i=1\\ \ne k\\ \ne m}}^{n} Y_{Ki}^*\ V_i^* + V_K^2\ Y_{KK}^2 + V_R\ Y_{Km}^*\ V_m^* \quad ......(22)$$

$$= V_K \sum_{\substack{i=1\\ \ne k\\ \ne m}}^{n} Y_{Ki}^*\ V_i^* - V_K^2 \sum_{\substack{j=1\\ \ne m}}^{n} Y_{Kj}^* - S_{Km} \quad …..(23)$$

$$P_K = V_K \sum_{\substack{i=1\\ \ne k\\ \ne m}}^{n} (g_{Ki} \cos\theta_{Ki} + \sin\theta_{Ki})\ V_i - V_K^2 \sum g_{Kj} - P_{Km} \quad ..(24)$$

$$Q_K = V_K \sum_{\substack{i=1\\ \ne k\\ \ne m}}^{n} (g_{Ki} \sin\theta_{Ki} - \cos\theta_{Ki})\ V_i - V_K^2 \sum_{\substack{j=1\\ g\ne m}} b_{Kj} - Q_{Km} \quad ......(25)$$

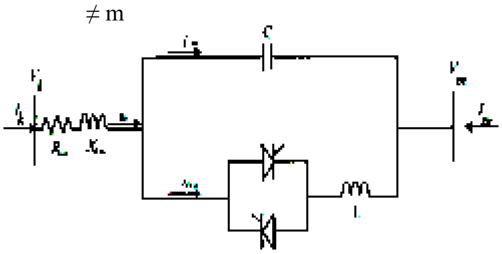


Fig.1 Model of TCSC [2]

The TCSC linearized power equation with respect to firing angle are

$$E_1 = \frac{\partial P_K}{\partial\alpha} = -\frac{\partial P_{Km}}{\partial\alpha}$$

$$= -V_K^2 \frac{\partial g_{Km}}{\partial\alpha} + V_K V_m \left(\cos\delta_{Km} \frac{\partial g_{Km}}{\partial\alpha} + \sin\delta_{Km} \frac{\partial b_{Km}}{\partial\alpha}\right)$$

$$= \frac{\partial P_m}{\partial\alpha}$$

$$= -V_m^2 \frac{\partial g_{Km}}{\partial\alpha} + V_K V_m \left(\cos\delta_{Km} \frac{\partial g_{Km}}{\partial\alpha} + \sin\delta_{Km} \frac{\partial b_{Km}}{\partial\alpha}\right)$$

$$E_2 = -\frac{\partial Q_{Km}}{\partial\alpha}$$

$$= -V_K^2 \frac{\partial b_{Km}}{\partial\alpha} + V_K V_m \left(\sin\delta_{Km} \frac{\partial g_{Km}}{\partial\alpha} - \cos\delta_{Km} \frac{\partial b_{Km}}{\partial\alpha}\right)$$

$$= \frac{\partial Q_m}{\partial\alpha} = -V_m^2 \frac{\partial b_{Km}}{\partial\alpha} + V_K V_m \left(\sin\delta_{Km} \frac{\partial g_{Km}}{\partial\alpha} - \cos\delta_{Km} \frac{\partial b_{Km}}{\partial\alpha}\right)$$

$$E_3 = \frac{\partial P_{Km}}{\partial\delta_K} = V_K V_m(-g_{Km} \sin\delta_{Km} + b_{Km} \cos\delta_{Km})$$

$$= \frac{\partial P_{Km}}{\partial\delta_m} = V_K V_m(-g_{Km} \sin\delta_{Km} + b_{Km} \cos\delta_{Km}) \quad ....(28)$$

$$E_4 = \frac{\partial P_{Km}}{\partial|V_m|} = 2V_K g_{Km} - V_m(g_{Km} \cos\delta_{Km} + b_{Km} \sin\delta_{Km})$$

$$= \frac{\partial P_{Km}}{\partial|V_m|} = -V_K(g_{Km} \cos\delta_{Km} + b_{Km} \sin\delta_{Km}) \quad .... 29)$$

$$E_5 = \frac{\partial P_{Km}}{\partial\alpha} = V_K^2 \frac{\partial g_{Km}}{\partial\alpha} - V_K V_m\left(\cos\delta_{Km} \frac{\partial g_{Km}}{\partial\alpha} + \sin\delta_{Km} \frac{\partial b_{Km}}{\partial\alpha}\right)$$

3. Computational Procedure For Newton – Raphson Method

The computational procedure for Newton-Raphson method using polar coordinates is as follows :

Step 1: Form Y bus

Step 2: Assume initial values of bus voltages $|V_i|$ and phase angles δ_i for i = 2,3,….n for load buses and phase angles for PV buses. Normally we set the assumed bus voltage magnitude and its phase angle equal to the 1.0 pu. For slack bus its voltage magnitude is given and its phase angle assumed to 0.

Step 3: Compute the errors ΔP_i and ΔQ_i for each load bus and power flow mismatch ΔP_{km} for TCSC connected line from the NR relation given by the equation 10 to 12. For PV buses, the exact value of Q_i is not specified but its limits are known. If the calculated value of Q_i exceeds the limits, then an appropriate limit is imposed and ΔQ_i is also calculated by subtracting the calculated value of Q_i from the appropriate limit. The bus under consideration is now treated as a load PQ bus.

Step 4: Compute the elements of Jacobian matrix as given in equation 9, by using the estimated $|V_i|$ and δ_i from step 2.

Step 5: Obtain the values of $\Delta|V_i|$, $\Delta\delta_i$ and $\Delta\alpha$ by solving the equation (9).

Step 6: Using the values of $\Delta|V_i|$, $\Delta\delta_I$ and $\Delta\alpha$ in step 6, modify the voltage magnitude and phase angle at all load buses by the equations –

$$|V_i^{(j+1)}| = |V_i^j| + \Delta|V_i^j|$$
$$\delta_i^{(j+1)} = \delta_i^j + \Delta\delta_i^j$$
$$\alpha^{(j+1)} = \alpha^j + \Delta\alpha^j$$

Start new iteration cycle from step 2 with these modified $|V_i|$, δ_i and α.

Step 7: Continue until the error ΔP_i^j, ΔQ_i^j and ΔP_{km}^j for all load buses and TCSC connected line are within a specified tolerance.

$$\Delta P_i^j \le \epsilon$$
$$\Delta Q_i^j \le \epsilon$$
$$\Delta P_{km}^j \le \epsilon$$

Where € denotes the tolerance level.

Step 8: Calculate the line flows and power losses and power at all buses as given by the equations 23, 24 and 25.

4. Under Consideration - BUS SYSTEM

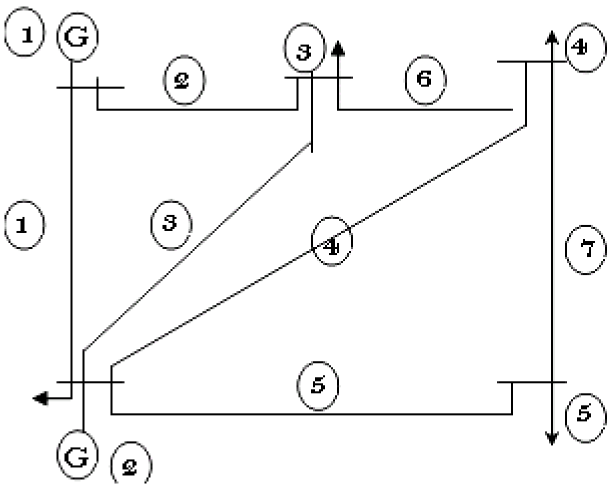


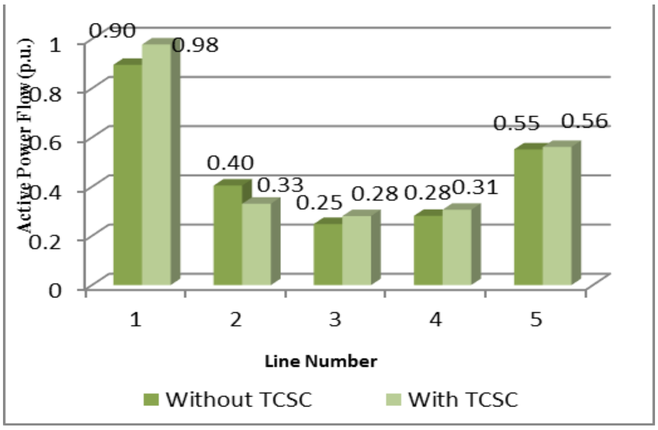
Fig.2 Five Bus System

Table – 1 - Five Bus System Parameters

Bus Code p-q	Impedance Z_{pq}	Line Charging $Y_{pq}/2$
1-2	0.02 + j0.06	0.0 + j0.030
1-3	0.08 + j0.24	0.0 + j0.025
2-3	0.06 + j0.18	0.0 + j0.020
2-4	0.06 + j0.18	0.0 + j0.020
2-5	0.04 + j0.12	0.0 + j0.015
3-4	0.01 + j0.03	0.0 + j0.010
4-5	0.08 + j0.24	0.0 + 0.025

Table -2 Scheduled Generation / Load / Voltages

Bus Code p	Assumed Bus Voltage	Generation		Load	
		MW	MVar	MW	MVar
1	1.06 + j 0.0	0	0	0	0
2	1.046 - j 0.05	40	Qg2	20	10
3	1.0 + j 0.0	0	0	45	15
4	1.0 + j 0.0	0	0	40	5
5	1.0 + j 0.0	0	0	60	10



ALPHA=150.0210°

Fig.3 Comparision of Power Flow with and withour TCSC for a 5 bus System-TCSC Location line 1

Power Flow Analysis using TCSC has been undertaken for a 5 bus system and is presented figure 2:

A 5 bus system as shown in Figure 1 below has been considered. The system parameters are given in Table-1 and Load and Generation data are as presented in Table - 2. The bus voltage at bus 2 is maintained at 1.05 pu. The maximum and minimum reactive power limits of generator bus 2 are 20 and 60 Mvar respectively. Bus 1 is taken as slack bus. A TCSC of capacitive reactance – 0.04 pu has been adopted. Out of seven lines available in the system, solution for specific lines have been presented as rest of the lines fail to provide better power flow control.

Specified power flow control over the transmission lines has been achieved by determining the converged firing angle (α).

Five graphs present the computed increase in power flows on introduction of TCSC in the five lines in comparison to power flows without TCSC respectively for the sample five bus system. The Table - 3 gives the summary of %age increase of power flows across the five lines.

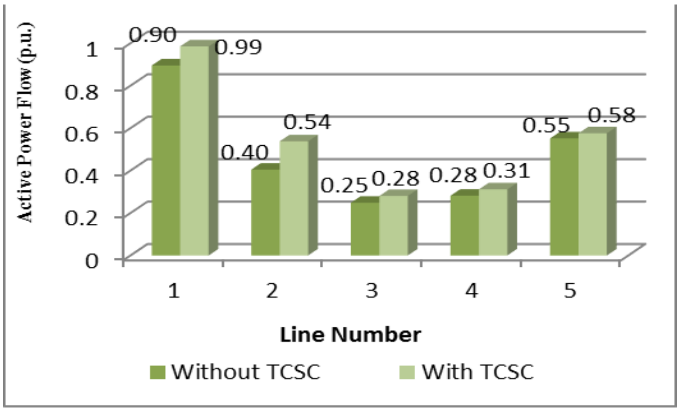


Fig. 4 Comparision of power with and without TCSC for a 5 bus system-TCSC Location Line 2

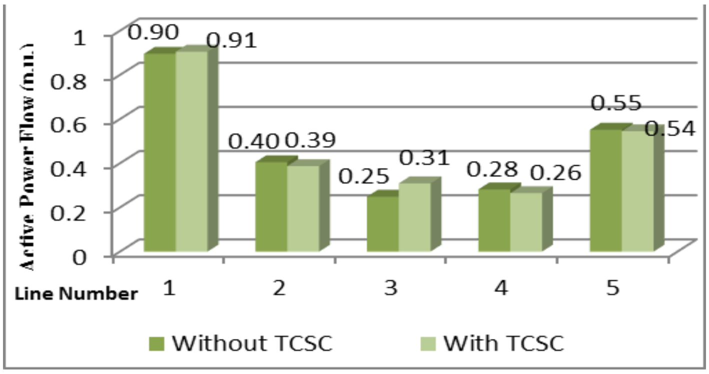


Fig. 5 Comparison of Power Flow with and without TCSC for a Bus System –TCSC Location line 3

ALPHA=150.4728°

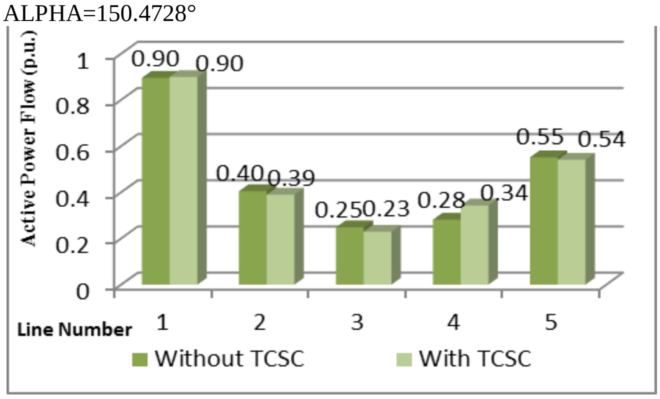


Fig.6 Comparision Of Power Flow With And Without Tcsc For A 5 Bus System-Tcsc Location Line 4

ALPHA=150.4421°

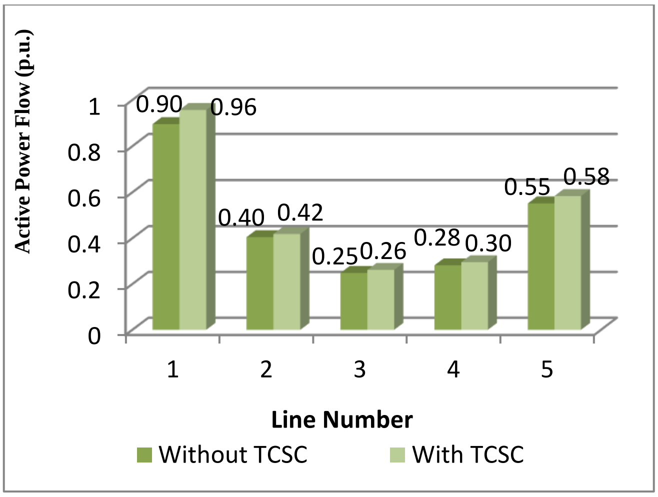


Fig. 7 Comparision of Power flow with and without TCSC for a 5 Bus System-TCSC Location Line 7
ALPHA=152.3273°

Table – 3 Percentage Increase in Power

TCSC Location	**% Increase in Power**				
	Line 1	**Line 2**	**Line 3**	**Line 4**	**Line 5**
1	9.23	-18.26	13	8.80	1.83
2	**10.028**	**32.93**	**12.96**	**10.65**	**4.35**
3	1.094	-4.37	24.31	-6.03	-1.21
4	0.4	-3.73	-7.76	21.73	-1.95
7	6.84	3.33	5.35	4.82	5.76

5. Conclusions

This paper has presented a Newton Raphson Load Flow analysis algorithm for power flow calculation in power system with TCSC. This algorithm is can solve power networks very consistently. A 5 bus system has been used to show the proposed method but can be used over a broad range in power systems.

It has been observed that:

- TCSC can increase power transfer capability in a power system.
- Simulation results shows that TCSC has a positive effect on power transfer capabilities in all lines of a power system.
- The location of TCSC was found to be most effective on line 2 (1-3) with a maximum percentage increase of 32.95.
- The increase in voltage magnitude (± 0.1 p.u) and voltage angle (± 5°) is within limits.
  Firing Angle was varied from 140° – 180° so that TCSC operates in capacitive mode Only.

With the proposed algorithm it is possible to find the best location of TCSC in a system to improve the system performance.

References

[1.] Abdel Moamem MA, Narayana Prasad Padhy. Newton Raphson TCSC Model For Power Flow Solution of Practical Power Networks

[2.] Abdel Moamen M K & Naryana Prasad Padhy. Multi Objective Optimal Power Flow Model with TCSC for Practical Power Networks –Thyristor Controlled Series Compensator Model for Power Flow Solution of Practical Power Network – CR Fuerte Esquivel, Acha & H. Ambriz Peraz. IEEE transactions on Power Systems, l. 15(1), 2000.

[3.] NG Hingorani, Laszlo Gyugy. Understanding Facts Concepts and Technology of Flexible AC Transmission System– IEEE press.

[4.] CR.Fuerte Esquivel, E.Acha. A Newton Type Algorithm for The Control of Power Flow in Electrical Power Network-IEEE transactions on Power System, 12(4), 1997.

[5.] Ramesh Bahri, K.R. Suri, Rajesh Kumar, Rajil Srivastava. Flexible AC Transmission System - A Case Study –Using Facts Controllers to Maximize Available Transfer Capability Bank Power Systems Dynamics and Control - Claudio A. Canizares, Alberto Berizzi, and Paolo Marannino IV. Restructuring, August 24-28, 1998, Santorini, Greece.

[6.] Reactance Power Management – D.M. Tagare, Tata Mcgraw- Hill Publication copyright 2004.

[7.] Sujatha Subhash, A.K. Tripathy, KR Padiyar, Satish Nayyar, Manoj Kumar, PJ Thakkar and KK Arya. SSR Study for the Thyristor Controlled Series Compensation Application on the Kanpur-Ballabgarh 400KV in Dudina.

[8.] WG Stagg, Ahmed Albiad. Computer Methods and Power System Analysis.