

Voltage Profile and Power Flow Enhancement with FACTS Controllers

Sunil Kumar Singh, Lobzang Phunchok and Y.R.Sood

Abstract— As a consequence of the electric utility industry deregulation and liberalization of electricity markets as well as increasing demand of electric power, the amount of power exchanges between producer and consumer are increases. In this process, the existing transmission lines are overloaded and lead to unreliable system. The countries like India with increasing demand of electric power day by day it is difficult to expand the existing transmission system due to difficulties in right of way and cost problem in transmission network expansion. So, we need power flow controllers to increasing transmission capacity and controlling power flows. Flexible alternating current transmission system (FACTS) controllers are capable of controlling power flows and enhancing the usable capacity of existing transmission lines. In this paper we have done the comprehensive modeling of FACTS devices for power flow study and its impact on system voltage. The effectiveness of modeling has been tested and analyzed on IEEE-5 bus system.

Index Terms—FACTS controllers, SVC, TCSC, Power flow

I. INTRODUCTION

As a result of ever-increasing demand of electric power, the electricity supply industry is undergoing profound transformation worldwide. This makes the existing power transmission system highly complex. To meet the increasing demand of electricity in a power system it is essential to increase the transmitted power either by installing new transmission lines or by improving the existing transmission lines by adding new devices. Installation of new transmission lines in a power system leads to the technological complexities such as economic and environmental considerations that includes cost, delay in construction as so on. Flexible alternating current transmission system (FACTS) technology gave up new ways for controlling power flows and enhancing the usable capacity of transmission lines. FACTS are system comprised of static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increasing the power transfer capability of the power system network. The concept of FACTS was first defined by N.G. Hingorani in 1988. It usually refers to the

application of high power semi conductor devices to control different parameters and electrical variables such as voltage, impedance, and phase angle, current, active and reactive power. FACTS controllers can be divided into four categories:

- Series controllers.
- Shunt controllers.
- Combined series-series controllers.
- Combined series-shunt controllers.

The benefits of using FACTS controllers in transmission system are-

- Increased transmission system reliability.
- Better utilization of existing power transmission system.
- It damp out power oscillations and increases the transient stability.

This paper addresses the static modeling of Static Var Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC), and their capabilities to improve the voltage profile and power flow of the bus to that it is connected is evaluated.

II. STATIC VAR COMPENSATOR

SVC can be defined as a shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage). SVCs are primarily used in power systems for voltage control or for improving system stability [1].

A. Principle of operation (SVC)

Static Var Compensator as shown in Fig.1 composed of thyristor controlled reactor (TCR), thyristor switched capacitor (TSC) and harmonic filters connected in parallel to provide dynamic shunt compensation. The current in the thyristor controlled reactor is controlled by the thyristor valve that controls the fundamental current by changing the fire angle, ensuring the voltage limited to an acceptable range at the injected node. Current harmonics are inevitable during the operation of thyristor controlled rectifiers, thus it is essential to have filters to eliminate harmonics in the SVC system. The filter banks not only absorb the risk harmonics but also produce the capacitive reactive power [2].

A. Sunil Kumar Singh, M.Tech student in Department of Electrical Engineering NIT Hamirpur-177005, India

B. Lobzang Phunchok, M.Tech student in Department of Electrical Engineering NIT Hamirpur-177005, India

C. Dr. Y. R. Sood, Professor in Department of Electrical Engineering NIT Hamirpur-177005, India.

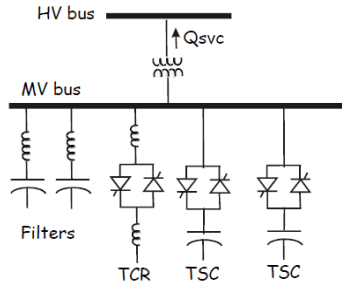


Fig. 1 Circuit diagram of SVC

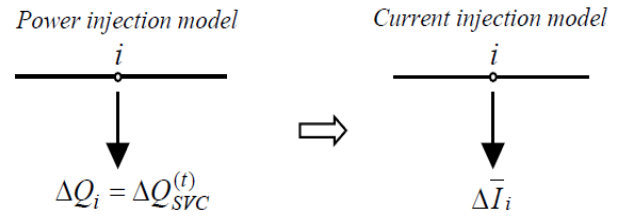


Fig. 3. Mathematical model of SVC

B. V-I Characteristic of SVC

As shown in Fig. 2, the dynamic characteristics of an SVC are the plots of bus voltages versus current or reactive power. In Fig. 2, the voltage \$V_{ref}\$ is the voltage at the terminals of the SVC when it is neither absorbing nor generating any reactive power. The reference voltage value can be varied between the maximum and minimum limits, \$V_{ref\ max}\$ and \$V_{ref\ min}\$, using the SVC control system. The linear range of the SVC control passing through \$V_{ref}\$ is the control range over which the voltage varies linearly with the current or reactive power [3]. In this range, the power is varied from capacitive to inductive.

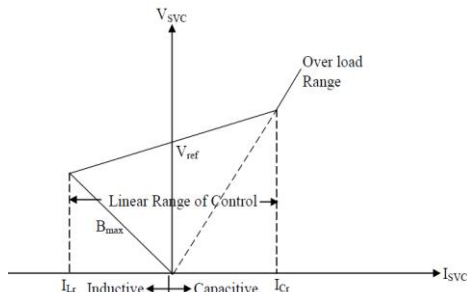


Fig. 2 V-I Characteristics SVC

C. Modeling of SVC

The SVC can be operated at both inductive and capacitive compensation. In the steady-state and dynamic analysis, the injected power at bus \$i\$ at the time \$t\$, \$\Delta Q_i = Q_{SVC}^{(t)}\$, which is the controlled variable, can be transferred into injected current at bus \$i\$ according to Equation (1), where \$V_i^{(t)}\$ is the terminal voltage of SVC at the time \$t\$. The mathematical model of SVC is shown in Fig. 3.

$$\Delta I_i = \frac{Q_{SVC}^{(t)}}{V_i^{(t)}} \tag{1}$$

D. Admittance Matrix Formulation with SVC

For an SVC connected at a bus bar \$i\$ of a line section represented by the quadruple \$(y_{i0}, y_{ik}, y_{k0})\$ as shown in Fig. 4, the contribution of the SVC [4] to the new admittance matrix relates to the element shunt. It results in the admittance matrix of the line.

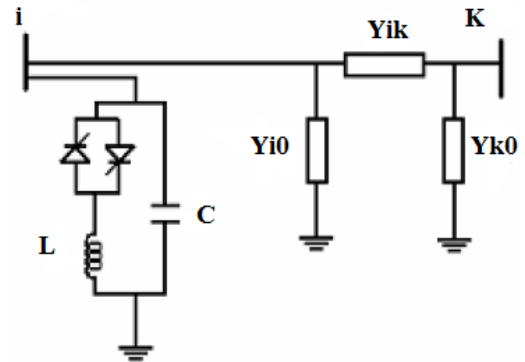


Fig. 4. SVC Connected to Bus i

$$Y_{new\ line} = \begin{pmatrix} Y_{ik} + Y_{i0} + Y_{svc} & -Y_{ik} \\ -Y_{ik} & Y_{ik} + Y_{k0} \end{pmatrix} \tag{2}$$

$$Y_{svc} = j \frac{1}{X_L X_C} \left[X_L - \frac{X_C}{\pi} \left(2\pi - \alpha + \sin 2\alpha \right) \right] \tag{3}$$

The SVC reactance is given as the following expression:

$$X_{svc} \alpha = j \frac{\pi X_L}{2\pi - \alpha + \sin 2\alpha - \pi \frac{X_L}{X_C}} \tag{4}$$

III. THYRISTOR CONTROLLED SERIES COMPENSATOR

A TCSC can be defined as a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance [1]. The basic conceptual TCSC module comprises a series capacitor, \$C\$, in parallel with a thyristor-controlled reactor, \$L_s\$, as shown in Fig. 5.

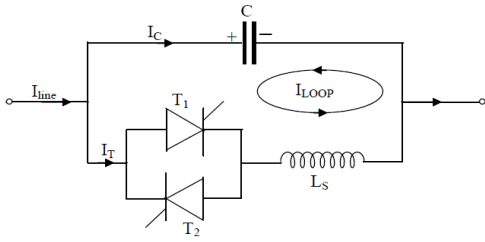


Fig.5. Structure of TCSC

E. Principle of operation (TCSC)

A TCSC is a series-controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. From the system viewpoint, the principle of variable-series compensation is simply to increase the fundamental-frequency voltage across a fixed capacitor (FC) in a series compensated line through appropriate variation of the firing angle, α [5]. This enhanced voltage changes the effective value of the series-capacitive reactance. A simple understanding of TCSC functioning can be obtained by analyzing the behavior of a variable inductor connected in parallel with an FC, as shown in Fig. 6.

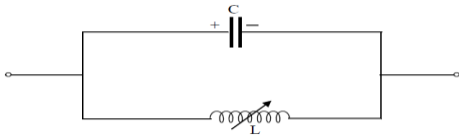


Fig.6. A variable Inductor in shunt to FC

The equivalent reactance

$$X_{TCSC} \alpha = \frac{X_C X_L \alpha}{X_L \alpha - X_C} \tag{5}$$

$$X_L \alpha = X_L \frac{\pi}{\pi - 2\alpha - \sin \alpha} \tag{6}$$

$$X_L \leq X_L \alpha \leq \infty \tag{7}$$

$X_L = \omega L$ and α is the delay angle measured from the crest of the capacitor voltage or equivalently, the zero crossing of the line current. Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor, X_L is smaller than that of the capacitor, X_C , the TCSC has two operating ranges around its internal circuit resonance: one is the $\alpha_{Clim} \leq \alpha \leq \pi/2$ range, where $X_{TCSC} \alpha$ is capacitive, and the other is the $0 \leq \alpha \leq \alpha_{Llim}$ range, where $X_{TCSC} \alpha$ is inductive as illustrated in Fig. 7 [1].

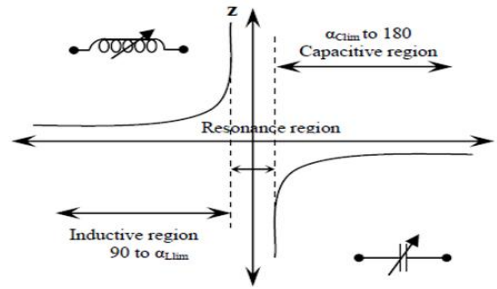


Fig.7. Impedance Vs delay angle Characteristics

F. Modeling of TCSC

For static applications, TCSC can be modeled by Power Injection Model (PIM) [6, 7]. The injection model describes the FACTS as a device that injects a certain amount of active and reactive power to a node, so that the FACTS device is represented as PQ elements. The advantage of PIM is that it does not destroy the symmetrical characteristic of the admittance matrix and allows efficient and convenient integration of FACTS devices into existing power system analytical tools [6].

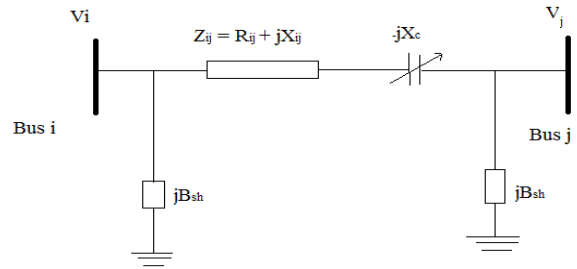


Fig.8. TCSC located in Transmission line

Fig.8. shows a model of transmission line with TCSC connected between buses i and j . The transmission line is represented by its lumped π -equivalent parameters connected between the two buses. During steady state operation, the TCSC can be considered as a static reactance $-jX_C$. The controllable reactance X_C is directly used as the control variable in the power flow equations. The active and reactive power injections due to series capacitor (TCSC) at buses i and j are given by the following equations-

$$P_i^f = V_i^2 \Delta G_{ij} - V_i V_j \left[\Delta G_{ij} \cos \delta_i - \delta_j + \Delta B_{ij} \sin \delta_i - \delta_j \right] \tag{8}$$

$$Q_i^f = -V_i^2 \Delta B_{ij} - V_i V_j \left[\Delta G_{ij} \sin \delta_i - \delta_j + \Delta B_{ij} \cos \delta_i - \delta_j \right] \tag{9}$$

$$P_j^f = V_j^2 \Delta G_{ij} - V_i V_j \left[\Delta G_{ij} \cos \delta_i - \delta_j - \Delta B_{ij} \sin \delta_i - \delta_j \right] \tag{10}$$

$$Q_j^f = -V_j^2 \Delta B_{ij} + V_i V_j \left[\Delta G_{ij} \sin \delta_i - \delta_j + \Delta B_{ij} \cos \delta_i - \delta_j \right] \tag{11}$$

Where

$$\Delta G_{ij} = \frac{X_c R_{ij} X_c - 2X_{ij}}{R_{ij}^2 + X_{ij}^2 R_{ij}^2 + X_{ij} - X_c^2} \quad (12)$$

$$\Delta B_{ij} = \frac{-X_c R_{ij}^2 - X_{ij}^2 + X_c X_{ij}}{R_{ij}^2 + X_{ij}^2 R_{ij}^2 + X_{ij} - X_c^2} \quad (13)$$

The corresponding power injection model of TCSC incorporated within the transmission line is shown in Fig. 9.

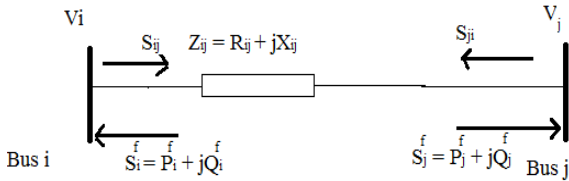


Fig.9. Power Injection Model of TCSC

IV. POWER FLOW ANALYSIS

For planning the operation of existing power system, its improvement and also its future expansion require following studies such as load flow studies, short circuit studies and stability studies. Load flow studies [8-9] are used to ensure that electrical power transfer from generators to consumers through the grid system is stable, reliable and economic. Load flow studies are most important of all power system analysis, because these are used in planning studies of power system network to determine if and when specific elements will become overloaded. This is important, as the magnitudes of voltages at every bus are required to be held within a specified limit. The objectives of any load-flow study is to provide the following information-

- Voltage magnitude and phase angle at each bus.
- Real and Reactive power flowing in each element.

Once the bus voltage magnitudes and their angles are computed using the load flow, the real and reactive power flow through each line can be computed. Also based on the difference between power flow in the sending and receiving ends, the line losses in any particular line can also be calculated. It is helpful in determining the best location as well as optimal capacity of proposed generating station, substation and new lines. In the power flow problem, it is assumed that the real power P and reactive power Q at each Load Bus are known. For this reason, Load Buses are also known as PQ Buses. For Generator Buses, it is assumed that the real or active power generated P and the voltage magnitude V is known. For the Slack Bus, it is assumed that the voltage magnitude V and voltage phase angle of the buses are known. In this work Newton Raphson method for load flow is used, because of its reliability towards convergence and not sensitive nature to the starting solution. In large-scale power flow studies, the Newton raphson has proved most successful because of its strong convergence characteristics. The power flow Newton Raphson algorithm is expressed as following relationship [10].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \Delta P/\Delta\theta & \Delta P/(\frac{\Delta V}{V}) \\ \Delta Q/\Delta\theta & \Delta Q/(\frac{\Delta V}{V}) \end{bmatrix} \begin{bmatrix} \Delta\theta \\ (\frac{\Delta V}{V}) \end{bmatrix} \quad (14)$$

$\Delta P = P_{\text{specf}} - P_{\text{cal}}$ is the real power mismatch vector

$\Delta Q = Q_{\text{specf}} - Q_{\text{cal}}$ is the reactive power mismatch vector

$\Delta\theta$ and ΔV are the vectors of incremental changes in nodal voltage magnitudes and angles.

Jacobian is the matrix of partial derivatives of real and reactive powers with respect to voltage magnitudes and angle.

Therefore,

$$\frac{\partial P_k}{\partial \theta_k} = V_k V_m [G_{km} \sin \theta_k - \theta_m - B_{km} \cos \theta_k - \theta_m] \quad (15)$$

$$\frac{\partial P_k}{\partial V_m/V_m} = V_k V_m [G_{km} \cos \theta_k - \theta_m + B_{km} \sin \theta_k - \theta_m] \quad (16)$$

$$\frac{\partial Q_k}{\partial \theta_m} = -\frac{\partial P_k}{\partial V_m/V_m} \quad (17)$$

$$\frac{\partial Q_k}{\partial V_m/V_m} = \frac{\partial P_k}{\partial \theta_m} \quad (18)$$

V. CASE STUDY

IEEE 5 bus system has been used for case study to run the load flow using power system analysis tool box (PSAT). The simulation of 5 bus system with and without FACTS devices (SVC and TCSC) is done on PSAT. Initially we run the load flow without any FACTS devices and check the voltage magnitude each bus. Then after we connected the FACTS devices (SVC and TCSC) at different buses and different lines and again run the load flow. After the connection of FACTS devices we found that the voltage profile is improved to those buses where SVC are connected and power flows in the transmission lines were increased in those lines having TCSC connected in it. The SVC installed at different buses has initial susceptance 0.02pu, inductive reactance 0.288pu, capacitive reactance 1.07pu and the initial capacitive reactance of TCSC is 0.015pu.

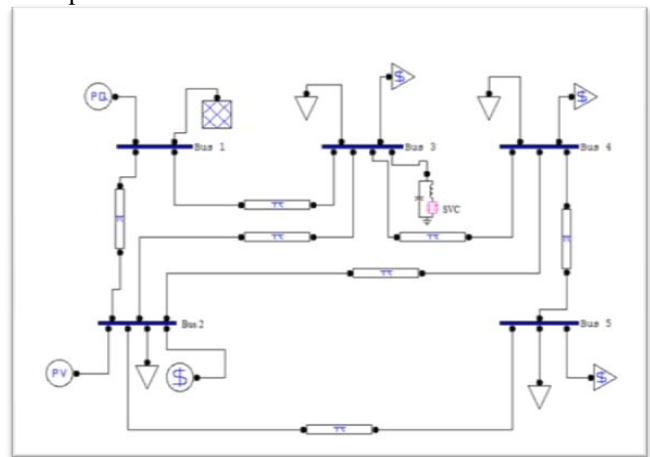


Fig.10. Simulink model IEEE-5 bus system

In the above model bus one is slack bus, second bus is P-V or generator bus and rest three buses are P-Q or load buses.

TABLE I
VOLTAGE PROFILE

Bus No.	Voltage (pu) Without SVC	Voltage (pu) With SVC at Bus 3	Voltage (pu) With SVC at Bus 4	Voltage (pu) With SVC at Bus 5
1	1.06	1.06	1.06	1.06
2	1.0	1.022	1.023	1.012
3	0.997	1.014	1.016	1.014
4	0.992	1.011	1.012	1.012
5	0.974	0.996	0.997	1.024

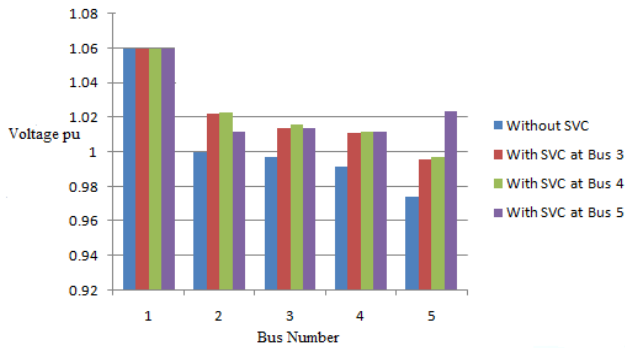


Fig.10. Voltage (pu) at various Buses

TABLE III
POWER FLOW IN LINES

From Bus	To Bus	P_{ij} (pu) without TCSC	P_{ij} (pu) with TCSC in line (1-2)	P_{ij} (pu) with TCSC in line (1-3)	P_{ij} (pu) with TCSC in line (2-3)	P_{ij} (pu) with TCSC in line (2-4)	P_{ij} (pu) with TCSC in line (3-4)	P_{ij} (pu) with TCSC in line (4-5)	P_{ij} (pu) with TCSC in line (2-5)
1	3	0.3049	0.3330	0.9062	0.2999	0.3012	0.3015	0.2998	0.3003
1	2	0.9442	1.4110	0.9583	0.9391	0.9296	0.9362	0.9387	0.9445
2	3	0.0861	0.0711	0.0961	0.2219	0.0894	0.0881	0.0850	0.0873
3	4	0.3817	0.3962	0.3691	0.3832	0.4317	0.4553	0.3768	0.3800
2	4	0.1498	0.1331	0.1578	0.1483	0.5703	0.1483	0.1483	0.1510
4	5	0.1287	0.1387	0.1243	0.1288	0.1286	0.1287	0.4058	0.1283
2	5	0.4821	0.4770	0.4806	0.4815	0.4864	0.4816	0.4867	0.9961

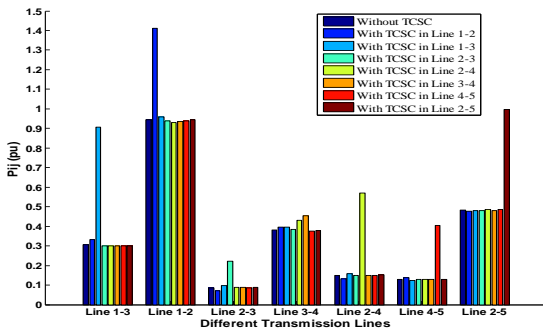


Fig.10. Flow in transmission line without and with TCSC

VI. RESULT AND DISCUSSION

After running the power flow with SVC it is found that the voltage profile at all buses where SVC is connected i.e bus 3, bus 4 and 5 are improved. Initially without SVC the voltage magnitude in per unit (pu) at bus 3 is 0.997, at bus 4 it is 0.992 and at bus 5 it is 0.974 but after applying SVC voltage magnitude improved to 1.014, 1.012 and 1.024 pu. Similarly the power flows in various lines are increased after the incorporation of TCSC in lines. From table.2 we can observed that power flows in lines such as in line 1-3 power flow increased from 0.3049 to 0.9062 pu, in line 1-2 power flow increased from 0.9442 to 1.4110 pu and others also after the incorporation of TCSC in the transmission lines.

VII. CONCLUSION

This paper depicts that the voltage profile of the power system is improved with the incorporation of Static VAR compensator (SVC) and power flows in lines were increased with the incorporation of Thyristor Controlled Series Compensator. SVC was able to effectively regulate the bus voltage magnitude at which it is connected over its full range of operation when there is a need. TCSC reduces the overloading and unreliability of the transmission system.

VIII. REFERENCES

- [1] N.G. Hingorani and L. Gyugi. Understanding FACTS concepts and technology of flexible AC transmission systems. IEEE Press, New York, 2000.
- [2] Naresh Acharya, Arthit Sode-Yome, Nadarajah Mithulananthan, "Facts about Flexible AC Transmission Systems (FACTS) Controllers: Practical Installations and Benefits", AUPEC, Vol.1.2, 2005.
- [3] Y. Y. Hsu and C. H. Cheng, "Design of a Static VAR Compensator Using Model Reference Adaptive Control", *Electric Power Systems Research*, 13(1987), pp. 129-138.
- [4] A. E. Hammad, "Analysis of Power System Stability Enhancement by Static VAR Compensators", *IEEE Trans. PWRs*, 1(4) (1986), pp. 222-227.
- [5] Fuerte-Esquivel, C.R. Acha, E. Ambriz-Perez, H. " A Thyristor Controlled Series Compensator Model for th Power flow Solution of Practical Power Network", IEEE Trans. Power System Vol.15 No.1Feb-2000, pp.58-64
- [6] E. Acha, C.R. Fuerte-Esquivel, H. Ambriz-Perez and C. Angeles-Camacho. FACTS modeling and simulation in power network. 1st Edn, John wiley and sons inc, New York, 2004.
- [7] R. T. Byerly, D. T. Poznaniak, and E. R. Taylor, "Static Reactive Compensation for Power Transmission System", *IEEE Trans. PAS-101*, 1982, pp. 3998-4005.
- [8] W.D. Stevenson Jr., 'Element of power system analysis', McGraw-Hill, 4th edition, 1982.
- [9] A.E. Guile and W.D. Paterson, 'Electrical power system, Vol. 2', Pergamon Press, 2nd edition, 1997.
- [10] T.T. Nguyen and C.T. Vu. Complex-Variable Newton-Raphson Load-flow analysis with FACTS devices. IEEE 2006.
- [11] Y.H Song, A.T. Jhons Flexible AC transmission system (FACTS), IEEE, 1999.
- [12] W.F. Tinney. Power flow Solution by Newton's Method. IEEE Tran. Power apparatus and systems.
- [13] S. Arabi and P. Kundur. A versatile FACTS device model for power flow and stability simulations. IEEE Tran. Power syst.vol 11, 1996.
- [14] R.M. Mathur and R.K. Varma. Thyristor-based FACTS controllers for electrical transmission system. IEEE Press, Piscataway, 2002.
- [15] Xiao-Ping Zhang, B. Pal and Christian Rehtanz. AC Transmission System modeling and control. Springer, Berlin Heidelberg 2006.