

POWER FLOW MODEL OF STATIC VAR COMPENSATOR AND ENHANCEMENT OF VOLTAGE STABILITY

H. B. Nagesh¹ and P. S. Puttaswamy²

¹Department of Electrical and Electronics Engineering, Bangalore Institute of Technology, Bangalore, India.

²Department of Electrical and Electronics Engineering, PES College of Engineering, Mandya, Karnataka, India.

ABSTRACT

Voltage stability analysis is the major concern in order to operate any power system as secured. In this context there are many research work has been carried out to improve the voltage stability. This study demonstrates the use of latest Power System Analysis Toolbox (PSAT) package for network analysis of alternative means of improving existing transmission system voltage stability. This paper presents the investigation on enhancement of voltage stability using FACTS controllers such as Static Var Compensator (SVC) device. The proposed method explains how voltage stability can be improved with the continuation power flow methods in case of increasing loading of contingency. Voltage stability assessment on standard IEEE-14 system has been simulated to test the effectiveness of increasing loadability. This paper presents the simple method for identifying the weak bus and also optimal value of reactive power support needed for that. A comparative study between the base case and SVC are presented to demonstrate the effectiveness of SVC. The propose methodology found advantages because it is simple, faster and very convenient to apply for voltage stability analysis

KEYWORDS: SVC, L-index, loading margin

I. INTRODUCTION

Electricity plays a fundamental role in the economic development of the country. All countries seek to ensure supply of electricity that is affordable, reliable and secure in order to sustain modern ways of living. The availability of electricity greatly facilitates industrialization, because electricity is a convenient way to transport energy as other sources are also converted into electricity for transmission, distribution and consumption [1], [2]. Hence all over the world electricity network are interconnected not only across the states or region but spread across countries and also between the continents in future. This entails transmission of electricity over a long distance. However, transmission of electricity stably requires all the variables to be kept within the limits [1], [2], [3].

1.1. Power Transfer Capability

The electricity supply industry of the world is always changing, causing new opportunities and challenges to the uses of high voltage transmission systems. The ratings of the various network components and the operating state determine the maximum power carrying capability of the network elements [1], [2], [3], [4]. However, the configuration of the network can further limit the overall power-transfer capability. These stem mainly from the strong increase in interregional and/or international power transfer, the effects of deregulation, and political, economic, and ecological consideration on the building of new transmission facilities. Technically, limitations on power transmission capability in a grid can always be removed by adding of new transmission and/or generation capacity. This, however, may not be practicable or desirable in the real case. Therefore adding of new lines and/or extending of existing substations may be too costly and time-consuming

[5], [6], [7]. Concessions for new right of way may be hard or impossible to come by. And lastly, environmental impact aspects today are much more important than they used to be and need to be addressed in a serious way in conjunction with transmission development procedures[7],[8].

The basic operating requirements of an AC power system are that the synchronous generators must remain in synchronism and the voltages must be kept close to their rated values. The capability of a power system to meet these requirements in the face of possible disturbances (line faults, generator and line outages, load switching, etc.) is characterized by its transient, dynamic and voltage stability. The stability requirements usually determine the maximum transmittable power at a stipulated system security level [6], [7]. The power transmission capability of transmission lines can be increased by reactive compensation [7]. The voltage profile along the line can be controlled by reactive shunt compensation; the series line inductance by series capacitive compensation. The transmission angle can be varied by phase shifting [6].

Traditionally, reactive power compensation and phase angle control have been applied by fixed or mechanically switched circuit elements (capacitors, reactors, and tap-changing transformers) to improve steady-state power transmission [7]. The recovery from dynamic disturbances was accomplished by generous stability margins at the price of relatively poor system utilization. The implementation of the above objectives requires the development of high power compensators and controllers. The technology needed for this is high power (multi-hundred MVA) electronics with its real-time operating control [6], [7].

In the late 1980's, the electric Power Research Institute formulated the vision of the Flexible AC transmission System (FACTS) in which various power electronics based controllers regulate power flow[6],[7],[9], transmission voltage and mitigate dynamic disturbances through rapid control actions. The main objectives of FACTS are to increase the available transmission capacity of lines and control power flow over designated transmission routes. The Electric Power Research Institute, after years of supporting the development of high power electronics for applications such as High voltage DC Transmission and reactive compensation of AC lines, in the late 1980's formalized the broad concept of Flexible AC Transmission (FACTS)[9],[10].

1.2. FACTS Controllers

The first groups of controllers are the Static Var compensators (SVC), Thyristor Controlled Series Capacitor (TCSC) and phase-shifter [3], [6], [10]. These controllers employ conventional thyristor's (i.e., those having no intrinsic turn-off ability) in circuit arrangements which are similar to breaker-switched capacitors and reactors and conventional (mechanical) tap-changing transformers, but have much faster response and are operated by sophisticated controls. Each of these controllers can act on one of the three parameters determining power transmission voltage (SVC), transmission impedance (TCSC), and transmission angle (phase-shifter)[3],[10].

The second groups of controllers employ self-commutated, voltage-sourced switching power converters to realize the rapidly controllable static and synchronous ac voltage or current sources[3],[7]. This approach, when compared to conventional compensation methods employing thyristor-switched capacitors and thyristor-controlled reactors. Generally provides superior performance characteristics and uniform applicability for transmission voltage, effective line impedance, and angle control. It also offers the unique potential to exchange real power directly with the ac system, providing a powerful new option for flow control and the counteraction of dynamic disturbances. The group of FACTS controllers employing switching converter-based synchronous voltage sources and the Static Synchronous Compensators (STATCOM), the Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controller (UPFC) and the Interline Power Flow Controller (IPFC)[3],[10].

Rest of the paper is organized as follows: Section II introduces the continuation power flow method in general. A brief introduction of SVC operation, stability model and determination of its parameter for power flow studies are presented in section III. A test system and analytical tool are briefly stated in section IV. In section V the simulated results by identifying the weak bus are presented. Finally, major contribution and conclusions are presented in section VI.

II. CONTINUATION POWER FLOW METHOD

The propose of continuation load flow is to find a continuum of load flow solutions for a given load/generation change scenario [8],[9],[12]. It is capable of solving the whole PV-curve. The singularity of continuation load flow equations is not a problem; therefore the voltage collapse point can be solved. The continuation load flow finds the solution path of a set of load flow equations that are reformulated to include a continuation parameter. This scalar equation represents the phase conditions that guarantee the non-singularity of the set of equations. The method is based on the prediction-correction technique. The prediction-correction technique applied to the PV-curve solution illustrated in figure. The intermediate results of the continuation process also provide valuable insight into the voltage stability of the system and the areas prone to voltage collapse.

The prediction step estimates the next PV-curve solution based on a known solution [12]. Taking an appropriately sized step in a chosen direction to the solution path can make the prediction of the next PV-curve solution. However, the prediction is not necessary, especially at the flat part of the PV-curve. The simplest prediction is the secant the last two PV-curve solutions. The computation of the secant is fast and simple [12]. The tangent of the last PV-curve solution is more accurate than the secant, but also requires more computation. The advantage of the tangent direction is most valuable around the PV-curve nose. The step size should be chosen so that the predicted solution is within the radius of convergence of the corrector. The determination of the step size can be based on the slope of tangent or the difference between the previous predicted and exact solutions [8], [9], [12].

The maximum loading point can be sensed easily using the tangent vector of the PV-curve solution [12]. The tangent component corresponding to the continuation parameter is zero at the maximum loading point and becomes negative beyond the maximum point. This method indicates whether or not the maximum loading point has been passed. The exact location of the maximum loading point requires searching with a decreasing step size around the maximum point, which is why the point of collapse method and the optimization method are more effective than the continuation load flow to find the exact voltage collapse point.

The tangent vector can be used for a sensitivity analysis so that a stability index and identification of the weak buses are obtained [8], [9]. A good method to decide which bus is nearest to its voltage stability limit is to find the bus with the largest ratio of differentia; change in voltage to different change in active load for the whole system. This ratio can also be used as a voltage stability index.

The load flow equation consists of load factor (λ) can be written as [12]

$$F(\delta, V, \lambda) = 0 \quad (1)$$

Where λ = the load parameter

δ = the vector of bus voltage angle, and

V = the vector of bus voltage magnitude.

The Newton-Raphson load flow calculation is expressed as:

$$P_i = \sum_{j=1}^n Y_{ij} V_i V_j \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \quad (2)$$

$$Q_i = \sum_{j=1}^n Y_{ij} V_i V_j \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \quad (3)$$

The system has n node and n_q number of source including slack bus. The total number of equations equal $2n - n_q - 1$

The new load flow equations consists of load factor (λ) are expressed as :

$$P_{Li} = P_{L0} + \lambda(K_{Li} S_{\Delta base} \cos \phi_i) \quad (4)$$

$$Q_{Li} = Q_{L0} + \lambda(K_{Li} S_{\Delta base} \sin \phi_i) \quad (5)$$

Where

P_{Li}, Q_{Li} = the active and reactive power respectively,

K_{Li} = the constant for load changing at bus i , and

$S_{\Delta base}$ = the apparent power which is chosen to provide appropriate scaling of λ .

Then the active power generation term can be modified to

$$P_{Gi} = P_{G0}(1 + \lambda K_{Gi}) \quad (6)$$

Where

P_{G0} = the initial value of active power generation,

P_{Gi} = the active power generation at bus i , and

K_{Gi} = the constant of changing rate in generation.

2.1. Predictor step

In the predictor step, a linear approximation is used to estimate the next solution in order to adjust the state variables[12]. Taking the derivative of both side of equation (1), it can be expressed as:

$$F_{\delta}d\delta + F_VdV + F_{\lambda}d\lambda = 0 \tag{7}$$

$$\begin{bmatrix} F_{\delta} & F_V & F_{\lambda} \end{bmatrix} \begin{bmatrix} d\delta \\ dV \\ d\lambda \end{bmatrix} = 0 \tag{8}$$

2.2. Corrector step

The load flow [12] equations are selected by

$$\begin{bmatrix} F(\delta, V, \lambda) \\ X_k - \eta \end{bmatrix} = [0] \tag{9}$$

Where

X_k =the state variable selected as continuation parameter at k iterative and
 η =the predicted value of X_k .

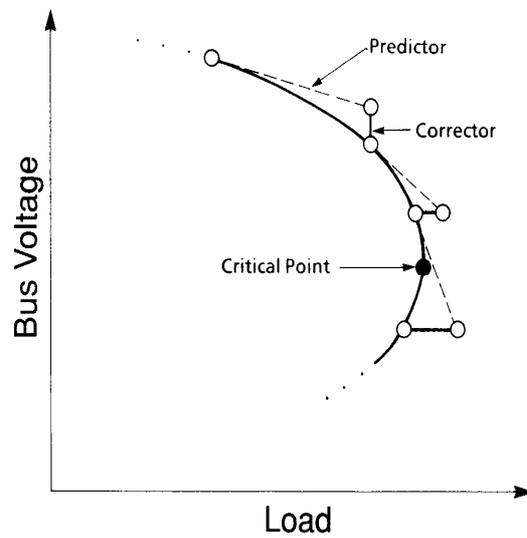


Figure1.The predictor-corrector scheme used in the continuation power flow

III. STATIC VAR COMPENSATOR

Static Var Compensator (SVC) is a shunt connected FACTS controller whose main functionality is to regulate the voltage at a given bus by controlling its equivalent reactance [3], [13], [14]. Basically it consists of a fixed capacitor (FC) and a thyristor controlled reactor (TCR).Generally there are two configurations of the SVC, and as shown in figure below 2(a) and 2(b).

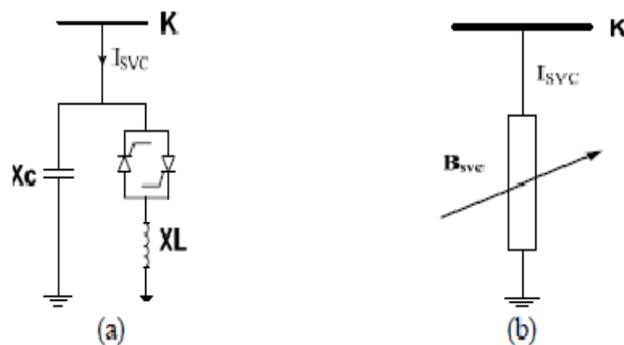


Figure2. (a) SVC firing angle model (b) SVC total susceptance model.

The first model is SVC firing angle model [3],[4],[6]. In this model the equivalent reactance X_{SVC} , is considered as a function of a change in firing angle α , is made up of the parallel combination of a thyristor controlled reactor (TCR) equivalent admittance and a fixed capacitive reactance as shown in Fig.2 (a). This model provides information about SVC firing angle required to achieve a given level of compensation. The second model known as total susceptance model [4]. In this model change in susceptance B_{svc} represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC as shown in Fig.2 (b)

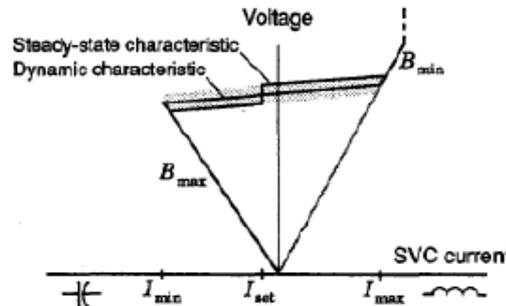


Figure3. Steady state and dynamic voltage/current characteristics of the SVC.

Fig.3 shows the steady-state and dynamic voltage-current characteristics of the SVC. In the active control range, current/susceptance and reactive power is varied to regulate voltage according to a slope (droop) characteristic. The slope value depends on the desired voltage regulation, the desired sharing of reactive power production between various sources and other needs of the system. The slope is typically 1-5%. At the capacitive limit, the SVC becomes a shunt capacitor. At the inductive limit, the SVC becomes a shunt reactor (the current or reactive power may also be limited [4], [13], [14], [15]. SVC firing angle model is implemented in this paper. Thus the model can be developed with respect to sinusoidal voltage. SVC parameters have to be determined according to the compensation requirements. With Q_{SVC} as the capacity of the SVC and the bus voltage (voltage at the bus where SVC is to be connected) V_{bus} , the value of the capacitance and TCR inductance are $X_C = \frac{V_{bus}^2}{Q_{SVC}}$ and $X_L = \frac{X_C}{2}$. For a given frequency 'f' Hz, $c = \frac{1}{2\pi f X_C}$ and $L = \frac{X_L}{2\pi f}$.

After sizing the capacitance and inductance [4], [15], it is necessary to determine the initial operating condition of the SVC. Then select the initial firing angle α in such a way that under this operating condition the SVC does not exchange any power with the AC system. This firing angle corresponds to the case when effective reactance's X_C and X_L cancel each other out. Under this operative condition, the SVC effective reactance X_{SVC} is infinite and there is no current leaving or entering the SVC which indicates the power exchange between the SVC and the AC system is zero[3], [4].

According to the inductive and capacitive reactance's, each SVC has its own firing angle – reactive power characteristics, $Q_{SVC}(\alpha)$ which is a function of the inductive and capacitive reactance's. The firing angle initial condition may be determined using a graph similar to that shown in the fig.3. The following steps may be used to determine this plot. Firstly, it is necessary to obtain the effective reactance X_{SVC} as a function of the firing angle α , using the fundamental frequency TCR equivalent reactance X_{TCR} . $X_{TCR} = \frac{\pi X_L}{\sigma - \sin\sigma}$ and $\sigma = 2(\pi - \alpha)$, where X_L is the reactance of the linear inductor, σ and α are the thyristor conduction and firing angles, respectively. At $\alpha = 90^\circ$ the TCR conducts fully and the equivalent reactance X_{TCR} becomes X_L . At $\alpha = 180^\circ$, the TCR is blocked and its equivalent reactance becomes extremely large i.e. infinite [4], [13].

The total effective reactance of the SVC, including the TCR and capacitive reactance's, is determined by the parallel combination of both these components.

$$X_{SVC} = \frac{X_C X_{TCR}}{X_C + X_{TCR}} = \frac{\pi X_C X_L}{X_C(\sigma - \sin\sigma) + \pi X_L}$$

Where X_{SVC} is a function of the conduction angle σ .

Effective reactance of the SVC is a function of the firing angle.

The reactive power $Q_{SVC}(\alpha)$ is given by

$$Q_{SVC}(\alpha) = V_{bus}^2 \frac{X_C[2(\pi-\alpha)+\sin 2\alpha]-\pi X_L}{\pi X_C X_L} \quad (10)$$

As indicated by equation (10), Q_{SVC} takes a value of zero when the effective reactance X_{SVC} is extremely large i.e. infinite. This condition is satisfied when the following relationship approaches zero [4][13],[14].

$$X_C[2(\pi - \alpha) + \sin 2\alpha] - \pi X_L = 0 \quad (11)$$

The value of the firing angle α that satisfies the equation (11) is used as initial condition in the open-loop control of the SVC.

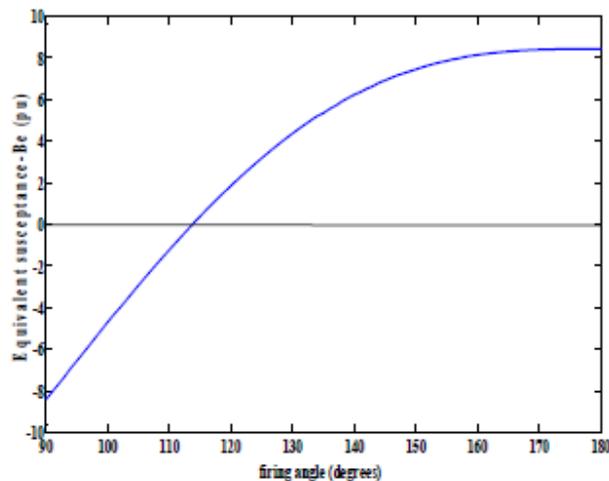


Figure4. SVC equivalent susceptance profile

Fig.4 shows that the SVC equivalent susceptance ($B_{SVC} = -1/X_{SVC}$) profile as function of firing angle, does not have discontinuities, i.e. B_{SVC} varies in a continuous, smooth variation in both operative regions. Hence, linearization of the SVC power flow equations based on B_{SVC} with respect to firing angle, will exhibit a better numerical behavior than the linearized model based on X_{SVC} , when $X_{TCR} = X_C$ i.e. $Q = 0$ corresponding to firing angle 114° , for chosen parameters of L and C i.e. $X_L = 0.3333\Omega$ and $X_C = 0.6667\Omega$ [13],[15].

IV. TEST SYSTEM AND ANALYTICAL TOOLS

A Single line diagram of the IEEE 14 bus test system is depicted in Fig.5. It consists of the five synchronous machines including three synchronous compensators which are used only for reactive power support. There are twenty branches and fourteen buses with eleven loads totaling of 259MW and 81.4 MVar [8]. All the results presented in the paper are produced with the help of the Power System Analytical Tool, PSAT [16]. PSAT is a research tool that has been designed to calculate the maximum loading margin of a power system associated with a saddle node and limit-induced bifurcation for a given load and generation direction. The program has detailed static models of various power system elements like generators, loads, HVDC links, and various FACTS controllers [8].

In this study, all loads are represented as constant PQ and they are increased simultaneously according to equation (12) to maintaining constant power factor [8].

$$P_L = P_0(1 + \lambda) \quad \text{and} \quad Q_L = Q_0(1 + \lambda) \quad (12)$$

Where P_0 and Q_0 correspond to the base loading conditions and λ is the loading factor (LF).

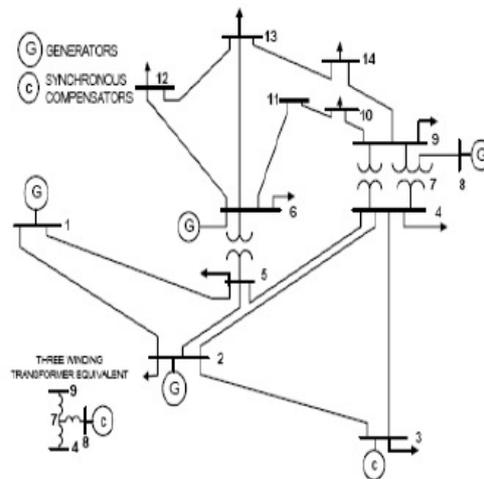


Figure5. Single line diagram of IEEE 14 bus test system

V. RESULT AND DISCUSSION

5.1. Identification of weak bus by L-index

The best location for reactive power compensation for the improvement of static voltage stability margin is by considering the identified “weakest bus” of the system. The weakest bus of the system is identified using the L- indices [11] for a given load condition, and is computed for all load buses. The estimated value of L-index is varying between 0 and 1. Based on this value, it is possible to identify the voltage stability margin. If the estimated value approaches 1 refers the voltage collapse where as the estimated value approaches 0 refers the under no-load condition, otherwise the system is under normal operating condition. The higher values for L-indices are indicative of most critical buses and thus maximum of L-indices (L_{max}) is an indicator of proximity in the system to represent voltage collapse. Table 1 show the first four weakest buses and bus 14 and bus 9 are considered as the best location to provide desired reactive power support. Based on the studies carried out with the developed model the following are the results obtained based on L-index method.

5.2. Rated capacities of SVC

Once the weakest bus has been identified the next objective is to provide the required compensation [11]. In order to get approximate reactive power [8] support needed at the weakest bus for the corresponding load margin, for a given load and generation direction, a synchronous compensator without limit on reactive power has been used at the weakest bus. The amount of reactive power generated at the maximum loading point from the synchronous compensator was found to be 150 MVar.

Table 1. L-index of the first four weakest buses.

Load bus	8	9	10	14
L-index	0.0376	0.0664	0.0633	0.0767

5.3. Simulation and Results

14-bus test system is used to assess the effectiveness of SVC model proposed in this paper. For the detailed study two cases are chosen and they are

(i) SVC is connected at bus 14 (ii) SVC connected at bus 9

5.3.1. Case 1

If SVC is connected to bus 14, the aim of control is to keep the voltage at that bus at 1.0 pu, when it is near to the peak load condition i.e. for loading factor $\lambda = 1.6$. Here it is found that the SVC injects

30.927 MVAR to bus 14 in order to keep the voltage magnitude at 1.0 pu, with final firing angle of 119.65° . Table 2 gives the voltage magnitude in pu for all buses of the system with and without SVC. The result obtained shows that improvement of voltage magnitude in most of the buses as compared to the system without any FACTS controllers.

Table 2. Voltage magnitude for 14-bus test system with and without SVC

Bus	Without FACTS	SVC at Bus 14	SVC at Bus 9
1	1.06	1.06	1.06
2	0.9745	0.99534	0.99679
3	0.88537	0.92268	0.92564
4	0.89695	0.94262	0.94647
5	0.90962	0.95131	0.9534
6	0.92067	1.0077	1.0009
7	0.9126	0.99056	1.003
8	0.95679	1.0315	1.0435
9	0.88738	0.98278	1.0
10	0.87903	0.97433	0.98746
11	0.89295	0.9848	0.98818
12	0.89159	0.98835	0.97677
13	0.88173	0.98533	0.96999
14	0.84942	1.0	0.9555

5.3.2. Case 2

If SVC is connected to bus 9, the aim of control is to keep the voltage at that bus at 1.0 pu, when it is near to the peak load condition i.e. for loading factor $\lambda = 1.6$. Here the SVC injects 32.683 MVAR to bus 9 in order to keep the voltage magnitude at 1.0 pu, with final firing angle of 120.0° . Table 2 gives the voltage magnitude in pu for all buses of the system with SVC. The results obtained had shown the improvement of voltage magnitude in almost all buses as compared to the system without any FACTS controllers.

VI. CONCLUSIONS

In this paper, voltage stability assessment of the standard IEEE -14 bus test system with base case and SVC are studied. The continuation power flow simulation studies have been carried out to investigate the loadability on the test system based on identification of weak bus using L-index method. FACTS device such as SVC is employed for enhancing voltage stability. The proposed scheme presents the simple method for identifying the weak bus and also optimum value of reactive power support needed for it. The paper also deals with the optimal location of SVC to minimize the reactive power loss which results in enhancement of voltage stability margin. The simulated results shown in Table 2 clearly shows the voltage magnitude of buses 9 and 14 which were identified as weakest buses with SVC are maintained at 1.0 pu, for the loading factor $\lambda=1.6$ and there is a voltage improvement in other buses of the test system also.

REFERENCES

- [1] T.J.E.Miller, Reactive Power Control in Electric Systems, Wiley Interscience, 1982.
- [2] C.W.Taylor, Power system Voltage Stability, McGraw-Hill, Inc., New York, USA, 1993.
- [3] K.R.Padiyar, FACTS Controllers in Power Transmission and Distribution. New Age International Publishers

- [4] Enrique Acha, C.R.F.Esquivel,H.APerez , FACTS Modeling and Simulation in Power Networks. John Wiley & Sons,Ltd.
- [5] Ambriz,H.Perez,E.Ache,C.RFuerte,Esquivel,AdvancedSVC Models for the Newton –Raphson loadflow and Newton optimal power flow studies. IEEE Transactions on power systems,February 2000.vol-15, No.1, pp 129-136.
- [6] C.A.Canizares , Power flow and transient stability models of FACTS controllers for the voltage and angle stability studies, Proceedings of the 2000 IEEE-PES winter meeting, Singapore, January 2000.
- [7] N.Mithulanathan ,C.A.Canizores , and J.Reeve Comparison of PSS, SVC and STATCOM Controllers for Damping Power System Oscillations, IEEE Trans.Power System, 18(2003), 786-792.
- [8] Arihit Sode –Yome, Nadarajah Mithulanathan ,Static Voltage Stability Margin Enhancements usingSTATCOM, TCSC, and SSSC 2005 IEEE/PES , Transmission and Distribution. Conference and Exhibition: Asia and Pacific, Dalian, China.
- [9] Arihit Sode-Yome, and N.Mithulanathan , Comparison of Shunt Capacitor, SVC and STATCOM in Static Voltage Stability Margin Enhancement.International Journal of Electrical Engineering Education, UMSIT, Vol 41, No.3, July 2004.
- [10] Cigre95TP108, FACTS overview, IEEE Power Engineering Society 1995
- [11]D. Thukaram , Abraham Lomi Selection of static VAR compensator Location and Size for System Voltage Stability Improvements Electrical Power System Research 54(2000), 139-150.
- [12]P.Kundur,Power System Stability and Control , McGraw- Hill, Inc.,1994.
- [13]Mohammed Osman Hassan,S.J.Cheng ,Zakaria Anwar Zakaria,. Steady-State Modeling of SVC and TCSC for Power Flow Analysis. IMECS 2009, March 18-20, 2009, Hong Kong.
- [14] Ying Xiao,Y.H.Song and Y.Z.Sun , Power flow control approach to power systems with embedded FACTS devices. , IEEE Transactions on power systems, vol.17, No.4, Nov.2002, pp.943-950.
- [15] Vinod K.Yedidi,Brian K Johnson, Design of TCSC for Classroom and Research Applications on an Analog Model Power System., IEEE, 2006.
- [16]Power System Analysis Toolbox version 2.1.2, June 26, 2008.

Authors

H. B. Nagesh received the BE degree in Electrical and Electronics Engineering from University of Mysore, Mysore, India in 1991, Post Graduation in Power Systems from University of Mysore, Mysore, India in 1994.His areas of interests are power systems operation and control, voltage stability and applications of FACTS controllers in transmission systems.



P. S. Puttaswamy received the BE degree in Electrical Power from University of Mysore, Mysore, India in 1983, post graduation in power apparatus and electric drives in Indian Institute of Technology, Roorkee, India in 1989.The PhD degree in power apparatus and electric drives at Indian Institute of Technology, Roorkee, India in 2000.The area of research interests are power converters, Image processing, electric drives and controls, and soft computing techniques. He has several research papers published at national and international level conferences and journals.

