A review on pi control of statcom for voltage regulation

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ABSTRACT

Because of growing demand and restrictions in building new lines Transmission systems are becoming stressed in maintaining the stability of the system. In transmission networks, Flexible AC Transmission System (FACTS) is a power electronic based technology to enhance controllability, stability and power transfer capability of ac transmission system. FACTS devices are found to be very effective for stability followed by a disturbance. Static Synchronous Compensator (STATCOM) which is a shunt device of FACTS family is efficient in regulating voltage either by absorbing or by generating reactive power. Compared to other FACTS devices, STATCOM can provide fast and efficient reactive power support to maintain power system voltage stability. This paper proposes a PI control model that controls the voltage during a disturbance. The proposed controller is implemented under MATLAB/SIMULNK environment. In the simulation test, the PI control shows consistent excellence under various operating conditions, such as different initial control gains, different load levels, and change of transmission network, consecutive disturbances, and a severe disturbance.

KEY WORDS: Transmission networks, FACTS, proportional-integral control, STATCOM, reactive power compensation, voltage stability.

1. INTRODUCTION

Electric power system being a complex system in its structure and operation is facing many challenges day by day. The major problem in power system is its instability. Power system stability is the capability of the system to maintain an operating equilibrium point after being subjected to a disturbance for given initial operating conditions. Traditionally voltage regulation is performed by the excitation system and thereby helps in controlling the system voltage. Suitable devices like Automatic Voltage Regulators (AVR) are used for the regulation of generated voltage. AVR's normally maintain the generator voltage magnitude at a specified level. AVRs are extensively used on the dynamic or steady state stability of the power system as low frequencies oscillations persist for a long period and may affect the capability of power transfer. Electrical power demand is rising at a very higher rate because of rapid industrial development. In order to satisfy the demand, power transmission has to be raised along with the existing facilities. Thus it is essential to concentrate for the power flow control. The power system should be flexible to adapt itself to any momentary changes in system conditions. In an AC power system, there must be a balance between the generated power and variations in load demand while keeping the system frequency and voltage levels as constant. If generation is not sufficient, the voltage and frequency drop, and the load decreases to balance the total generation minus losses in transmission. But there are only a few percent margins for such a self-regulation. Hence the system is collapsed. Generator excitation controller normally improves stability for smaller faults but not suitable for larger faults that occur near to generator terminals. Thus, traditional methods have to be reviewed and new concepts have to be created that emphasizes an efficient use of resources of existing power system maintaining stability and security of the system.

In the late 1980s, a new approach was introduced by the Electric Power Research Institute to overcome the problem of designing and operating power systems; the proposed concept is known as Flexible AC Transmission Systems (FACTS). IEEE defines FACTS as "a new technology based on power electronics offering an opportunity to enhance controllability, stability and increase power transfer capability of ac transmission system.

Basically, FACTS devices are classified into: Series Controller, Shunt Controller, and Combined series-series Controller, Combined series-shunt Controller.

The improvements in voltage stability can be achieved through tap changer transformers that change their turn's ratio, switched capacitors and reactors. FACTS devices can offer fast and reliable control over three phase AC transmission system parameters such as voltage, line impedance and phase angle thereby to control voltage stability.

Table.1.Comparison of FACTS Controllers

Name	Type	Controller Used	Controlling parameter
STATCOM	Shunt	GTO	Voltage
SSSC	Series	GTO	Power flow
TCSC	Series	Thyristor	Power flow
SVC	Shunt	Thyristor	Voltage
UPFC	Shunt and Series	GTO	Voltage and power flow
TCPAR	Series and Series	Thyristor	Power flow

Major applications of FACTS in power system are:

- Power flow and Voltage control
- Reactive power compensation
- Reduction of temporary overvoltage
- Increase of transmission capability
- Damping of power system oscillations
- Power quality improvement

Voltage stability is the ability of a system to maintain steady voltages at all its buses even after subjected to a disturbance from an initial operating point. It may be either a short term or a long term problem. The short term problems may be due to small change in load whereas the long term problems are due to system faults, load losses and loss of generation. The static synchronous compensator (STATCOM) is a popular FACTS device used for control of reactive power based on gate turnoff (GTO) thyristor. Also various control methods have been proposed for STATCOM control in the past years. The control logic for PI controllers is implemented in many STATCOM models. The gains and control parameters play a key factor in the performance of STATCOM.

1.1. STATCOM – Operating principle: STATCOM is a FACTS device, Voltage Source Converter (VSC)-based device, having a voltage source behind a reactor. STATCOM regulates voltage by generating or absorbing reactive power. During low system voltages, it acts as STATCOM capacitive by generating reactive power. During high system voltages, it acts as STATCOM inductive by absorbing reactive power. Variation in reactive power is handled by the VSC which is connected to the secondary of a coupling transformer. The active power capability of STATCOM is very less because the VSC using GTOs or IGBTs synthesizes only the voltage source from a DC capacitor. But if an energy storage device is connected across the DC capacitor STATCOMs active power capability can be increased. The performance of STATCOM is similar to that of SVC but if the system voltage is at lower voltage regulation range, STATCOM is able to generate large amount of reactive power than that of the SVC. Also the response time is less while using STATCOM because of the VSC, no delay is associated with the firing of thyristors. A model of STATCOM is given in Fig. 1.

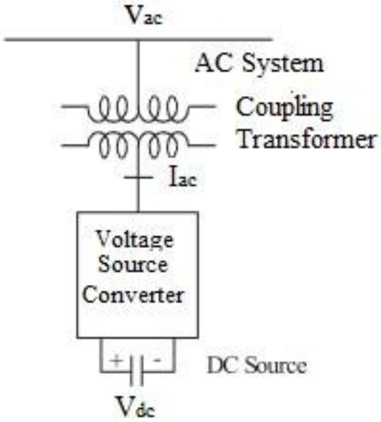


Fig.1.STATCOM model

The relation between the fundamental component of the converter ac voltage output and voltage across dc capacitor is given as

$$V_{out} = kV_{dc} \qquad (1)$$

Where k is coefficient that depends on the number of switching pulses, converter configuration and the converter controls. The fundamental component of the converter voltage output i.e. V_{out} is dependent on V_{dc}, can be controlled by varying the dc voltage across capacitor which can be done by varying the phase angle α of the converter switching. The direction of reactive power flow either from system to the coupling transformer or from coupling transformer to the system is decided by the difference between the converter voltage output and the ac system bus voltage. The dc capacitor is charged to a satisfactory dc voltage level by the real power supply into the converter. During the course of each switching cycle, the capacitor is charged and discharged, but under steady state conditions, the average capacitor voltage remains unchanged. In steady state, the ac system power is used to replenish the switching losses. The ability of STATCOM to supply/absorb real power is determined by the size of dc capacitor and the active power switching losses. Whenever the dc capacitor and the losses are relatively small, the amount of real power transfer is also relatively small. This implies that the STATCOM's output ac current I_{ac}, has to be approximately + 90^0 with respect to ac system voltage at its line terminals. Varying the converter three-phase output voltage V_{out} controls the reactive power generation/absorption of the STATCOM. If the converter output voltage amplitude V_{out} is increased more than the ac system bus voltage amplitude V_{ac} then the ac current I_{ac}, flows through the transformer reactance from the converter to the ac system generating reactive power. In such case, capacitive current will be drawn by the system which leads the system voltage by an angle of 90^0. Assume the converter losses as zero. The ac current flow takes place from the ac system to the VSC if the converter output voltage amplitude is reduced below that of the ac system voltage, and the converter absorbs reactive power consequently. Similarly for an inductive operation, the current lags the system voltage by an angle of 90^0. Again assume that the converter losses are zero. If the ac system voltage and converter output voltage amplitudes are equal, there will be no ac current flow in/out of the converter and hence there will be no reactive power generation/absorption and the magnitude of ac current can be determined by

$$I_{ac} = \frac{V_{out} - V_{ac}}{X} \qquad (2)$$

Assuming that the AC current flows from the converter to the ac system.

Where V_{out} - converter output voltage, V_{ac} - ac system voltage magnitude, X – leakage reactance of coupling transformer.

The reactive power exchanged can be given as follows:

$$Q = \frac{V_{out}^2 - V_{out}V_{ac}\cos\alpha}{X} \qquad (3)$$

The real power exchange between the voltage source converter and the ac system can be given as:

$$P = \frac{V_{ac}V_{out}\sin\alpha}{X} \qquad (4)$$

2. MODEL OF STATCOM

2.1. System Configuration: Fig. 2. Shows the equivalent circuit of STATCOM. In this system, R_s is the series resistance with the voltage source inverter (VSI). It is the sum of the inverter conduction losses and the transformer winding resistance losses. L_s is the transformer leakage inductance. R_c is the shunt resistance with the capacitor. It represents the sum of the power losses in the capacitor and the switching losses of the inverter. In Fig. 2. V_{al}, V_{bl} and V_{cl} are the three phase bus voltages; V_{as}, V_{bs} and V_{cs} are the three phase output voltages; and i_{as}, i_{bs} and i_{cs} are the three phase output currents.

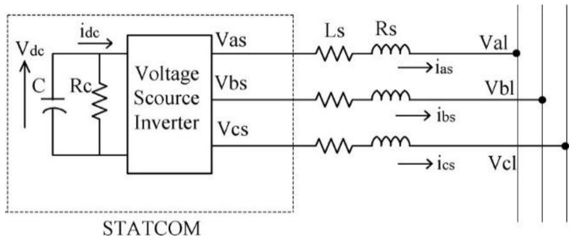


Fig.2.STATCOM - Equivalent circuit

2.2. Dynamic Model of STATCOM: The mathematical expressions of the STATCOM are given as [8], [9]:

$$L_s\frac{di_{as}}{dt} = -R_s i_{as} + V_{as} - V_{al} \qquad (5)$$

$$L_s\frac{di_{bs}}{dt} = -R_s i_{bs} + V_{bs} - V_{bl} \qquad (6)$$

$$L_s\frac{di_{cs}}{dt} = -R_s i_{cs} + V_{cs} - V_{cl} \qquad (7)$$

$$\frac{d}{dt}\left(\frac{1}{2}CV_{dc}^2(t)\right) = -[V_{as}i_{as} + V_{bs}i_{bs} + V_{cs}i_{cs}] - \frac{V_{dc}^2(t)}{R_c} \qquad (8)$$

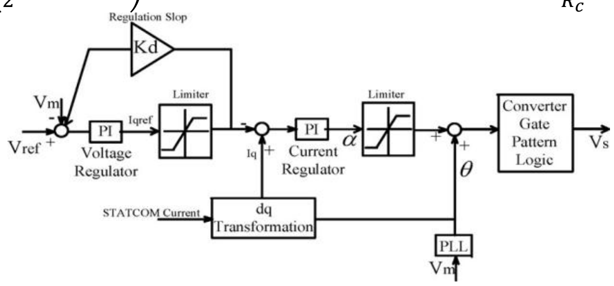


Fig.3.Traditional STATCOM PI control block diagram

By using the abc/dq transformation, the equations can be rewritten as

$$\frac{d}{dx}\begin{bmatrix} i_{ds} \\ i_{qs} \\ V_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \omega & \frac{K}{L_s}cos\alpha \\ -\omega & -\frac{R_s}{L_s} & \frac{K}{L_s}sin\alpha \\ -\frac{3K}{2C}cos\alpha & -\frac{3K}{2C}sin\alpha & -\frac{1}{R_cC} \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ V_{dc} \end{bmatrix} - \frac{1}{L_s}\begin{bmatrix} V_{dl} \\ V_{ql} \\ 0 \end{bmatrix} \quad (9)$$

Where i_{ds} and i_{qs} are the d and q currents corresponding to i_{as}, i_{bs} and i_{cs}; K is a factor that relates the dc voltage to the peak phase to neutral voltage on the ac side; V_{dc} is the dc side voltage; α is the phase angle at which the output voltage leads the bus voltage; ω is the rotating angular speed of the voltage vector and V_{dl} and V_{ql} represent d and q axis voltage corresponding to $V_{al},\ V_{bl}$ and V_{cl}. The active and reactive powers can be determined as follows:

$$p1 = \frac{3}{2}V_{dl}\ i_{ds} \quad (10)$$

$$q1 = \frac{3}{2}V_{dl}\ i_{qs} \quad (11)$$

The traditional control strategy can be determined based on the equation shown above and the block diagram of STATCOM is shown in Fig. 3.

As shown in Fig. 3, the phase-locked loop (PLL) synchronizes on the positive sequence component of the three phase primary voltage. The PLL output computes the direct axis and quadrature axis components of voltage and current. Measurement systems of STATCOM measure the d and q components. The measured bus line voltage V_m and the reference voltage V_{ref} are compared and the required value of reactive reference current is provided by the voltage regulator. Also the reactive current I_q of STATCOM and reference current I_{qref}, are compared and the current regulator provides the angle phase shift of the inverter voltage with regard to the system voltage as its output. STATCOMs' capability of maximum reactive power can be controlled by the limiter which is the limit imposed on the value of control.

2.3. STATCOM WITH PI CONTROL

PI Control:

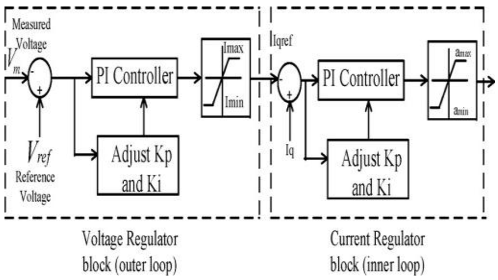


Figure.4.Control block of PI for STATCOM

The PI control can be applied with STATCOM to reach the desired and acceptable responses in the power system when there are changes in system operating condition (e.g., loads or transmissions). A PI control method is used to get the desired responses. And suitable parameters have to be found for PI controllers whie installing a new STATCOM in a power system. In Fig. 4, $V_m(t)$ is the measured voltage, $V_{ref}(t)$ is the reference voltage, I_{qref} is the quadrature axis reference current and I_q is the quadrature axis current. All these are in per-unit values. K_{p_V} and $Ki_{\_V}$ are the proportional and integral gains of the voltage regulator respectively. Similarly, the proportional and integral gains of the current regulator are represented by K_{p_I} and $Ki_{\_I}$ respectively.

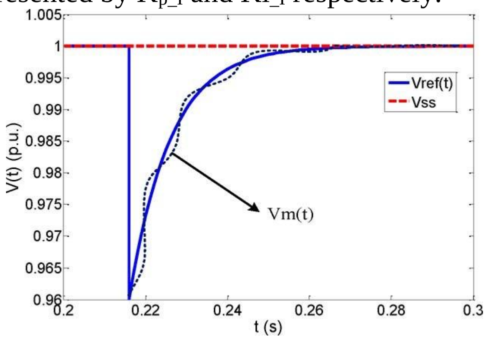


Fig.5.Reference voltage curve

In this system, K_d is set to 0 as the allowable voltage error. Also the K_{p_V}, K_{i_V}, K_{p_I} and $Ki_{\_I}$ can be set to an arbitrary initial value as 1.0.

Equations: Both the inner and outer loop controls are similar and the mathematical model is determined for PI controller gain adjustments in the outer loop. Similarly inner loop gains can also be adjusted. $V_{dl}(t)$ and $V_{ql}(t)$ can be computed with the d-q transformation.

$$\begin{bmatrix} V_{dl}(t) \\ V_{ql}(t) \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_{al}(t) \\ V_{bl}(t) \\ V_{cl}(t) \end{bmatrix} \quad (12)$$

$$V_m(t) = \sqrt{{V_{dl}}^2(t) + {V_{ql}}^2(t)} \quad (13)$$

$$V_{ref}(t) = V_{ss} - \left(V_{ss} - V_m(t)\right)e^{-\frac{1}{\tau}} \quad (14)$$

$$K_{p\_V}(t) = \frac{K_V \times \Delta V(t)}{(\Delta V(t) + m_V \times \int_t^{t+T_s} A dt)} \quad (15)$$

$$K_{i\_V}(t) = m_V \times K_{p\_V}(t) \quad (16)$$

$$K_{p\_I}(t) = \frac{K_I \times \Delta I_q(t)}{(\Delta I_q(t) + m_I \times \int_t^{t+T_s} B dt)} \quad (17)$$

$$K_{i\_I}(t) = m_I \times K_{p\_I}(t) \quad (18)$$

2.4. PI Control Procedure flowchart: Fig.6 is a flowchart of the PI control for STATCOM corresponding to the block diagram of Fig. 4. The process of PI control begins at Start. The measured bus voltage over time $V_m(t)$ is sampled to a desired sampling rate and is then compared with V_{ss}. There is no need to change any of the parameters, $K_{p\_V}(t)$, $K_{i\_V}(t)$, $K_{i\_I}(t)$ and $K_{p\_I}(t)$ if, $V_m(t) = V_{ss}$. And it is considered as the smooth run of the power system. But the PI control will begin if, $V_m(t) \neq V_{ss}$. The measured bus voltage $V_m(t)$ is compared with $V_{ref}(t)$. Then, gain adjustments on K_{p_V} and K_{i_V} are done in the outer loop i.e., voltage regulator block, based on (15) and (16), and thereby an updated I_{qref} is obtained through the current limiter as shown in Fig. 4. Then, this I_{qref} and measured q-current I_q are compared. The control gains $K_{i\_I}(t)$ and $K_{p\_I}(t)$ can be adjusted based on (17) and (18). At last the phase angle α is determined and given through a limiter for output, that decides the required reactive power output from the STATCOM.

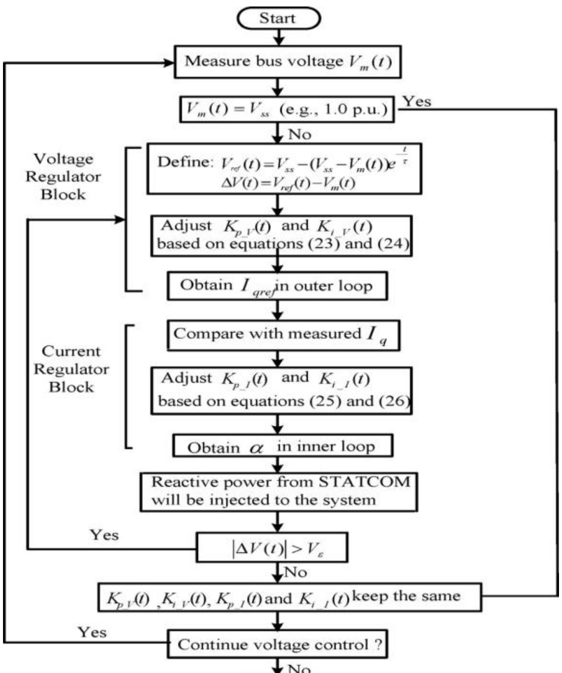


Fig.6.Flowchart of PI Control

Then check whether $|\Delta V(t)|$ is within the tolerance threshold, i.e., 0.0001 p.u. If it is not so, the outer and inner loop operations have to be repeated until the change is less than the given tolerance threshold. Thus the values of $K_{p\_V}(t)$, $K_{i\_V}(t)$, $K_{i\_I}(t)$ and $K_{p\_I}(t)$ are maintained. If the voltage control process needs to be performed continuously, then the process returns to the measured bus voltage. Else, the voltage-control process stops (i.e., the STATCOM control is deactivated).

3. RESULTS

System:

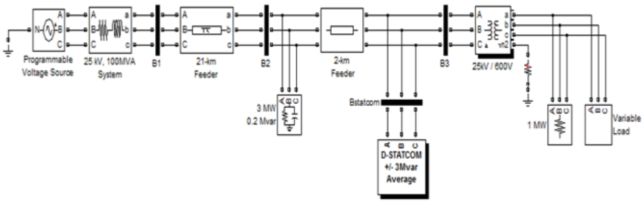


Fig.7.Studied system

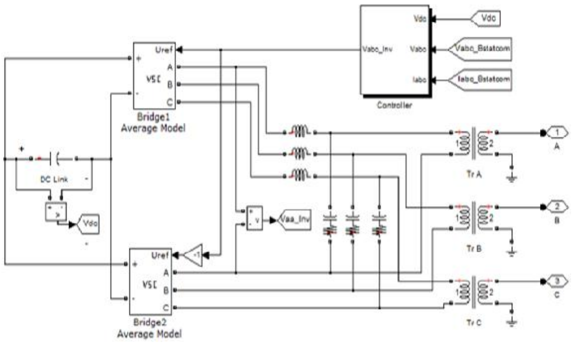
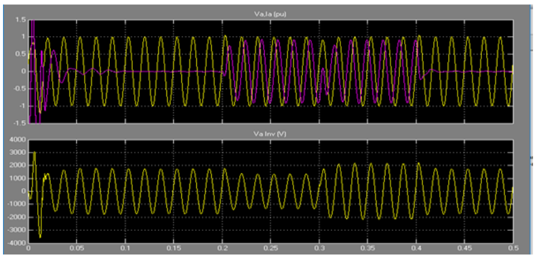


Fig.8.STATCOM

Fig. 7 shows the diagram of the simulation. Here a 25kV distribution network is used that requires voltage regulation. The voltage regulation is done by using a D-STATCOM. Power is transmitted through two feeders to the loads at buses B2 and B3. A 600V load is connected to bus B3 through a 25kV/600V transformer. The magnitude of variable load current is modulated at a frequency of 5kHz and so its apparent power varies between 1MVA and 5.2MVA while keeping a 0.9 lagging power factor. The STATCOM is operated in bus voltage regulation mode. In this model, The D-STATCOM either by absorbing or generating the reactive power regulates the voltage of bus B3. And the power transfer takes place through the coupling transformer leakage reactance by generating a secondary voltage in phase with the primary voltage. A voltage sourced PWM inverter provides this voltage. The D-STATCOM will absorb reactive power i.e., acts like an inductance if the secondary voltage of the transformer is less than the bus voltage. Similarly the D-STATCOM will generate reactive power i.e., acts like a capacitor if the secondary voltage of the transformer is higher than the bus voltage.

Responses of the Model:



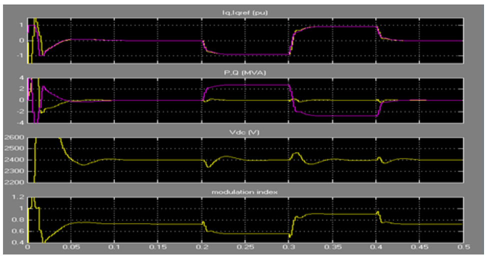


Fig.9.Results of bus voltage and current (Va and Ia) **Fig.10.Results of Iq, Iqref, P, Q, Vdc**

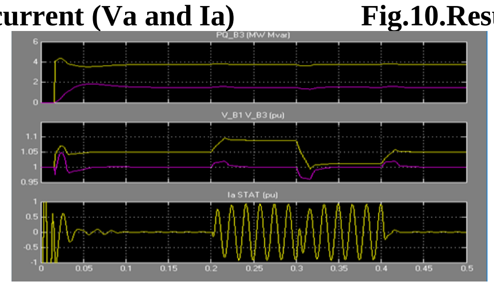


Fig.11.Results of P, Q in B3

4. CONCLUSION AND FUTURE WORK

In most of the literatures, various STATCOM control models have been discussed and also PI controller applications are included. The control parameters of the PI controller has to be adjusted for the optimal performance of STATCOM at a given or different operating points. An adaptive PI control model can be preferred, that can self-adjust the controller gain parameters dynamically under disturbances thereby the performance of the entire system always matches the desired response, regardless of the change of operating conditions. This work can be applicable under various operating conditions, such as different initial control gains, change of the transmission network, different load levels, consecutive disturbances and a severe disturbance. Future work can be carried with the investigation of multiple STATCOMs, because the interaction among different STATCOMs may affect each other. Also, the extension to other power system control problems can be explored.

REFERENCES

Cong L, Wang Y, Co-ordinated control of Generator excitation and STATCOM for Rotor angle stability and voltage regulation enhancement of Power systems, IEEE Proc.Gen.Trans.Distrib., 149 (6), 2002, 659-666.

Hingorani and N.G.Gyungi N.G, Understanding Facts Devices, IEEE Press, 2000.

Jain A, Joshi K, Behal A, and Mohan N, Voltage regulation with STATCOMs: Modeling, control and results, IEEE Trans. Power Del., 21 (2), 2006, 726–735.

Li H, Li F, Kueck J.D, and Rizy D.T, Adaptive voltage control with distributed energy resources: Algorithm, theoretical analysis, simulation and field test verification, IEEE Trans. Power Syst., 25 (3), 2010, 1638–1647.

Li H, Li F, Xu Y, Rizy D.T, and Adhikari S, Autonomous and adaptive voltage control using multiple distributed energy resources, IEEE Trans. Power Syst., 28 (2), 2013, 718–730.

Matlab, and Simulink, GTO-based STATCOM Dec. 2013, [Online], Available: http://www.mathworks.com/help/physmod/sps/powersys/ug/gto-based-statcom.html, Feb. 2012.

Moursi M.S.E, and Sharaf A.M, Novel controllers for the 48-pulse VSC STATCOM and SSSC for voltage regulation and reactive power compensation, IEEE Trans. Power Syst., 20 (4), 2005, 1985–1997.

Norouzi A.H, and Sharaf A.M, Two control schemes to enhance the dynamic performance of the STATCOM and SSSC, IEEE Trans. Power Del., 20 (1), 2005, 435–442.

Papic I, Zunko P, and Povh D, Basic control of unified power flow controller, IEEE Trans. Power Syst., 12 (4), 1997, 1734–1739.

Rao P, Crow M.L, and Yang Z, STATCOM control for power system voltage control applications, IEEE Trans. Power Del., 15 (4), 2000, 1311–1317.

Schauder C and Mehta H, Vector analysis and control of the advanced static VAr compensators, Proc. Inst. Elect. Eng.Gen.Transm.Distrib., 140 (4), 1993, 299–306.

Sen K.K, Static synchronous compensator—Theory, modeling and applications, presented at the IEEE Power Eng. Soc. Winter Meeting, Edmonton, AB, Canada, 1999.

Yao Xu and Fangxing Li, Adaptive PI Control of STATCOM for Voltage Regulation, IEEE Transactions on Power Delivery, 29 (3), 2014.