IARJSET
ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
National Conference on Emerging Trends in Engineering and Technology (NCETET'16)
Lourdes Matha College of Science & Technology, Thiruvananthapuram
Vol. 3, Special Issue 3, August 2016

Modelling and Control of Static Synchronous Compensator using Pi Controller

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Abstract: STATCOM is a shunt connected reactive power compensation equipment .There is different types of FACTS devices, but the STATCOM. It offers better performance due to high dynamic performance and its compensation does not depend on coupling voltage. This paper deals with the dynamic model and analysis of static synchronous compensator (STATCOM). The STATCOM have been modeled and the mathematical equations that explain their behaviour have been introduced Simulation results prove the validity of the model. PI controller is implemented to control STATCOM that tracks the voltage.

Key Words: STATCOM, VSC, transformer, reactive power, PI controller

I. INTRODUCTION

VOLTAGE stability is a critical consideration in improving the reliability of power systems. The static compensator (STATCOM), a popular device for reactive power control based on gate turnoff (GTO) thyristors, has gained much interest in the last few years for improving power system stability. In the control of electric power systems, reactive power compensation is an important issue. Reactive power transmission system losses, reduces power transmission capabilities, and may cause large amplitude variations in the receiving-end voltages. Moreover, rapid changes in reactive power consumption may lead to terminal voltage amplitude oscillations. These voltage variations, which was caused by fluctuating reactive power, can change the power demand in the power system, resulting in power oscillations. Over the last two decades, reactive power compensators based on force- commutated solid state power electronic devices, such as Thyristor-controlled Reactors (TCR) and Thyristor-switched Capacitor, have gained popularity. In these devices the effective reactance connected to the system is controlled by the fire angle of thyristors. These devices improved the dynamics and precision. However, they strongly depended on the power system line condition at the point–of-common-coupling voltage. Therefore they are very good steady state solution, but frequently exhibit poor transient dynamics. With the developments in power electronics, a new kind of compensator was introduced. This compensator is static synchronous compensator - STATCOM, which is based on self-commutated solid state power electronic devices to achieve advanced reactive power control. STATCOM is capable of high dynamic performance and its compensation does not depend on the common coupling voltage. Therefore, STATCOM is very effective during the power system disturbances.

Moreover, much research confirms several advantages of STATCOM.

These advantages include:

- Size, weight, and cost reduction
- Equality of lagging and leading output
- Precise and continuous reactive power control with fast response
- Possible active harmonic filter capabilities.

II.SYSTEM DESCRIPTION

The figure 1 shows the one line diagram of STATCOM. It consist of a dc source, voltage source converter (VSC), a coupling transformer which is connected to the grid.

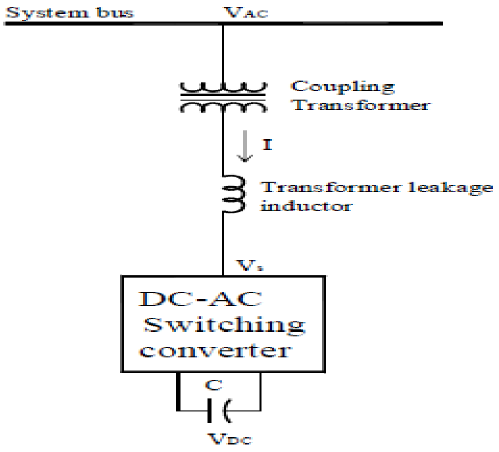

Fig.1.One line diagram of STATCOM

The Static Synchronous Compensator (STATCOM) is a shunt connected reactive compensation equipment which is capable of generating and/or absorbing reactive power whose output can be varied so as to maintain control of specific parameters of the electric power system. The STATCOM provides operating characteristics is same to a rotating synchronous compensator without the mechanical inertia, due to the STATCOM employ solid state power switching devices it provides rapid controllability of the three phase voltages, both in magnitude and phase angle. The STATCOM basically consists of a step-down transformer with a leakage reactance, a three-phase GTO or IGBT voltage source inverter (VSI), and a DC capacitor. The AC voltage difference across the leakage reactance produces reactive power exchange between the STATCOM and the power system, such that the AC voltage at the bus bar can be regulated to improve the voltage profile of the power system, which is the primary duty of the STATCOM. A secondary damping function can be added into the STATCOM for enhancing power system oscillation stability.
The principle of STATCOM operation is as follows. The VSI generates a controllable AC voltage source behind the leakage reactance. We are comparing this voltage with the AC bus voltage; when the AC bus voltage magnitude is above than the other the AC system sees the STATCOM as an inductance connected to its terminals. Otherwise, if the VSI voltage magnitude is above that of the AC bus voltage magnitude, the AC system sees the STATCOM as a capacitance connected to its terminals. If the voltage magnitudes are equal, the reactive power exchange is zero. If the STATCOM has a DC source or energy storage device on its DC side, it can supply real power to the power system. This can be achieved adjusting the phase angle of the STATCOM terminals and the phase angle of the AC power system. When the phase angle of the AC power system leads the VSI phase angle, the STATCOM absorbs real power from the AC system; if the phase angle of the AC power system lags the VSI phase angle, the STATCOM supplies real power to the AC power system.

III.SYSTEM MODELLING

The voltage source converter based STATCOM is the dominant topology in practice.

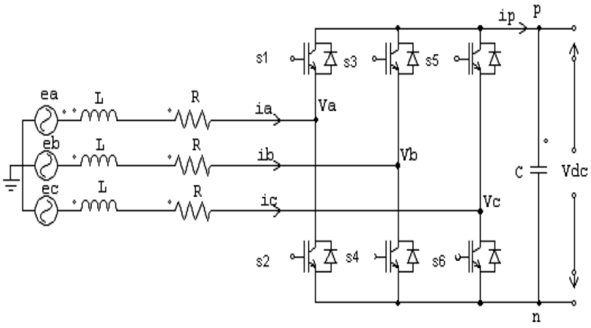

Fig.2. Circuit diagram of STATCOM

From power electronics principles we get

$$i_p = \begin{bmatrix} D_{ap} - D_{bp} \\ D_{bp} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix}^T \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (1)$$

Where Dkp are switching functions and k=a,b,c

$$i_{ab} = \frac{1}{3}(i_a - i_b),\ i_{bc} = \frac{1}{3}(i_b - i_c),\ i_{ca} = \frac{1}{3}(i_c - i_a)$$

$$\begin{bmatrix} V_a - V_b \\ V_b - V_c \\ V_c - V_a \end{bmatrix} = \begin{bmatrix} D_{ap} - D_{bp} \\ D_{bp} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix} V_{pn} \quad (2)$$

From circuit principle,

$$Ri_a + L\frac{di_a}{dt} = e_a - V_a \quad (3)$$

$$Ri_b + L\frac{di_a}{dt} = e_b - V_b \quad (4)$$

$$Ri_c + L\frac{di_c}{dt} = e_c - V_c \quad (5)$$

$$L\frac{di_{ab}}{dt} = \frac{1}{3}L\left(\frac{d_{ia}}{dt} - \frac{d_{ib}}{dt}\right) \quad (6)$$

this equation can be expanded as below,

$$L\frac{di_{ab}}{dt} = \frac{1}{3}[(e_a - e_b) - (V_a - V_b)] - i_{ab}R \quad (7)$$

$$L\frac{di_{bc}}{dt} = \frac{1}{3}[(e_b - e_c) - (V_b - V_c)] - i_{bc}R \quad (8)$$

$$L\frac{di_{ca}}{dt} = \frac{1}{3}[(e_c - e_a) - (V_c - V_a)] - i_{ca}R \quad (9)$$

Putting equations (7),(8) and (9) together we get,

$$\frac{d}{dt}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3L}\begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} - \frac{1}{3L}\begin{bmatrix} V_a - V_b \\ V_b - V_c \\ V_c - V_a \end{bmatrix} - \frac{R}{L}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (10)$$

$$C\frac{dV_{pn}}{dt} = i_p = \begin{bmatrix} D_{ap} - D_{bp} \\ D_{bp} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix}^T \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (11)$$

It is common practical in power system application to transform 3 phase AC dynamics into orthogonal components in a rotating reference frame. Here components are referred to as the real and reactive components, those that lead to useful work and those that do not respectively.

From the power system theory we get the real and reactive currents relative to a rotating reference frame with angular frequency ω as

$$\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} = P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$P = \frac{2}{3}\begin{bmatrix} \cos(\omega t) & \cos\left(\omega t - \frac{2}{3}\pi\right) & \cos\left(\omega t + \frac{2}{3}\pi\right) \\ -\sin(\omega t) & -\sin\left(\omega t - \frac{2}{3}\pi\right) & -\sin\left(\omega t + \frac{2}{3}\pi\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{12}$$

Where id is the active current component and iq is the reactive current component

$$\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} i_a - i_b \\ i_b - i_c \\ i_c - i_a \end{bmatrix} = \frac{1}{3}\left(\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} i_b \\ i_c \\ i_a \end{bmatrix}\right) = \bar{T}^{-1}\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix}$$

$$\bar{T}^{-1} = \frac{1}{\sqrt{3}}\begin{bmatrix} -\sin\left(\omega t - \frac{1}{3}\pi\right) & \cos\left(\omega t - \frac{1}{3}\pi\right) & 1 \\ \sin(\omega t) & -\cos(\omega t) & 1 \\ -\sin\left(\omega t + \frac{1}{3}\pi\right) & \cos\left(\omega t + \frac{1}{3}\pi\right) & 1 \end{bmatrix}$$

(13)

if we set T as the first two 2×3 subspace of matrix T ,

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = T \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \tag{14}$$

$$\begin{bmatrix} e_d \\ e_q \end{bmatrix} = T \begin{bmatrix} e_{ab} \\ e_{bc} \\ e_{ca} \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} D_d \\ D_q \end{bmatrix} = T \begin{bmatrix} D_{ab} \\ D_{bc} \\ D_{ca} \end{bmatrix} \tag{16}$$

Applying equations (15) and (16) to equation (11)

$$\frac{dT^{-1}}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + T^{-1}\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \frac{1}{3L}T^{-1}\begin{bmatrix} e_d \\ e_q \end{bmatrix} - \frac{1}{3L}T^{-1}\begin{bmatrix} D_d \\ D_q \end{bmatrix}V_{pn} - \frac{R}{L}T^{-1}\begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

(17)

From power system principle,

$$e_d = V_m$$

$$e_q = 0$$

$$T\frac{dT^{-1}}{dt} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \tag{18}$$

multiply T to both side of equation (17) and applying equation (19), we obtain

$$\begin{bmatrix} \overset{\bullet}{id} \\ \overset{\bullet}{iq} \\ \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & -\frac{Dd}{3L} \\ -\omega & -\frac{R}{L} & -\frac{Dq}{3L} \\ & & \end{bmatrix}\begin{bmatrix} id \\ iq \\ Vdc \end{bmatrix} + \begin{bmatrix} \frac{1}{3L} \\ 0 \\ 0 \end{bmatrix}Vm \tag{19}$$

By applying equations (14) and (15) to equation (12) we have,

$$\frac{dVdc}{dt} = \frac{1}{C}i_p = \frac{1}{C}\begin{bmatrix} D_{ap} - D_{bp} \\ D_{bp} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix}^T \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \begin{bmatrix} D_d \\ D_q \end{bmatrix} T^{-T} T^{-1}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{3}{2C}\begin{bmatrix} D_d \\ D_q \end{bmatrix}^T \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

$$\frac{dVdc}{dt} = \frac{dVpn}{dt} = \frac{1}{C}i_p = \frac{3}{2C}\begin{bmatrix} D_d \\ D_q \end{bmatrix}^T \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

(20)

Rearranging equations (19) and (20) we get,

$$\overset{\bullet}{id} = -\frac{R}{L}id + iq\,\omega - \frac{Vdc}{3L}Dd + \frac{1}{3L}Vm \tag{21}$$

$$\overset{\bullet}{iq} = -id\,\omega - \frac{R}{L}iq - \frac{Vdc}{3L}Dq \tag{22}$$

$$\overset{\bullet}{Vdc} = \frac{3}{2C}idDd + \frac{1}{2C}iqDq \tag{23}$$

Finally we find that we can represent the "outer loop" dynamics of STATCOM, thedynamics resulting from any arbitrary switching function Dk , by representing equation (2.25) in its standard state space form

$$\begin{bmatrix} \overset{\bullet}{id} \\ \overset{\bullet}{iq} \\ \overset{\bullet}{Vdc} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & -\frac{Dd}{3L} \\ -\omega & -\frac{R}{L} & -\frac{Dq}{3L} \\ \frac{3}{2C}Dd & \frac{3}{2C}Dq & 0 \end{bmatrix}\begin{bmatrix} id \\ iq \\ Vdc \end{bmatrix} + \begin{bmatrix} \frac{1}{3L} \\ 0 \\ 0 \end{bmatrix}Vm \tag{24}$$

DOI 10.17148/IARJSET

This completes the non switching dynamic model of STATCOM.

1V. PI CONTROLLER

Proportional integral controller improves the steady state performance. Here the STATCOM voltage Vdc and reactive current component is tracked by using the PI controller.

The general transfer function of the PI controller is given as follows,

$$G(s) = kp + \frac{ki}{s} \qquad (25)$$

Where the controller parameters kp and ki is obtained by using

trial and error approach or tuning method.

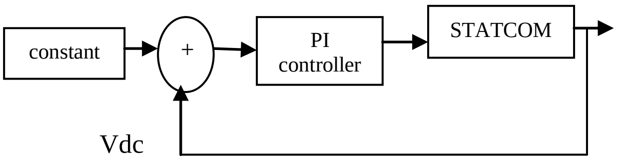

Fig 3 : Block diagram shows the control of STATCOM voltage using PI controller

Any constant value of voltage can be given and the PI controller tracks the voltage. Similarly the reactive current component iq can also be tracked using PI controller.

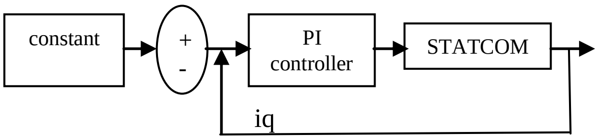

Fig 4: Block diagram shows the control of iq using PI controller.

V. SIMULATION RESULTS

The mathematical model of STATCOM is studied and to evaluate the system and its corresponding output the detailed modelling of each component in MATLAB/Simulink is done.The parameters used in the study are given in the Table1.

TABLE 1

Description	Symbol	Units	Values
Resistance of line reactor	R	Ω	0.02
Inductance of line reactor	L	mH	2.8
DC side capacitor	C	F	0.1
Active current component	id	A	0
Reactive current component	iq	A	178
DC side voltage	Vdc	Vlts	10000
Measured bus voltage	Vm	Vlts	5882

By substituting the parameters equations become,

$$\begin{bmatrix} \dot{id} \\ \dot{iq} \\ \dot{Vdc} \end{bmatrix} = \begin{bmatrix} -7.1429 & 314.2 & 0 \\ -314.2 & -7.1429 & 9.6675 \\ 0 & 9.6675 & 0 \end{bmatrix} \begin{bmatrix} id \\ iq \\ Vdc \end{bmatrix} + \begin{bmatrix} -199.05 \\ 0 \\ 0 \end{bmatrix} Vm \qquad (26)$$

From this we will obtain A matrix , B matrix and C matrix, where C is an identity matrix. The next step is to check whether the matrix is controllable and observable. For analysing the controllability and observability, it is enough to find the rank and its proven that the rank obtained is 3. Now the state space model is converted to transfer function form and obtained transfer function is as follows,

$$\frac{Iq(s)}{Vm(s)} = \frac{37410\, s}{s^3 + 14 s^2 + 98679\, s - 668}$$
$$\frac{Vdc(s)}{Vm(s)} = \frac{361620}{s^3 + 14 s^2 + 98679\, s - 668} \qquad (27)$$

For finding the stability Eigen value is obtained and it is founded that there is one non negative pole implies the system is unstable. So to make the system stable, pole placement technique is used. By analysis it is obtained that two poles lie on the left half and one pole lie on the right half. So relocate the pole lying on right half by pole placement technique which makes the system stable.

The new transfer function of the system after pole placement technique is given by

$$\frac{Iq(s)}{Vm(s)} = \frac{s^2 + 7.204\, s + 0.2152}{s^3 + 14.02 s^2 + 98708\, s + 1974}$$
$$\frac{Vdc(s)}{Vm(s)} = \frac{s + 1.8}{s^3 + 14.02 s^2 + 98708\, s + 1974}$$

Thus a stable system is obtained.

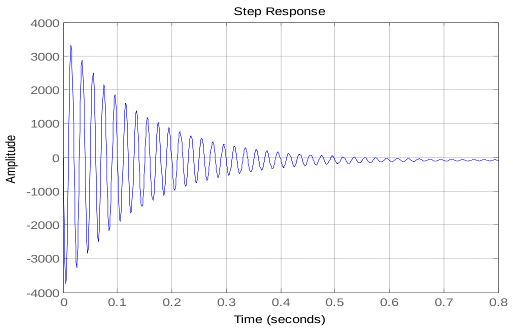

Fig.5.Simulation of reactive current component iq(unstable)

A large number of oscillation is present which shows the system is unstable. So we use pole placement technique which makes the system stable .Figure 4 shows the stable response of reactive current component

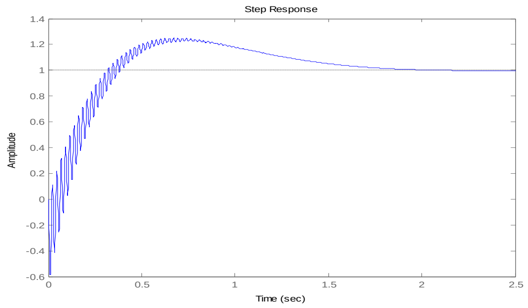

Fig.6 .Response of iq (stable)

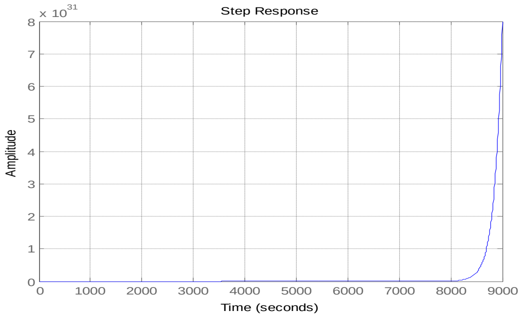

Fig 7: Response of Vdc (stable)

Here the STATCOM voltage response is unstable and to make stable pole placement technique is adopted and the response after pole placement is as follows,

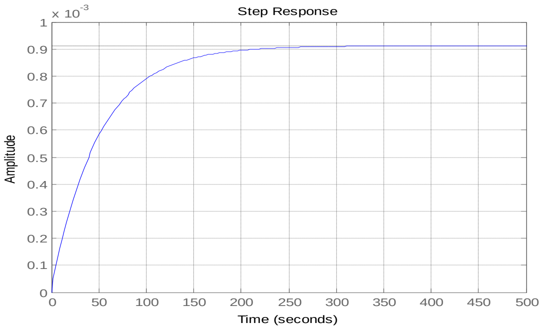

Fig.8.Response of Vdc (stable)

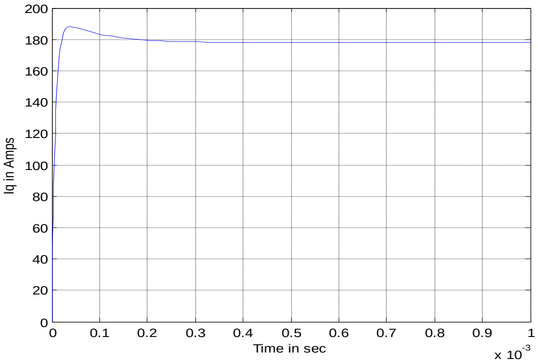

Fig 9: Tracking of iq using PI controller

Here by using the PI controller the reactive current component of 178 A is tracked and the settling time rise time as well as the overshoot is less.

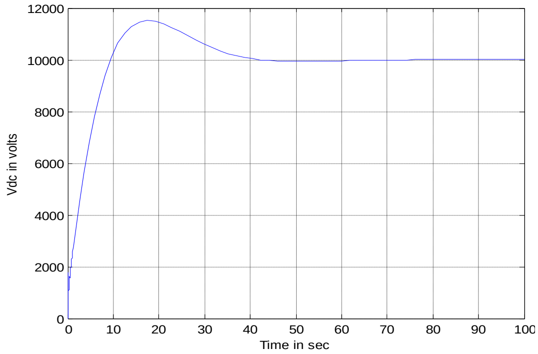

Fig 10: Tracking of Vdc using PI controller

By using PI controller the STATCOM voltage Vdc of 10000 V is tracked

VI.CONCLUSIONS

The Static Synchronous Compensator (STATCOM) is a shunt connected reactive compensation equipment which is capable of generating and/or absorbing reactive power.It provides rapid controllability of the three phase voltages, both in magnitude and phase angle .Modeling of STATCOM is done and hence controllability as well as observability is being checked and the system is controllable and observable but the system is unstable. By pole placement technique the system become stable. The STATCOM voltage Vdc and reactive current component iq is tracked using PI controller. From simulation results its clear that the rise time settling time and overshoot is less.

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