Design and Simulation of Current and Voltage Linear Controller of a STATCOM for Reactive Power Compensation using variation of DC link voltage

Sushanta Kumar Sethy*

Department of Electrical Engineering
Dhaneswar Rath Institute of Engineering and Management Studies,
Tangi, Cuttack, Orissa – 754022, India
E-mail: sushanta_sethy1975@yahoo.co.in
*Corresponding author

Pratap Chandra Pradhan

Department of Electrical Engineering
Dhaneswar Rath Institute of Engineering and Management Studies,
Tangi, Cuttack, Orissa – 754022, India
E-mail: pratap_pin@yahoo.com

Abstract: The STATCOM (STATic synchronous COMpensator) is a shunt connected voltage source converter using self-commutating device and can be effectively used for reactive power control. Its principle of operation is similar to that of a synchronous condenser. This paper describes the modeling of STATCOM along with design of linear current and voltage controllers. The design of controllers for the converters can be realized in two ways. The first method is a non-linear realization, which results in simple control rules with faster dynamics. The second method is a linear method, which requires system modeling. The second approach is adopted and simulated waveforms are presented in the paper.

Keywords: Controller design, PI Controller, STATCOM.

References to this paper should be as follow : Sethy, Sushanta Kumar., Swain, Pradhan, Pratap Chandra (2013**)** "Design and Simulation of Current and Voltage Linear Controller of a STATCOM for Reactive Power Compensation using variation of DC link voltage ", *Int. J. Intelligent Computing and Applied Sciences*, Vol. 1, Issue. 1, pp 50-64

1 Introduction

In recent years power systems have become very complex with interconnected long distance transmission lines. The interconnected grids tend to become unstable as the heavy loads vary dynamically in their magnitude and phase angle and hence power factor. Commissioning new transmission systems are extremely expensive and take considerable amount of time to build up. Therefore, in order to meet increasing power demands, utilities must rely on power export/import arrangements through the existing transmission systems. Power electronic devices are gaining popularity for applications in the field of power transmission and distribution systems. The reactive power (VAR) compensation and control have been recognized [1] as an efficient & economic means of increasing power system transmission capability and stability. The FACTS (Flexible AC Transmission Systems) devices, such as STATCOM has been introduced more recently which employs a VSI with a fixed DC link capacitor as a static replacement of the synchronous condenser. In a traditional synchronous condenser, the field current of the synchronous motor controls the amount of VAR absorbed/injected and hence in a similar way, the firing instant of the 3-phase inverter controls the VAR flow into or out of the STATCOM. Large numbers of capacitor banks or inductor banks are no more required. Only a fixed set of capacitor provides the required VAR control, with a rapid control of bus voltage and improvement of utility power factor. It offers several advantages over conventional thyristorised converters [2] in terms of speed of response. The penalty paid for this improvement is in terms of introduction of some harmonics, which requires separate handling using active filtration techniques. Moran et al [3] have shown in details how the utilization of Sinusoidal Pulse Width Modulation (SPWM) techniques reduces harmonic distortion. It has also been shown that an increase of modulation index reduces the size of the link reactor and stress on switches which are significant issues in practical implementation. The modeling and analysis of STATCOM steady state and dynamic performance with conventional control method have been studied by Schauder and Mehta [4] using non-linear controller. In [6] the dynamic responses and steady state behavior of STATCOM with Space Vector Pulse Width Modulation (SVPWM) has been studied and the advantages of introducing SVPWM inverter with higher values of modulation index are highlighted.

The controllable reactive power allows for a rapid control of bus voltage and power factor at the system or at the load end. To compensate for the distorted current drawn by the rectifiers from the utility grid, the STATCOM and its current controller must have the capability to track source PWM (Pulse Width Modulation) converters. The linear control is more suitable for STATCOM application reported in [7-8]. The present paper suggests the design of a linear current controller and voltage controller on the basis of gain and time constant adjustment along with the parameter of the coupling inductor and storage capacitor.

The present paper goes on to develop closed loop model for investigating transient performance of the STATCOM by using controller parameter. First, in Section 2 focuses on state space model of the STATCOM with the system. Secondly, in Section 3, a current and voltage controllers are designed. The simulated responses with the designed controller parameters are presented. This scheme is both an extension and a significant improvement of the scheme suggested by Shauder et al [4] and Sensarma et al [9].The results obtained have been compared and appropriate conclusions have been drawn.

Modeling of The Statcom And Analysis

2.1 Operating principle

As is well known, the STATCOM is, in principle, a static (power electronic) replacement of the age-old synchronous condenser. Fig.1 shows the schematic diagram of the STATCOM at PCC through coupling inductors. The fundamental phasor diagram of the STATCOM terminal voltage with the voltage at PCC for an inductive load in operation, neglecting the harmonic content in the STATCOM terminal voltage, is shown in Fig.2. Ideally, increasing the amplitude of the STATCOM terminal voltage $\vec{V}_{oa}$ above the amplitude of the utility voltage $\vec{V}_{sa}$ causes leading (capacitive) current $\vec{I}_{ca}$ to be injected into the system at PCC as shown in Fig.2.

2.2 Modeling

The modeling of the STATCOM, though well known, is reviewed in the lines below, for the sake of convenience. The modeling is carried out with the following assumptions:

1) All switches are ideal
2) The source voltages are balanced
3) R_s represents the converter losses and the losses of the coupling inductor

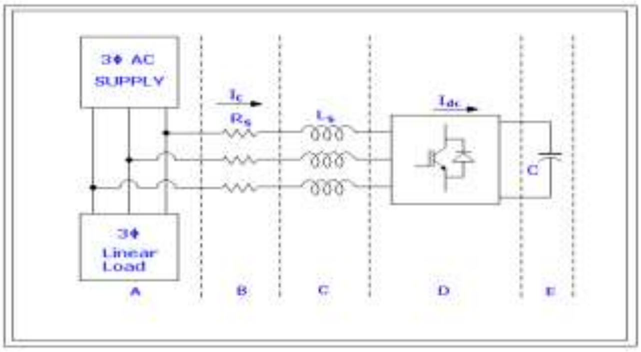

Fig.1: Schematic diagram of STATCOM

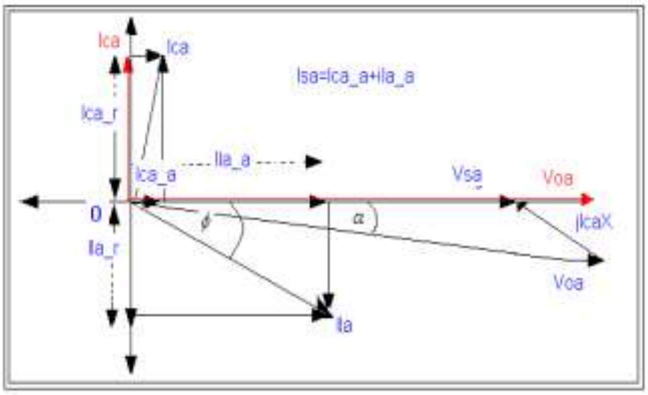

Fig.2: Phasor diagram for inductive load operation

4) The harmonic contents caused by switching action are negligible

The 3-phase stationary abc coordinate vectors with 120^0 apart from each other are converted into $\alpha\beta$ 2-phase stationary coordinates (which are in quadrature). The α axis is aligned with a axis and leading β axis and both converted into dq two-phase rotating coordinates. The Park's abc to dq transformation matrix is

$$K = \sqrt{\frac{2}{3}}\begin{bmatrix} Cos(\varpi t) & Cos(\varpi t - 2\pi/3) & Cos(\varpi t + 2\pi/3) \\ Sin(\varpi t) & Sin(\varpi t - 2\pi/3) & Sin(\varpi t + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{1}$$

The actual proposed circuit is too complex to analyze as a whole, so that it is partitioned into several basic sub-circuits, as shown in Fig.1. The 3-phase system voltage $v_{s,abc}$ lagging with the phase angle α to the STATCOM output voltage $v_{o,abc}$ and differential form of the STATCOM currents are defined in (2) and (3).

$$v_{s,abc} = \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} V_S \begin{bmatrix} Sin(\omega t - \alpha) \\ Sin(\omega t - \alpha - \frac{2\pi}{3}) \\ Sin(\omega t - \alpha + \frac{2\pi}{3} \end{bmatrix} \tag{2}$$

$$L_S \frac{d}{dt}\left(i_{c,abc}\right) = -R_S i_{c,abc} + v_{s,abc} - v_{o,.abc} \tag{3}$$

where , V_s, ϖ, R_s and L_s have their usual connotations. The above voltages and currents are transformed into dq frame

$$L_s \frac{d}{dt}\left(i_{cq}\right) = -R_s i_{cq} - wL_s i_{cd} + v_{sq} - v_{oq} \tag{4a}$$

$$L_s \frac{d}{dt}\left(i_{cd}\right) = wL_s i_{cq} - R_s i_{cd} + v_{sd} - v_{od} \tag{4b}$$

The switching function *S* of the STATCOM can be defined as follows

$$S = \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \sqrt{\frac{2}{3}} m \begin{bmatrix} Sin(wt) \\ Sin(wt - \frac{2\pi}{3}) \\ Sin(wt + \frac{2\pi}{3}) \end{bmatrix} \tag{5}$$

The modulation index, being constant for a programmed PWM, is given by,

$$MI = \frac{v_{o,peak}}{V_{dc}} = \sqrt{\frac{2}{3}} m \tag{6}$$

The STATCOM output voltages in dq transformation are

$$v_{o,qdo} = m\begin{bmatrix}0 & 1 & 0\end{bmatrix}^T v_{dc} \tag{7}$$

The dc side current in the capacitor in dq transformation

$$i_{dc} = m\begin{bmatrix}0 & 1 & 0\end{bmatrix}\begin{bmatrix}i_{cq} & i_{cd} & i_{co}\end{bmatrix}^T \tag{8}$$

The voltage and current related in the dc side is given by

$$\frac{dv_{dc}}{dt} = \frac{m}{C} i_{cd} \tag{9}$$

The complete mathematical model of the STATCOM in dq frame is obtained as given in (10)

$$\frac{d}{dt}\begin{bmatrix}i_{cq}\\ i_{cd}\\ v_{dc}\end{bmatrix} = \begin{bmatrix}-\frac{R_s}{L_s} & -w & 0\\ w & -\frac{R_s}{L_s} & -\frac{m}{L_s}\\ 0 & \frac{m}{C} & 0\end{bmatrix}\begin{bmatrix}i_{cq}\\ i_{cd}\\ v_{dc}\end{bmatrix} + \frac{V_s}{L_s}\begin{bmatrix}-Sin\alpha\\ Cos\alpha\\ 0\end{bmatrix} \tag{10}$$

2.3. *Steady State and transient Analysis*

The detailed steady state and transient responses with the Table.1 are given in Fig.3-6 and responses suggest the static and dynamic conditions of the STATCOM. It can be seen that the transient responses take about one and half power cycle to reach at their steady state values.

Table.1

Sl	Parameters	Symbol	Values
1	Frequency	f	50 Hz
2	Angular Frequency	W	314 rad/sec
3	RMS line-to-line Voltage	V_s	230V
4	Coupling Resistance	R_s	1.0 Ω
5	Coupling Inductance	L_s	5.0mH
6	DClink capacitor	C	500 μF
7	Modulation Index	M	0.979
8	Phase angle	α	$\mp 5^0$
9	Load Resistance	R_L	52Ω
10	Load Inductance	L_L	126mH
11	Load Power factor	ϕ	0.79

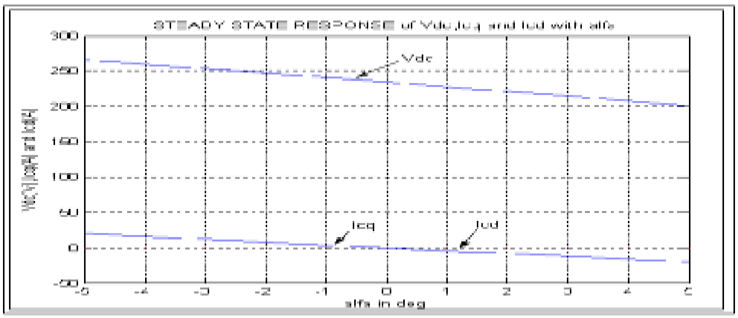

Fig.3: Steady state responses of I_{cq} , I_{cd} and V_{dc}

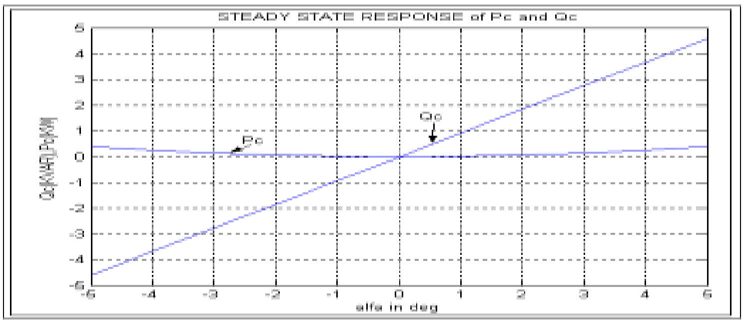

Fig.4: Steady state responses of P_c and Q_c

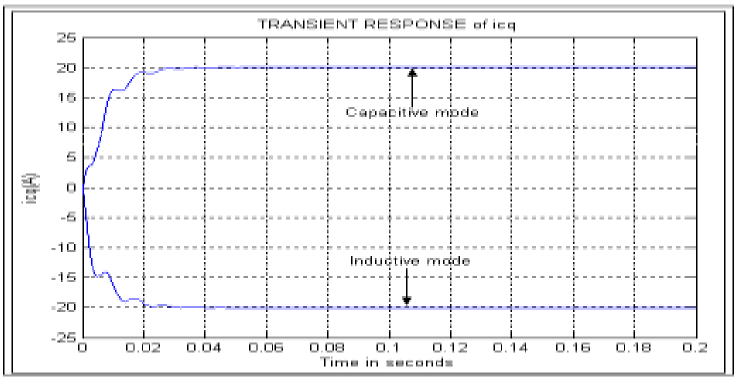

Fig.5: Transient responses of i_{cq} in capacitive and inductive

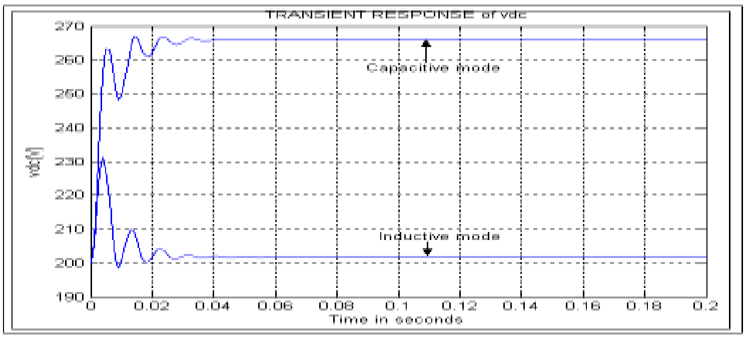

Fig.6: Transient responses of v_{dc} in capacitive and inductive

3. Design Of Controllers For Statcom

With the assumption of the system voltage and STATCOM output voltage are in phase and hence the equation (10) can be modified as given in equation (11)

$$\frac{d}{dt}\begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_S} & -\omega \\ \omega & -\frac{R_S}{L_S} \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} + \frac{1}{L_S}\left[\begin{bmatrix} v_{sq} \\ v_{sd} \end{bmatrix} - \begin{bmatrix} v_{oq} \\ v_{od} \end{bmatrix}\right] \tag{11}$$

So the equation (11) is a Multiple Input and Multiple Output (MIMO) system and its input and output are given in equation (12)

$$[u] = \begin{bmatrix} v_{oq} \\ v_{od} \end{bmatrix}, [y] = \begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} \tag{12}$$

The block diagram of the STATCOM in d-q transformation as per (11) is shown in Fig.7.The instantaneous voltage of the system and the STATCOM are independent, but the active and the reactive currents are coupled with each other through the reactance of the coupled inductor. So it is very essential to decouple the active and reactive current from each other and design the controller for tracking the required value.

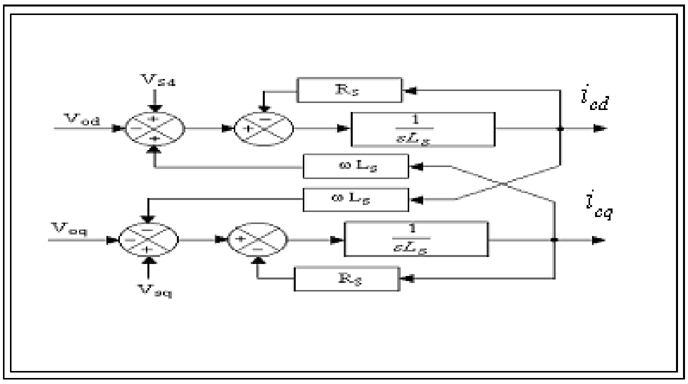

Fig.7: Equivalent Diagram on a.c.side of STATCOM

3.1. *Design of current controller.*

The current controller design for the above system can be done using the strategy [8-9] attempts to decouple the d and q axes equations, so that the MIMO system reduces to two independent Single Input Single Output (SISO) system. Hence, the control inputs v_{od} and v_{oq} are configured as

$$\begin{aligned} v_{oq} &= -v_{oq}^{*} - wL_S i_{cq} + v_{sq} \\ v_{od} &= -v_{od}^{*} + wL_S i_{cd} + v_{sd} \end{aligned} \tag{13}$$

The equation (14) can be obtained by replacing (11) by (13). Hence each row of (14) is independent of each other and thus defines an independent SISO system. Conventional frequency-domain design methods can now be directly applied for current controller. Taking the Laplace transformation of both sides of (14) and rearranging terms are given by (15) and their decoupled SISO system is shown in Fig.8.

$$\begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} = \begin{bmatrix} -\dfrac{R_S}{L_S} & 0 \\ 0 & -\dfrac{R_S}{L_S} \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} + \frac{1}{L_S} \begin{bmatrix} v^*_{oq} \\ v^*_{od} \end{bmatrix} \tag{14}$$

$$G_q(s) = \frac{I_q(s)}{V^*_{oq}(s)} = \frac{1}{R_S + sL_S}, G_d(s) = \frac{I_d(s)}{V^*_{od}(s)} = \frac{1}{R_S + sL_S} \tag{15}$$

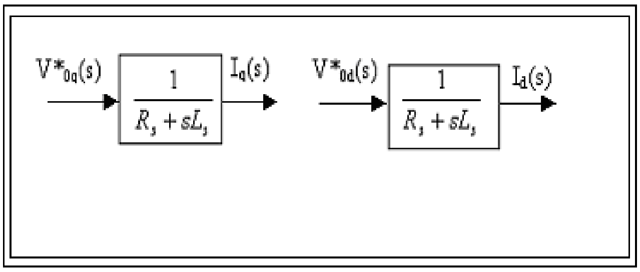

Fig.8: Current control of inverter of equivalent decoupled SISO systems

For similar dynamic behaviour of the d and q - axis currents, both the d and q - axis controllers are identical and its transfer function is given in (16)

$$G_i(s) = \frac{I_{cq}(s)}{V^*_{oq}(s)} = \frac{I_{cd}(s)}{V^*_{od}(s)} = \frac{1}{R_S + sL_S} \tag{16}$$

The transfer function of a PI controller is

$$G_{pi}(s) = K\left(1 + \frac{1}{s\tau_i}\right) = K_p + \frac{K_i}{s} \tag{17}$$

With $K_p = K, K_i = \dfrac{K}{\tau_i}$. The transfer function in open loop of PI controller associated with the transfer function on the a.c. system is

$$\left[G_{pi}(s).G_i(s)\right] = K\left[1 + \frac{1}{s\tau_i}\right]\left[\frac{1/R_S}{1 + s\,L_S/R_S}\right] \tag{18}$$

While taking $\tau_i = \dfrac{L_S}{R_S}$ and on simplification reduces to

$$\left[G_{pi}(s).G_i(s)\right] = \frac{K}{sL_S} \tag{19}$$

The closed loop transfer function is

$$T = \frac{1}{1 + s\frac{L_S}{K}} \tag{20}$$

Thus the system behaves like a first order with an apparent time constant as

$$\tau_i = \frac{L_s}{K} \tag{21}$$

The gain of K can be adjusted such a way that if it is increased too high then the system behaves as second order, otherwise responses very slow. Hence the numerical values for K_p and K_i are decided from the circuit parameters L_S and R_S from the required value of K. So the parameters of PI controller are defined as

$$K_p = K, K_i = \frac{KR_S}{L_S} \tag{22}$$

where, $\tau_i = \frac{L_s}{K_p}$ which is taken as 0.3mseconds and with the parameters given in Table-1, value of $K_{pi} = 16.9$ and $K_{ii} = 3.3 \times 10^3$ are calculated. These parameters are used in d and q - axis current controller. The structure of the effective closed loop system is shown in Fig.9 and is replicated in both the d and q - axis current controllers. Bode plot of the system with controller is shown in Fig.10, which is a first order system.

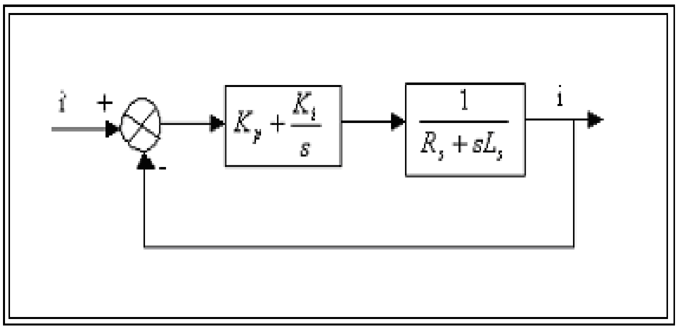

Fig.9: Effective closed loop current control system

3.2. DESIGN OF VOLTAGE CONTROLLER

The relation between dc voltage v_{dc} and dc current i_{dc} is

$$v_{dc} = \frac{1}{C}\int i_{dc}\,dt \tag{23}$$

The transfer function can be written as

$$G_V(s) = \frac{V_{dc}}{I_{dc}} = \frac{1}{sC}$$

(24)

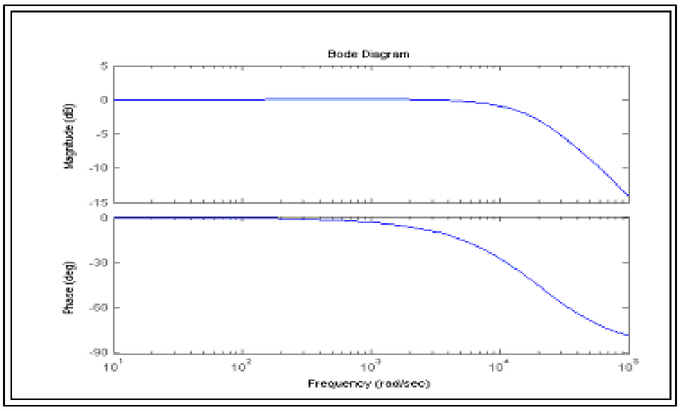

Fig.10: Bode plot of the system with PI controller

Neglecting the power loss in the source resistance and power losses in the switches, balancing the power on both sides,

$$v_{sd} i_{cd} = v_{dc} i_{dc} \tag{25}$$

From the above equation, we have

$$\frac{i_{dc}}{i_{cd}} = \frac{v_{sd}}{v_{dc}} = \frac{V_s}{V_{dc}} = \frac{230}{500} = 0.46 \tag{26}$$

The DC bus voltage is maintained at 400 volts.

With V_{dc} as the reference, the voltage control loop is shown in Fig.12 and it consists of inner d - axis current control loop. The active power is supplied by the d -axis current which is nothing but the ripple current of the capacitor. To make the steady state error of the voltage loop zero Proportional control is adopted here and it produces the reference d -axis current for the control of the d -axis current. The design of voltage controller is as follows:

The open loop transfer function of DC bus voltage controller is

$$G_{op} = \frac{K * K_{dc}}{sC} \tag{27}$$

The closed loop transfer function with unity feed back gain is

$$G_{cl} = \frac{1}{1 + \frac{sC}{K * K_{dc}}} \tag{28}$$

where , $\tau_v = \frac{C}{K * K_{dc}}$ and taking $\tau_v = 1$msecond and with the parameters of Table. I, the value of

$K_{dc} = 1.08$

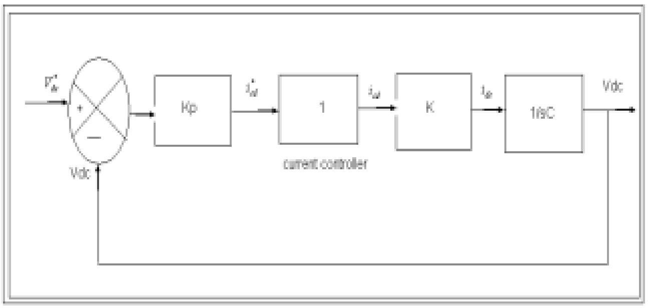

Fig.12: DC link voltage control loop

Then Proportional Integral controller is considering for the voltage control. Hence, the transfer function of PI controller in (18) is associated with the transfer function on dc side is

$$\left[G_v(s).G_{pi}(s)\right]_{ol} = K\left(1+\frac{1}{s\tau_v}\right)\left(\frac{1}{sC}\right) \tag{29}$$

After taking $\tau_v = C$ and on simplification

$$\left[G_v(s).G_{pi}(s)\right]_{ol} = K\left(\frac{1+s\tau_v}{s^2\tau_v^2}\right) \tag{30}$$

The transfer function in closed loop

$$\left[G_v(s).G_{pi}(s)\right]_{cl} = \left(\frac{1+s\tau_v}{1+s\tau_v+\dfrac{s^2\tau_v^2}{K}}\right) \tag{31}$$

So the system behaves like a second order system. As $\tau_v >> \frac{\tau_v^2}{K}$ and magnitude plot in Fig.10 shows the initial slop at break point is approximately –20db/decade and hence it reduces to first order system. The value of K can be determined form root locus with approximate settling time as

$$K_{pv} = K = 0.15, K_{vi} = \frac{K}{C} = 200 \tag{32}$$

As per the value of i_{cq} obtained in steady state and transient, the authors are interested to control the reactive current as per the load. The simulations of the reference reactive current of 15A and reference DC_link voltage of 500V are shown in Fig.13 and 14. These Figs show that the output current and voltage are Properly follow the reference values.

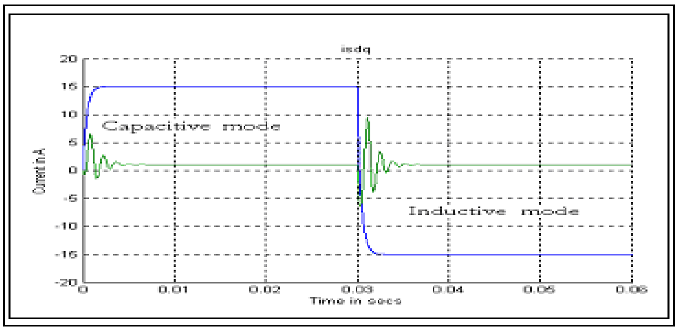

Fig.13: Current control with reference

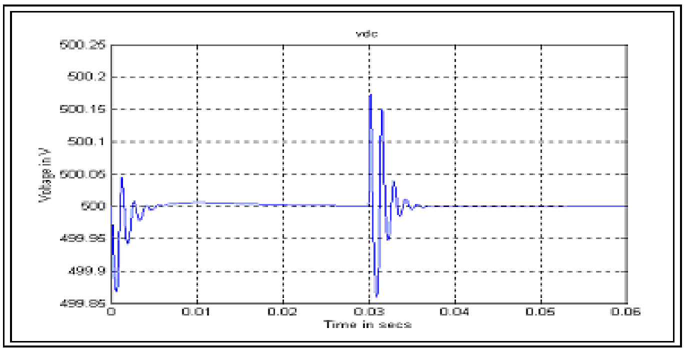

Fig.14: Voltage Control with reference

4. Simulations Using Above Controllers

The control scheme for controlling DC link voltage as well as d and q axes current of STATCOM simultaneously as shown in Fig.15 is implemented with MATLAB SIMULINK with the parameters given in Table. I. The PI controller is applied at DC link voltage and reference current for controlling q axis current of STATCOM is generated from the q axis of the linear load currents. The generated reference output voltages of d and q -axes are transformed to α and β axis and then abc axes. All the relevant outputs are shown in Fig.16 to Fig.19. The significance of the Fig.17 is the improvement of power factor to unity from 0.79 as per Fig.16 after one power cycle with a under shoot of 30A of the system current before coming to unity power factor.Fig.18 shows the dynamics of STATCOM current with the same under shoot of the system current. Fig.19 shows that the maximum overshoot of DC link voltage is to 640 volts and remains constant at 400 volts after one power cycle. The control strategy has been proposed on the basis of unity modulation index and zero phase angle. The unity modulation index and the phase angle of STATCOM are shown in Fig. 20 of plot I and plot II respectively.

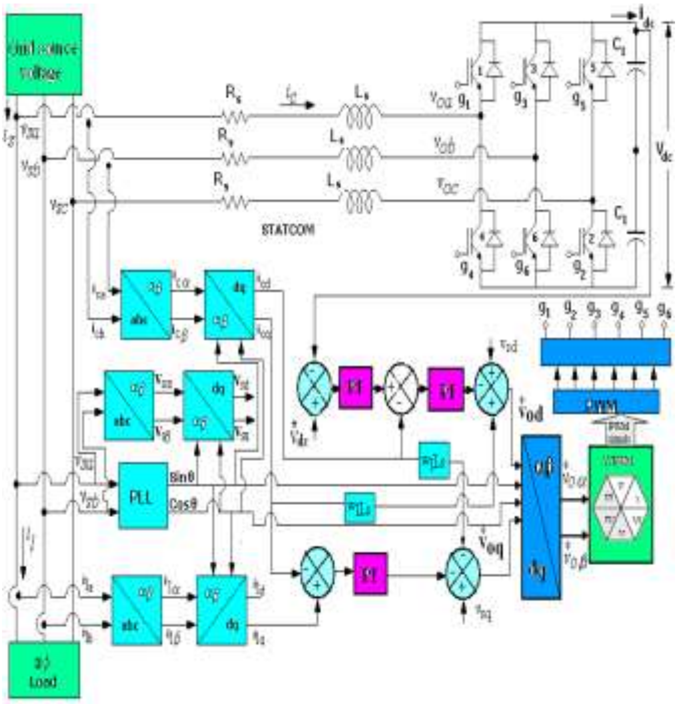

Fig.15: Implementing scheme of STATCOM

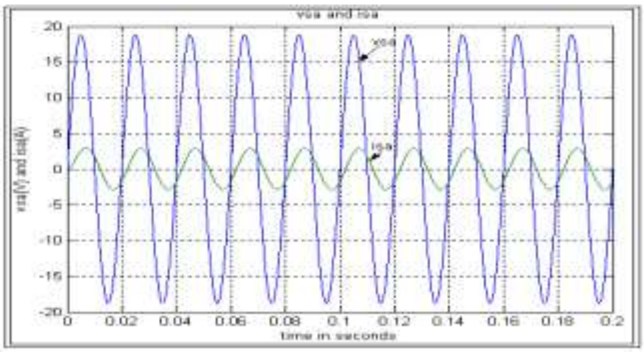

Fig.16: System voltage and current before compensation

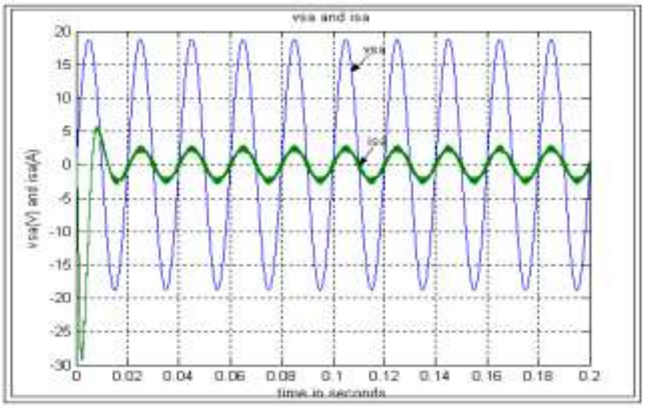

Fig.17: System voltage and current after compensation

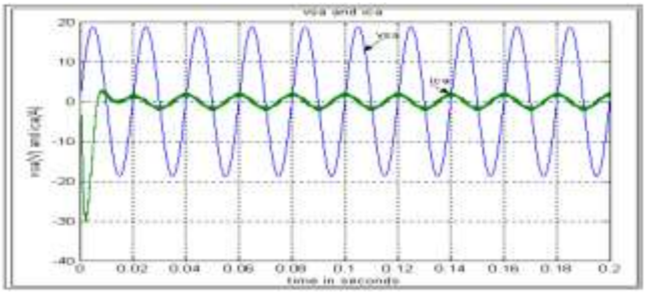

Fig.18: System voltage and STATCOM current

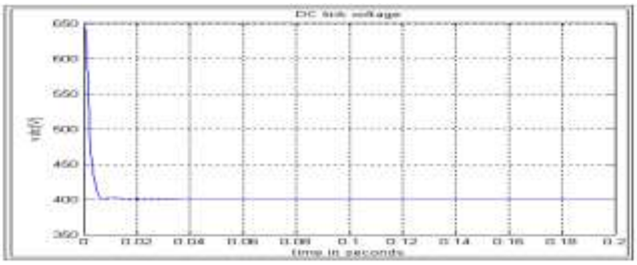

Fig.19: DC link voltage

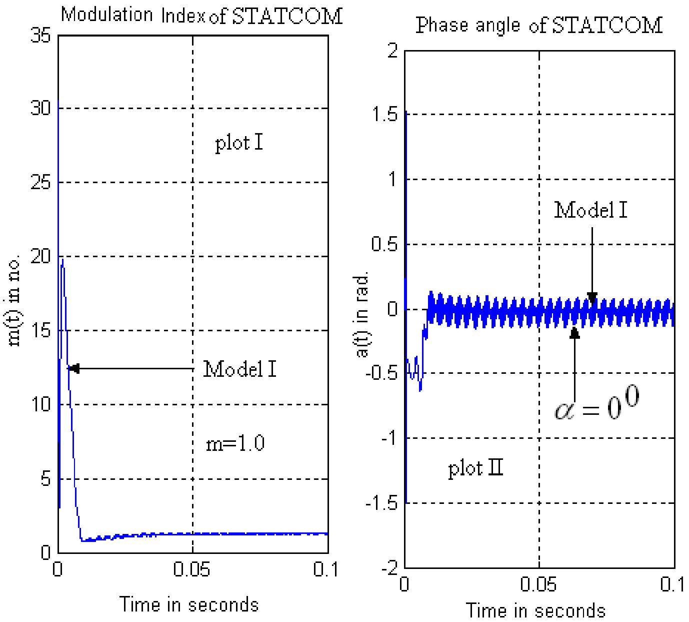

Fig.20: Modulation index and phase angle

5. Conclusion

The complete analysis and models of reactive current and voltage controllers of the STATCOM application are presented. The controllers are designed on the basis of parameters of the STATCOM and time constant. The simulated figures are given which have been controlled the desired values. The settling time of the system by using the PI controller is faster than other controllers. In this paper, the proposed scheme is easier to implement compared to [4] and [9].However, in practice the issue of the charging the DC link voltage to the required value is quite significant. In most cases, there is a separate charging circuit for the DC link voltage. The authors are working on a plausible method of eliminating such an extra starting arrangement, so that the controller may become operational while the DC link voltage is at a low value.

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Biographical Notes :Sushanta Kumar Sethy is presently working as Associate Professor and Head in the department of Electrical Engg., DRIEMS, Tangi, Cuttack. He has 14 years of teaching experience. He completed his B. Tech. in Electrical Engineering from College of Engineering and Technology and obtained his M.Tech degree from Bengal Engineering and Science University, Shibpur He has published many research papers in national and international journals. His areas of interest include application of Power electronics to power System. He has authored two books to his credit.

Pratap Chandra Pradhan is presently working as Assistant Professor in the department of Electrical Engg., DRIEMS, Tangi, Cuttack. He has 11 years of teaching experience and continuing his Ph.D in Sambalpur University. He received his M.E from VJTI university of Mumbai in power System Engineering. His area of interest includes power quality improvement, Automatic generation control.