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Design, Analysis and Simulation of Linear Model of a STATCOM for Reactive Power Compensation with Variation of DC-link Voltage

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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 linear modeling of STATCOM along with design of current and voltage controllers. The designed controllers with variation of DC-link voltage have been applied to the STATCOM and suitable DC-link voltage has been selected on basis of spike and over shoot of the responses. The values of the passive parameters decided on basis of selected DC-link voltage are used for the design and fabrication of a STATCOM. All responses are obtained through MATLAB SIMULINK tool box and presented here for clarity of the control strategy.

***Index Terms*-: Linear model, Controller design, PI Controller, STATCOM**

I. INTRODUCTION

Now-a-days power systems have become very complex with interconnected long distance transmission lines [1]-[3]. The interconnected Grids become unstable as the heavy loads vary dynamically in their magnitude and phase angle and hence power factor [4]-[6]. Therefore, in order to meet increasing power demands, utilities must rely on power export/import arrangements through the existing transmission systems. The capacitor banks are used to improve power factor but having a number of disadvantages [7].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 [8]-[11] 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. 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 [12] 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 [13] 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 [14] using non-linear controller. In [16] 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 [17],[18]-[21]. 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. These controllers are used in STATCOM and control the reactive power for improvement of power factor on variation of DC link voltage. DC link voltage is very important factor for operating STATCOM to fulfill the objective.

The present paper goes on to develop a linear 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 on variation of DC link voltage are presented in Section 4. This model is both an extension and a significant improvement of the scheme suggested by Shauder et al [14] and Sensarma et al [19].The results obtained have been compared and appropriate conclusions have been drawn.

II. MODELING AND ANALYSIS

A. Operating Principles

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

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Volume 2, Issue 5, November 2012

leading (capacitive) current $\vec{I}_{ca}$ to be injected into the system at PCC as shown in Fig.2.

B. 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
4) The harmonic contents caused by switching action are negligible.

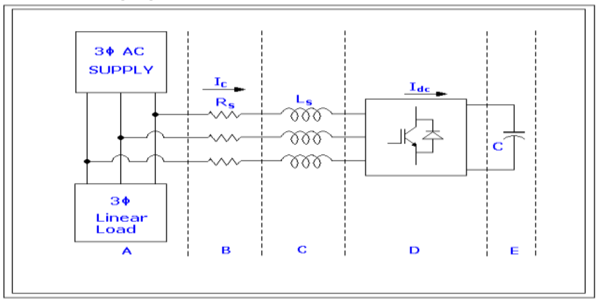

Fig.1: Schematic Diagram of STATCOM

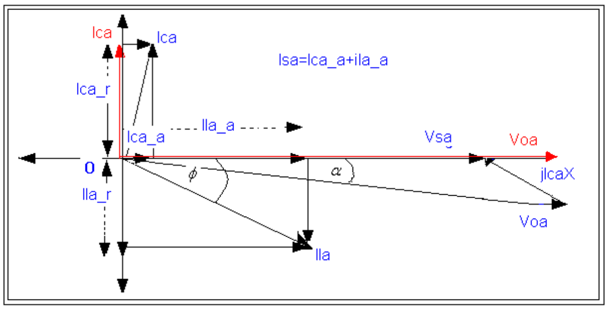

Fig.2: Phasor Diagram for Inductive Load Operation

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 used here. 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 (1) and (2).

$$v_{s,abc} = \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} V_S \begin{bmatrix} Sin(\omega t - \alpha) \\ Sin(\omega t - \alpha - \frac{2\pi}{3}) \\ Sin(\omega t - \alpha + \frac{2\pi}{3}) \end{bmatrix} \quad (1)$$

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

(2)

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

$$L_s \frac{d}{dt}\left(i_{cq}\right) = -R_s i_{cq} - wL_s i_{cd} + v_{sq} - v_{oq} \quad (3a)$$

$$L_s \frac{d}{dt}\left(i_{cd}\right) = wL_s i_{cq} - R_s i_{cd} + v_{sd} - v_{od} \quad (3b)$$

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

$$S = \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \sqrt{\frac{2}{3}} m \begin{bmatrix} Sin(\omega t) \\ Sin(\omega t - \frac{2\pi}{3}) \\ Sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (4)$$

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

$$MI = \frac{v_{o,peak}}{V_{dc}} = \sqrt{\frac{2}{3}} m \quad (5)$$

The STATCOM output voltages in dq transformation are

$$v_{o,qdo} = m[0 \quad 1 \quad 0]^T v_{dc} \quad (6)$$

The dc side current in the capacitor in dq transformation

$$i_{dc} = m[0 \quad 1 \quad 0]\begin{bmatrix} i_{cq} & i_{cd} & i_{co} \end{bmatrix}^T \quad (7)$$

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

$$\frac{dv_{dc}}{dt} = \frac{m}{C} i_{cd} \quad (8)$$

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

$$\frac{d}{dt}\begin{bmatrix} i_{cq} \\ i_{cd} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -w & 0 \\ w & -\frac{R_s}{L_s} & -\frac{m}{L_s} \\ 0 & \frac{m}{C} & 0 \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \\ v_{dc} \end{bmatrix} + \frac{V_s}{L_s}\begin{bmatrix} -Sin\alpha \\ Cos\alpha \\ 0 \end{bmatrix} \quad (9)$$

C. Steady State and Transient Analysis

The detailed steady state and transient responses with the Table.1 are given in Fig.3-4 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	415V
4	Coupling Resistance	R_s	1.0 Ω
5	Coupling Inductance	L_s	5.0mH

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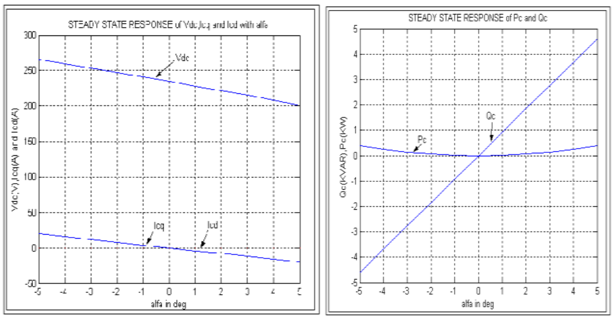
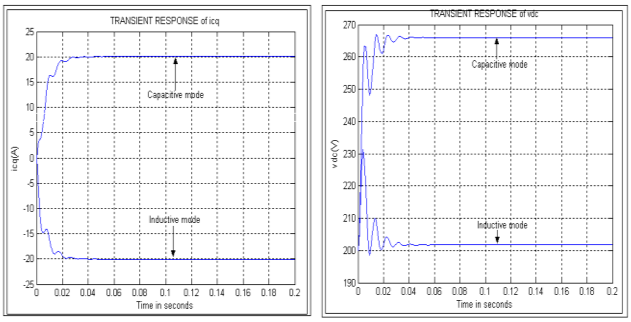
Volume 2, Issue 5, November 2012

6	DC-link 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



(a) (b)

Fig.3: Steady state responses: (a) I_{cq}, I_{cd}, V_{dc} and (b) P_c and Q_c



(a) (b)

Fig.4: Transient responses in capacitive and inductive mode: (a) i_{cq} and (b) v_{dc}

III. DESIGN OF CONTROLLERS

With the assumption of the system voltage and STATCOM output voltage are in phase and hence the equation (3) can be modified as given in equation (10)

$$\frac{d}{dt}\begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -\omega \\ \omega & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} + \frac{1}{L_s}\left[\begin{bmatrix} v_{sq} \\ v_{sd} \end{bmatrix} - \begin{bmatrix} v_{oq} \\ v_{od} \end{bmatrix}\right] \tag{10}$$

So the equation (10) is a Multiple Input and Multiple Output (MIMO) system and its input and output are given in equation (11)

$$[u] = \begin{bmatrix} v_{oq} \\ v_{od} \end{bmatrix}, [y] = \begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} \tag{11}$$

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 (10). So it is very essential to decouple the active and reactive current from each other and design the controller for tracking the required value.

A. Design of Current Controller

The current controller design for the above system can be done using the strategy [18]-[21] 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

$$\begin{aligned} v_{oq} &= -v_{oq}^{*} - wL_s i_{cq} + v_{sq} \\ v_{od} &= -v_{od}^{*} + wL_s i_{cd} + v_{sd} \end{aligned} \tag{12}$$

The equation (13) can be obtained by replacing (10) by (12). Hence each row of (13) 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 (14).

$$\begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & 0 \\ 0 & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} v_{oq}^{*} \\ v_{od}^{*} \end{bmatrix} \tag{13}$$

$$G_i(s) = \frac{I_{cq}(s)}{V_{oq}^{*}(s)} = \frac{I_{cd}(s)}{V_{od}^{*}(s)} = \frac{1}{R_s + sL_s} \tag{14}$$

The transfer function of a PI controller is

$$G_{pi}(s) = K\left(1 + \frac{1}{s\tau_i}\right) = K_p + \frac{K_i}{s} \tag{15}$$

With $K_p = K, K_i = \frac{K}{\tau_i}$. While taking $\tau_i = \frac{L_s}{R_s}$ which is taken as 0.3mseconds on closed loop transfer function, 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 given in Table.1. So the parameters of PI controller are defined as

$$K_{pi} = 16.9 \text{ and } K_{ii} = 3.3\times10^3 \tag{16}$$

These parameters are used in d and q - axis current controller.

B. Design of Voltage Controller

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

$$v_{dc} = \frac{1}{C}\int i_{dc}\,dt \tag{17}$$

The transfer function can be written as

$$G_v(s) = \frac{V_{dc}}{I_{dc}} = \frac{1}{sC} \tag{18}$$

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International Journal of Engineering and Innovative Technology (IJEIT)
Volume 2, Issue 5, November 2012

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

$$v_{sd} i_{cd} = v_{dc} i_{dc} \quad (19)$$

From the above equation, we have

$$\frac{i_{dc}}{i_{cd}} = \frac{v_{sd}}{v_{dc}} = \frac{V_s}{V_{dc}} = \frac{230}{500} = 0.46 \quad (20)$$

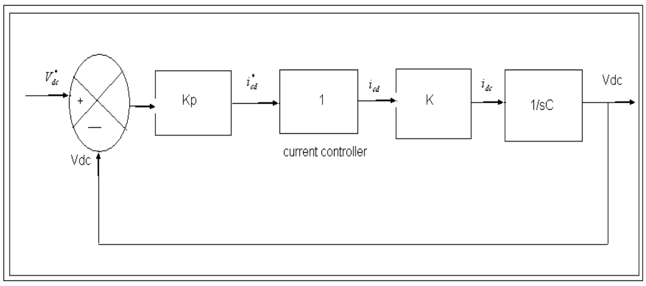

Fig.5: DC-link voltage control loop

The DC bus voltage is maintained at 400 volts. With V_{dc} as the reference, the voltage control loop is shown in Fig.5 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: Then Proportional Integral controller is considering for the voltage control. Hence, the transfer function of PI controller in (25) is associated with the transfer function on dc side is

$$\left[G_v(s).G_{pi}(s)\right]_{ol} = K\left(1+\frac{1}{s\tau_v}\right)\left(\frac{1}{sC}\right) \quad (21)$$

After taking $\tau_v = C$ and on simplification, 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

$$K_{pv} = K = 0.15, K_{vi} = \frac{K}{C} = 200 \quad (22)$$

IV. SIMULATIONS RESULTS

The control scheme for controlling DC link voltage as well as d and q axes current of STATCOM simultaneously as shown in Fig.6 is implemented with MATLAB SIMULINK with the parameters given in Table. I.

A. Simulation of Linear Load

The grid phase a voltage and current with linear load is shown in Fig.7. This Fig.7 depicts the lagging power factor of 0.7. The proposed control strategy will help for improving the power factor from 0.7 to nearly unit and this logic will also derive the conclusion for using DC link voltage.

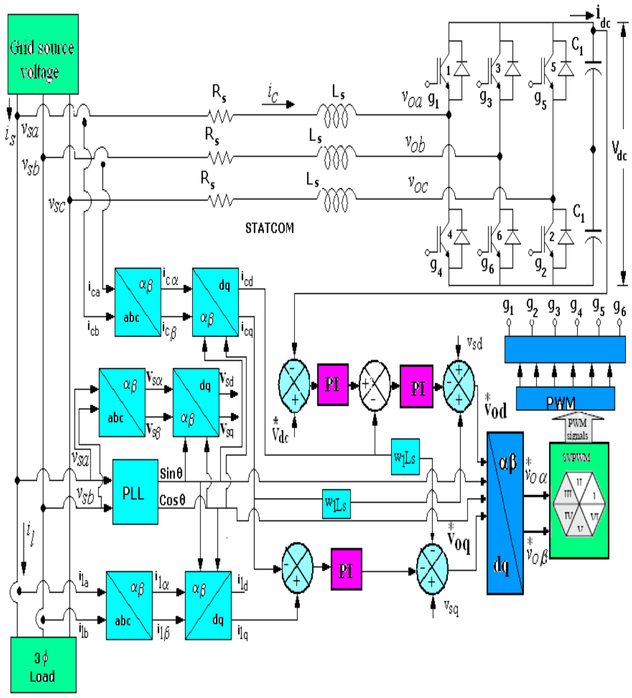

Fig.6: Implementing Scheme of STATCOM

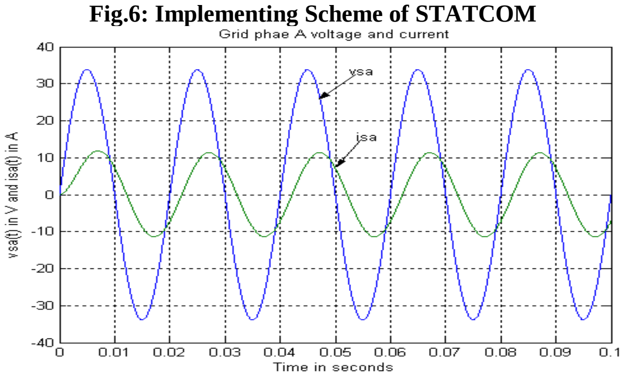

Fig.8: Grid Phase a Voltage and Phase a Load Current

B. Dc Link Capacitor Charged To 100v

These controllers work and STATCOM functions at initial value of DC link voltage of 100V with larger current peak as shown in Fig.9.

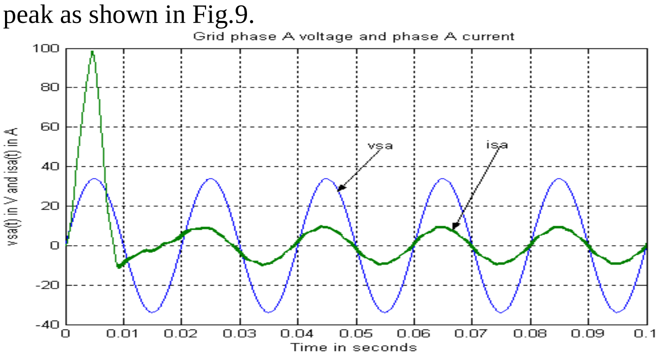

Fig.9: Grid Phase a Voltage and Phase a Current

C. DC link capacitor charged to 550V

At initial value of DC link voltage of 550V, the STATCOM operates well and the relevant outputs are shown in Fig.10 to Fig.18 .Fig.10 shows the dynamics of grid phase A voltage and phase A current and it shows the over shoot of only $8A$ and the same dynamics is obtained in case of STATCOM phase A current with a over shoot of

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International Journal of Engineering and Innovative Technology (IJEIT)
Volume 2, Issue 5, November 2012

$1A$ as shown in Fig.11. Fig.12 shows the dynamics of active and reactive components of the STATCOM current. The dynamics of active and reactive power of STATCOM is shown in Fig.13.DC link voltage with over shoot of $640V$ and settles at two power cycles as shown in Fig.14. The zero phase angle and unity modulation index are shown in Fig.15. The grid phase A voltage and the STATCOM phase A output voltage are shown in Fig.16 and both are in-phase as it signifies for linear model and no spike. Fig.17 and Fig.18 show the change of STATCOM phase A current and DC link bus voltage due to change of reference current (reactive current of load).

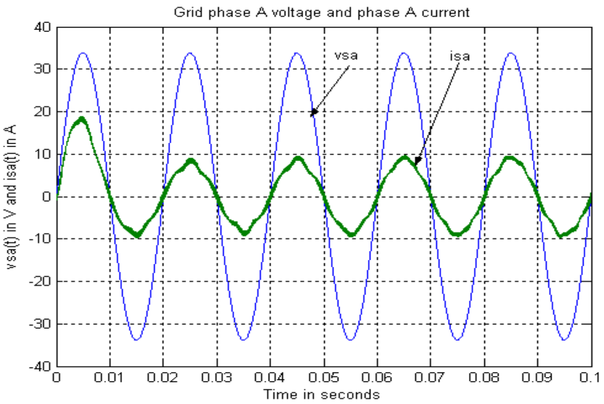

Fig.10: Grid Phase a Voltage and Phase a Current

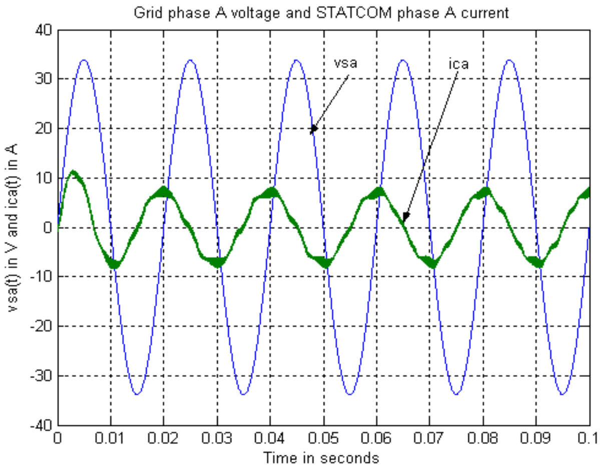

Fig.11: Grid Phase a Voltage and STATCOM Phase a Current

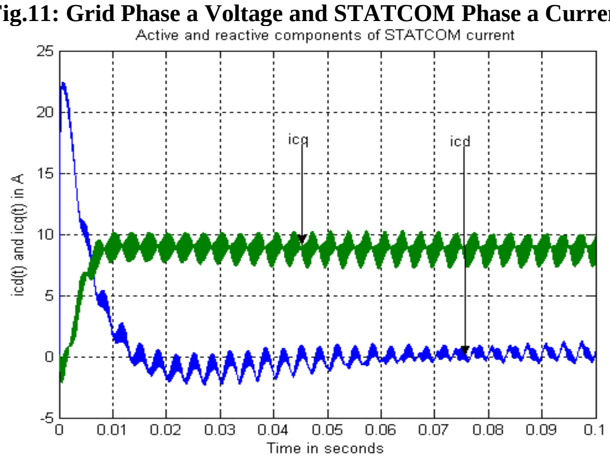

Fig.12: Active and Reactive Components of STATCOM Current

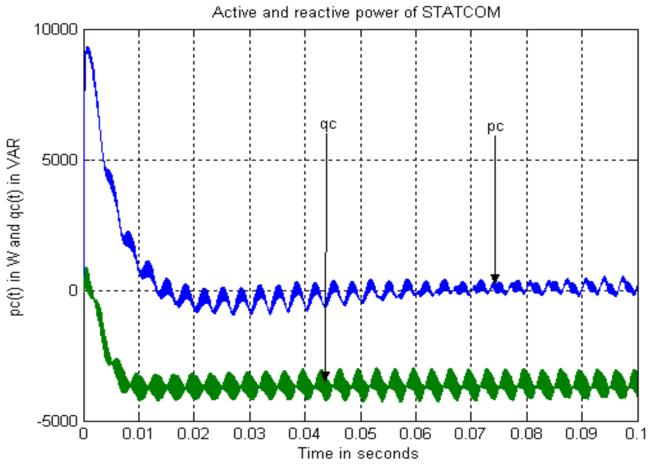

Fig.13: Active and Reactive Power of STATCOM

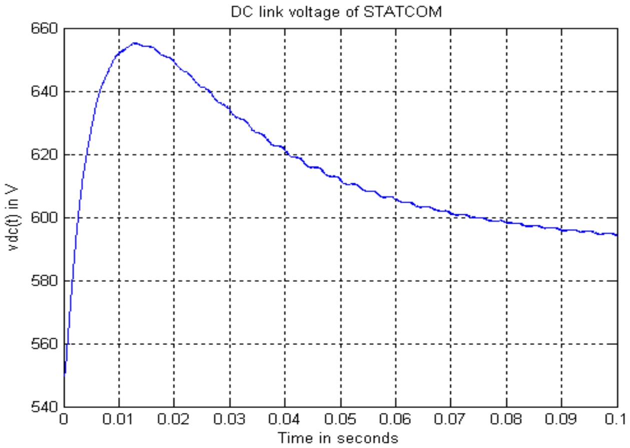

Fig.14: DC Link Voltage of STATCOM

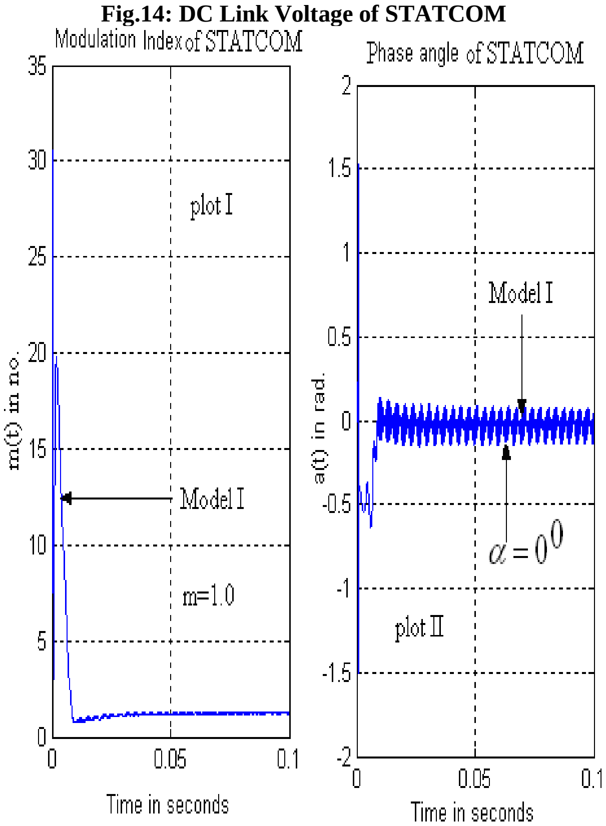

Fig.15: Modulation Index and Phase Angle

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Volume 2, Issue 5, November 2012

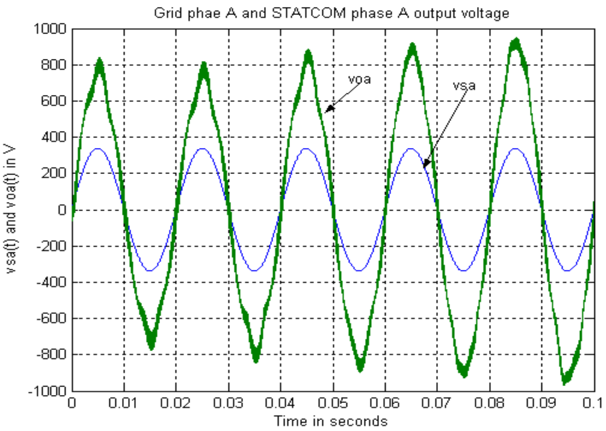

Fig.16: Grid and STATCOM Output Phase a Voltage

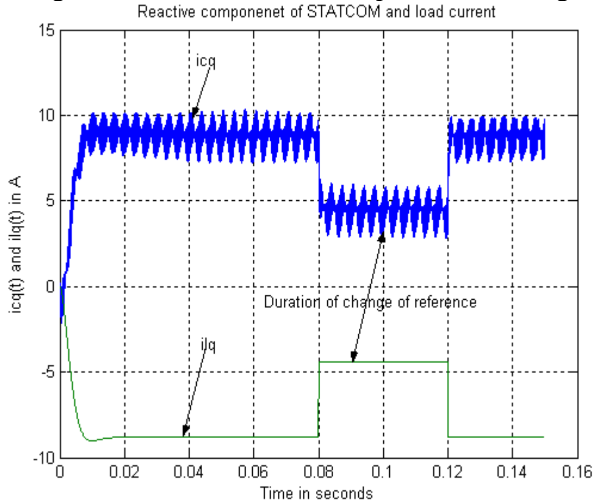

Fig.17: Change Of STATCOM Phase A Current Due to Change of Reference Current (Load Current)

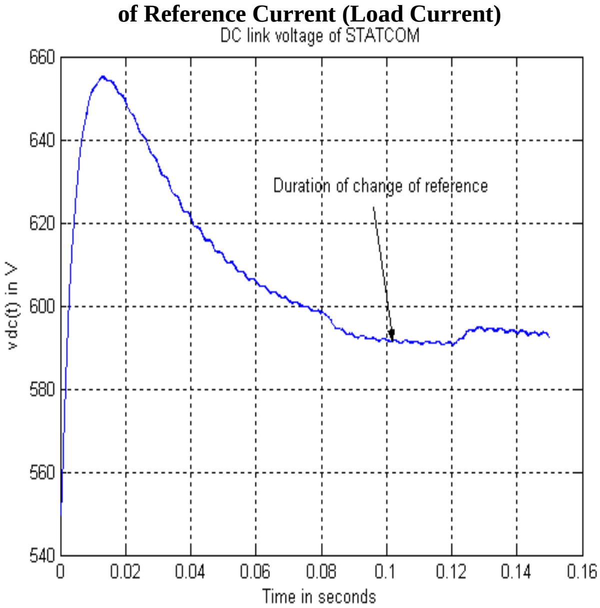

Fig.18: DC-Link Voltage of STATCOM Due to Change of Reference Current (Load Current)

D. DC Link Capacitor Charged To 600V:

These Controllers Work Well With A Very Small Spike And Improves Power Factor In A Half A Power Cycle At Initial Voltage Of 600V As Shown In Fig.19 Of Grid Phase A Voltage And Phase A Current.

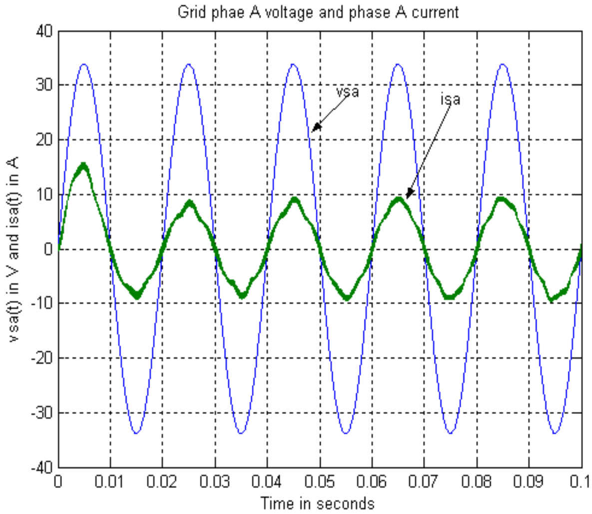

Fig.19: Grid Phase a Voltage and Phase a Current

V. 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 with designed controllers and on variation of DC link voltages 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 [14] and [19].However, in practice the issue of the charging the DC link voltage to the required value is quite significant. On increasing the magnitude of DC link voltage, the overshoot of all signals decreases. DC link voltage at 600V is suitable for proper operation of the STATCOM. 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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