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Design and Simulation of Distributed Statcom Controller for Power Factor Improvement

Swagat Satapathy
M.Tech,
Dept of EEE,
Centurion University.

Prasanna Kumar Karjee
Assistant Professor,
Dept of EEE,
Centurion University.

Abstract:

The STATCOM is a static reactive power compensator. It is connected to the grid through ac side reactors and has a capacitor on the DC-link side. This DC-link capacitor is maintained at a given voltage under closed-loop control while a set amount of reactive current is fed according to load requirements. The operating frequency of the VSC is also controlled in a PLL (phase locked loop) manner. Hence, it is essential to have a closed-loop feedback control operation of the STATCOM. The state space model of the STATCOM is non-linear. The non-linear model of the STATCOM is linearized. A linear model of the STACOM is proposed. In this model, the grid voltage and the fundamental component of the STATCOM VSC terminal voltage are assumed to be in-phase and the modulation index is kept within unity. PI-controllers for the active and reactive currents as well as the DC-link voltage of the STATCOM have been designed. The model, with PI controllers has been simulated in MATLAB/SIMULINK environment with variation of the pre-charge voltage on the DC-link capacitor with linear loads (inductive). Improvement of the power factor of the grid current is achieved for linear loads.

Keywords:

STATCOM (Static Synchronous Compensator), Power Factor(PF), PI Controllers,switched mode power supply (SMPS)

Introduction:

The Load are classified as linear and non-linear loads. The linear loads are R, R-L, R-L-C ,motors, heaters and incandescent lamps while non-linear loads are power electronic apparatus like diodes or thyristor rectifiers, switched mode power supply (SMPS), adjustable speed drives, ferromagnetic devices, arcing equipment's, induction heating systems etc. As is well known, the current is proportional to the voltage in case of a linear load whereas the current is not proportional to the voltage in case of non-linear load. A linear load draws active power from the grid with only fundamental component being present in the current and absorbs/injects reactive power from/to the grid. However, a non-linear load draws active power from the grid, where the current has fundamental and harmonics. These harmonics do not provide extra power but unnecessarily, yet unavoidably, increase the system volt-ampere (VA). This shows up as an increase in the *RMS* current in the lines and leads to an extra heating of the transmission conductors and system elements. The injection of harmonics thus has a number of disadvantages, as reported in [2]. Hence, the compensation of reactive power is necessary for both linear and non-linear loads. Harmonic compensation up to standard values [3],[4] and power factor improvement are main issues for such loads The power factor *PF* is defined as the ratio of the active power*P* to the apparent power *S*. Thus

$$PF= [P/S] \qquad (1)$$

For purely sinusoidal voltage and current, the standard expression is obtained as

$$PF=\cos\varphi \quad (2)$$

Wherecosφ is popularly known as the displacement factor. The expression of the power factor is not validated for non-sinusoidal current due to non-linear load. Hence, for sinusoidal voltage and non-sinusoidal current, equation (1) can be expressed as:

$$PF = \frac{V_{s,rms}\ I_{s1,rms}\ Cos\varphi}{V_{s,rms}\ I_{s,rms}} \quad (3)$$

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$$= \frac{I_{s1,rms}\ Cos\varphi}{I_{s,rms}}$$

$\mathbf{k_p} = \frac{\mathbf{I_{s1,rms}}}{\mathbf{I_{s,rms}}}$ = Harmonic Content of the current and is 1 at best when there is no harmonics

System Description:

Static Synchronous Compensator (STATCOM):

The STATCOM, in principle, is a static power-electronic version of the synchronous condenser. It is a shunt-connected reactive power compensation equipment as shown in Fig.1. It provides operating characteristics similar to a rotating synchronous condenser. It has the advantage that it operates with a very fast transient response, thus appearing to be almost without any inertia, unlike the synchronous condenser. It provides virtually step-less compensation for reactive VARs and maintains the desired power factor set as control reference automatically, even in the event of load fluctuations. It can be controlled to provide leading or lagging VARs and adjusts itself automatically as per load VAR requirement. In the event of increase in plant load, putting additional units in parallel can increase compensation capacity. It is a low maintenance equipment.

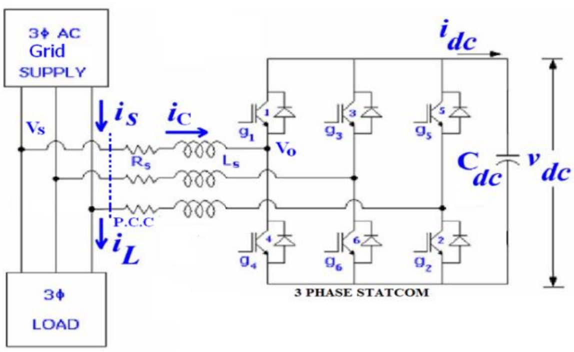

Fig 1: Schematic diagram of the STATCOM

Generalised Modelling of Statcom and Its Transformation

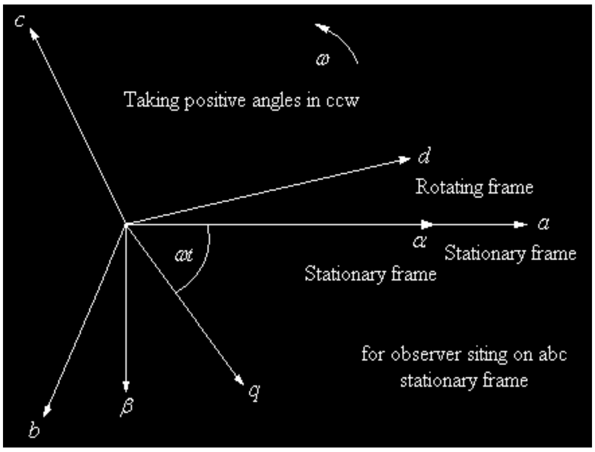

Fig 2: Relationship between vectors [17]

Referring to Fig 2,The modeling of STATCOM is done by d-q transformation [5-15].Grid Voltage $V_{s,abc}$lags STATCOM

Voltage$V_{o,abc}$ phase angle difference of alpha (α).

$$V_{s,abc} = \begin{bmatrix} v_{sa}(t) \\ v_{sb}(t) \\ v_{sc}(t) \end{bmatrix} = \sqrt{\frac{2}{3}} V_s \begin{bmatrix} \sin(wt - \propto) \\ \sin(wt - \frac{2\pi}{3} - \propto) \\ \sin(wt + \frac{2\pi}{3} - \propto) \end{bmatrix} (4)$$

The Three Phase STATCOM current dynamics is represented in equation given below

$$Ls\frac{d}{dt}\begin{bmatrix} i_{ca}(t) \\ i_{cb}(t) \\ i_{cc}(t) \end{bmatrix} = -Rs\begin{bmatrix} i_{ca}(t) \\ i_{cb}(t) \\ i_{cc}(t) \end{bmatrix} + \begin{bmatrix} v_{sa}(t) \\ v_{sb}(t) \\ v_{sc}(t) \end{bmatrix} - \begin{bmatrix} v_{oa}(t) \\ v_{ob}(t) \\ v_{oc}(t) \end{bmatrix}$$
(5)

Neglecting the current unbalance we have used a three-wire connection. The zero sequence component of current is zero as

$$I_{ca} + I_{cb} + I_{cc} = 0 \qquad (6)$$

From Fig 2, resultant α-β components by transformation

$$\begin{bmatrix} x_\alpha(t) \\ x_\beta(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/_2 & -1/_2 \\ 0 & \sqrt{3}/_2 & -\sqrt{3}/_2 \end{bmatrix} \begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix} \quad (7)$$

Where $[x]_{abc}$are phase quantities without zero sequence component and $[x]_{\alpha\beta}$ are equivalent transformed quantities. The α-β are orthogonal reference axes of *dq* rotating at an angular speed of ω rad/sec, and is represented by following transformation

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$$\begin{bmatrix} x_d(t) \\ x_q(t) \end{bmatrix} = \begin{bmatrix} \sin(wt) & -\cos(wt) \\ \cos(wt) & \sin(wt) \end{bmatrix} \begin{bmatrix} x_\alpha(t) \\ x_\beta(t) \end{bmatrix} \quad (8)$$

Where$[x]_{dq}$are the set of equivalent transformed in dqreference frame, the balanced three-phase abc co-ordinate axes are directly transformed to orthogonal co-ordinate axes rotating at an angular speed ω $rad/\sec$ are as follows:

$$\begin{bmatrix} x_d(t) \\ x_q(t) \\ x_0(t) \end{bmatrix} = k \begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix} \quad (9)$$

Where$K$ is,

$$k = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(wt) & \sin(wt - \frac{2\pi}{3}) & \sin(wt + \frac{2\pi}{3}) \\ \cos(wt) & \cos(wt - \frac{2\pi}{3}) & \cos(wt + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} (10)$$

C.Switching Of Converter:

We have assumed that harmonic components generated by switching action is negligible, and S as switching function for three phase

$$S = \begin{bmatrix} S_a(t) \\ S_b(t) \\ S_c(t) \end{bmatrix} = \sqrt{\frac{2}{3}} m_c \begin{bmatrix} \sin(wt) \\ \sin(wt - \frac{2\pi}{3}) \\ \sin(wt + \frac{2\pi}{3}) \end{bmatrix} \quad (11)$$

Where m_c is modulation conversion index and is expressed as Modulation Index(m)=$\frac{V_{o,peak}}{V_{dc}}$and $\sqrt{\frac{2}{3}}$is multiplying factor in transformation of three phase stationary abc axes to rotating dq axes.

The active and Reactive Power injected/drawn to/by STATCOM is given by

$$p_c(t) = v_{sd}(t) i_{cd}(t) + v_{sq}(t) i_c(t)$$

$$= -V_s(t) i_{cd}(t) \cos \propto + V_s(t) i_{cq}(t) \sin \propto (12)$$

$$q_c(t) = v_{sq}(t) i_{cd}(t) + v_{sd}(t) i_{cq}(t)$$

$$= -V_s(t) i_{cd}(t) \cos \propto - V_s(t) i_{cq}(t) \sin \propto (13)$$

The states of, $I_{cd}(s)$, $I_{cq}(s)$ and $V_{dc}(s)$ of the STATCOM are represented in frequency domain as:

$$I_{cd}(s) = \frac{V_s \left[s^2 \frac{\cos \propto}{Ls} + s \left(\frac{R_s}{{L_s}^2} \cos \propto - \frac{w}{Ls} \sin \propto \right) \right]}{s^3 + 2s^2 \frac{R_s}{Ls} + s \left(w^2 \frac{{R_s}^2}{{L_s}^2} + \frac{{m_c}^2}{L_s C_{dc}} \right) + {m_c}^2 \frac{R_s}{{L_s}^2 C_{dc}}}$$

(14)

$$I_{cq}(s) = \frac{-V_s \left[s^2 \frac{\sin \propto}{Ls} + s \left(\frac{R_s}{{L_s}^2} \sin \propto + \frac{w}{Ls} \cos \propto \right) + \frac{m_c}{{L_s}^2 C_{dc}} \sin \propto \right]}{s^3 + 2s^2 \frac{R_s}{Ls} + s \left(w^2 \frac{{R_s}^2}{{L_s}^2} + \frac{{m_c}^2}{L_s C_{dc}} \right) + {m_c}^2 \frac{R_s}{{L_s}^2 C_{dc}}}$$

(15)

$$V_{dc}(s) = m_c V_s \frac{\left[\frac{s \cos \propto}{L_s C_{dc}} + \left(\frac{R_s}{{L_s}^2 C_{dc}} \cos \propto - \frac{w}{L_s C_{dc}} \sin \propto \right) \right]}{s^3 + 2s^2 \frac{R_s}{Ls} + s \left(w^2 \frac{{R_s}^2}{{L_s}^2} + \frac{{m_c}^2}{L_s C_{dc}} \right) + {m_c}^2 \frac{R_s}{{L_s}^2 C_{dc}}}$$

(16)

TABLE 1: PARAMETERS AND VARIABLES OF THE STATCOMSYSTEM

SL NO	MEANING	SYMBOL	VALUES
1	FUNDAMENTAL FREQUENCY	$F=F_1$	50hz
2	FUNDAMENTAL ANGULAR FREQUENCY	$\Omega=\Omega_1$	314rad/sec
3	RMS LINE – LINE VOLTAGE	V_S	415v
4	EFFECTIVE	R_S	1.0Ω

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	COUPLING RESISTANCE		
5	COUPLING INDUCTANCE	L_S	5.44mh
6	DC-LINK CAPACITOR	C_{DC}	680μF
7	MODULATION INDEX(MODULATION CONVERSION INDEX	M (M_C)	0.866-1.0 (0.979-1.22)
8	LOAD RESISTANCE	R_L	23Ω
9	LOAD INDUCTANCE(WITH ITS INHERENT RESISITANCE)	L_L (R_L)	60MH(2.06 Ω)

Closed Loop Controller Design of STATCOM

In this model α as well as m (modulation index m is related to the modulation conversion index m_c as m = $\sqrt{\frac{2}{3}}m_c$And hence a change in m will change m_c too both may are assumed to remain constant at given values. Here, the grid side voltage and the STATCOM converter terminal voltage are assumed to be in-phase with each other (as phase angle difference $\alpha = 0^0$). Therefore this model is referred to as "Model I". It is a modification over the model given in [16]. In that model, the authors have done on-line dynamic computation of 'α'and 'm'. However, we have designed the controllers for the same model without computing 'α'and 'm' (as $\alpha = 0^0$ and m is within unity)

The Modified d-q Transformation of Grid Voltages and STATCOM currents are represented below in their respective equations as given by:

$$\begin{bmatrix} V_{sd}(t) \\ V_{sq}(t) \end{bmatrix} = V_s \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (17)$$

$$L_s \frac{d}{dt}\begin{bmatrix} i_{cd}(t) \\ i_{cq}(t) \end{bmatrix} = \begin{bmatrix} -R_s & \omega_1 L_s \\ -\omega_1 L_s & -R_s \end{bmatrix}\begin{bmatrix} i_{cd}(t) \\ i_{cq}(t) \end{bmatrix} + \begin{bmatrix} V_{sd}(t) \\ V_{sq}(t) \end{bmatrix} - \begin{bmatrix} V_{od}(t) \\ V_{oq}(t) \end{bmatrix} \quad (18)$$

For the above MIMO system we have considered input to be "u" and output to be"y"

$$[u] = \begin{bmatrix} V_{od}(t) \\ V_{oq}(t) \end{bmatrix}, \quad [y] = \begin{bmatrix} i_{cd}(t) \\ i_{cq}(t) \end{bmatrix} \quad (19)$$

Design of Controller

Current Controller

The block diagram of the closed-loop current controller is shown in and is replicated for both *d* and *q* axes currents.

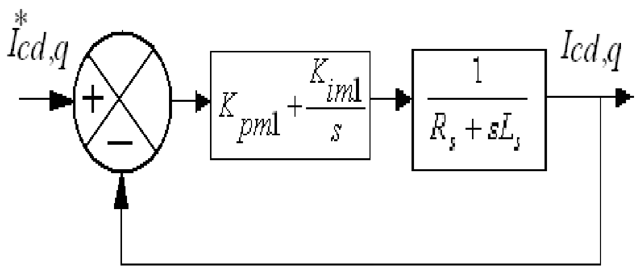

Fig 3: Generalized Block Diagram of Current Controller

The PI-controller bandwidth is chosen at $1kHz$ which is 10 times slower than the switching time of the STATCOM. The integrating time constant, τ can be chosen to be smaller than the PWM switching time of the STATCOM. Then the system operates faster but there is a possibility of saturation of the integrator.

DC Link Voltage Controller

The block diagram for the closed-loop control of the DC-link voltage of the STATCOM is shown below

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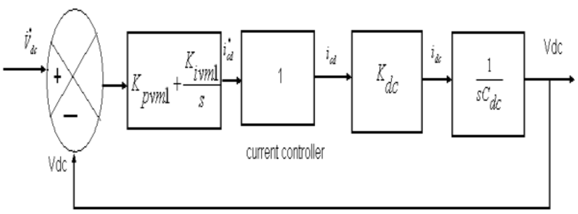

Fig 4: DC-link voltage control loop

The open loop transfer function "G_{ov}"between the PI controller andV_{dc} The root locus of the transfer function is drawn by varying K_{pvm1} from zero to infinity. By choosing the damping ratio $\xi = 0.72$, K_{pvm1} is found as 1.824

Controller Implementation In MATLAB Simulation:

The block diagram for practical realization of the linear model proposed is given in Fig 7. In a 3-wire system, for obvious reasons, only two out of the 3-phase voltages on the grid side, two out of the 3-phase currents of the STATCOM and two out of the 3-phase load currents are sensed and feedback. These 3-phase quantities are converted to two-phase $\alpha - \beta$ variables. The $\alpha - \beta$ variables are then converted to rotating $d - q$ variables with the help of 'unit vectors'. For this, the instantaneous phase angle of these quantities needs to be dynamically estimated in a PLL fashion. The sensed v_{dc} is summed with (proper sign) the reference voltage of V_{dc}^{*} and fed to a PI-controller. Thus, these controllers generate references which are converted back to $\alpha - \beta$ variables by help of unit vectors (inverse transformation). The gate pulses of the converter are generated by SVPWM principle using STATCOM converter reference $\alpha - \beta$ (stationary) co-ordinate voltages.

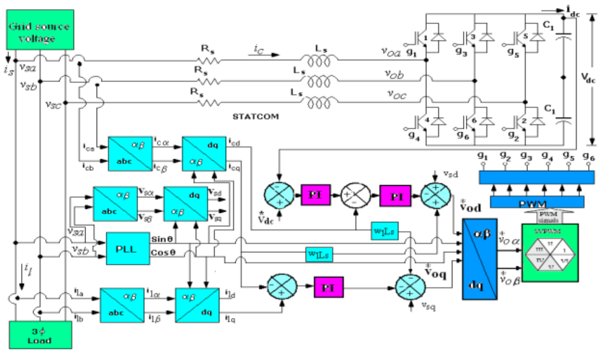

Fig 5: Proposed controller technique of closed-loop system

Controller Strategy:

The entire control (for both d-axis and q-axis controllers) is implemented as per the strategy of Fig 7. in real-time . Thus, these controllers generate references which are converted back to $\alpha - \beta$ variables by help of unit vectors (inverse transformation). The gate pulses of the converter are generated by SVPWM principle using STATCOM converter reference $\alpha - \beta$ (stationary) co-ordinate voltages. The above PI-controllers are implemented in MATLAB environment as given in Fig 8.The reference current is taken as the q component of the load current.

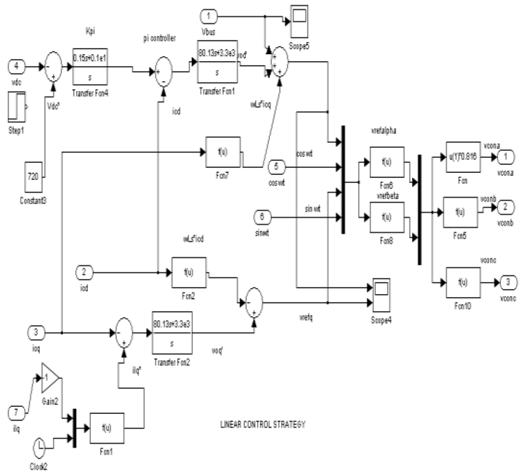

Fig.6: Current Controlling Block

Simulation Results

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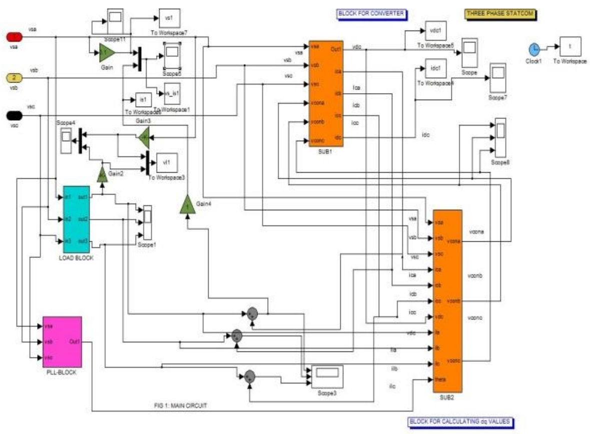

Fig 7.Final Simulation done in MATLAB

A linear load, simulated with $R-L$ parameters (given in Table 1)is connected to the grid. The waveforms of the grid side phase-a voltage (v_{sa}) and current (i_{sa}) at point of common connection (PCC) (without the STATCOM in operation) are shown in Fig.4.4. It may be mentioned that here and elsewhere (unless otherwise mentioned) v_{sa} is plotted to a reduced scale of $10:1$. Under steady state it is seen that the power angle is 39.64(so that power factor is 0.77). The STATCOM will now act in closed-loop with this system along with the proposed controllers in order to improve this power factor.

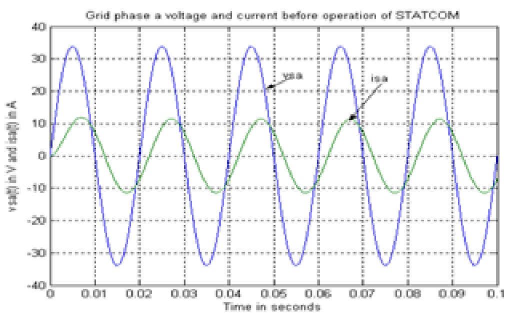

Fig.8 Grid phase-a voltage and current with $R-L$ load before operation of the STATCOM

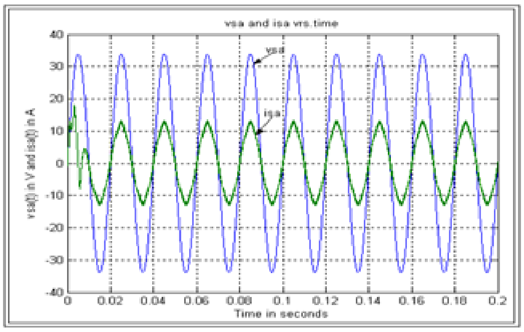

Fig 9: System voltage and system current using Proportional controller

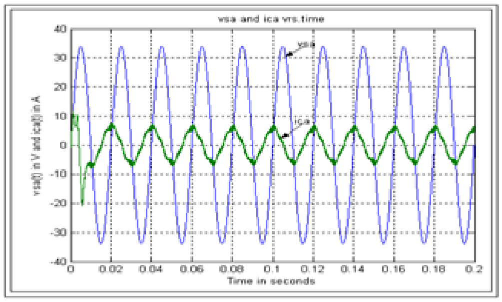

Fig 10: System voltage and STATCOM current using Proportional controller

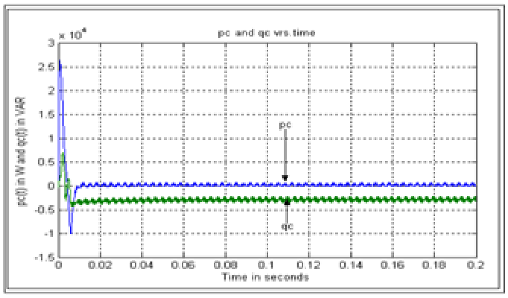

Fig 11: Active and Reactive power generated by STATCOM

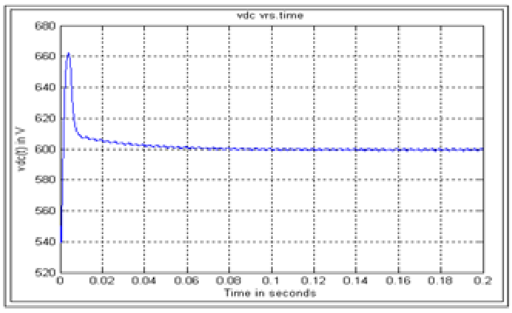

Fig12: DC link voltage using Proportional controller

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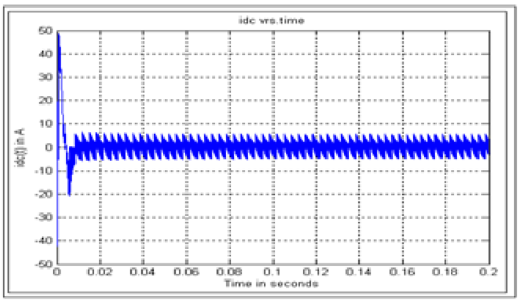

Fig 13: DC link current using Proportional controller

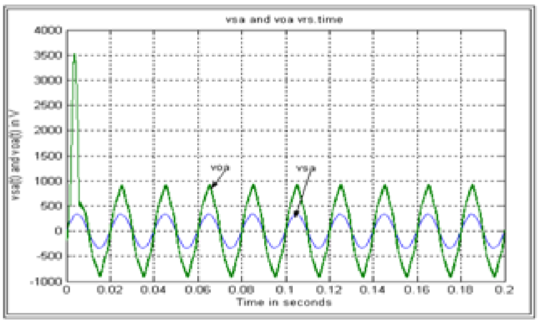

Fig 14: System and STATCOM output voltage using Proportional controller

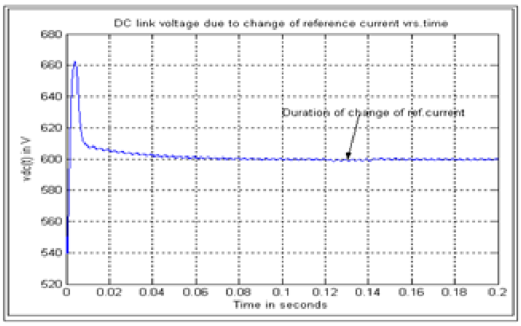

Fig 15: DC link voltage due to change of reference current using Proportional controller

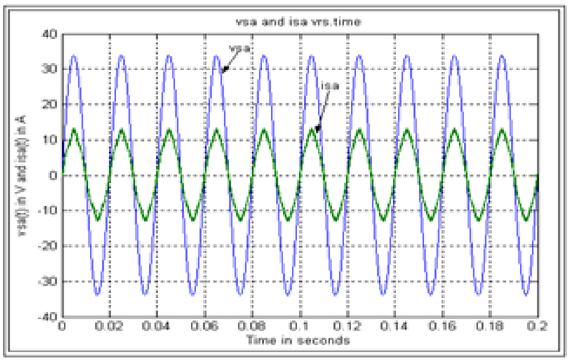

Fig 16: System voltage and system current using Proportional controller

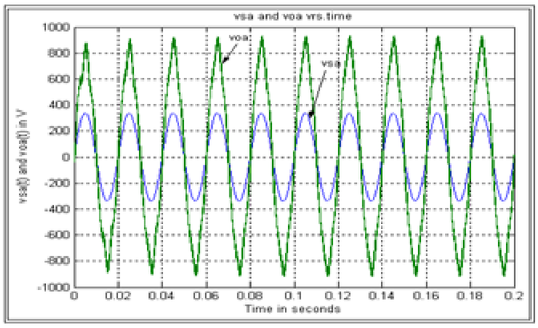

Fig 17: System and STATCOM output voltage using Proportional controller

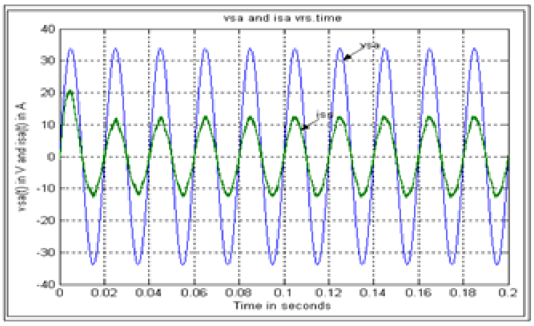

Fig 18: System voltage and system current using PI controller

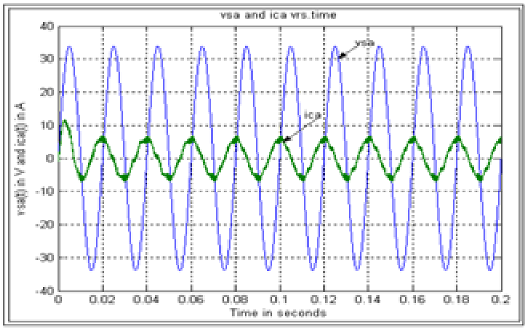

Fig 19:System voltage and STATCOM current using PI controller

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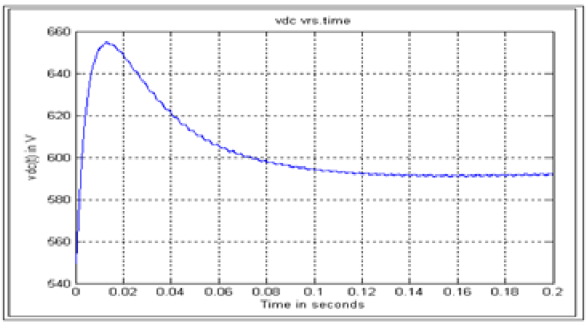

Fig 20: DC link voltage using PI controller

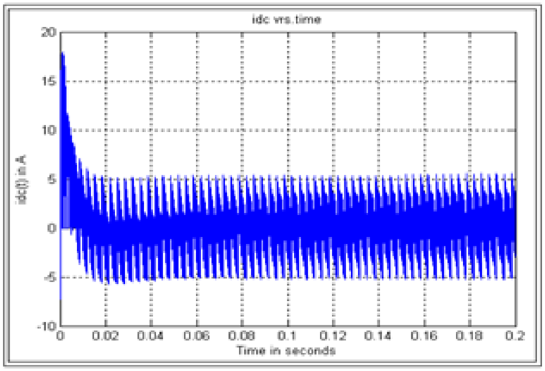

Fig 21: DC link current using PI controller

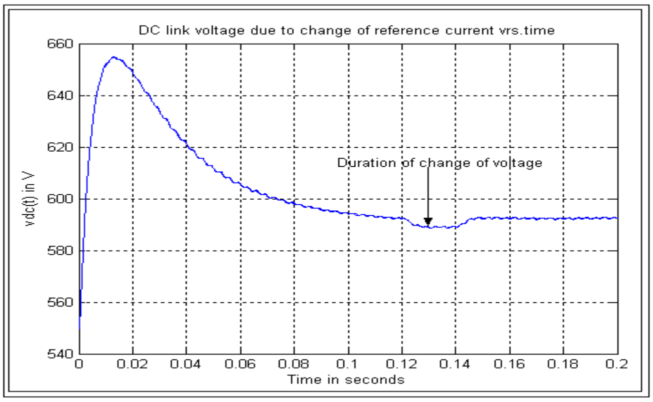

Fig 22: DC link voltage due to change of reference current using PI controller

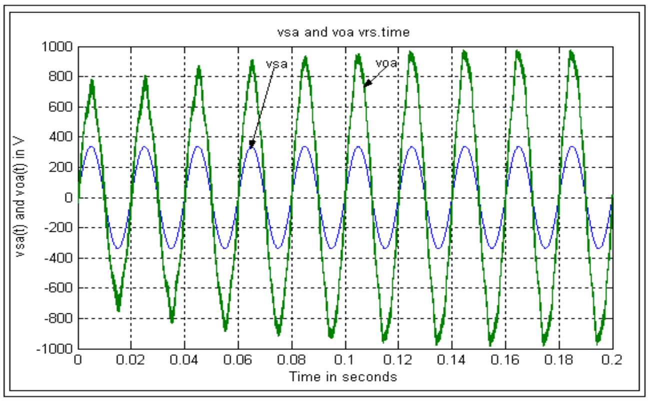

Fig 23: System and STATCOM output voltage using PI controller

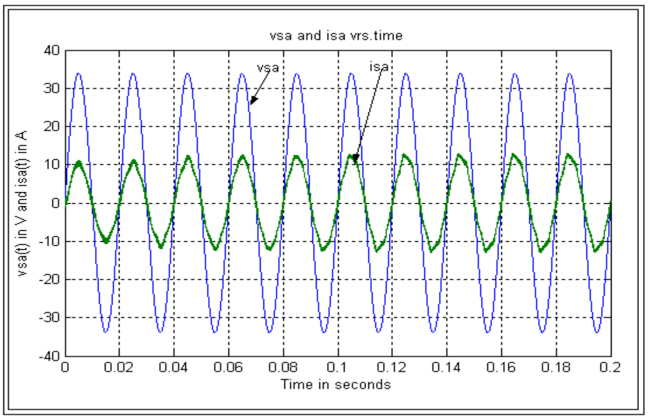

Fig. 24: System voltage and system current using PI controller with 700DC link voltage

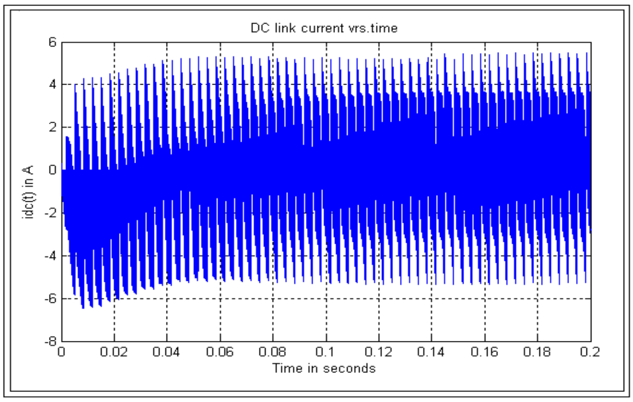

Fig 25: DC link current using PI controller with 700DC link voltage

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Conclusion:

A linear model of the STATCOM is proposed considering the grid voltage to be in-phase with the fundamental component of the STATCOM converter output voltage. The PI-controllers have been designed with relation to the parameters of the STATCOM and based on root locus method after linearizing the non-linear model of the STATCOM. The strategy has been simulated using MATLAB/SIMULINK environment for different pre-charge voltage on the DC-link, with linear load. The STATCOM is applied for improving the power factor of the grid current in this case.

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