THE INTERNATIONAL JOURNAL OF SCIENCE & TECHNOLEDGE

Implementating a Linear Controller of STATCOM Design in DC Link Voltage

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Abstract:
Power demand is increasing day by day, the new generation requires enough of resources, time period and budget allocation, and it is observed in the transmission system the percentage of power is wasted in the form of loss, and these is especially due to reactive power, by proper compensation of the reactive power through a FACTS device, known as statcom, the power can be effectively transmitted and can meet the demand. This project describes the modeling of statcom along with the design of Linear Controllers, even though the statcom is a nonlinear device due to its complexity in mathematical modeling, design of controllers for the converters is done by linear method with the linear controller and the method is adopted and simulated waveforms are presented. The designed controllers with variation of DC link voltage have been applied to the compensator. All responses are obtained through MATLAB SIMULINK tool box.

Keywords*: Controller design, DC-link voltage, FACTS- statcom, Power factor*

1. Introduction

Power Generation and Transmission is a complex process, requiring the working of many components of the power system in tandem to maximize the output. One of the main components to form a major part is the reactive power in the system. It is required to maintain the voltage to deliver the active power through the lines. Loads like motor loads and other loads require reactive power for their operation. To improve the performance of ac power systems, we need to manage this reactive power in an efficient way and this is known as reactive power compensation. There are two aspects to the problem of reactive power compensation: load compensation and voltage support. Load compensation consists of improvement in power factor, balancing of real power drawn from the supply, better voltage regulation, etc. of large fluctuating loads. Voltage support consists of reduction of voltage fluctuation at a given terminal of the transmission line. Two types of compensation can be used: series and shunt compensation. These modify the parameters of the system to give enhanced VAR compensation. In recent years, static VAR compensators like the STATCOM have been developed. These quite satisfactorily do the job of absorbing or generating reactive power with a faster time response and come under Flexible AC Transmission Systems (FACTS). This allows an increase in transfer of apparent power through a transmission line, and much better stability by the adjustment of parameters that govern the power system i.e. current, voltage, phase angle, frequency and impedance.

In this paper, first, a popularly accepted mathematical model is derived for the STATCOM. Then, the control strategy of the model which been proposed and described. The controller for this model has also been derived. This model has been simulated with designed controller by variation of pre-charge voltage on dc-link of the STATCOM.Finally simulation results are presented and demonstrated.

2. Modeling of the Statcom

2.1. Operating Principal

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.

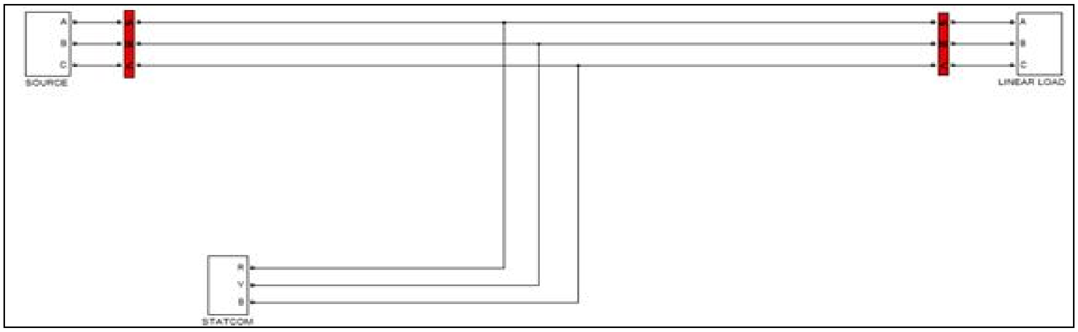


Figure 1: schematic diagram of statcom

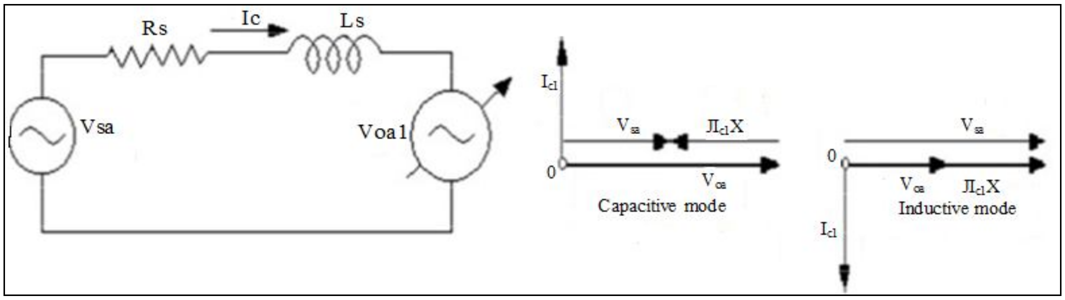


Figure 2: shows per phase fundamental equivalent circuit and phasor diagrams in capacitive and inductive mode

The per-phase fundamental equivalent circuit is as shown in fig.2.shows the source voltage, load and coupling inductor of the STATCOM with neglecting the harmonic content. If the fundamental component of the output voltage of the STATCOM is in-phase with the supply voltage then the current flowing out or towards the STATCOM is always 90° lagging or leading to the supply voltage as given in Fig.2 The STATCOM can also operate, when terminal voltage (fundamental) of the STATCOM is greater than the supply and lagging (and then current will lead the supply voltage). The STATCOM will then operate in fully capacitive mode supplying reactive power of the system. In case STATCOM current lags the system voltage, the STATCOM will operate in inductive mode injecting reactive VARs into the system as shown in fig.2.

2.2. Modelling

The modeling is carried out with the following assumptions:

- All switches are ideal.
- The source voltages are balanced.
- *Rs* represents the converter losses and Ls represents losses of the coupling inductor.
- The harmonic contents caused by switching action are negligible.

The primary modeling of the STATCOM has been presented by using (d-q) transformation. However, for easy reference, the modeling of the above is briefly revisited here. The 3-phase grid voltage, vs;abc lagging with the phase angle difference ‘a’ to the STATCOM converter terminal voltages vo;abc can be expressed as

$$v_{s,abc}(t) = \begin{bmatrix} v_{sa}(t) \\ v_{sb}(t) \\ v_{sc}(t) \end{bmatrix} = \sqrt{\frac{2}{3}}V_s \begin{bmatrix} \sin(\omega_1 t - \alpha) \\ \sin(\omega_1 t - \frac{2\pi}{3} - \alpha) \\ \sin(\omega_1 t + \frac{2\pi}{3} - \alpha) \end{bmatrix} \text{------(1)}$$

In the $(d-q)$ reference frame of (1) is

$$v_{s,dqo}(t) = Kv_{s,abc}(t) = V_s[\cos\alpha \quad -\sin\alpha \quad 0]^T \text{--------(2)}$$

where

$$K = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\omega_1 t) & \sin\left(\omega_1 t - \frac{2\pi}{3}\right) & \sin\left(\omega_1 t + \frac{2\pi}{3}\right) \\ \cos(\omega_1 t) & \cos\left(\omega_1 t - \frac{2\pi}{3}\right) & \cos\left(\omega_1 t + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

The above voltages and currents are transformed into *dq* frame as,the relationship between the grid voltage and statcom current i_{cabc},in the series inductor,Ls,in dq frame is given by

$L_s\, d(i_{cd}(t)) = wL_s i_{cq}(t) - R_s i_{cd}(t) + v_{sd}(t) - v_{od}(t)$------(3)

Ls d(i_{cq}(t))=w$L_s i_{cd}$(t)-$R_s i_{cq}$(t)+v_{sq}(t)-v_{oq}(t)------(4)
The voltage and current related in dc side is, dv_{dc}/dt=i_{dc}/c---------(5); i_{dc}=m[0 1 0][i_{cq} i_{cd} i_{co}]^T-------------(6)
Now by comparing (5) and (6), dv_{dc}/dt=m/c(i_{cd})
The complete mathematical model of statcom,

$$\frac{d}{dt}\begin{bmatrix} i_{cq} \\ i_{cd} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -w & 0 \\ w & -\frac{R_s}{L_s} & -\frac{m}{L_s} \\ 0 & \frac{m}{C} & 0 \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \\ v_{dc} \end{bmatrix} + \frac{V_s}{L_s}\begin{bmatrix} -Sin\alpha \\ Cos\alpha \\ 0 \end{bmatrix} \text{--------(7)}$$

2.3. Design Of Controllers For Statcom

With the assumption of the system voltage and statcom output voltage are in phase and hence the equation (3) and (4) can be modified as,

$$\frac{d}{dt}\begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_S} & -\omega \\ \omega & -\frac{R_S}{L_S} \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} + \frac{1}{L_S}\left[\begin{bmatrix} v_{sq} \\ v_{sd} \end{bmatrix} - \begin{bmatrix} v_{oq} \\ v_{od} \end{bmatrix}\right] \text{--------(8)}$$

So equation(8) is MIMO system, its input and output are given in equation(10).Both active and reactive currents are coupled with each other, through reactance of coupled inductor, so it is very essential to decouple both active and reactive current from each other and design the controller for tracking the required value.

2.4. Design of Current Controller

The current controller design for the above system can be done using the d and q axes equations, so that the MIMO system reduces to two independent Single Input Single Output (SISO) system as,

$$\begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_S} & 0 \\ 0 & -\frac{R_S}{L_S} \end{bmatrix} \begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix} + \frac{1}{L_S}\begin{bmatrix} v_{oq}^{*} \\ v_{od}^{*} \end{bmatrix} \text{--------(9)}$$

Taking laplace transform on both side of above equation,we get

$$G_i(s) = \frac{I_{cq}(s)}{V_{oq}^{*}(s)} = \frac{I_{cd}(s)}{V_{od}^{*}(s)} = \frac{1}{R_S + sL_S} \text{--------(10)}$$

The T.F of a PI controller is,

$$G_{pi}(s) = K\left(1 + \frac{1}{s\tau_i}\right) = K_p + \frac{K_i}{s} \text{ --------(11)}$$

With kp=k and ki=k/τ_i, The transfer function in open loop of PI controller associated with the transfer function on the a.c. system is

$$\left[G_{pi}(s).G_i(s)\right] = K\left[1 + \frac{1}{s\tau_i}\right]\left[\frac{1/R_S}{1 + s\,L_S/R_S}\right] = k/sL_s \text{--------(12)}$$

The closed loop transfer function is given,

$$T = \frac{1}{1 + s\frac{L_S}{K}} \text{--------(13)}$$

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 *Ki* are decided from the circuit parameters *Ls* and *Rs* from the required value of K. So the parameters of PI controller are defined as

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

Where, τ_i which is taken as 0.3mseconds and with the parameters given in Table-1. These parameters are used in d and q - axis current controller.

2.5. Design of Voltage Controller

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

$$v_{dc} = \frac{1}{C}\int i_{dc}dt \text{ --------(14)}$$

The transfer function can be written as,

$$G_V(s) = \frac{V_{dc}}{I_{dc}} = \frac{1}{sC} \text{ --------(15)}$$

Neglecting the power loss in the source resistance and power losses in the switches, balancing the power on both sides, $V_{sd}\, i_{cd}= V_{dc}i_{dc}$ The DC bus voltage is maintained at 400 volts. With *dc V* 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 is associated with the transfer function on dc side is,

$$\left[G_V(s).G_{pi}(s)\right]_{ol} = K\left(1+\frac{1}{s\tau_v}\right)\left(\frac{1}{sC}\right) \text{ --------(16)}$$

After taking $C=\tau_v$ and on simplification

$$\left[G_v(s).G_{pi}(s)\right]_{ol} = K\left(\frac{1+s\tau_v}{s^2\tau_v^2}\right) \text{ --------(17)}$$

The transfer function in closed loop

$$\left[G_v(s).G_{pi}(s)\right]_{cl} = \left(\frac{1+s\tau_v}{1+s\tau_v+\frac{s^2\tau_v^2}{K}}\right) \text{ --------(18)}$$

The value of K can be determined form root locus with approximate settling time as 1/200 and 1/400.

3. Simulation Results

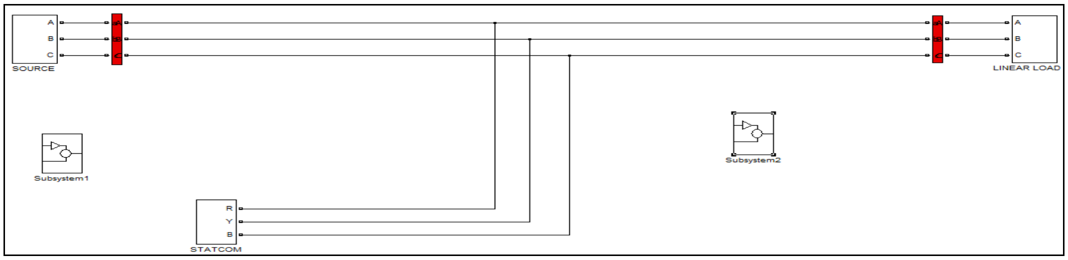


Figure 3: Implementing scheme of STATCOM

The control scheme for controlling DC link voltage as well as *d* and *q* axes current of STATCOM simultaneously as shown in Fig.4 is implemented with MATLAB SIMULINK with the parameters given in Table. I.and sub system1 shows 3Φ to dq transformation as in fig.5,and subsystem2 shows measurements as in fig.6 and statcom in fig.7.

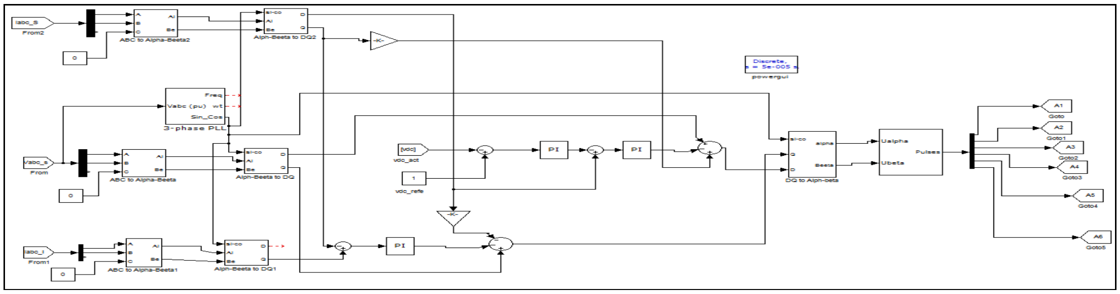


Figure 4: Shows subsystem1

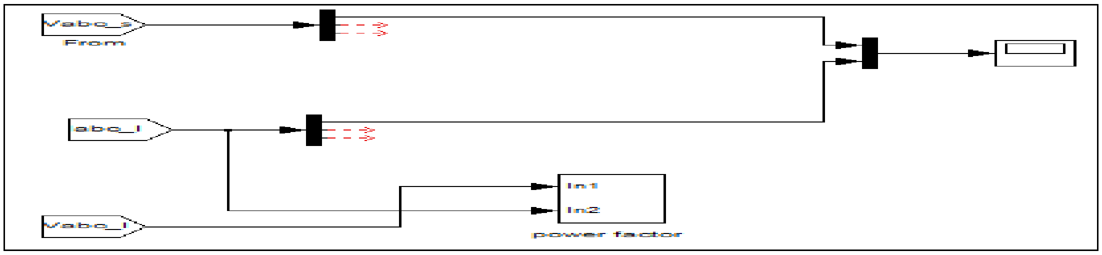


Figure 5: Shows subsystem 2

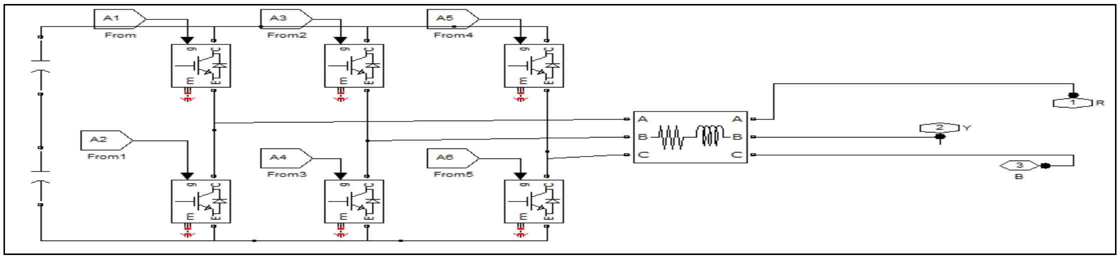


Figure 6: shows statcom

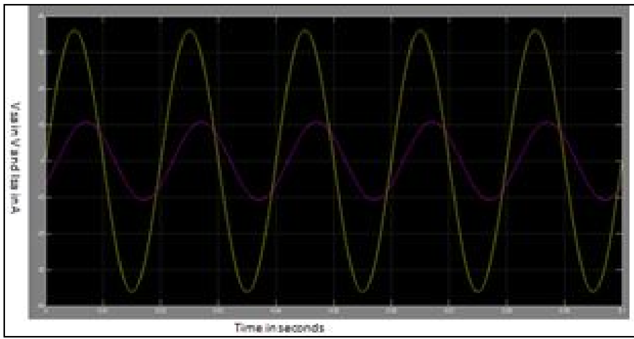
Sl. no	Parameters	Symbol	Values
1	Frequency	f	50hz
2	Angular frequency	W	314 rad/sec
3	RMS L-L voltage	Vs	230V
4	Coupling resistance	Rs	1ohm
5	Coupling inductance	LS	5mH
6	DC link capacitor	C	500µF
7	Modulation index	M	0.979
8	Phase angle	Φ	$\pm 5^0$
9	Load resistance	R_L	52ohm
10	Load inductance	L_L	126mH

Table 1: shows the system parameters with values

fig.7 depiets 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.

3.1. DC link capacitor charged to 100V

These controllers work well and STATCOM functions at initial value of DC link voltage of 100V with larger current peak as shown in fig.8



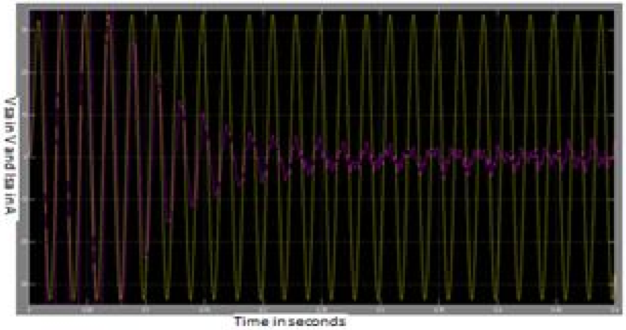
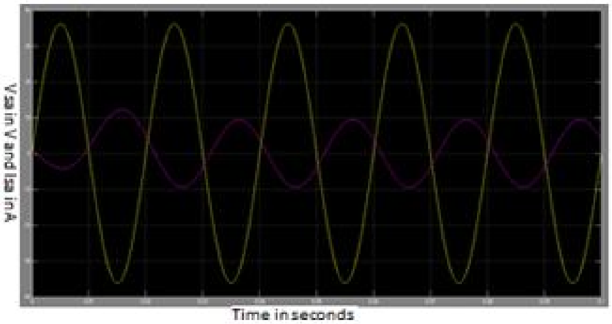


Figure 7: phase A voltage and load current *Figure 8: phase A voltage and current*

3.2. DC link capacitor charged to 550V

At initial value of DC link voltage of 550V the statcom operates well and the relevant waveforms as shown in fig(9) to fig(13).fig.(9) shows the phase A voltage and current in which the peak value of current is raised to 11A and making the power factor value, nearly to unity ,and showing the active and reactive power variation in fig(10) and fig(11),in which the active component steadies with respect to reactive component. Fig(12) shows the value of modulation index becoming nearly to unity, and as the load is of linear, their change in reference current, changes the load current as shown in fig(13),therefore with charging of the capacitor between 550 to 600,the power factor and stability improvement of the system is seen.



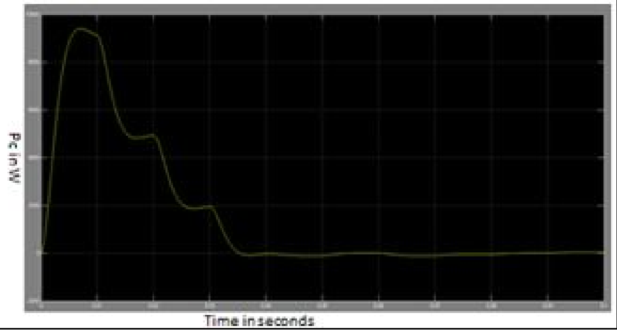
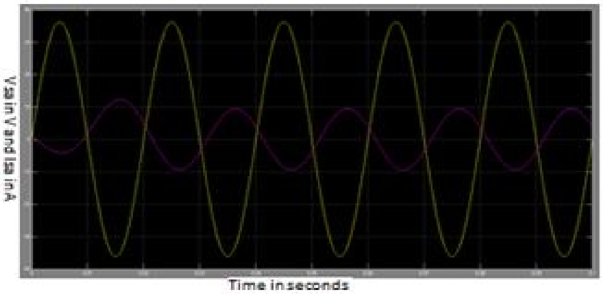


Figure 9: phase A voltage and current *Figure 10: active component of statcom*



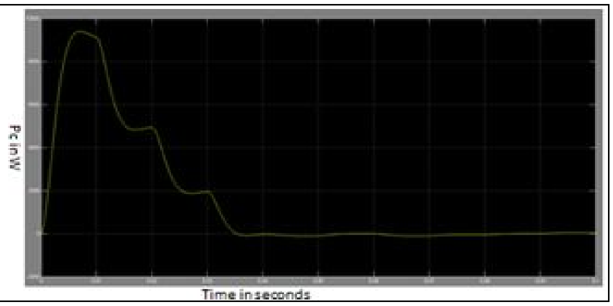
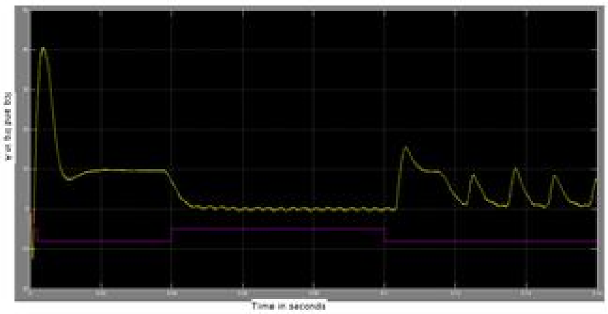


Figure 11: reactive component of statcom *Figure 12: modulation index*



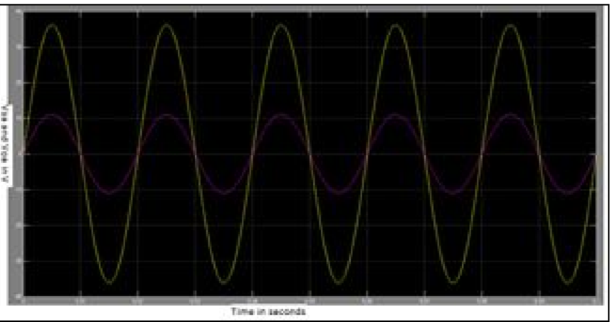


Figure 13: change of statcom phase A current due to change of reference current (load current).
Figure 14: phase A voltage and current

3.3. 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.14 of grid phase A voltage and phase A current.

4. Conclusion

The strategy works well for the power factor improvement of the grid side current with linear loads. The model is simulated in MATLAB/SIMULINK environment. However in practice the issue of the charging the dc link voltage to the required value is quit significant, on increasing the magnitude of dc link voltage the overshoot of all signals decreases. Therefore DC link voltage at 600v is suitable for proper operation of the statcom.

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