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Mitigation of Subsynchronous Resonance in Power System through STATCOM and Auxiliary Controller

Vipin Jain* and Narendra Kumar**

In FACTS devices, auxiliary signals are widely used to enhance damping and mitigate Subsynchronous Resonance in Power System. Subsynchronous Resonance occurs due to series capacitor in Power System. In this paper a novel auxiliary controller of STATCOM is designed with auxiliary signal ω_g i.e. accelerating frequency of generator rotor mode. Auxiliary controller is superimposed on conventional PI controller. The study system is IEEE First Benchmark Model. Alone PI is not able to damp all the modes of First Benchmark Model.

Keywords: *STATCOM, Auxiliary signals, Accelerating frequency, PI controller, IEEE First Benchmark Model.*

1.0 INTRODUCTION

The STATCOM is a shunt connected reactive power compensation device that is capable of generating and/or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system [1]. In STATCOM type '1' or type '2' converters can be used. The converters where both 'K_{cs}' and 'α' are controlled are termed as type '1' converters while they are termed as type '2' if only 'α' can be controlled. In type '2' converters generally 'K_{cs}' is fixed. For 'p' pulse converter $K_{cs}=(p/6)(\sqrt{6}/\pi)$ [2]. For 12 pulse converter $K_{cs}= 2\sqrt{6}/\pi$. 'α' is the angle difference between 'E_t' and 'E_s'. 'α' is kept very small (maximum value of 'α' is kept 1°). At low value of 'α', reactive component of I_s (Statcom current) is proportional to 'α' [1-3]. As the 'α' varies, V_{dc} varies, in turn magnitude of 'E_s' varies ($K_{cs}= |Es|/V_{dc}$), which controls reactive power supplied/absorbed by STATCOM.

2.0 STUDY SYSTEM

Study system considered is IEEE First Benchmark Model [4]. It contains twenty differential equations. A PI controller is used. Six differential equations belong to Generator, Twelve for Mechanical system, Two for Transmission network (i.e. series capacitor). STATCOM is incorporated at Generator bus as shown in Figure 1. [5].

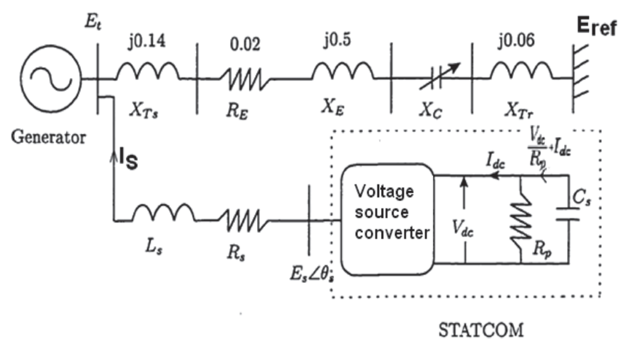

FIG. 1 STATCOM AND FIRST BENCHMARK MODEL

*Electrical Engineering Department, Bharat Institute of Technology, Meerut-250 103, India. E-mail : vipinjain71@rediffmail.com, Mobile : +91 9761988929
**Electrical Engineering Department, Delhi Technological University, Bawana Road, Delhi-110 042, India. E-mail: narendra.kumar@dce.edu

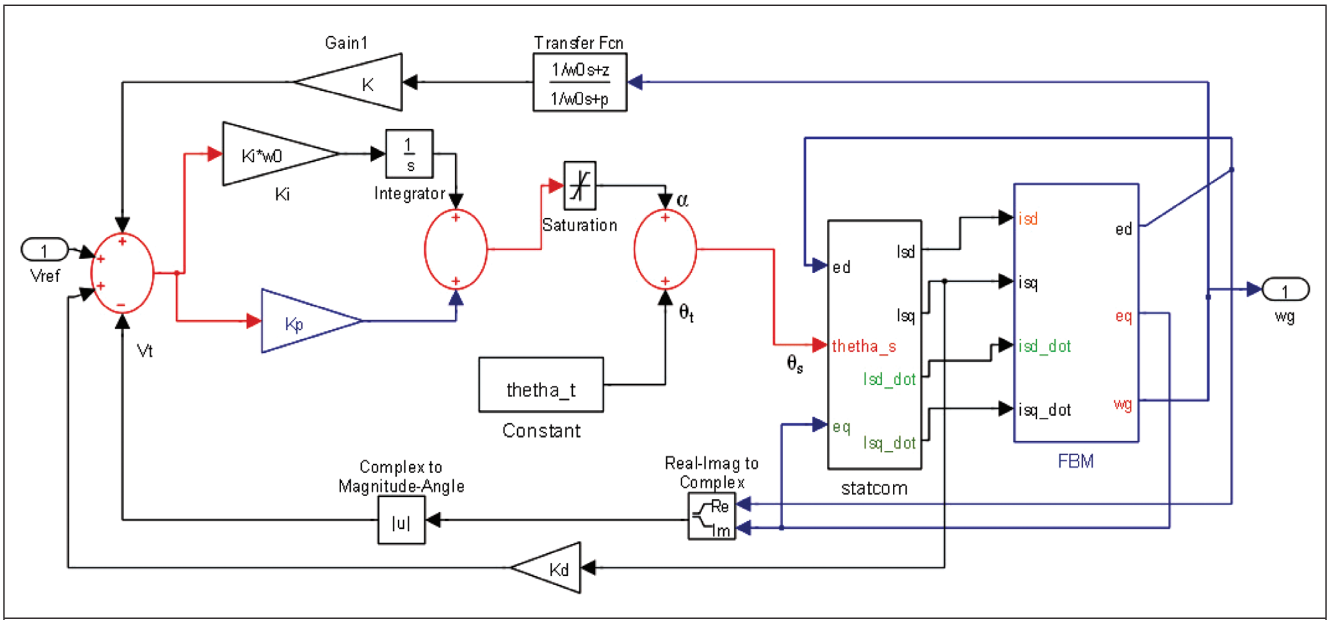

FIG. 2 BLOCK DIAGRAM DEVELOPED IN SIMULINK

STATCOM contains three differential equations. All the equations of First Benchmark Model (FBM) are written as equations 1-20. (which contains STATCOM current I_{sd} & I_{sq} also). Equations 21-23 shows STATCOM dynamics [5]. Equation 24 represents PI controller dynamics. All the equations are developed in simulink and kept in different subsystem (Figure 2). In Figure 2, Subsystem 'FBM' contains 1-20 differential equations. Subsystem 'STATCOM' contains 21-23 differential equations. Output of STATCOM is current I_{sd} & I_{sq}. Input to STATCOM is STATCOM bus voltage e_d & e_q. Output of PI controller is 'α'. The value of 'α' is very low. For low value of 'α', Reactive power supplied by STATCOM have linear relationship with 'α'. By keeping all the differential equations in a subsystem in MATLAB, these can be linearised and subsequently eigenvalue, impulse response, step response can be obtained. The whole system is then kept in one subsystem as shown in Figure 3.

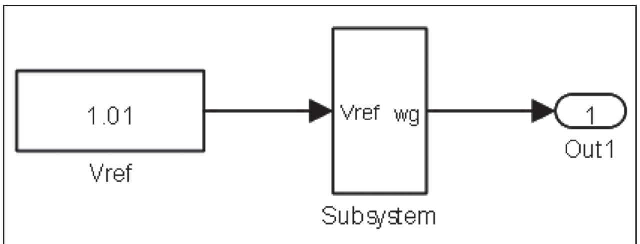

FIG. 3 SUBSYSTEM TO KEEP WHOLE SYSTEM SYSTEM

The block diagram of system is shown in Figure 4.

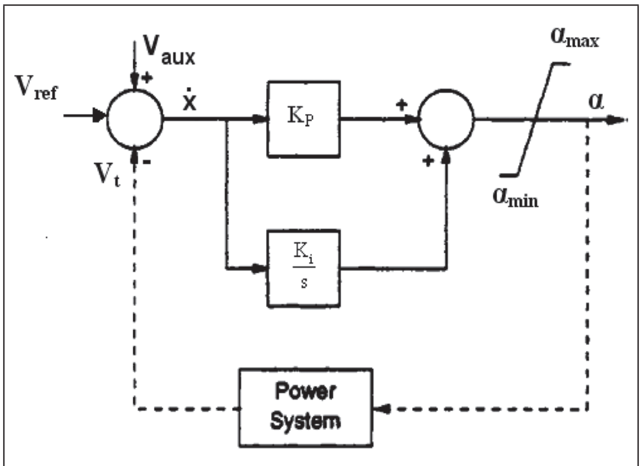

FIG. 4 BLOCK DIAGRAM WITH PI CONTROLLER SYSTEM

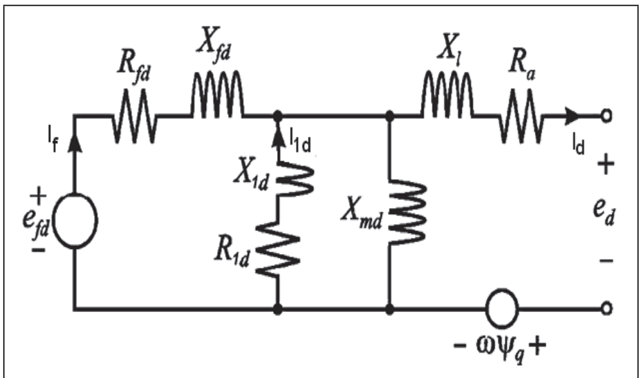

FIG. 5 GENERATOR D-AXIS MODEL SYSTEM

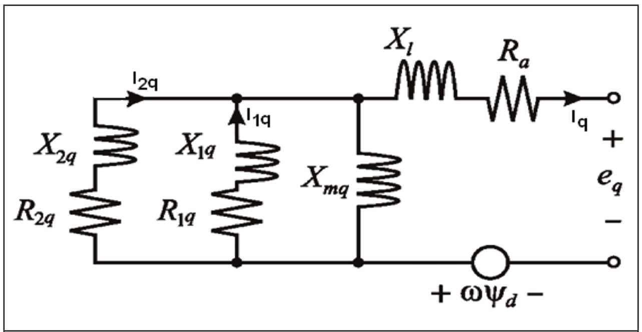

FIG. 6 GENERATOR Q-AXIS MODEL SYSTEM

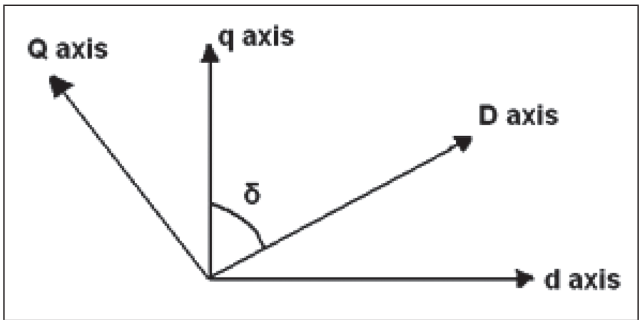

FIG. 7 D-Q AXIS (MACHINE REFRENCE FRAME) & D-Q AXIS (NETWORK REFRENCE FRAME) SYSTEM

Generator circuit is shown in Figure 5 & 6. Equations 1-6 are obtained from Figure 5 & 6. All the equations 1-24 are written in d-q reference frame. d-q axis is machine axis and D-Q axis is network axis (Figure 7). E_{ref} is along the 'D' axis. Equation 'A' & 'B' is the output equation of First Benchmark Model. (which is input to the STATCOM).

3.0 DYNAMIC EQUATIONS

Dynamic equations of whole system are as follows:

$$-\frac{(X_l+X_{md})}{\omega_0}\dot{I}_d+\frac{X_{md}}{\omega_0}\dot{I}_f+\frac{X_{md}}{\omega_0}\dot{I}_{1d}=R_aI_d-\omega(X_l+X_{mq})I_q+\omega X_{mq}I_{1q}+\omega X_{mq}I_{2q}+e_d \quad ....(1)$$

$$\frac{-(X_l+X_{mq})}{\omega_0}\dot{I}_q+\frac{X_{mq}}{\omega_0}\dot{I}_{1q}+\frac{X_{mq}}{\omega_0}\dot{I}_{2q}=\omega(X_l+X_{md})I_d+R_aI_q-\omega X_{md}I_f+\omega X_{md}I_{1d}+e_q \quad ...(2)$$

$$\frac{-X_{md}}{\omega_0}\dot{I}_d+\frac{X_{fd}+X_{md}}{\omega_0}\dot{I}_f+\frac{X_{md}}{\omega_0}\dot{I}_{1d}=-R_{fd}I_f+e_{fd} \quad ....(3)$$

$$\frac{-X_{md}}{\omega_0}\dot{I}_d+\frac{X_{md}}{\omega_0}\dot{I}_f+\frac{X_{1d}+X_{md}}{\omega_0}\dot{I}_{1d}=-R_{1d}I_{1d} \quad ....(4)$$

$$\frac{-X_{mq}}{\omega_0}\dot{I}_q+\frac{X_{1q}+X_{mq}}{\omega_0}\dot{I}_{1q}+\frac{X_{mq}}{\omega_0}\dot{I}_{2q}=-R_{1q}I_{1q} \quad ....(5)$$

$$\frac{-X_{mq}}{\omega_0}\dot{I}_q+\frac{X_{mq}}{\omega_0}\dot{I}_{1q}+\frac{X_{2q}+X_{mq}}{\omega_0}\dot{I}_{2q}=-R_{2q}I_{2q} \quad ....(6)$$

$$\frac{2H_E}{\omega_0}\dot{\omega}_E=K_{EG}(\delta-\delta_E)-D_E\omega_E \quad ....(7)$$

$$\frac{1}{\omega_0}\dot{\delta}_E=\omega_E \quad ....(8)$$

$$\frac{2H_G}{\omega_0}\dot{\omega}_G=K_{GB}(\delta_B-\delta)-T_e-K_{EG}(\delta-\delta_E)-D_G\omega_G \quad ....(9)$$

$$\frac{1}{\omega_0}\dot{\delta}=\omega_G \quad ....(10)$$

$(\omega_G=\omega-\omega_s)$ (appendix '3')

$$\frac{2H_B}{\omega_0}\dot{\omega}_B=T_{LPB}+K_{BA}(\delta_A-\delta_B)-K_{GB}(\delta_B-\delta)-D_B\omega_B \quad ....(11)$$

$$\frac{1}{\omega_0}\dot{\delta}_B=\omega_B \quad ....(12)$$

$$\frac{2H_A}{\omega_0}\dot{\omega}_A=T_{LPA}+K_{AI}(\delta_I-\delta_A)-K_{BA}(\delta_A-\delta_B)-D_A\omega_A \quad ....(13)$$

$$\frac{1}{\omega_0}\dot{\delta}_A=\omega_A \quad ....(14)$$

$$\frac{2H_I}{\omega_0}\dot{\omega}_I=T_{IP}+K_{IH}(\delta_H-\delta_I)-K_{AI}(\delta_I-\delta_A)-D_I\omega_I \quad ....(15)$$

$$\frac{1}{\omega_0}\dot{\delta}_I=\omega_I \quad ....(16)$$

$$\frac{2H_H}{\omega_0}\dot{\omega}_H=T_{HP}-K_{IH}(\delta_H-\delta_I)-D_H\omega_H \quad ....(17)$$

$$\frac{1}{\omega_0}\dot{\delta}_H=\omega_H \quad ....(18)$$

$$e_d - E_{ref}\sin\delta - V_{cd} = R_L\,(I_d + I_{sd}) - \omega X_L\,(I_q + I_{sq}) + \frac{X_L}{\omega_0}(\dot{I}_d + \dot{I}_{sd})$$

$$\text{or, } e_d = E_{ref}\sin\delta + V_{cd} + R_L\,(I_d + I_{sd}) - \omega X_L\,(I_q + I_{sq}) + \frac{X_L}{\omega_0}(\dot{I}_d + \dot{I}_{sd}) \quad -(A)$$

$$e_q - E_{ref}\cos\delta - V_{cq} = R_L\,(I_q + I_{sq}) + \omega X_L\,(I_d + I_{sd}) + \frac{X_L}{\omega_0}(\dot{I}_q + \dot{I}_{sq})$$

$$\text{or, } e_q = E_{ref}\cos\delta + V_{cq} + R_L\,(I_q + I_{sq}) + \omega X_L\,(I_d + I_{sd}) + \frac{X_L}{\omega_0}(\dot{I}_q + \dot{I}_{sq}) \quad -(B)$$

$$\frac{\dot{V}_{cd}}{\omega_0} = \omega V_{cq} + X_c\,(I_d + I_{sd}) \quad ....(19)$$

$$\frac{\dot{V}_{cq}}{\omega_0} = -\omega V_{cd} + X_c\,(I_q + I_{sq}) \quad ....(20)$$

$$E_{sd} - e_d = R_s I_{sd} - \omega X_s I_{sq} + \frac{X_s \dot{I}_{sd}}{\omega_0} \quad ....(21)$$

$$E_{sq} - e_q = R_s I_{sq} + \omega X_s I_{sd} + \frac{X_s \dot{I}_{sq}}{\omega_0} \quad ....(22)$$

$$\frac{\dot{V}_{dc}}{\omega_0} = -\frac{1}{C_s}\left[\frac{V_{dc}}{R_p} + K_{cs} I_{sd}\cos\theta_s + K_{cs} I_{sq}\sin\theta_s\right] \quad ....(23)$$

$$\frac{\dot{x}}{\omega_0} = V_{aux} + V_{ref} - |E_t| + K_d I_{sq} \quad ....(24)$$

All the differential equations are solved in simulink and linearized in simulink. Solution of equations 19-20 is shown in Figure 8

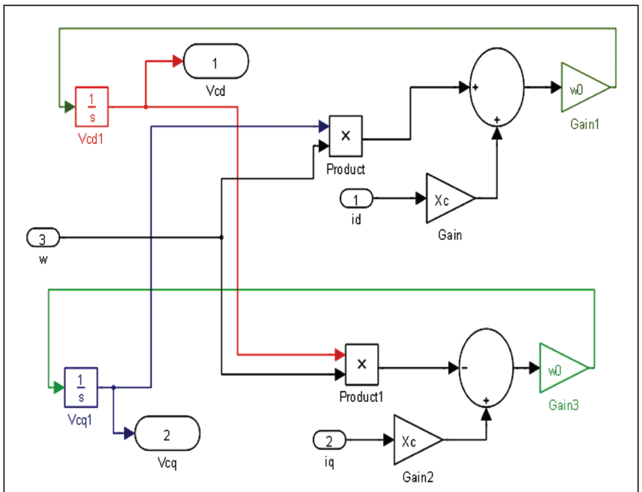

FIG. 8 SOLUTION OF TWO DIFFERENTIAL EQUATIONS 19 & 20 SYSTEM

Eigenvalues and time response analysis of nonlinear differential equations is carried out. Through linearized command in simulink eigenvalues are obtained, which are tabulated in Table 1. Natural damping in all the cases are zero. FBM has four unstable modes. From eigenvalue analysis, it is clear that a STATCOM with PI controller is not sufficient. With auxiliary controller having feedback signal 'ω_g', all the modes are stable.

4.0 AUXILIARY CONTROLLER DESIGN

Various Auxiliary signals are considered. But accelerating frequency of Generator rotor mode 'ω_g' i.e. deviation in frequency of rotor mode is able to damp out all modes of first benchmark model satisfactorily. Auxiliary signal (deviation in frequency) is passed through lead compensation. Output of lead compensation is 'V_{aux}', which is added to V_{ref}. The data of lead compensation is given in appendix 1.

5. RESULTS AND CONCLUSION

The eigenvalues are summarized in Table 1. Column 1 shows eigenvalues without any controller. Column 2 shows eigenvalues with PI controller, but without any Auxiliary controller. Column 3 shows eigenvalues with Auxiliary controller.

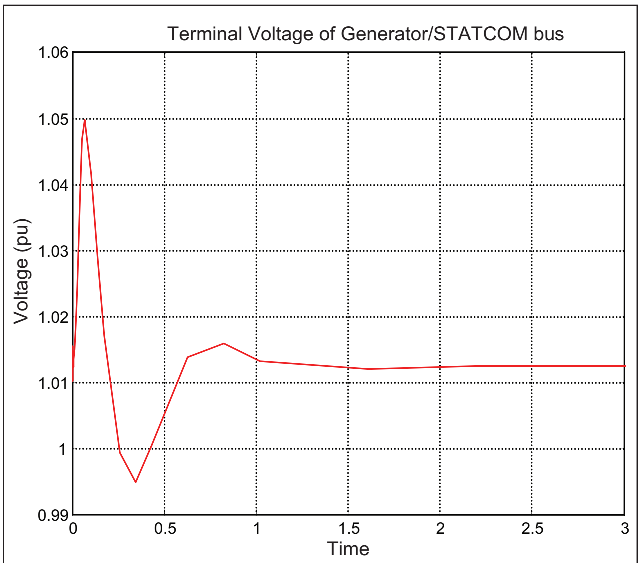

FIG. 9 TIME RESPONSE OF GENERATOR TERMINAL VOLTAGE SYSTEM

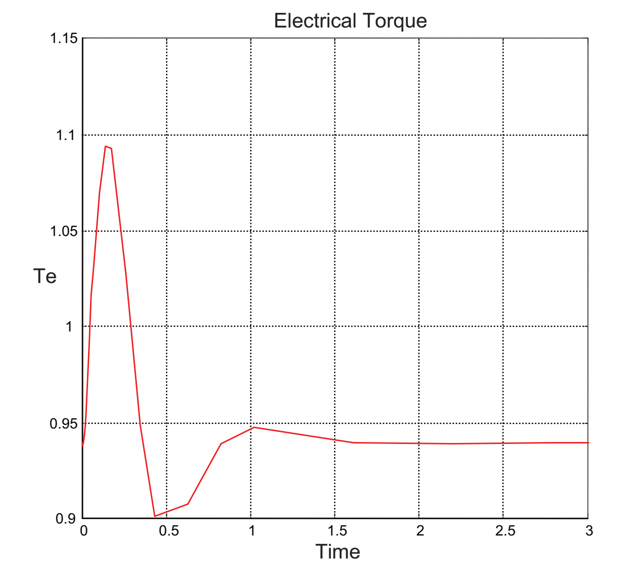

FIG. 10 TIME RESPONSE OF 'TE' SYSTEM

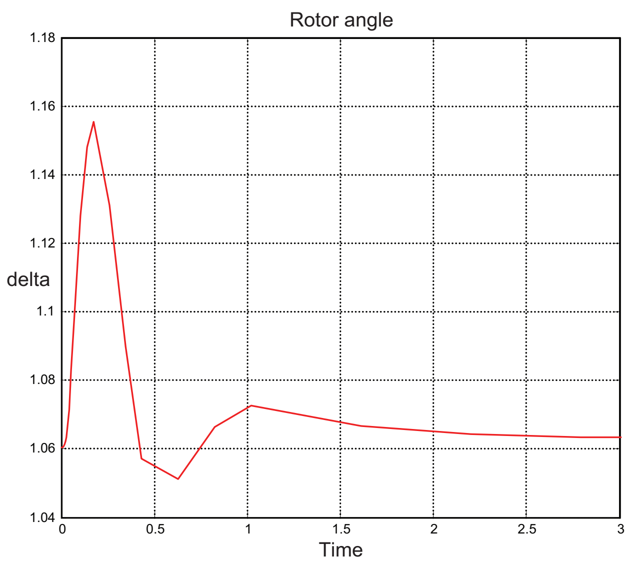

FIG. 11 TIME RESPONSE OF 'Δ'SYSTEM

Time response are shown in Figure 9-11. Disturbance is simulated in Mechanical torque. 30% disturbance in Mechanical torque is applied for 0.1 second. Figure 9 shows Time response of Generator Terminal Voltage.

Figure 10 shows Time response of Generator Electrical Torque (T_e). Figure 11 shows Time response of rotor angle 'δ'. All the values reached to steady state with in two seconds. From the eigenvalue analysis & time response, it can be concluded that accelerating frequency of Generator rotor mode passed through lead compensation is the most suitable auxiliary signal to enhance damping of STATCOM. It is able to damp all the modes of First benchmark model. Only PI controller is not sufficient to damp all the modes.

TABLE 1

Description	**First Benchmark model**	**First Benchmark model with STATCOM & PI controller**	**First Benchmark model with STATCOM, PI controller and auxiliary controller**
Supersynchronous	-4.7204±626.66i	-10.255±628.64i	-10.994±628.02i
Torsional	-4.782e-007±298.18i	-9.306e-006±298.18i	-0.000408± 298.18i
Torsional	**0.00003796±202.82i**	**0.075883±202.72i**	-1.8589 ±204.6i
Torsional	**0.011407±160.38i**	**0.06569±160.38i**	-1.1144 ±161.7i
Subsynchronous	-3.4353 ±126.6i	-7.0744 ±109.5i	-5.7927 ±117.44i
Torsional	**0.70548 ±126.92i**	**0.068843 ±126.86i**	-0.77699 ±127.51i
Torsional	**0.099234 ±100.2i**	**1.4321 ±101.35i**	-0.52707 ±94.865i
Electromechanical	-0.66416 ±11.069i	-0.68941±11.082i	-1.2769 ±10.623i
Generator	-33.015	-35.866	-35.393
Generator	-20.45	-20.844	-20.972
Generator	-3.9799	-6.6664	-7.2073
Generator	-0.31852	-0.61379	-0.59698
Statcom currents		-3101.2±10440i	-3104.3 ±10430i
PI controller & V_{dc}		-89.271±296.91i	-83.4±295.99i
Lead Compensation (Auxiliary Controller)			-37693

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APPENDIX 1

Initial Condition of the system (all quantities are in pu)

- Current supplied by Generator $I_G = 0.927 + j0.404$. Terminal Voltage of Generator is E_t. Where $E_t =$

  $$\left|E_t\right| \angle\theta_t = e_d + je_q = 1.013\angle 46.956°$$

  $=0.691+j0.7401$. In steady state, damper winding currents are zero (i.e. $I_{1d}= I_{2d}=I_{2q}=0$). $\psi_q= -I_q(X_l+X_{mq})= -0.6912$, $R_a=0$.

  $e_d= -R_aI_d-\omega\psi_q=0.6912$ (ω=1 pu). Similarly, $\psi_d= -I_d(X_l+X_{md})+ I_f X_{md} = 0.74$, $e_q= -R_a I_q + \omega \psi_d= 0.74$. ($I_f = 1.445$, $V_{fd} = 0.002032$)

- $I_s= -0.103+j0.091$. I_s is the current supplied by statcom. Statcom is consuming active power to meet out losses in R_s and R_p. STATCOM is supplying reactive component of current i.e. consuming Reactive power, because $\left|E_t\right|$ =1.013 & E_s=0.992, Therefore STATCOM is in inductive mode. Infinite bus is E_{ref}= 0.955 (along the 'D' axis). But in d-q reference frame it is 0.955<29.24°, (Figure 7).

- X_c= 0.38.

- STATCOM circuit data: R_s= 0.01, X_s = 0.15, R_p= 125, C_s = 0.015, α = 0.05°, $\theta_s=\theta_t+\alpha$. $K_{cs}=2\sqrt{6}/\pi$, $Es = K_{cs}V_{dc}$= 0.992. V_{dc}=0.63615

- PI controller data: K_p= -1, K_i= -1.25. K_d = 0.0001. Auxiliary signal data: K = 870, z = 1.5, p = 100,

- In steady state current through capacitor 'C_s' (DC side capacitor of converter) is zero. In steady state Converter consume current equal to $\frac{V_{dc}}{R_p} = 0.00509$, which is to meet out the losses of converter. R_p represents switching losses.

- $\dot{x} = V_{ref} + V_{aux} - |E_t|$

APPENDIX 2

$\theta_s= \theta_t+\alpha$, after linearization $\Delta\theta_s= \Delta\theta_t+\Delta\alpha$ but $\Delta\theta_t$=0, Hence $\Delta\theta_s= \Delta\alpha$. ($\theta_t$ is a constant due to phase locked loop).

APPENDIX 3

'ω' is the rotor angular frequency, i.e. the frequency at which d-q axis is rotating. 'ω_s' is the frequency at which D-Q axis is rotating. 'ω_G' is accelerating frequency of generator $\omega_G=\omega- \omega_s$. In steady state '$\omega$'= '$\omega_s$'=1 pu. In steady state $\omega_E = \omega_G= \omega_B = \omega_A = \omega_I = \omega_P =0$. $\omega_0 = 2\pi f$=377rad/sec. In equations 1-24 all values are in per unit except ω_0. In all equations ω_0 is multiplied with differential operator to make the system pu.