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Designing of supplementary controller for STATCOM for mitigation of sub-synchronous resonance in series compensated power system

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In FACTS devices supplementary signals are widely used to enhance damping and mitigation of Subsynchronous Resonance in Power System. Subsynchronous Resonance occurs due to series capacitor in the Power Systems. High value of series capacitive reactance may destabilize low frequency mode which is more dangerous. In this paper modeling of STATCOM with IEEE first benchmark model is presented. Then a supplementary signal is developed which is capable to make the system stable for all critical values of series compensation. The eigenvalues are presented for all four critical values of series compensation.

Keywords: *STATCOM, supplementary signals, power system stability, IEEE first benchmark model.*

1.0 INTRODUCTION

A Static Synchronous Compensator (STATCOM) is also known as an advanced static VAR compensator. It is capable of generating or absorbing reactive power [1]. STATCOM is a shunt connected device and used to control the transmission line voltage but when supplementary signal is used as a feedback signal then it can enhance the damping of the system. In STATCOM type '1' or type '2' converters can be used. In type '1' converters both K_{cs} and 'α' are controlled and a DC battery is provided in parallel with capacitor. Magnitude of E_s and voltage across DC side capacitor is controlled by controlling K_{cs} therefore reactive power is controlled through K_{cs}. Active power of STATCOM is controlled through 'α'. In type '2' converters only 'α' can be controlled and 'K_{cs}' is kept fixed. 'α' alone can control Magnitude and angle of E_s, voltage across DC side capacitor, active power consumed by the STATCOM and reactive power consumed (or supplied) by the STATCOM. For 'p' pulse converter K_{cs}= (p/6) (√6π/) [2]. For 12 pulse converter K_{cs}=2(√6π/). 'α' is the angle difference between E_t and E_s. 'α' is kept very small (maximum value of 'α' is kept ±1°). Low value of 'α' can control desired reactive power and voltage of the system. For low value of 'α', Reactive power supplied by STATCOM have linear relationship with 'α'. STATCOM consume small amount of active power [3-6]. As the 'α' varies, V_{dc} (Voltage across DC side capacitor) varies, then magnitude of 'E_s' varies. |Es| (=$K_{cs}V_{dc}$), which controls reactive power supplied (or absorbed) by the STATCOM.

2.0 STUDY SYSTEM

Study system considered is IEEE First Benchmark Model [7]. IEEE First Benchmark Model has twenty differential equations. Its generator equivalent circuit has six differential equations, Mechanical system has twelve differential equations, Transmission network (i.e. series capacitor) has two differential equations. STATCOM is incorporated at Generator bus as shown in Figure 1. X_{Ts} is the sending end transformer leakage reactance and X_{Tr} is the receiving end transformer leakage reactance.

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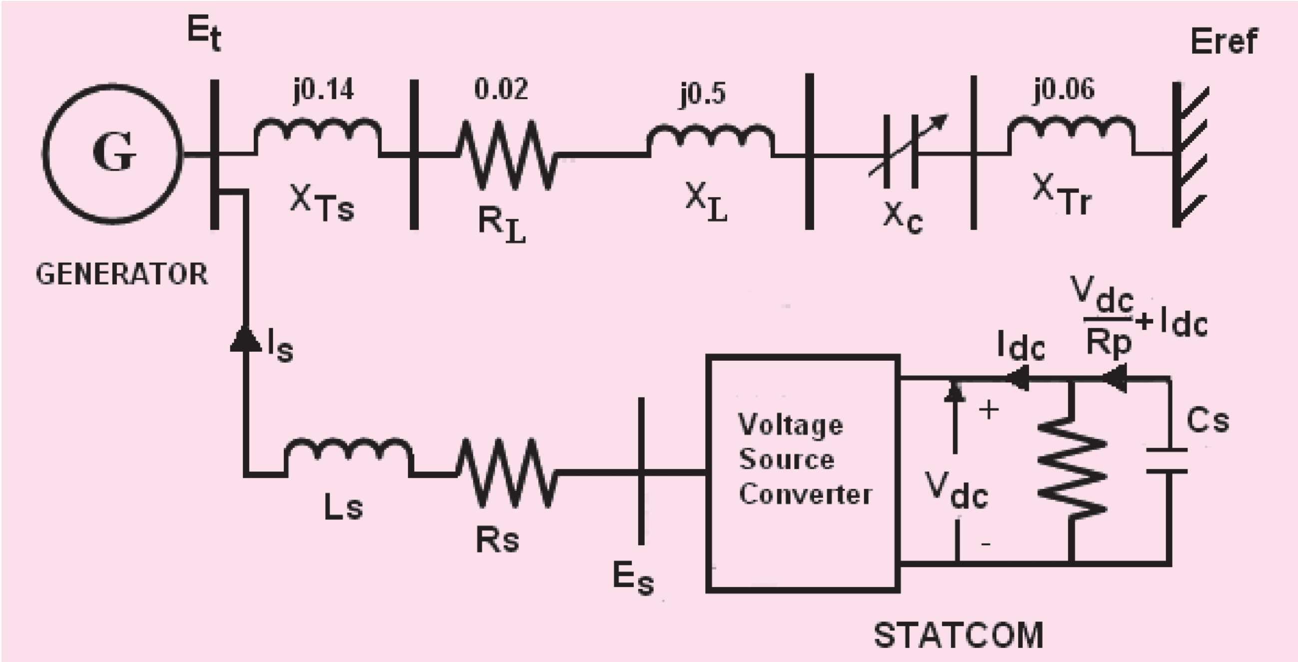

FIG. 1 STATCOM WITH FIRST BENCHMARK MODEL

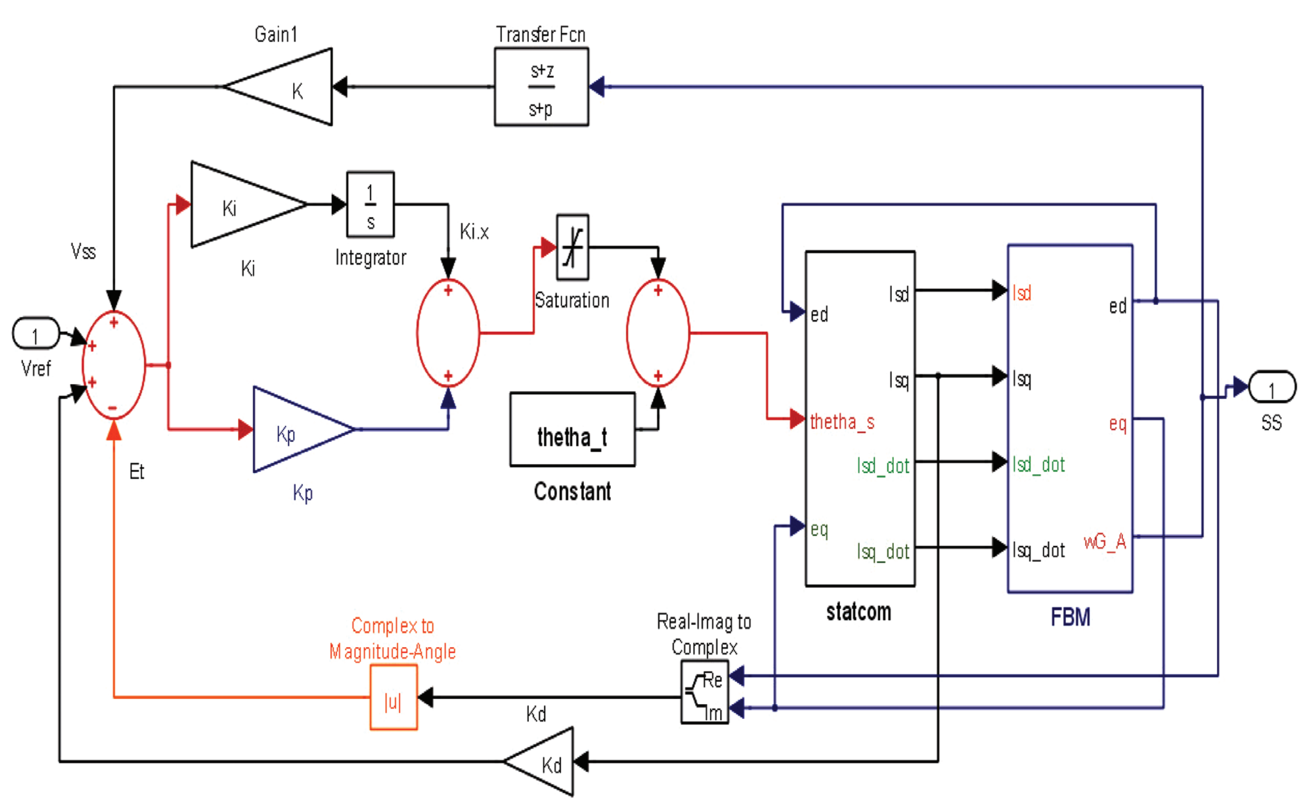

FIG. 2 SIMULINK MODEL TO SOLVE ALL DIFFERENTIAL EQUATIONS

STATCOM has three differential equations. Two differential equation of STATCOM are due to currents through STATCOM (I_{sd} & I_{sq}) and one differential equation is due to V_{dc}. Generator and turbine system have six masses. All the equations of First Benchmark Model are written as equations 1-6 & 9-20. (This contains STATCOM currents Isd & Isq also). Equations 21-23 show STATCOM dynamics. Equation 24 shows PI controller dynamics. All the equations are developed in simulink and kept in different subsystems as shown in Figure 2.

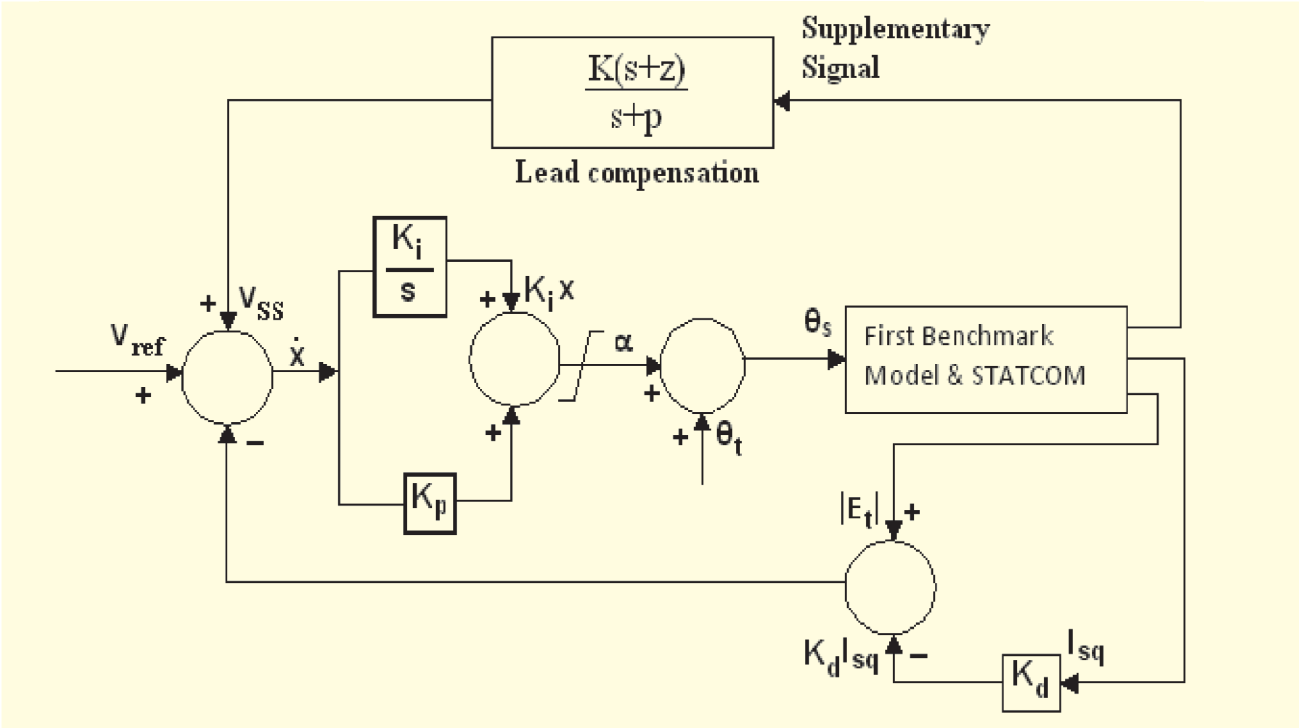

FIG. 3 BLOCK DIAGRAM OF THE COMPLETE SYSTEM WITH PI CONTROLLER AND SUPPLEMENTARY SIGNAL

Output of STATCOM is current I_{sd}, I_{sq}, $\dot{I}_{sd}$ and $\dot{I}_{sq}$. Input to STATCOM is STATCOM bus voltage (or Generator terminal voltage) e_d & e_q. By keeping all the differential equations in a subsystem these can be linearized and subsequently eigenvalues, impulse response, root locus, observability etc. can be obtained. The block diagram of system is shown in Figure 3. The whole system is kept in one subsystem as shown in Figure 4 to linearise the system and obtain the eigenvalues and root locus. Generator circuit is shown in Figures 5 & 6. Equations 1-6 are obtained from Figures 5 & 6. I_{1d}, I_{1q}, I_{2q} are the damper winding currents. I_f is field winding current. All the equations 1-26 are written in d-q reference frame. d-q axis is machine reference frame and D-Q axis is network reference frame (Figure 7). D-Q axis is rotating at synchronous speed. E_{ref} is along the 'D' axis. E_{ref} is infinite bus bar. 'A' & 'B' are the output equations of FMB. (This is input to the STATCOM). Output of PI controller is 'α', which is input to the STATCOM. Equation 'C' is the output equation of PI controller. Angle of bus E_s is $\theta_s=\theta_t+\alpha$. θ_t is angle of E_t. In case of disturbance θ_t varies but as an input to θ_s it remain constant due to phase locked loop (PLL). PLL synchronizes GTO pulses to the system voltage and provides a reference angle to the measurement system. In lineaisation $\Delta\theta_s=\Delta\theta_t+\Delta\alpha$, but $\Delta\theta_t=0$. Hence $\Delta\theta_s=\Delta\alpha$. Feedback supplementary signal is passed through lead compensation.

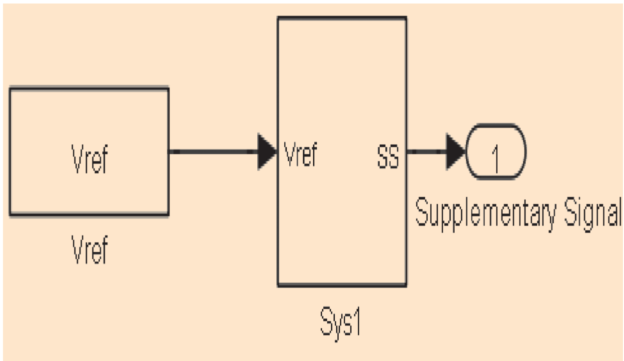

FIG. 4 SUBSYSTEM TO KEEP WHOLE SYSTEM WITHOUT SUPPLEMENTARY SIGNAL

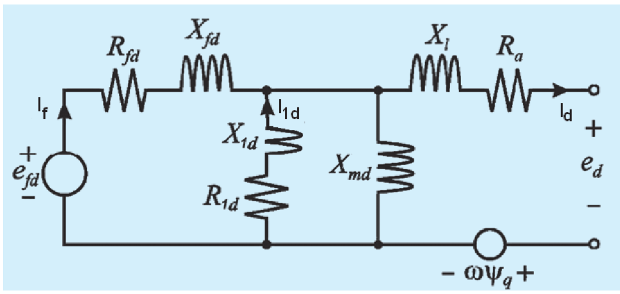

FIG. 5 GENERATOR D - AXIS MODEL

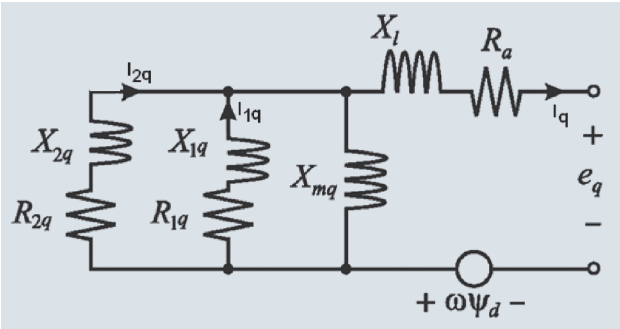

FIG. 6 GENERATOR Q - AXIS MODEL

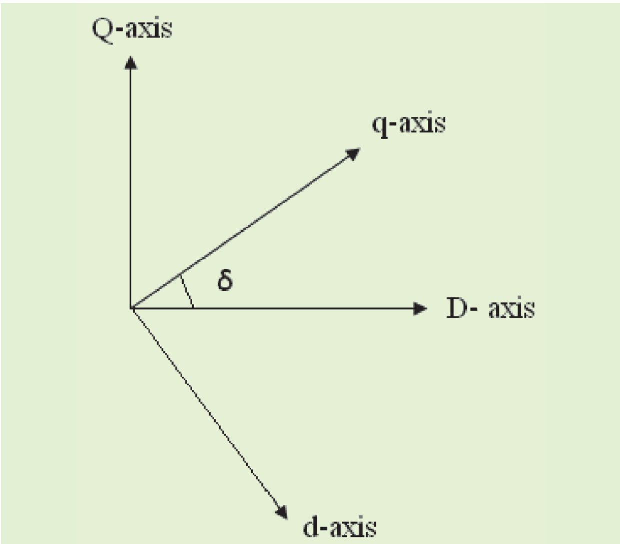

FIG. 7 d-q AXIS (MACHINE REFERENCE FRAME) & D-Q AXIS (NETWORK REFERENCE FRAME)

3.0 DIFFERENTIAL EQUATION OF THE SYSTEM

3.1 Generator Equations

$$e_d = -R_a I_d - \frac{(X_l+X_{md})}{\omega_0}\dot{I}_d + \frac{X_{md}}{\omega_0}\dot{I}_f + \frac{X_{md}}{\omega_0}\dot{I}_{1d} - \omega\psi_q$$

$$\psi_q = -(X_l+X_{mq})I_q + X_{mq}I_{1q} + X_{mq}I_{2q}$$

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

$$e_q = -R_a I_q - \frac{(X_l+X_{mq})}{\omega_0}\dot{I}_q + \frac{X_{mq}}{\omega_0}\dot{I}_{1q} + \frac{X_{mq}}{\omega_0}\dot{I}_{2q} + \omega\psi_d$$

$$\psi_d = -(X_l+X_{md})I_d + X_{md}I_f + X_{md}I_{1d}$$

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

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

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

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

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

3.2 Mechanical System Equations

Exciter equations are :

$$2H_E\,\dot{\omega}_{E\_A} = K_{GE}(\delta - \delta_E) - D_E\omega_{E\_A} \qquad \text{....(7)}$$

$$\frac{1}{\omega_0}\dot{\delta}_E = \omega_{E\_A} \qquad \text{....(8)}$$

ω_{E_A} is accelerating frequency of the exciter mode. $\omega_{E\_A} = \omega_E - \omega_S$ where ω_E is the angular speed of exciter mode. ω_S is the synchronous speed of rotating reference frame. In steady state $\omega_E = \omega_S = 1$ pu. In Transient period ω_E may be other than 1, but $\omega_S = 1$. Hence $\dot{\omega}_s = 0$.

Therefore equations 7 & 8 can be written as

$$2H_E\,\dot{\omega}_E = K_{GE}(\delta - \delta_E) - D_E(\omega_E - \omega_S) \qquad \text{....(9)}$$

$$\frac{1}{\omega_0}\dot{\delta}_E = \omega_E - \omega_S \qquad \text{....(10)}$$

similarly generator rotor mode equations are

$$2H_G\dot{\omega}=K_{BG}(\delta_B-\delta)-T_e-K_{GE}(\delta-\delta_E)-D_G(\omega-\omega_S) \quad ....(11)$$

$$\frac{1}{\omega_0}\dot{\delta}=\omega-\omega_S \quad ....(12)$$

where, T_e is electrical torque generated

$T_e=\psi_d I_q-\psi_q I_d$

$T_e=-(X_l+X_{md})I_d I_q+X_{md}I_f I_q+X_{md}I_{1d}I_q+(X_l+X_{mq})I_q I_d-X_{mq}I_{1q}I_d-X_{mq}I_{2q}I_d$

LP-B turbine equations are

$$2H_B\dot{\omega}_B=T_{LPB}+K_{AB}(\delta_A-\delta_B)-K_{BG}(\delta_B-\delta)-D_B(\omega_B-\omega_S) \quad ....(13)$$

$$\frac{1}{\omega_0}\dot{\delta}_B=\omega_B-\omega_S \quad ....(14)$$

LP-A turbine equations are

$$2H_A\dot{\omega}_A=T_{LPA}+K_{IA}(\delta_I-\delta_A)-K_{AB}(\delta_A-\delta_B)-D_A(\omega_A-\omega_S) \quad ....(15)$$

$$\frac{1}{\omega_0}\dot{\delta}_A=\omega_A-\omega_S \quad ....(16)$$

IP turbine equations are

$$2H_I\dot{\omega}_I=T_{IP}+K_{HI}(\delta_H-\delta_I)-K_{IA}(\delta_I-\delta_A)-D_I(\omega_I-\omega_S) \quad ....(17)$$

$$\frac{1}{\omega_0}\dot{\delta}_I=\omega_I-\omega_S \quad ....(18)$$

HP turbine equations are

$$2H_H\dot{\omega}_H=T_{HP}-K_{HI}(\delta_H-\delta_I)-D_H(\omega_H-\omega_S) \quad ....(19)$$

$$\frac{1}{\omega_0}\dot{\delta}_H=\omega_H-\omega_S \quad ....(20)$$

3.3 Transmission Line Equations

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

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

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

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

$$\frac{\dot{V}_{cd}}{\omega_0}=\omega V_{cq}+X_c(I_d+I_{sd}) \quad ....(21)$$

$$\frac{\dot{V}_{cq}}{\omega_0}=-\omega V_{cd}+X_c(I_q+I_{sq}) \quad ....(22)$$

where X_{TL} is the effective reactance of Transmission line i.e. $X_{TL}=X_{TS}+X_L+X_{Tr}$

(V_{cd} and V_{cq} are the voltage across series capacitor)

3.4 Statcom Circuit Equations

$$E_{sd}-e_d=R_s I_{sd}-\omega X_s I_{sq}+\frac{X_s\dot{I}_{sd}}{\omega_0} \quad ....(23)$$

$$E_{sq}-e_q=R_s I_{sq}+\omega X_s I_{sd}+\frac{X_s\dot{I}_{sq}}{\omega_0} \quad ....(24)$$

$E_{sd}=K_{cs}V_{dc}\cos\theta_s$, $E_{sq}=K_{cs}V_{dc}\sin\theta_s$

Linearization of E_{sd} & E_{sq} is given here:

$$\Delta E_{sd}=K_{cs}.\Delta V_{dc}.\cos\theta_{s0}+K_{cs}V_{dc0}(-\sin\theta_{s0})\Delta\alpha$$

$$\Delta E_{sq}=K_{cs}.\Delta V_{dc}.\sin\theta_{s0}+K_{cs}V_{dc0}\cos\theta_{s0}\Delta\alpha$$

STATCOM DC side Power and AC side active power at node E_s must be equal. In steady state:

$$V_{dc}I_{dc}=\text{Real}\left[(E_{sd}+jE_{sq})(I_{sd}+jI_{sq})^*\right]=E_{sd}I_{sd}+E_{sq}I_{sq}$$

$$\text{or, } V_{dc}I_{dc}=K_{cs}V_{dc}\cos\theta_s I_{sd}+K_{cs}V_{dc}\sin\theta_s I_{sq}$$

$$\text{or, } I_{dc}=K_{cs}\cos\theta_s I_{sd}+K_{cs}\sin\theta_s I_{sq}$$

This is the expression of DC side current. In steady state numerical value of I_{dc} should be negative because R_p is consuming DC power, while I_{dc} shown in Figure 1 is in opposite direction. Current through DC side capacitor

$$= C_s \dot{V}_{dc} = -(I_{dc} + \frac{V_{dc}}{R_p})$$

$$\text{or, } \dot{V}_{dc} = -\frac{1}{C_s}(\frac{V_{dc}}{R_p} + K_{cs} I_{sd} \cos\theta_s + K_{cs} I_{sq} \sin\theta_s) \quad ....(25)$$

3.5 PI Controller Equation

$$\dot{x} = V_{aux} + V_{ref} - |E_t| + K_d I_{sq} \quad ....(26)$$

Output equation of PI controller is:

$$\alpha = K_i x + K_p \dot{x} \quad ....(C)$$

All the differential equations are developed in simulink and linearized in simulink.

4.0 SUPPLEMENTARY CONTROLLER DESIGN

To design a supplementary controller whole system is kept in the subsystem as shown in Figure 4. The system is termed as 'sys1'. Output of system may be any state variable or a quantity (eigenvalues do not depend on output). Various supplementary signals are tested such as deviation of speed of generator rotor mode (ω-ω_s), deviation in reactive power (ΔQ), deviation in active power (ΔP), deviation in generator current magnitude (ΔI), deviation in STATCOM current magnitude (ΔI_s), deviation in Statcom DC side capacitor current ($C_s \dot{V}_{dc}$). It is found that ω-ω_s is most suitable supplementary signal. It is shown in Table 1-4 that with this supplementary signal all eigenvalues are in the left Half of s-plane. Table 1 shows the eigenvalues when X_c= 0.185. This critical value of X_c makes the Torsional mode 4 most unstable, because SSR frequency (subsynchronous frequency) is also in the range of 202. When supplementary signal ω-ω_s is incorporated then all eigenvalues are shifted to left half of s-plane.Similarly Table 2 shows the eigenvalues when X_c= 0.284. This critical value of X_c makes the Torsional mode 3 most unstable, because SSR frequency is also in the range of 160. In this case also supplementary signal makes the system stable.Table 3 shows the eigenvalues when X_c= 0.379. This critical value of X_c tends the Torsional mode 2 most unstable, because SSR frequency is also in the range of 126. In this case also supplementary signal makes the system stable. Table 4 shows the eigenvalues when X_c= 0.473. This critical value of X_c makes the Torsional mode 1 most unstable, because SSR frequency is also in the range of 98. In this case also supplementary signal makes the system stable.

Time response for various quantities and shaft torque are shown in Figures 8-15. Time response is shown against X_c= 0.473.

5.0 CONCLUSION

From the above analysis it can be concluded that supplementary signal deviation in speed of generator rotor mode is a very suitable supplementary signal which can make the system against all four critical values of X_c. In our research we have also found that when Natural damping is kept equal to one for all six modes then without supplementary signal system is unstable against aforesaid four critical values of X_c but system is stable when supplementary signal is incorporated.

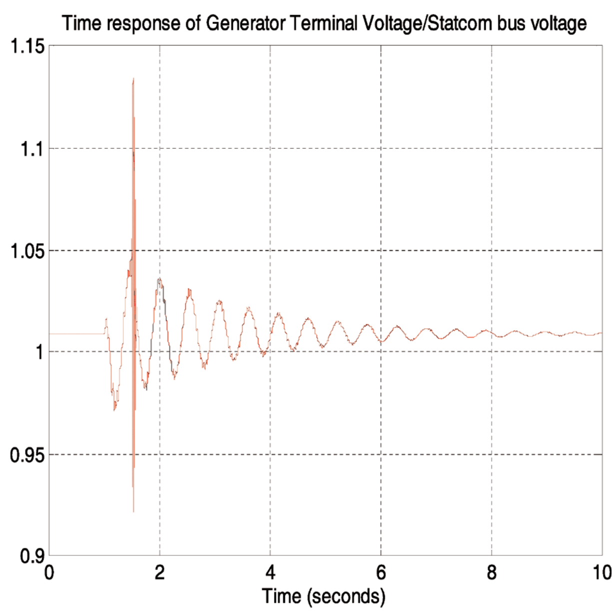

FIG. 8 TIME RESPONSE OF GENERATOR TERMINAL VOLTAGE

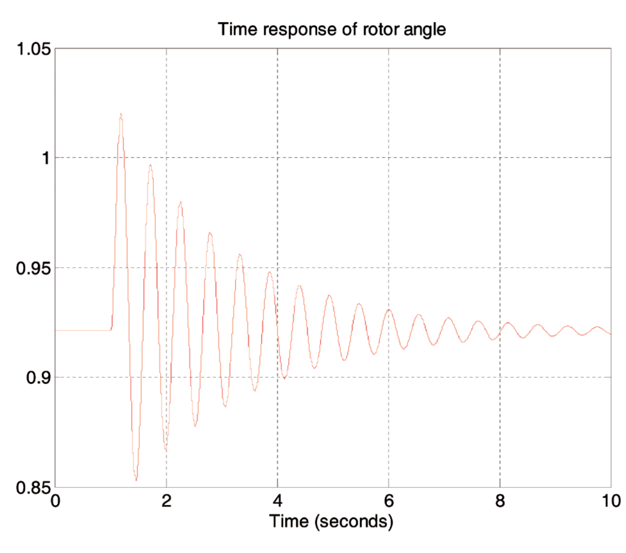

FIG. 9 TIME RESPONSE OF ROTOR ANGLE ‘δ’

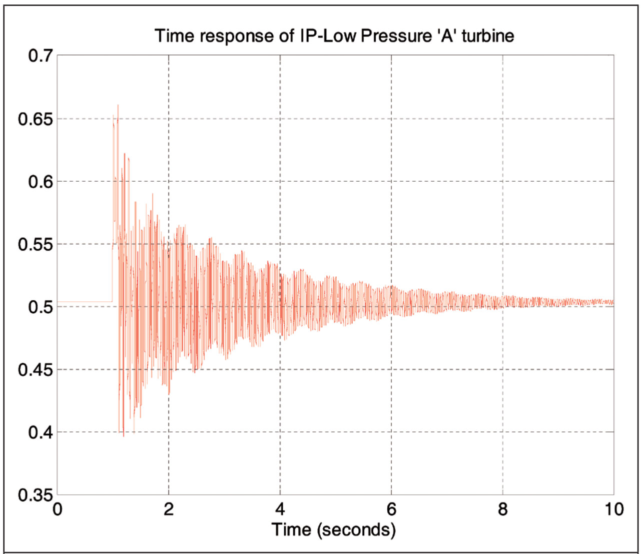

FIG. 12 SHAFT TORQUE BETWEEN IP TURBINE-LP- A TURBINE

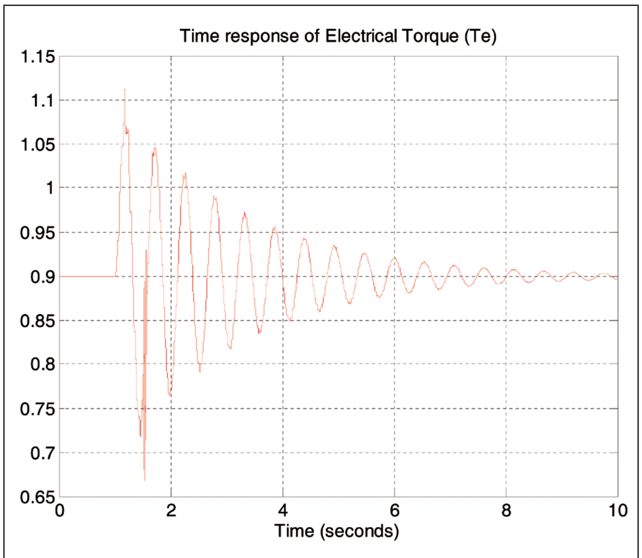

FIG. 10 TIME RESPONSE OF ELECTRICAL TORQUE ‘T_E’

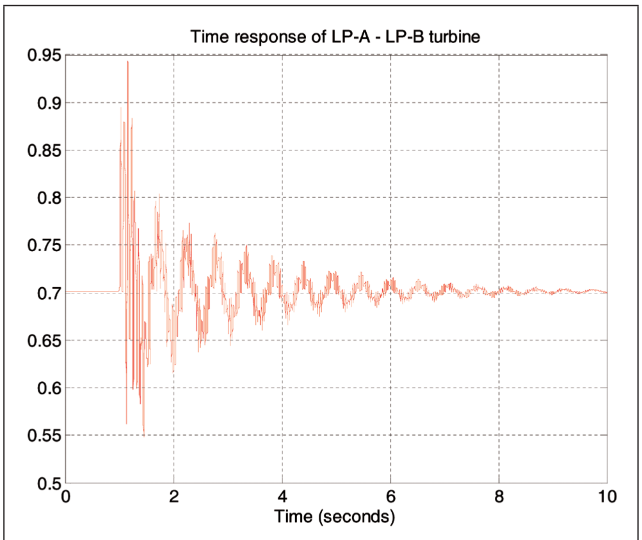

FIG. 13 SHAFT TORQUE BETWEEN LP-A TURBINE - LP- B TURBINE

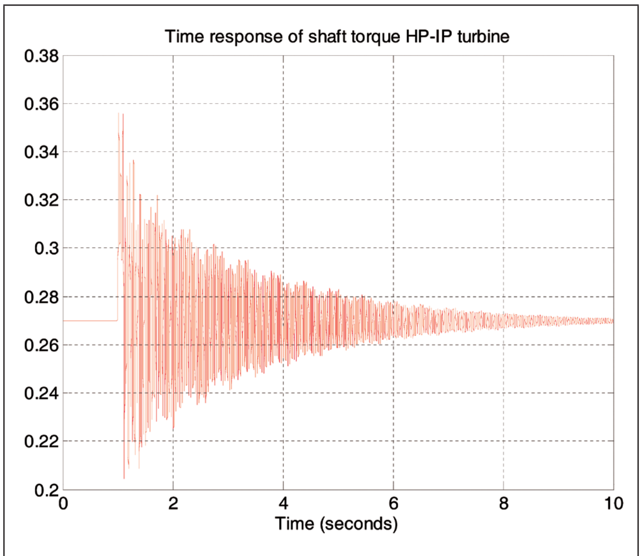

FIG. 11 SHAFT TORQUE BETWEEN HP TURBINE - IP TURBINE

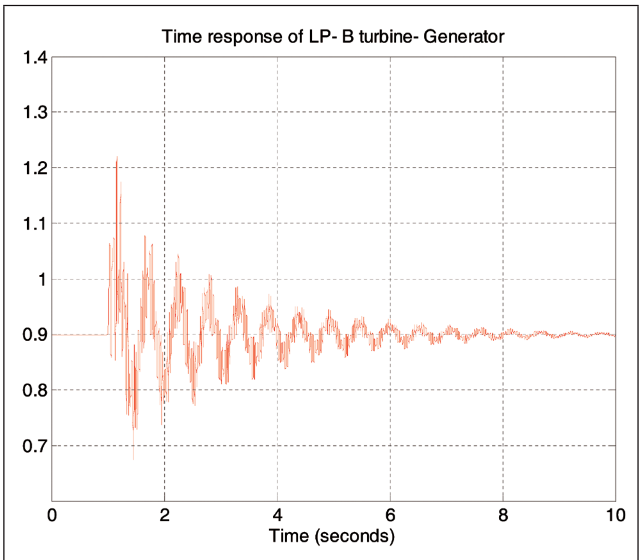

FIG. 14 SHAFT TORQUE BETWEEN LP-B TURBINE-GENERATOR

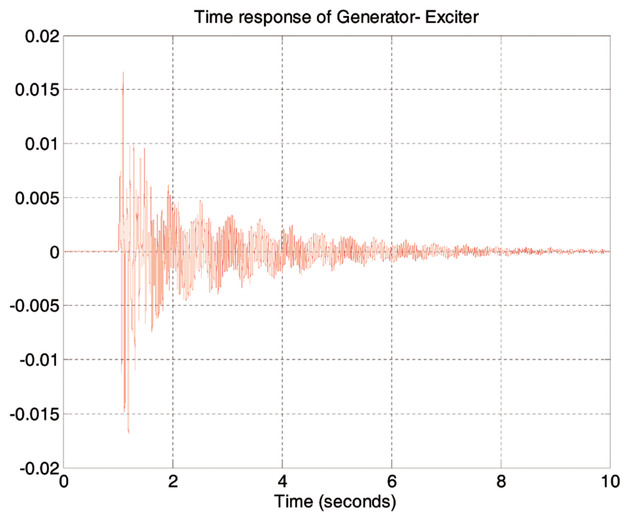

FIG. 15 SHAFT TORQUE BETWEEN GENERATOR-EXCITER

6.0 APPENDICES

Appendix A

- Initial Condition of the system at X_c=0.473 (all quantities are in pu, unless otherwise specified). Generator circuit data: R_a=0, X_l=0.13, X_{md}=1.66, R_{1d}=0.00408, X_{1d}=0.0055, R_{fd}=0.001406, X_{fd}=0.062, X_{mq}=1.58, R_{1q}=0.00822, X_{1q}=0.095, R_{2q}=0.01406, X_{2q}=0.326.
- Power supplied by generator P_g = 0.9, PF= 0.9(lagging). Current supplied by Generator I_G=0.914+j0.387. Terminal Voltage of Generator is E_t.

  Where $E_t = |E_t|\angle\theta_t = e_d + je_q = 1.0089\angle 49.04°$ In steady state, damper winding currents are zero (i.e. I_{1d}= I_{2d}=I_{2q}=0). ψ_q= -0.6613, ψ_d= 0.762. I_f = 1.445.
- I_s=-0.1717+j0.1442. 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 consuming Reactive power, because $|E_t|$ =1.0089 & $|E_s|$=0.975, Therefore STATCOM is in inductive mode. Infinite bus is E_{ref} = 0.963 (along the 'D' axis). But in d-q reference frame it is $0.963\angle 37.23°$, i.e. δ= 52.77° (Figure 7). STATCOM circuit data : R_s= 0.01, X_s=0.15, R_p=125, C_s=0.015, α=0.1°, $\theta_s=\theta_t+\alpha$. $K_{cs}=2\sqrt{6}/\pi$, $|E_s|$= $K_{cs}V_{dc}$=0.975, V_{dc}=0.625, Active Power consumed by STATCOM (i.e R_s and R_p)=0.00363, Active Power consumed by R_s= 0.0005028, Active Power consumed in switching losses (i.e. in R_p) = 0.003129. In steady state current through capacitor 'C_s' (DC side capacitor of converter) is zero. In steady state Converter consume current equal to $\frac{V_{dc}}{R_p}$, which is to meet out the losses of converter. R_p represents switching losses. I_{dc}= -0.005003. PI controller data: K_p= -1, K_i= -3.75 sec^{-1}. K_d= 0.001, Supplementary controller data: K=15, z=20 sec^{-1}, p=100 sec^{-1}.
- In steady State T_e= T_m=T_{HP}+T_{IP}+ T_{LPA}+T_{LPB}=0.9 (T_m is mechanical Torque applied).
  T_{HP}=0.3T_M, T_{IP}=0.26T_M, T_{LPA}=0.22T_M, T_{LPB}=0.22T_M, δ_H=0.975, δ_I=0.962, δ_A=0.947, δ_B=0.934, δ= δ_E =0.921 radian. Torque between HP-IP turbine=0.3T_m= $K_{HI}(\delta_H$- $\delta_I)$=0.270, Torque between IP- LP-A turbine=0.56T_m = $K_{IA}(\delta_I$- $\delta_A)$=0.504, Torque between LP-A– LP-B turbine=0.78T_m= $K_{AB}(\delta_A$- $\delta_B)$=0.701,Torque between LP-B- Generator=T_m= $K_{BG}(\delta_B$- δ) =0.9, Torque between Generator- Exciter=0. Natural Damping is zero i.e. D_E= D_G= D_B= D_A= D_I= D_H=0. The mechanical system with steady state conditions is shown in Figure 16. Values of K_{KI} K_{IA} etc. and H_E, H_G etc. are given in reference [7].

ω_0 = 2πf = 377rad/sec. In equations 1-26 all values are in per unit except ω_0, K_i and lead compensation data. Unit of x is seconds and $\dot{x}$ is pu. In lead compensation pole and zero have the unit $sec.^{-1}$. Unit of Inertia constants H_E, H_G, H_B, H_A,H_I, H_H are seconds.

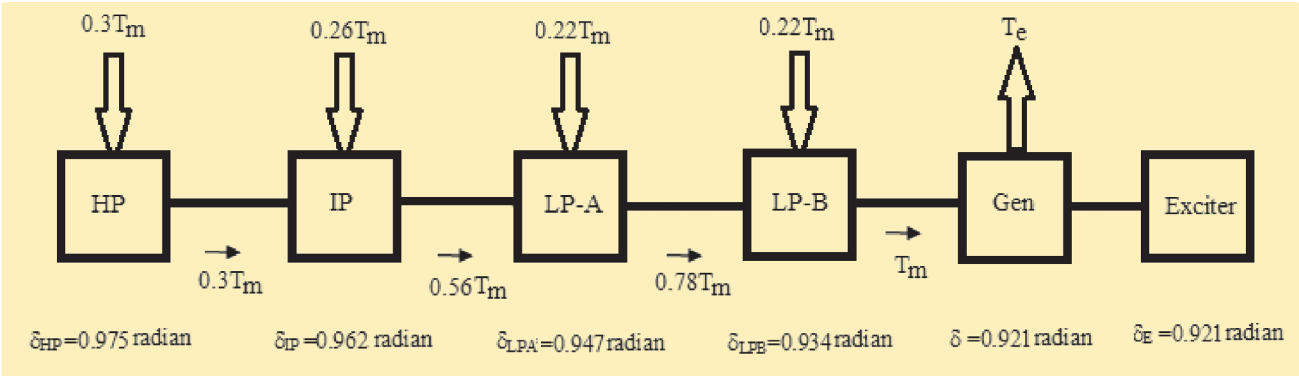

FIG. 16 VARIOUS MASSES OF GENERATOR AND TURBINE SYSTEM

Appendix B

ω_E, ω, ω_B, ω_A, ω_I, ω_H are the speed of all masses. In steady state $\omega_E = \omega = \omega_B = \omega_A = \omega_I = \omega_H = \omega_s = 1$ pu. In Transient period ω_s=1 pu, but the value of ω_E, ω, ω_B, ω_A, ω_I, ω_H may be different from 1 pu. 'ω' is the generator mode frequency and the frequency at which d-q axis is rotating. 'ω_s' is the frequency at which D-Q axis is rotating.

Linerarization of two equations 9 & 10 are given here for the convinience of the readers,

$$2H_E \Delta \dot{\omega}_E = K_{GE}(\Delta\delta - \Delta\delta_E) - D_E \Delta\omega_E \quad -(L9)$$

$$\frac{1}{\omega_0}\Delta\dot{\delta}_E = \Delta\omega_E \quad -(L10)\ (\Delta\omega_S = 0)$$

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TABLE 1

EIGENVALUES WITH SUPPLEMENTARY SIGNAL ω-ω_S WITH A LEAD COMPENSATION (AT X_C=0.185), P_G =0.9, PF=0.9 (LAGGING)

Description	Eigenvalues of First Benchmark Model without any controller	Eigenvalues with STATCOM	Eigenvalues with STATCOM and SupplementaryController
Supersynchronous	-4.6421±551.15i	-5.2555±550.47i	-5.5587±550.17i
Torsional Mode No. 5	-1.3799e-007±298.18i	-3.7351e-06±298.18i	-6.9351e-06±298.18i
Torsional Mode No. 4	1.6445±202.81i	0.76248±202.74i	-5.2892±200.79i
Torsional Mode No. 3	0.013438±160.74i	0.056129±160.72i	-0.24877±160.37i
Torsional Mode No. 2	0.00094107±127.04i	0.0068329±127.04i	-0.044871±126.99i
Torsional Mode No. 1	0.00048159± 99.317i	0.048232±99.258i	-0.40271±98.93i
Subsynchronous	-5.2438±202.58i	-11.296±202.01i	-4.8678±206.25i
Electromechanical mode	-0.43436±9.4829i	-0.36163±9.0812i	-0.45687±9.0046i
Statcom currents		-129.73±2286.6i	-130.29±2286.3i
V_{dc}		-223.69	-217.92
Lead Compensation			-102.76
others	-32.498	-32.214	-32.357
	-20.34	-21.721	-21.714
	-3.3559	-9.871	-9.9431
	-0.25653	-1.0991	-1.068
		-1.4044	-1.4396

TABLE 2

EIGENVALUES WITH SUPPLEMENTARY SIGNAL ω-ω_SWITH A LEAD COMPENSATION (AT X_C=0.284), P_G =0.9, PF=0.9 (LAGGING)

Description	Eigenvalues of First Benchmark Model without any controller	Eigenvalues with STATCOM	Eigenvalues with STATCOM and SupplementaryController
Supersynchronous	-4.6867±592.8i	-6.0257±591.98i	-6.376±591.66i
Torsional Mode No. 5	-3.9346e-07±298.18i	-4.1297e-06±298.18i	-5.6414e-06±298.18i
Torsional Mode No. 4	0.011845±202.72i	0.032417±202.7i	-0.4541±204.19i
Torsional Mode No. 3	1.5491±160.65i	0.50523±160.45i	-2.0409±160.58i
Torsional Mode No. 2	0.006224±127.09i	0.033788 ±127.07i	-0.054356±126.91i
Torsional Mode No. 1	0.013663±99.573i	0.14009±99.498i	-0.26428±98.681i
Subsynchronous	-4.7406±160.8i	-14.5±158.7i	-11.277±160.53i
Electromechanical mode	-0.54831±10.385i	-0.41946±9.9204i	-0.50479±9.8282i
Statcom currents		-129.72±2286.7i	-130.29±2286.5i
V_{dc}		-215.67	-211.53
Lead Compensation			-101.3
others	-32.724	-32.343	-32.499
	-20.384	-21.709	-21.702
	-3.567	-9.8483	-9.9203
	-0.3075	-1.1193	-1.0819
		-1.3775	-1.4203

TABLE 3

EIGENVALUES WITH SUPPLEMENTARY SIGNAL ω-ω_S WITH A LEAD COMPENSATION (AT X_C=0.379), P_G=0.9, PF=0.9 (LAGGING)

Description	**Eigenvalues of First Benchmark Model without any controller**	**Eigenvalues with STATCOM**	**Eigenvalues with STATCOM and SupplementaryController**
Supersynchronous	-4.7182±626.31i	-6.7181±625.45i	-7.0939±625.14i
Torsional Mode No. 5	-5.0166e-07±298.18i	-4.3304e-06 ±298.18i	-4.4248e-06±298.18i
Torsional Mode No. 4	0.00070737±202.81i	0.0048066±202.78i	-0.34714±203.95i
Torsional Mode No. 3	0.014779±160.36i	0.059281±160.39i	-0.54808±161.33i
Torsional Mode No. 2	0.76361±126.97i	0.13377±126.96i	-0.38242±126.94i
Torsional Mode No. 1	0.097558±100.29i	0.72912±99.885i	-0.3244±97.706i
Subsynchronous	-3.5038±126.82i	-18.148±122.28i	-16.07±125.98i
Electromechanical mode	-0.70054±11.35i	-0.45221±10.817i	-0.52844±10.7i
Statcom currents		-128.38±2288.7i	-128.94±2288.5i
V_{dc}		-205.96	-203.64
Lead Compensation			-99.155
others	-33.021	-32.363	-32.534
	-20.443	-21.728	-21.72
	-3.8582	-9.8743	-9.9464
	-0.3579	-1.1611	-1.1081
		-1.3289	-1.3886

TABLE 4

EIGENVALUES WITH SUPPLEMENTARY SIGNAL ω-ω_S WITH A LEAD COMPENSATION (AT X_C=0.473), P_G=0.9, PF=0.9 (LAGGING)

Description	**Eigenvalues of First Benchmark Model without any controller**	**Eigenvalues with STATCOM**	**Eigenvalues with STATCOM and SupplementaryController**
Supersynchronous	-4.743±655.53i	-7.3405±654.73i	-7.7269±654.43i
Torsional Mode No. 5	-5.7053e-07±298.18i	-4.4858e-06±298.18i	-2.2407e-06±298.18i
Torsional Mode No. 4	-0.001768±202.85i	-0.0026789±202.82i	-0.31307±203.88i
Torsional Mode No. 3	0.0010519± 160.47i	0.01664±160.46i	-0.38086±161.19i
Torsional Mode No. 2	0.0050084±126.93i	0.024419±126.96i	-0.21189±127.16i
Torsional Mode No. 1	5.0657±98.896i	1.3138±98.446i	-4.0006±98.086i
Subsynchronous	-6.9566±98.739i	-22.252±90.553i	-17.069±93.921i
Electromechanical mode	-0.93128±12.519i	-0.3943±11.892i	-0.45931±11.725i
Statcom currents		-125.93±2291.9i	-126.47±2291.6i
V_{dc}		-194.4	-194.43
Lead Compensation			-95.582
others	-33.44	-32.205	-32.392
	-20.527	-21.763	-21.755
	-4.265	-9.9189	-9.9905
	-0.41811	-1.2362±0.10198i	-1.1866
			-1.2934