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Damping of Oscillations in Series Compensated Power System through Wide Area Damping Controller of STATCOM

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In FACTS devices auxiliary signals are widely used to enhance damping and mitigation of Subsynchronous Resonance in Power System. Choice of auxiliary signal is indeed a difficult choice. Auxiliary signal may be local signal or remote signal. In this paper STATCOM is installed in the middle of Power system and it is shown that deviation in speed of generator rotor is one of the most suitable auxiliary signal. This signal is a remote signal hence a suitable time delay is considered. Study system is IEEE first benchmark model. Modeling of STATCOM with IEEE first benchmark model is presented in detail. All the differential equations and initial conditions are presented in the paper. Both, small signal and large signal stabilities are carried out.

Keywords: *STATCOM, auxiliary signals, power system stability, IEEE first benchmark model, Wide area damping controller.*

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. STATCOM is a shunt connected device and used to control the transmission line voltage but when auxiliary signal (AS) is used as a feedback signal then it can enhance the damping of the system. There may be two types of AS. One is locally measured signal (available at STATCOM or SVC bus) another is remote signal (available at generator bus or in any other parallel lines). It is almost established fact that if FACTS controller are at generator end then speed deviation in generator rotor is most suitable AS. If FACTS controller is away from generator end then in that case choice of AS is a very difficult choice. There are lot of discussions among research scholars about the choice between locally measurable signals and remotely communicated signals [1-5]. In this paper it is shown that speed deviation of generator rotor is a suitable AS in case of STATCOM installed in the middle of transmission line. Wide range of time delay is also considered for this remote signal. The damping controller in such case is called wide area damping controller. Though there may be oscillations in line current and voltage but the main aim of damping controller is to enhance the stability of turbine-generator set, particularly in a series compensated transmission system [6-9]. In STATCOM, type ‘1’ or type ‘2’ voltage source converters (VSC) 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 K_{cs} therefore reactive power is controlled through K_{cs}. Active power of STATCOM is controlled through ‘α’. In type 1 converter, STATCOM can supply small amount of active power and angle of voltage at

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point of connection can be controlled. In type '2' converters 'α' can be controlled and 'K_{cs}' is kept fixed. Alone 'α' 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. In type 2 converters STATCOM cannot supply active power. It consume small amount of active power to compensate losses in transformer and switching losses in VSC [10-15]. In this paper type 2 converter is used. Generally series compensation may be 20% to 60%, therefore in this paper eigenvalue analysis (small signal stability) results are shown at 20% and 60% series compensation. Transient response (large signal stability) results are shown at 60% series compensation.

2.0 STUDY SYSTEM

Study system is IEEE First Benchmark model (FBM) [16]. In FBM, sending end transformer reactance (X_{Ts}) is 0.14 pu, transmission line reactance is given 0.5 pu, receiving end transformer reactance (X_{Tr}) is 0.06 pu and transmission line resistance is 0.02 pu. In the present case STATCOM is installed in the middle of transmission line. Hence all values shown in Figure 1 can be easily understood. Study system has total twenty four differential equations without auxiliary controller. (Two are due to STATCOM current I_{sD} and I_{sQ}, one is due to STATCOM DC side capacitor and PI controller each and twenty due to IEEE First Benchmark model [17-20]. All differential equations are presented here. Generator equations are presented in d-q frame while STATCOM equations, Transmission system equations are presented in D-Q frame.

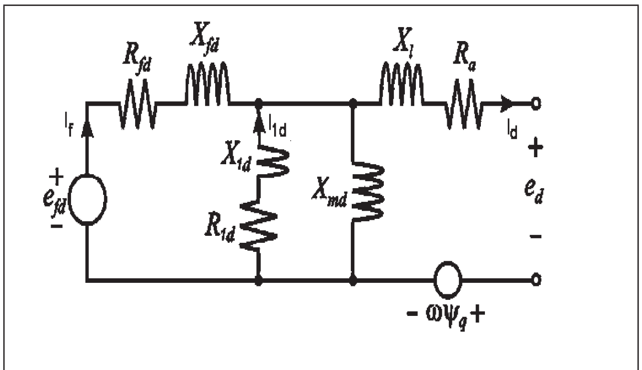


FIG. 1. GENERATOR D-AXIS EQUIVALENT CIRCUIT

2.1 Generator System Equations

Generator equivalent circuit is shown in Figures 2-3. Generator has three damper windings, one is at d-axis and two are at q-axis. Xl is leakage reactance of generator and Ra is its armature winding resistance. I1d, I1q, and I2q are the damper winding currents and If is field winding current. In steady state damper winding currents are zero. D-Q axes represent network reference frame and d-q axes represent machine reference frame as shown in Figure 4. D-Q axes frame and d-q axes frame both are rotating at synchronous speed in steady state. In transient period, speed of D-Q reference frame remains constant but speed of d-q frame oscillates, hence rotor angle 'δ' oscillates. In generator circuit, I_d and I_q (currents in generator circuit) are considered two different DC quantities instead of two components of a AC quantity. Generator equations, obtained from Figures 2-3 are as follows:

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

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

$$-\frac{(X_l + X_{md})}{\omega_0}\dot{I}_d + \frac{X_{md}}{\omega_0}\dot{I}_f + \frac{X_{md}}{\omega_0}\dot{I}_{1d}$$

$$= R_a I_d - \omega(X_l + X_{mq})I_q + \omega X_{mq} I_{1q} + \omega X_{mq} I_{2q} + e_d \quad \text{....(1)}$$

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

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

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

$$= \omega(X_l + X_{md})I_d + R_a I_q - \omega X_{md} I_f - \omega X_{md} I_{1d} + e_q \quad \text{.(2)}$$

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

$$\frac{-X_{mq}}{\omega_0}\dot{I}_q + \frac{X_{1q} + X_{mq}}{\omega_0}\dot{I}_{1q} + \frac{X_{mq}}{\omega_0}\dot{I}_{2q} = -R_{1q}I_{1q} \quad \text{....(4)}$$

$$\frac{-X_{md}}{\omega_0}\dot{I}_d + \frac{X_{md}}{\omega_0}\dot{I}_f + \frac{X_{1d} + X_{md}}{\omega_0}\dot{I}_{1d} = -R_{1d}I_{1d} \quad \text{....(5)}$$

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

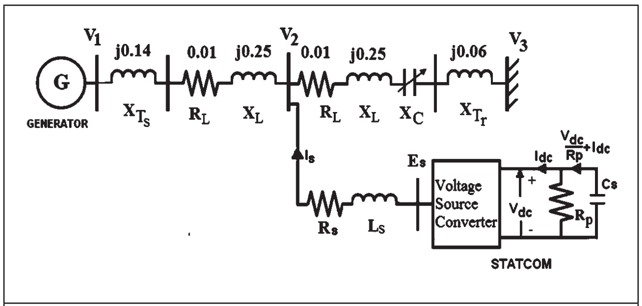


FIG. 2. STUDY SYSTEM

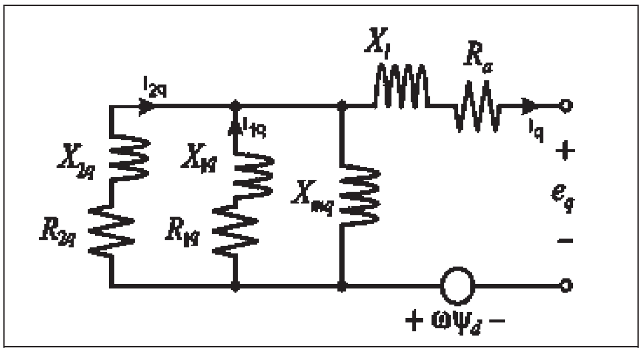


FIG. 3. GENERATOR Q-AXIS EQUIVALENT CIRCUIT

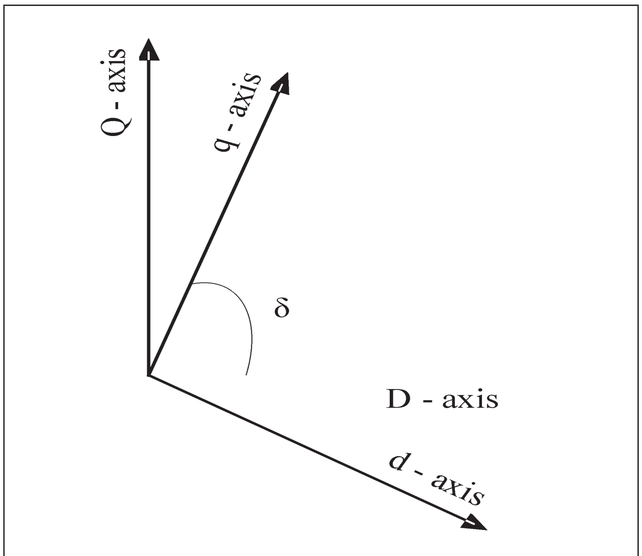


FIG. 4 D-Q AND D-Q REFERENCE FRAME.

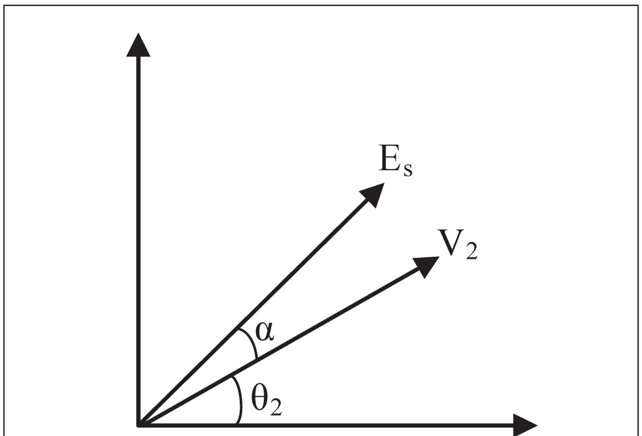


FIG. 5 VECTOR DIAGRAM RELATING E_S AND V_2

2.2 Mechanical System Equations

Exciter equations are:

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

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

$$2H_G \dot{\omega} = K_{BG}(\delta_B - \delta) - T_e - K_{GE}(\delta - \delta_E) - D_G(\omega - \omega_S) \quad ....(9)$$

$$\frac{1}{\omega_0}\dot{\delta} = \omega - \omega_S \quad ....(10)$$

where, T_e is electrical torque generated by generator.

$$T_e = \psi_d I_q - \psi_q I_d$$

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

All the six currents of generator system are input to mechanical system through T_e.

LP-B turbine equations are

$$2H_B \dot{\omega}_B = T_{LPB} + K_{AB}(\delta_A - \delta_B) - D_B(\omega_B - \omega_S) - K_{BG}(\delta_B - \delta) \quad ....(11)$$

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

LP-A turbine equations are

$$2H_A \dot{\omega}_A = T_{LPA} + K_{IA}(\delta_I - \delta_A) - D_A(\omega_A - \omega_S) - K_{AB}(\delta_A - \delta_B) \quad ....(13)$$

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

IP turbine equations are

$$2H_I \dot{\omega}_I = T_{IP} + K_{HI}(\delta_H - \delta_I) - D_I(\omega_I - \omega_S) - K_{IA}(\delta_I - \delta_A) \quad ...(15)$$

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

HP turbine equations are

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

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

There are two types of natural damping in mechanical system; one is self damping another is mutual damping. As the natural damping is kept zero in whole research hence in aforesaid equations, only self damping terms are mentioned. D_E, D_G, D_B, D_A, D_I, D_H are self damping of the turbine – generator masses. Mutual damping terms are ignored for the simplicity. δ_E, δ, δ_B, δ_A, δ_I, δ_H are angles of Exciter, generator rotor and four turbines. Mechanical system has six masses therefore it has twelve state variables. Inputs to mechanical system are T_{HP}, T_{IP}, T_{LPA}, T_{LPB}, T_e and outputs are ω and δ

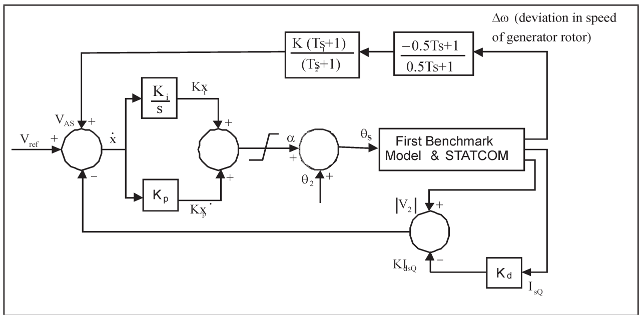


FIG. 6 BLOCK DIAGRAM OF THE SYSTEM

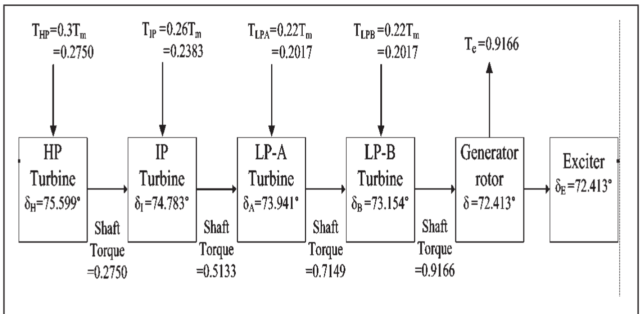


FIG. 7 TURBINE-GENERATOR SYSTEM WITH INITIAL CONDITIONS

2.3 FIRST HALF TRANSMISSION LINE EQUATIONS

$$V_{1D} - V_{2D} = R_1 I_D - \omega X_1 I_Q + \frac{X_1}{\omega_0}\dot{I}_D$$

$$\text{or, } V_{1D} = V_{2D} + R_1 I_D - \omega X_1 I_Q + \frac{X_1}{\omega_0}\dot{I}_D \quad \text{....(19)}$$

$$V_{1Q} = V_{2Q} + R_1 I_Q + \omega X_1 I_D + \frac{X_1}{\omega_0}\dot{I}_Q \quad \text{....(20)}$$

Its outputs are V_{1D} and V_{1Q}, which are converted to d-q reference frame as e_d and e_q; subsequently e_d and e_q are inputs to generator system.

2.4 Second Half Transmission Line Equations

$$V_{2D} = V_{3D} + V_{cD} + R_2(I_D + I_{sD}) - \omega X_2(I_Q + I_{sQ}) + \frac{X_2}{\omega_0}(\dot{I}_D + \dot{I}_{sD}) \quad \text{....(21)}$$

$$V_{2Q} = V_{3Q} + V_{cQ} + R_2(I_Q + I_{sQ}) + \omega X_2(I_D + I_{sD}) + \frac{X_2}{\omega_0}(\dot{I}_Q + \dot{I}_{sQ}) \quad \text{....(22)}$$

$$\frac{\dot{V}_{cD}}{\omega_0} = \omega V_{cQ} + X_c(I_D + I_{sD}) \quad \text{....(23)}$$

$$\frac{\dot{V}_{cQ}}{\omega_0} = -\omega V_{cD} + X_c(I_Q + I_{sQ}) \quad \text{....(24)}$$

V_{cD} and V_{cQ} are the D-Q components of voltage across series capacitor. Transmission line (TL) system has two state variables (V_{cD} and V_{cQ}). R_1 and X_1 are resistance and reactance of first half of TL and R_2 and X_2 are resistance and reactance of second half of TL. I_D+jI_Q is current in First half of TL. In second half of TL, STATCOM current is added.

2.5 STATCOM Equations

$$E_{sD} - V_{2D} = R_s I_{sD} - \omega X_s I_{sQ} + \frac{X_s}{\omega_0}\dot{I}_{sD} \quad \text{....(25)}$$

$$E_{sQ} - V_{2Q} = R_s I_{sQ} + \omega X_s I_{sD} + \frac{X_s}{\omega_0}\dot{I}_{sQ} \quad \text{....(26)}$$

K_{cs} is the constant relating the AC and DC voltage.

$|E_s| = K_{cs} V_{dc}$, $E_{sd} = K_{cs} V_{dc} \cos\theta_s$

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

Linearization of E_{sD} and 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

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

$$\text{or, } \dot{V}_{dc} = -\frac{1}{C_s}(\frac{V_{dc}}{R_p} + K_{cs} I_{sD} \cos\theta_s + K_{cs} I_{sQ} \sin\theta_s) \quad \ldots(27)$$

R_p is the resistance in parallel with DC side capacitor (C_s). $I_{dc}^2 R_p$ represent switching losses.

2.6 PI CONTROLLER EQUATION

$$\dot{x} = V_{AS} + V_{ref} - |V_2| + K_d I_{sQ} \quad \ldots(28)$$

K_d represents droop characteristics. Output equation of PI controller is

$$\alpha = K_i x + K_p \dot{x} \quad \ldots(29)$$

Equations 1-18, 23-28 are state equations. Equations 19-20 are output of TL. V_{1D} and V_{1Q} are output of TL, subsequently converted to e_d and e_q, which are input to generator system.

V_{1D} and V_{1Q} are converted to e_d and e_q as per following transformation:

$e_q = V_{1D}\cos\delta + V_{1Q}\sin\delta$, $e_d = V_{1D}\sin\delta - V_{1Q}\cos\delta$,

I_d and I_q (output of generator system) are converted to I_D and I_Q. I_D and I_Q (and $\dot{I}_D$ & $\dot{I}_Q$ also) are inputs to TL. Its transformation is as follows

$I_D = I_q\cos\delta + I_d\sin\delta$, $I_Q = I_q\sin\delta - I_d\cos\delta$,

These transformation are carried out vide Figure 4. All the differential equations are linearized to obtain eigenvalues and Transient response is obtained with the set of all differential equations without linearization. Simulink/MATLAB is used in whole programming and for the solution of all differential equations.

3.0 AUXILIARY CONTROLLER DESIGN AND RESULT ANALYSIS

In this research various local signals such as deviation in active power, deviation in reactive power, deviation in frequency are considered but not found suitable. Speed deviation of generator rotor ($\Delta\omega$) despite time delay is found to be the best suitable AS. A wide range of time delay (0.1 sec. to 1 sec.) is considered. Though approximately 0.1-0.2 seconds time delay is sufficient. In simulation, time delay can be expressed by a transfer function e^{-Ts}, where 'T' represents time delay. Its equivalent can be expressed by a first order Pade approximation, which is $\frac{-0.5Ts+1}{0.5Ts+1}$.

This transfer function will add one pole in the system. For more accuracy third order Pade approximation can be used, which will add three poles in the system. In this research first order Pade approximation is used as shown in Figure 6. Small signal stability results are presented in Tables1-2. Table 1 presents results at 20% compensation (X_C=0.1). Column 2 represents eigenvalues without STATCOM. SSR frequency is 248.69 rad/sec which is in between 298.18 (Torsional Mode No. 5) and 203.05 (Torsional Mode No. 4), hence both modes are unstable. With the inclusion of STATCOM, system is not stable (column 3), but with the incorporation of damping controller with input as deviation in generator rotor speed with time delay 0.1 sec., whole system is stable. Eigen values with time delay 1 sec. is also shown in last column, in this case also system is stable.

Table 2 presents results at 60% compensation (X_C=0.3). It can be seen that at higher series compensation SSR frequency reduced to 155.66 rad/sec. Now only torsional mode no. 5 is stable. In this case also it can be seen that system is completely stable with AS deviation in generator rotor speed. Large signal stability results (transient response) are shown at 60% compensation at the end of paper (just after appendix). Left column of the page shows transient response with AS and right column shows without AS. First, shaft torque results are shown subsequently speed deviations of the modes are shown. Disturbance is sudden thirty percent increase in mechanical torque for a period of 0.1 sec., after 1 second from the start of simulation. In whole study natural damping is kept zero.

4.0 CONCLUSION

In this paper STATCOM is located at the middle of transmission system. The main aim of STATCOM damping controller is to reduce the oscillations in turbine-generator set though the STATCOM is far away from generator bus. It can be concluded from the result analysis that speed deviation of generator rotor is very suitable auxiliary signal. If there is any delay in the signal despite that it adds the damping to the system. A damping controller should display satisfactory results in wide range of operating conditions; therefore results at series compensation 20% and 60% are presented in this paper. Transient response results at 60% compensation are presented which show satisfactory results.

APPENDIX

Initial Condition of the system at X_c=0.3 (60% compensation) are given here. All quantities are in pu and angles in degrees, unless otherwise specified.

- Generator circuit data: Ra=0, Xl=0.13, Xmd=1.66, R1d=0.00408, X1d=0.0055, Rfd=0.001406, Xfd=0.062, Xmq=1.58, R1q=0.008223, X1q=0.095, R2q=0.01406, X2q=0.326. TL data: R1=0.01, X1=0.25+0.14, R2=0.01, X2=0.25+0.06, Power supplied by generator Pg = 0.9166, PF = 0.9613 (lagging).$V_1 = 0.95987\angle 23.578°$, $V_2 = 0.92105\angle -0.08588°$, $V_3 = 0.90043\angle 0$

In steady state, damper winding currents are zero (i.e. $I_{1d} = I_{2d} = I_{2q} = 0$). Terminal voltage of generator (V_1) in d-q frame: $e_d = 0.7226$, $e_q = 0.6318$ or, $0.95987\angle 41.165°$. It can be found that angle difference in $V_{1\ (DQ\ frame)}$ and $V_{1\ (d\text{-}q\ frame)}$ is equal to $(\pi/2) - \delta$. (It can be analyzed from Figure 4). Magnitude in both the rotating frames is same.

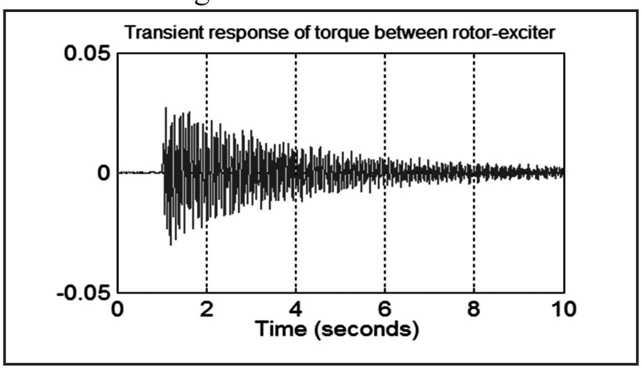
STATCOM circuit data: R_s=0.01, X_s=0.15, R_p=125, C_s=0.45, K_{cs}=1.559. Active power consumed by STATCOM = 0.09186, Reactive power supplied by STATCOM = 1.134, $E_s = 1.1056\angle -0.8859°$ α = -0.8°. It can be seen that $E_s > V_2$, α is negative, it proves that STATCOM is in capacitive mode. It is supplying reactive power to the system and consuming small amount of active power to meet out the losses in R_s and R_p (transformer losses and switching losses).

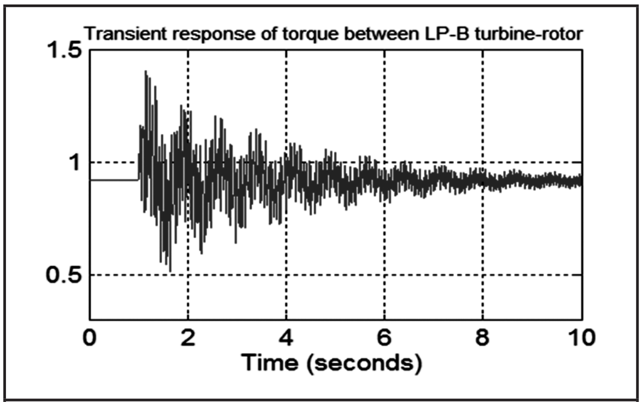
PI controller data: K_p= -0.1, K_i= -20 sec^{-1}. K_d= 0.01, Auxiliary controller data: K=1, T_1=1/6 sec, T_2=1/210 sec.

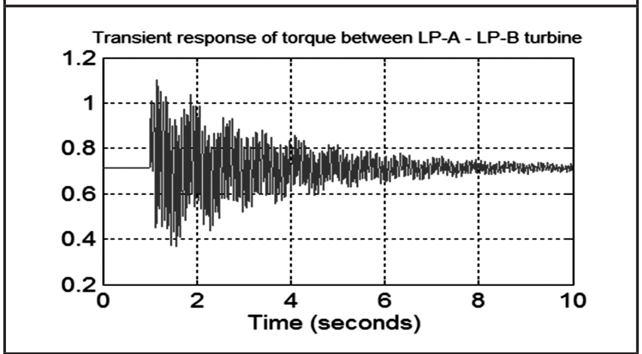
- In steady State $T_e = T_m = T_{HP} + T_{IP} + T_{LPA} + T_{LPB}$ =0.9166. (T_m is mechanical Torque applied). $T_{HP} = 0.3T_M$, $T_{IP} = 0.26T_M$, $T_{LPA} = 0.22T_M$, $T_{LPB} = 0.22T_M$, δ_H =75.599°, δ_I = 74.783°, δ_A=73.941°, δ_B=73.154°, $\delta = \delta_E$ = 72.413°. (It should be noted that $\delta_H > \delta_I > \delta_B > \delta_A > \delta$. Then only torque can be transferred from HP turbine to generator rotor as shown in Figure 7.
- Torque between HP-IP turbine = 0.2750, Torque between IP- LP-A turbine = 0.5133, Torque between LP-A– LP-B turbine = 0.7149, Torque between LP-B- Generator rotor = T_e= 0.9166, Torque between Generator- Exciter = 0. Natural Damping is zero i.e. $D_E = D_G = D_B = D_A = D_I = D_H = 0$. Mechanical system data is available in [16].
- In all the equations ω_0=376.99 rad/sec, while ω=1 pu. In transient period value of ω_0 remain same while ω oscillates. In Mechanical system modeling, in steady state $\omega_E = \omega = \omega_B = \omega_A = \omega_I = \omega_H = \omega_S$ =1. In transient period ω_S remains constant.

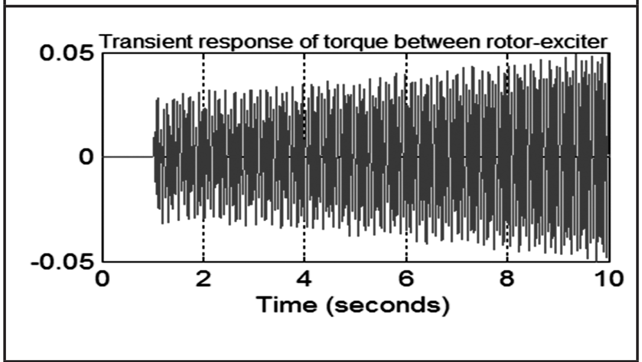
LARGE SIGNAL STABILITY RESULTS

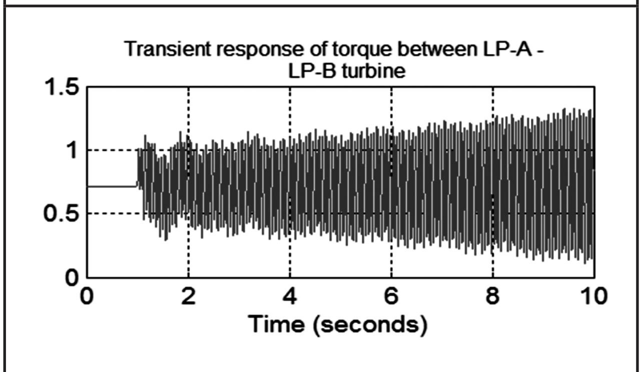
Left column of the page shows transient response with AS and right column shows without AS.

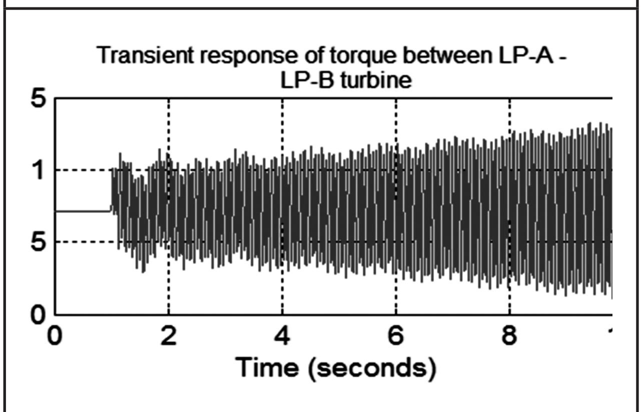


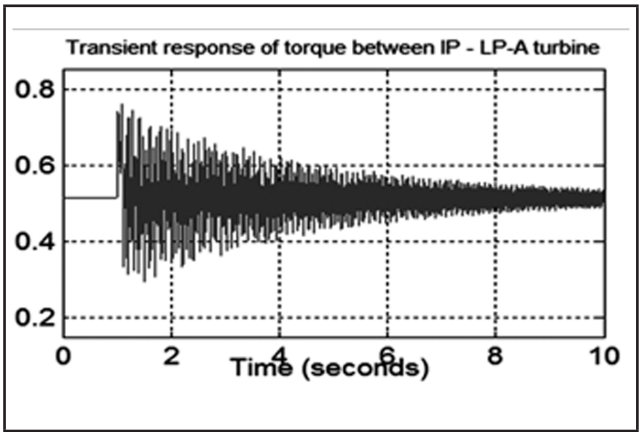

Transient response of torque between LP-B turbine-rotor
1.5
1
0.5
0
2
4
6
8
10
Time (seconds)

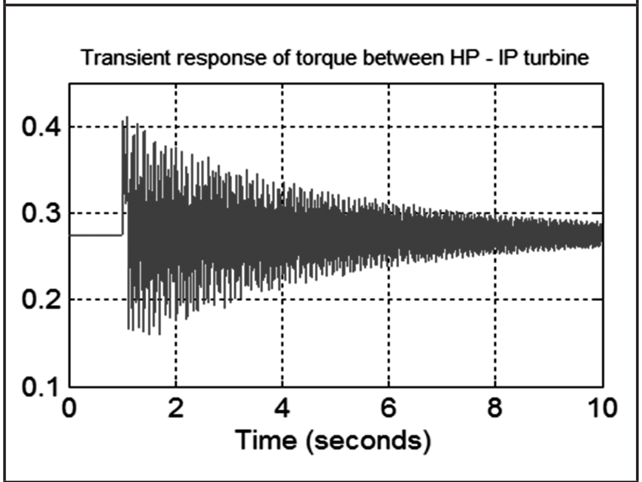

Transient response of torque between LP-A - LP-B turbine
1.2
1
0.8
0.6
0.4
0.2
0
2
4
6
8
10
Time (seconds)

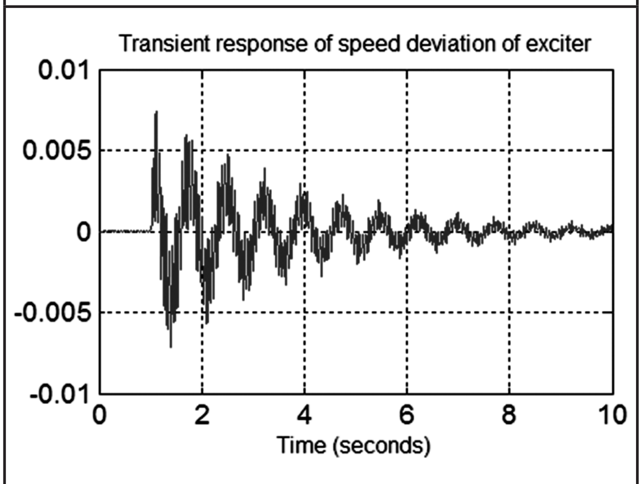

Transient response of torque between rotor-exciter
0.05
0
-0.05
0
2
4
6
8
10
Time (seconds)

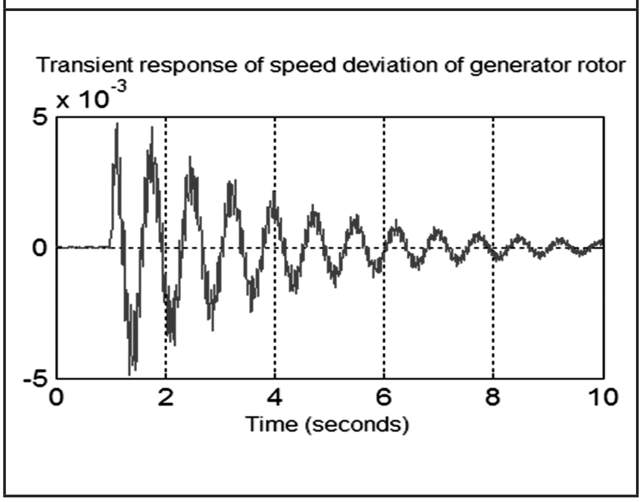

Transient response of torque between LP-A -
LP-B turbine
1.5
1
0.5
0
0
2
4
6
8
10
Time (seconds)

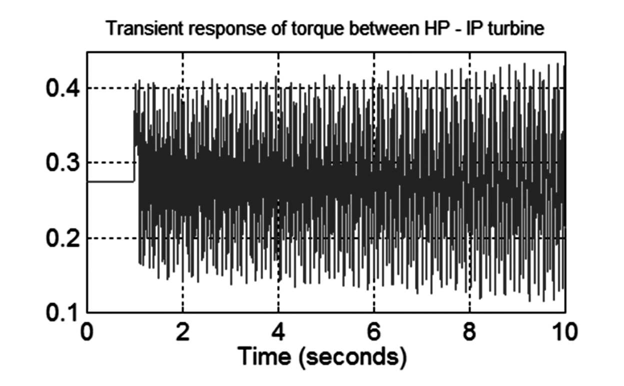

Transient response of torque between LP-A -
LP-B turbine
5
1
5
0
0
2
4
6
8
Time (seconds)

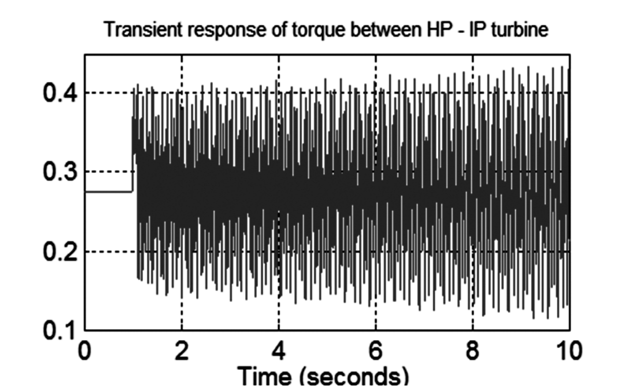

Transient response of torque between IP - LP-A turbine
0.8
0.6
0.4
0.2
0
2
4
6
8
10
Time (seconds)

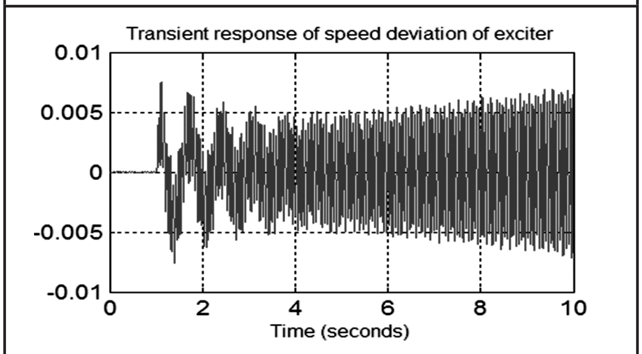

Transient response of torque between HP - IP turbine
0.4
0.3
0.2
0.1
0
2
4
6
8
10
Time (seconds)

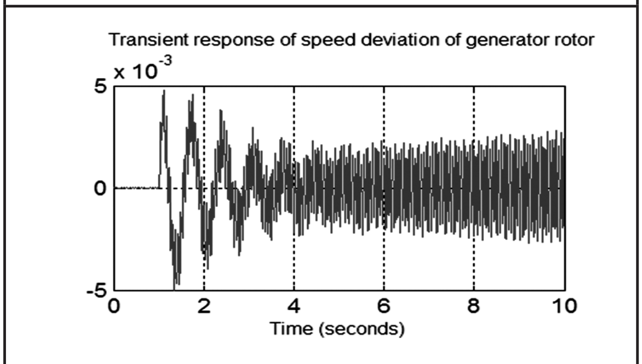

Transient response of speed deviation of exciter
0.01
0.005
0
-0.005
-0.01
0
2
4
6
8
10
Time (seconds)

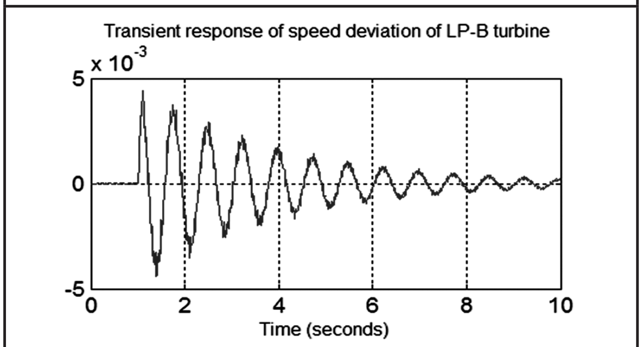

Transient response of speed deviation of generator rotor
x 10-3
5
0
-5
0
2
4
6
8
10
Time (seconds)

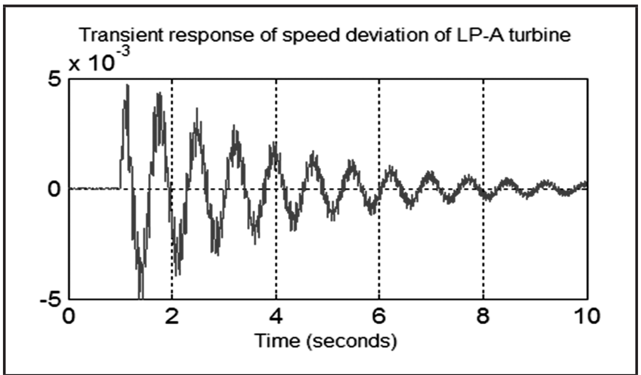

Transient response of torque between HP - IP turbine
0.4
0.3
0.2
0.1
0 2 4 6 8 10
Time (seconds)

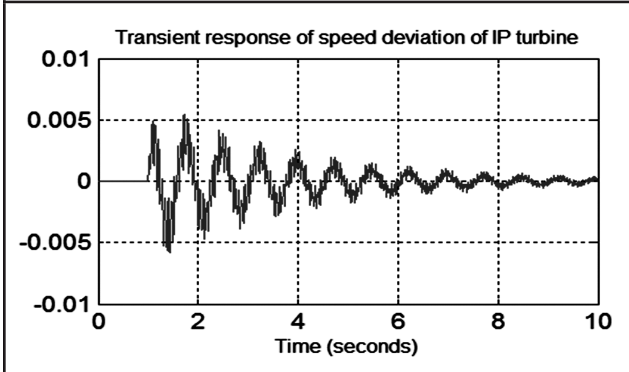

Transient response of torque between HP - IP turbine
0.4
0.3
0.2
0.1
0 2 4 6 8 10
Time (seconds)

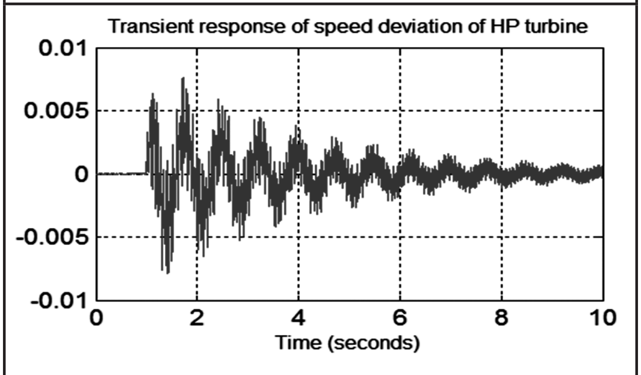

Transient response of speed deviation of exciter
0.01
0.005
0
-0.005
-0.01
0 2 4 6 8 10
Time (seconds)

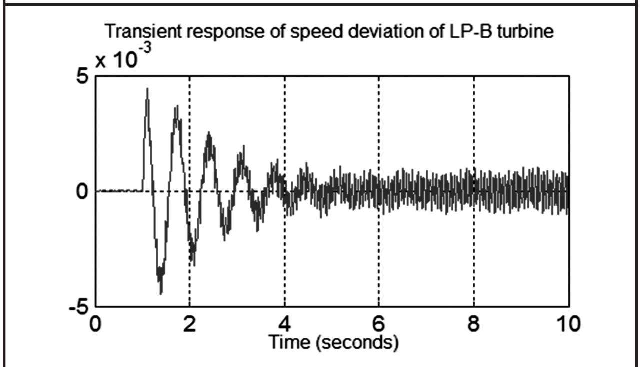

Transient response of speed deviation of generator rotor
x 10-3
5
0
-5
0 2 4 6 8 10
Time (seconds)

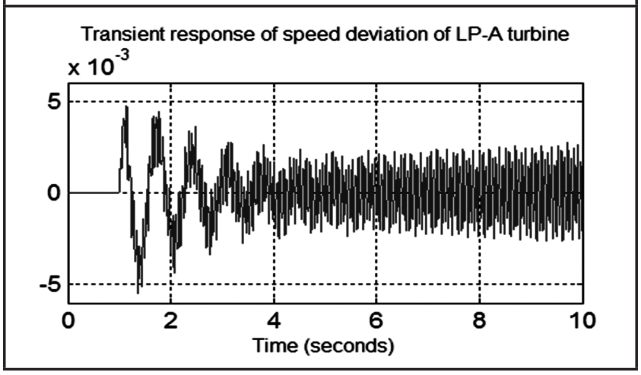

Transient response of speed deviation of LP-B turbine
x 10-3
5
0
-5
0 2 4 6 8 10
Time (seconds)

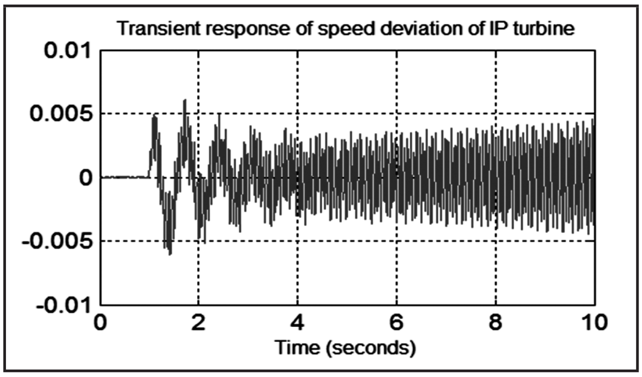

Transient response of speed deviation of LP-A turbine
x 10-3
5
0
-5
0 2 4 6 8 10
Time (seconds)


Transient response of speed deviation of IP turbine
0.01
0.005
0
-0.005
-0.01
0 2 4 6 8 10
Time (seconds)


Transient response of speed deviation of HP turbine
0.01
0.005
0
-0.005
-0.01
0 2 4 6 8 10
Time (seconds)


Transient response of speed deviation of LP-B turbine
x 10-3
5
0
-5
0 2 4 6 8 10
Time (seconds)


Transient response of speed deviation of LP-A turbine
x 10-3
5
0
-5
0 2 4 6 8 10
Time (seconds)



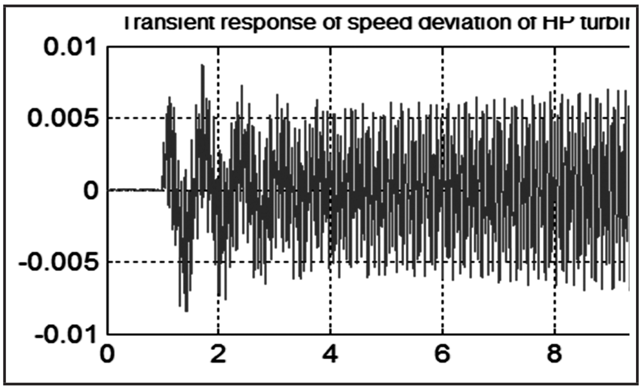


TABLE 1

EIGENVALUES AT 20% COMPENSATION (X_C=0.1)

Description	Eigenvalues of IEEE First Benchmark Model without any controller	Eigenvalues with STATCOM & PI controller but without AS	Eigenvalues with STATCOM, PI controller and AS, with time delay=0.1 sec	Eigenvalues with STATCOM, PI controller and AS, with time delay=1 sec
Supersynchronous	-4.5667±505.06i	-8.4619±560.68i	-8.6074±560.61i	-8.6115±560.62i
Torsional Mode No. 5	1.0163e-06±298.18i	8.379e-06±298.18i	-0.00028394±298.18i	-0.00030008±298.18i
Torsional Mode No. 4	0.00082108±203.05i	0.25525±202.91i	-0.061654±201.5i	-0.32586±201.53i
Torsional Mode No. 3	-0.0027683±160.62i	-0.006422±160.66i	-0.06348±160.64i	-0.064811±160.66i
Torsional Mode No. 2	-0.00093489±127.02i	-0.00098066±127.03i	-0.026706±127.02i	-0.028275±127.03i
Torsional Mode No. 1	-0.012146±99.082i	-0.0071228±99.209i	-0.28371±99.094i	-0.3065±99.198i
Subsynchronous	-3.885±248.69i	-5.8815±197.29i	-6.3895±198.23i	-6.192±198.34i
Electromechanical mode	-0.38413±7.6786i	-1.1454±7.0556i	-1.1469±7.2668i	-0.97367±6.9784i
STATCOM currents	-	-10.217±381.22i	-8.576±382.17i	-8.496±382.02i
V_{dc} &PI	-	-0.051517±12.643i	-0.1237±12.176i	-0.47925±12.787i
Lead Compensation	-	-	-210.06	-210.05
others	-32.367	-32.655	-32.734	-32.676
	-20.311	-20.345	-20.342±0.062181i	-20.345
	-3.2182	-3.6088	-3.6057	-3.6165
	-0.17363	-0.30033	-0.30073	-0.30086
Eigenvalue due to time delay transfer function	-	-	*	-1.9988
*It should be around -20. It got attached with -20.342±0.062181i				

TABLE 2				
EIGENVALUES AT 60% COMPENSATION (X_C=0.3)				
Description	**Eigenvalues of IEEE First Benchmark Model without any controller**	**Eigenvalues with STATCOM & PI controller but without AS**	**Eigenvalues with STATCOM, PI controller and AS, with time delay=0.1 sec**	**Eigenvalues with STATCOM, PI controller and AS, with time delay=1 sec**
Supersynchronous	-4.6725±598.87i	-9.2249±694.03i	-9.3328±693.96i	-9.336±693.97i
Torsional Mode No. 5	-2.4912e-06±298.18i	6.7093e-6±298.18i	-0.00024877±298.18i	-0.00026502±298.18i
Torsional Mode No. 4	0.00089585±202.72i	0.013931±202.96i	-0.36791±202.72i	-0.40575±202.79i
Torsional Mode No. 3	0.63578±159.69i	0.0094968±160.6i	-0.18078±160.47i	-0.20527±160.51i
Torsional Mode No. 2	0.0081753±127.08i	0.0036672±127.02i	-0.041042±126.98i	-0.049636±126.99i
Torsional Mode No. 1	0.01395±99.443i	0.083224±98.98i	-0.38522±98.459i	-0.53869±98.659i
Subsynchronous	-3.7506±155.66i	-4.1692±67.001i	-4.2189±67.063i	-4.1804±67.077i
Electromechanical mode	-0.5058±9.107i	-0.66096±9.3898i	-0.7894±9.0812i	-0.89249±9.5818i
STATCOM currents	-	-10.378±381.19i	-8.8853±382.24i	-8.7964±382.09i
V_{dc} &PI	-	-1.104±5.6807i	-1.0319±5.8614i	-0.98043±5.5593i
Lead Compensation	-	-	-210.07	-210.06
others	-32.76	-32.743	-32.788	-32.755
	-20.405	-20.404	-20.465	-20.405
	-3.887	-3.9088	-3.9064	-3.9137
	-0.179	-0.18661	-0.18687	-0.18691
Eigenvalue due to time delay transfer function	-	-	-20.217	-2.0097

REFERENCES

[1] K R Padiyar, FACTS Controllers in Power Transmission and Distribution, New Age International Publishers, Delhi, pp. 105-115, 2009.

[2] R M Mathur and R K Varma, Thyristor Based FACTS Controllers for Electrical Transmission Systems, John Wiley & sons, IEEE press, pp. 277-287 2002.

[3] P Kundur, Power System Stability and Control, McGraw-Hill, New York, pp. 1103-1125 1993.

[4] R Satija, Damping Subsynchronous Resonance in Power System using Static VAR system, PhD dissertation, University of Delhi, Delhi, 2007.

[5] J S Gasca, Coordinated Control of Two FACTS Devices for Damping Inter Area Oscillations, IEEE Trans. PS, Vol. 13, pp. 428-434, 1998.

[6] N Kumar and M P Dave, Application of supplementary controlled static VAR system for damping sub synchronous resonance in Power Systems, Electric Power Systems Research, Vol. 37, pp.189–201, 1996.

[7] K R Padiyar and R K Varma, Static var system auxiliary controllers for improvement of dynamic stability, International Journal of Electrical Power and Energy Systems, Vol. 12, pp. 287-297, 1990.

[8] K V Patil, J Senthil, J Jiang and R M Mathur, Application of STATCOM for damping torsional oscillations in series compensated AC systems, IEEE Transaction on Energy Conversion, Vol. 13, pp. 237-243, 1998.

[9] K V Patil, Dynamic compensation of Electrical Power systems using a New BVSI STATCOM, PhD dissertation, The University of Western Ontario, London, 1999.

[10] J J Gasca and J H Chow, Power System Reduction to Simplify the Design of Damping Controllers for Inter-Area Oscillations, IEEE Transactions on Power systems, Vol. 11, pp. 1342–1349, 1996.

[11] N Kumar and S Kumar, SSR Alleviation using BVLC Supplementary Controlled SVS of Series Compensated Power System, TELKOMNIKA Indonesian Journal of Electrical Engineering, Vol. 12, pp. 6551-6559, 2014.

[12] V Spitsa, A Alexandrovitz and E Zeheb, Design of a robust state feedback controller for a STATCOM using a zero set concept, IEEE Transactions on Power Delivery, Vol. 25, pp. 456–467, 2010.

[13] S K Gupta, A K Gupta and N Kumar, Subsynchronous Resonance in Power Systems, IEE proceedings- Generation, Transmission and Distribution, Vol. 149, No.6, pp. 679-688, 2002.

[14] N Kumar, V Jain and S Kumar, Comparison of Effectiveness of Auxiliary Signals Incorporated in STATCOM for improving Transient Performance of Power System, IEEE International conference on Power Electronics, Delhi Technological University, Delhi, pp. 1-5, 2012.

[15] V Jain and N Kumar, Mitigation of Subsynchronous Resonance in Power system through STATCOM and auxiliary controller, The Journal of CPRI, Vol. 10, pp. 239- 244, 2014.

[16] IEEE Subsynchronous Resonance Task Force, First benchmark model for computer simulation of subsynchronous resonance, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, pp. 1565-1572, 1977.

[17] V Jain and N Kumar, Designing of supplementary controller for STATCOM for mitigation of subsynchronous resonance in series compensated power system, The Journal of CPRI, Vol. 10, pp. 641-652, 2014.

[18] V Jain and N Kumar, Effect of TCSC on power system stability, The Journal of CPRI, Vol. 11, pp. 641-650, 2015.

[19] D Rai, Damping Subsynchronous Resonance Using Static Synchronous Series Compensators and Static Synchronous Compensator, PhD dissertation, University of Saskatchewan, Canada, 2008.

[20] G Tang, Damping subsynchronous resonance oscillations using a VSC HVDC back-to-back system, dissertation, University of Saskatchewan, Saskatoon, Saskatchewan, 2006.