Enhancement of Power System Dynamics through STATCOM

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***Abstract*—In FACTS devices auxiliary signals are widely used to enhance damping and mitigation of Subsynchronous Resonance in Power System. Choice of auxiliary signals is indeed a difficult choice. In this paper STATCOM is installed in the middle of Power system and it is shown that computed generator internal frequency is a very suitable auxiliary signal. 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. Results are shown at 50% series compensation.**

Keywords-STATCOM; supplementary signals; power system stability; IEEE first benchmark model

I. 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 is used as a feedback signal then it can enhance the damping of the system. 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. In type '2' converters '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 [1-4]. In FACTS devices, auxiliary signals (supplementary signals) are widely used to enhance the damping of the power system. The main purpose of auxiliary signal (AS) is to enhance the damping of generator-turbine system [5-6], because the line dynamics are much faster then generator dynamics. In the literature no major efforts are reported to develop a suitable AS for the STATCOM located away from generator end. In this paper STATCOM is installed in the middle of TL and with the signals available at STATCOM bus, derivative of generator rotor angle is computed and it is shown that it can damp all the modes of turbine- generator set. Derivative of generator rotor angle has resemblance with deviation in generator rotor speed (ω-ω_s). In the literature, various auxiliary signals has been tested for TCR-FC (Thyristor controlled reactor with fixed capacitor), where TCR-FC is located in the middle of transmission line.

It is found that generator end frequency computed through local signals, available at TCR-FC bus, is one of the most suitable AS

II. Study System

Study system is IEEE First Benchmark model (FBM) [7]. In the present case STATCOM is installed in the middle of transmission line. Hence all values shown in Figure I can be easily understood. In reference [8] STATCOM is installed at generator end, and all the system differential equations are given in this paper. In present paper STATCOM is in middle of TL hence TL differential equations are changed which are given here:

First Half Transmission Line Equations are

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

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

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

Second Half Transmission Line Equations are

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

$$V_{2Q} = V_{3Q} + V_{cQ} + R_2 (I_Q + I_{sQ}) + \omega X_2 (I_D + I_{sD}) + \frac{X_2}{\omega_0}(\dot{I}_Q + \dot{I}_{sQ}) \quad (4)$$

I_D and I_Q are current in first half of TL. In [8], Generator equations are presented in d-q frame while STATCOM equations, TL equations are presented in D-Q frame. Generator equivalent circuit is shown in Figure III-IV. Generator has three damper windings, one is at d-axis and two are at q-axis. X_l is leakage reactance of generator and R_a is its armature winding resistance. I_{1d}, I_{1q}, and I_{2q} are the damper winding currents and I_f is field winding current. In steady state damper winding currents are zero. D-Q axes present network reference frame and d-q axes present machine reference frame as shown in Figure V. D-Q axes frame and d-q axes frame both are rotating at synchronous speed. In transient period, speed of D-Q reference frame remains constant but speed of d-q frame oscillates, hence rotor angle 'δ' oscillates.

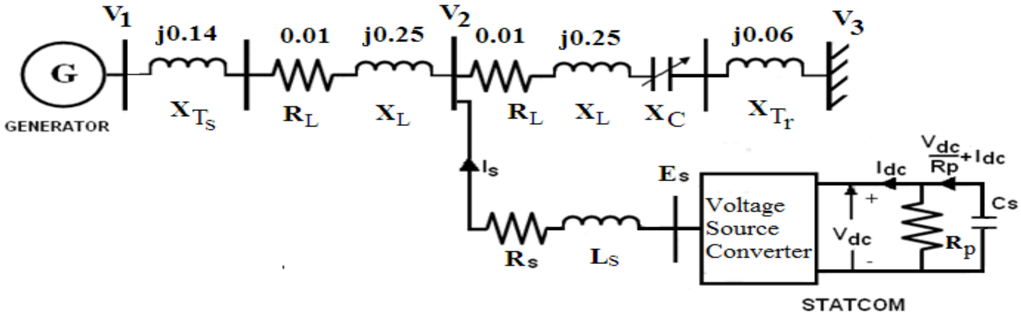

FIGURE I. STUDY SYSTEM

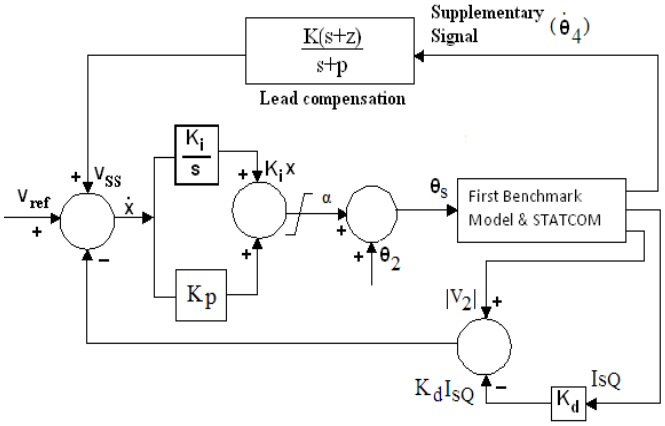

FIGURE II. BLOCK DIAGRAM OF THE SYSTEM

III. AUXILIARY CONTROLLER DESIGN

In references [8] it is shown that speed deviation of generator rotor is a very suitable auxiliary signal. Hence in this research derivative of rotor angle is derived with the signals available at bus V_2. For computation of $\dot{\delta}$ at bus V_2, four signals are needed to be measured, these are $V_{2D}, V_{2Q}, \dot{I}_D, \dot{I}_Q$. Impedance of first half of TL and generator reactances should be known. In actual system $\dot{V}_{2D}, V_{2Q}, \dot{I}_D, I_Q$ can be measured but for simulation purpose two signals $\dot{I}_D, I_Q$ are available and $\dot{V}_{2D}, V_{2Q}$ are not available because V_{2D} and V_{2Q} are not state variables, so $\dot{V}_{2D}$ and V_{2Q} are derived as follows

$$V_{2D} = V_{3D} + V_{cD} + R_2(I_D + I_{sD}) - \omega X_2(I_Q + I_{sQ})$$
$$V_{2Q} = V_{3Q} + V_{cQ} + R_2(I_Q + I_{sQ}) + \omega X_2(I_D + I_{sD})$$

Therefore $\dot{V}_{2D}$ and $\dot{V}_{2Q}$ are obtained as follows:

$$\dot{V}_{2D} = V_{cD} + R_2(\dot{I}_D + I_{sD}) - \omega X_2(\dot{I}_Q + I_{sQ})$$

$$\dot{V}_{2Q} = V_{cQ} + R_2(\dot{I}_Q + I_{sQ}) + \omega X_2(\dot{I}_D + I_{sD})$$

$\dot{I}_D, I_Q, \dot{I}_{sD}$ and I_{sQ} are state variables hence available signals for simulation purpose. Voltage at node 4 (V_{4D} and V_{4Q} in Figure III-IV) represent voltage generated by generator. In D-Q axes frame, angle of voltage at node 4 (θ_4) is almost equal to δ. $\dot{\theta}_4$ is derived and used as AS as follows:

$$V_{4D} = V_{2D} + R_1 I_D - \omega(X_1 + X_l + X_{md})I_Q \tag{5}$$

$$V_{4Q} = V_{2Q} + R_1 I_Q + \omega(X_1 + X_l + X_{mq})I_D \tag{6}$$

$$\text{or, } \dot{V}_{4D} = V_{2D} + R_1 \dot{I}_D - \omega(X_1 + X_l + X_{md}) I_Q \tag{7}$$

$$\text{similarly, } \dot{V}_{4Q} = V_{2Q} + R_1 \dot{I}_Q + \omega(X_1 + X_l + X_{mq}) I_D \tag{8}$$

$$\theta_4 = \tan^{-1}\frac{V_{4Q}}{V_{4D}} \text{ or, } \dot{\theta}_4 = \frac{V_{4D0}\dot{V}_{4Q} - V_{4Q0} V_{4D}}{V_{40}}$$

Subscript '0' represents initial conditions. Approximately δ = θ_4 hence $\dot{\delta} = \theta_4$, so $\dot{\theta}_4$ is used as AS. In equations 7-8 damper winding currents should be also taken into account but damper windings currents are not available at bus V_2 hence not the part of equations 7-8. Approximate steady state value of δ can be calculated with equations 5-6.

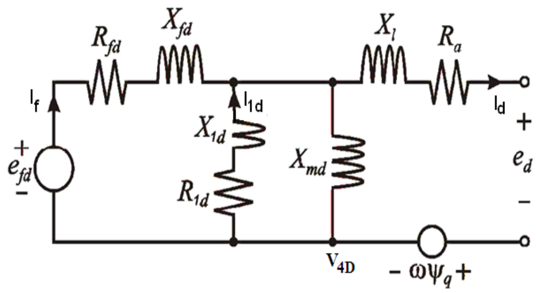

FIGURE III. GENERATOR D-AXIS EQUIVALENT CIRCUIT

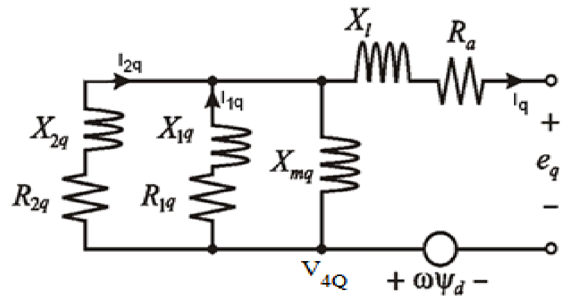

FIGURE IV. GENERATOR Q-AXIS EQUIVALENT CIRCUIT

IV. RESULTS AND DISCUSSIONS

Generally SSR problem occurs at high series compensation. Hence results and initial conditions are shown at 50% series compensation (X_c= 0.25). Eigenvalues are tabulated in Table 1. Column 2 shows results without STATCOM (i.e. FBM only). Column 3 shows results with STATCOM but without PI controller. In this case, system is as open loop transfer function having input α and output $|V_2|$. In column 4, eigenvalues are with STATCOM and PI controller and thereafter in column 5, eigenvalues are with STATCOM, PI controller and AS. Various Transient responses are shown in Figure VI-XI. Disturbance is sudden thirty percent increase in mechanical torque for a period 0.1 second, after 1 second from the start of simulation. In whole study natural damping is kept zero.

APPENDIX

Initial Condition of the system at X_c=0.25 (50% compensation). All quantities are in pu and angles in radians, 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= 0.807, PF= 0.823 (lagging). $V_1 = 1.097\angle 0.3566, V_2 = 0.936\angle 0.051, V_3 = 0.893\angle 0$. 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 = 0.592, e_q = 0.924 or, $1.097\angle 1.0015$. It can be found that angle difference in $V_{1\ (DQ\ frame)}$ and $V_{1\ (d\text{-}q\ frame)}$ is equal to $(\pi/2)-\delta$. (This can be analyzed from Figure V). Active power consumed by STATCOM = 0.00109, Reactive power supplied by STATCOM = 0.30508, E_s= $0.9845\angle 0.047$, α=-0.00349. It can be seen that $E_s > V_2$, α is negative therefore 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). STATCOM circuit data: R_s= 0.01, X_s=0.15, R_p=125, C_s=0.5968, K_{cs}=15.59,

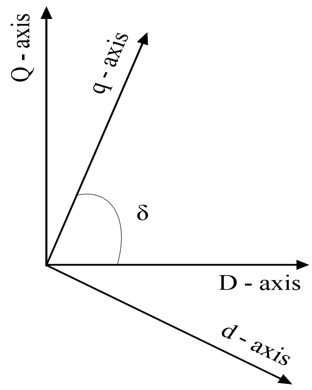

FIGURE V. D-Q AND d-q REFERENCE FRAME

- 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.

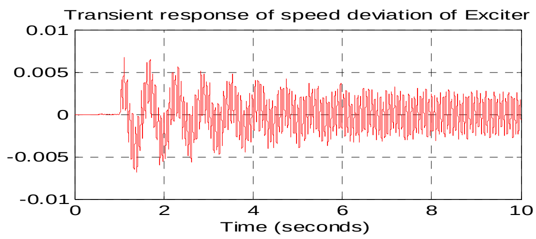

FIGURE VI. RESPONSE OF SPEED DEVIATION OF EXCITER WITH AS

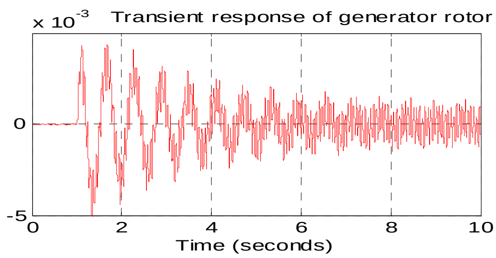

FIGURE VII. RESPONSE OF SPEED DEVIATION OF ROTOR WITH AS

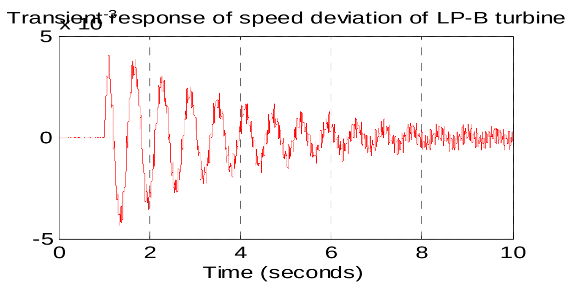

FIGURE VIII. RESPONSE OF SPEED DEVIATION OF LP-B TURBINE WITH AS

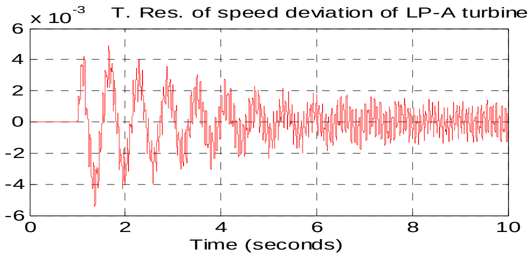

FIGURE IX. RESPONSE OF SPEED DEVIATION OF LP-A TURBINE WITH AS

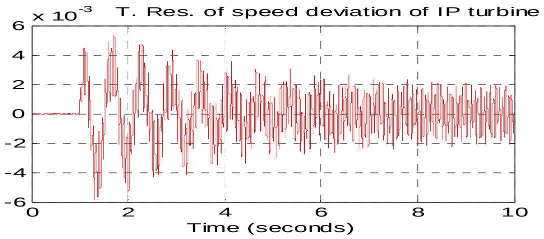

FIGURE X. RESPONSE OF SPEED DEVIATION OF IP TURBINE WITH AS

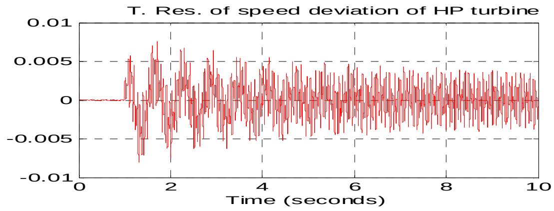

FIGURE XI. RESPONSE OF SPEED DEVIATION OF HP TURBINE WITH AS

TABLE I. EIGEN VALUES AT 50% COMPENSATION

Description	**Eigenvalues of IEEE First Benchmark Model without any controller**	**Eigenvalues with STATCOM only (without PI controller and AS)**	**Eigenvalues with STATCOM & PI controller but without AS**	**Eigenvalues with STATCOM, PI controller and AS**
Supersynchronous	-4.646± 579.54i	-3.2291± 547.02i	222.32± 554.16i	-52.061± 478.62i
Torsional Mode No. 5	-5.2871e-6± 298.18i	1.5109e-5± 298.18i	9.0137e-06± 298.18i	-7.7467e-06± 298.18i
Torsional Mode No. 4	-0.012035± 202.61i	1.5319± 203.01i	0.026638± 202.79i	-0.029263± 202.86i
Torsional Mode No. 3	0.17147± 161.03i	-0.03525± 160.83i	0.021433± 160.43i	-0.020023± 160.51i
Torsional Mode No. 2	0.0060428± 127.06i	-0.008165± 127.06i	0.020248± 126.9i	-0.0048197± 126.98i
Torsional Mode No. 1	0.026771± 99.373i	-0.073882± 99.466i	1.7288± 101.97i	-0.0064684± 98.512i
Subsynchronous	-3.5423± 173.98i	-8.5016± 200.18i	-4.1588± 105.73i	-10.102± 48.583i
Electromechanical mode	-0.56275± 9.3669i	-0.48089± 10.701i	-0.57262± 10.021i	-0.45441± 10.405i
STATCOM currents		-9.2442± 832.95i	1.5986± 624.36i	-41.667± 869.66i
V_{dc} &PI		-11.114	-229± 545.35i	-145.89, -4116.1
Lead Compensation				-24.868
others	-32.685	-33.002	-32.721	-33.276
	-20.36	-20.339	-20.375	-20.067
	-3.2221	-3.2923	-3.3105	-3.3465
	-0.38669	-0.40787	-0.41301	-0.42906

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