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SSR Alleviation using BVLC Supplementary Controlled SVS of Series Compensated Power System

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Abstract

The sub synchronous resonance (SSR) is a substantial problem in power system having a steam turbine generator connected to a series compensated transmission system. Flexible AC transmission systems (FACTS) controllers are widely applied to mitigate SSR. In this paper, a bus voltage and line current (BVLC) supplementary subsynchronous damping controller (SSDC) is proposed to alleviate subsynchronous resonance (SSR) and damping power system oscillations in a power system. Both eigenvalue investigation and time-domain simulation results verify that the proposed method can damp torsional oscillations of the power system with SVS bus voltage and line current (BVLC) supplementary controller.The results demonstrate that the proposed controller has a successful performance in minimizing the SSR.It is shown that the controller is able to stabilize all unstable modes. The study is performed on the system adapted from the IEEE first benchmark model. All the simulations are carried out in MATLAB/SIMULINK environment.

Keywords: *bus voltage and line current (BVLC), series compensation, sub synchronous resonance (SSR), supplementary controller, eigenvalue investigation*

1. Introduction

In electric power system series compensation in an AC transmission line is an effective means to enhance power transfer capacity and improve transient stability. However, one of the important problems in power systems employing series capacitors in AC transmission lines is the interaction between mechanical system comprising various stages of steam turbines, generator rotor and the series compensated electrical network. If any natural frequency of oscillation of the combined torsional system matches with the complement of the resonant frequency of the line inductance and series capacitance, growing oscillations of subsynchronous frequencies result in the power system. This phenomenon is called subsynchronous resonance. Two incidents of shaft failure occurred in 1970 and 1971.The SSR phenomenon was discovered during the extensive analysis work following these events [1-2].

After these incidents, great effort was directed from the utilities to avoid the risk of SSR during system operation. Subsynchronous oscillations due to the interactions of series capacitors with turbine-generator mechanical shaft system lead to the failure of the entire shaft system, causing electrical instability in a frequency range lower than the normal system frequency. Flexible AC Transmission System (FACTS) is a technology-based concept that can provide a full dynamic control over active and reactive power flow on transmission systems based on the key control variables such as transmission line impedance, phase angle and voltage. It also provides the needed corrections of transmission functionality in order to fully utilize existing transmission system and therefore, minimizing the gap between the stability and thermal levels. The concept of FACTS and FACTS controllers are high power electronics devices used to control the power flow and enhance stability, have become, not only common words in the power industry, but they have started replacing many mechanical control devices. They are certainly playing an important and a major role in the operation and control of modern power systems [3-6].

Successful application of Flexible AC Transmission Systems (FACTS) Controllers has been reported in past to mitigate subsynchronous resonance [3]. One of the widely referred examples of such applications is [7] where thyristor controlled VAR compensator is used for damping subsynchronous oscillations. They used a thyristor controlled VAR compensator

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connected in shunt at the synchronous generator bus to damp subsynchronous oscillations besides controlling the system voltage. A practical installation of SVC for SSR mitigation is reported in [8-16].

The IEEE First Benchmark (FBM) model is considered for the analysis of SSR [17] and the complete simulation of the power system is performed in the MATLAB/Simulink environment. The study is carried out based on damping torque analysis, eigenvalue analysis, and transient simulation. The results show that the suggested controller is satisfactory for damping SSR. This paper is structured as follows. Section 2 describes the modeling of power system. Section 3 introduces the development of supplementary controllers. Section 4 introduces the eigenvalues and time domain simulations. The major conclusions of the paper are given in section 5.

2. Study System Model

The study system, as shown in Figure 1, consists of a steam turbine driven synchronous generator supplying bulk power to an infinite bus over a long transmission line (IEEE first benchmark model) [17]. An SVS of switched capacitor and thyristor controlled reactor type is considered located at the central of the transmission line which provides continuously controllable reactive power at its terminals in response to bus voltage and line current (BVLC) supplementary controller. The series compensation is applied at the sending end of the line [18-20].

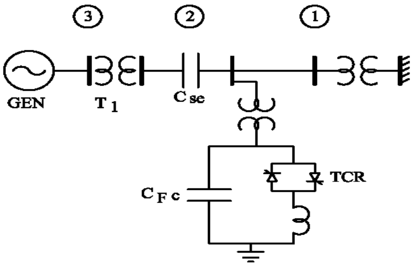

Figure 1. SMIB Study Power System with SVS [18]

2.1. Modeling of Generator

In the detailed machine model used in this paper, the stator is represented by a dependent current source parallel with the inductance. The generator model includes the field winding ‘f’ and a damper winding ‘h’ along d-axis and two damper windings ‘g’ and ‘k’ along q-axis. The IEEE type-1 excitation system is used for the generator [21-23].

The rotor flux linkages ‘ψ’ associated with different windings are defined by:

$$\begin{aligned}
\dot{\psi}_f &= a_1\psi_f + a_2\psi_h + b_1V_f + b_2I_d \\
\dot{\psi}_h &= a_3\psi_f + a_4\psi_h + b_3I_d \\
\dot{\psi}_g &= a_5\psi_g + a_6\psi_k + b_5I_q \\
\dot{\psi}_k &= a_7\psi_g + a_8\psi_h + b_6I_q
\end{aligned} \tag{1}$$

Where V_f is the field excitation voltage. Constants a_1 to a_8 and b_1 to b_6 are defined in [24]. i_d, i_q are d, and q axis components of the machine terminal current respectively which are defined with respect to machine reference frame. To have a common axis of representation with the network and SVS, these flux linkages are transformed to the synchronously rotating D-Q frame of reference using the following transformation:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} I_D \\ I_Q \end{bmatrix} \tag{2}$$

Where i_D, i_Q are the respective machine current components along D and Q axis. δ is the angle by which d-axis leads the D-axis. Currents I_d and I_q, which are the components of the dependent current source along d and q axis respectively, are expressed as:

$$I_d = c_1\psi_f + c_2\psi_h$$
$$I_q = c_3\psi_g + c_4\psi_k \tag{3}$$

Where constants c_1- c_4 are defined in [20]. The above nonlinear differential equations are used in the power system modeling.

2.2. Modeling of Mechanical System

In the mechanical model detailed shaft torque dynamics [2] has been considered for the analysis of torsional modes due to SSR. The mechanical system is described by the six spring-mass model as shown in Figure 2. This shows the electromechanical mass-spring damper system. It consists of Exciter (EXC), Generator (GEN), Low Pressure of two sections (LPA and LPB), intermediate pressure (IP) and High Pressure (HP) turbine sections. Every section has its own angular momentum (M) and damping coefficient (D), and every two successive masses have their own shaft stiffness constant (K). All masses are mechanically connected to each other by elastic shafts [25]. The data for electrical and mechanical system are provided in appendix.

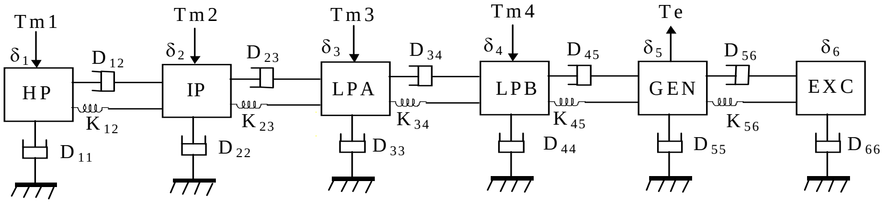

Figure 1. Six Mass Spring Mechanical System (Typical SSR Studies) [18]

The leading equations and the state and output equations are given as follows:

$$\delta_i = \omega_i \qquad i=1, 2, 3, 4, 5, 6$$

$$\frac{d}{dt}\omega_1 = \frac{1}{M_1}\left[-(D_{11}+D_{12})\,\omega_1 + D_{12}\,\omega_2 - K_{12}\,(\delta_1-\delta_2) + T_{M_1}\right]$$

$$\frac{d}{dt}\omega_2 = \frac{1}{M_2}\left[D_{12}\,\omega_1 - (D_{12}+D_{22}+D_{23})\,\omega_2 + D_{23}\omega_3 - K_{12}\,(\delta_2-\delta_1) + T_{M2}\right]$$

$$\frac{d}{dt}\omega_3 = \frac{1}{M_3}\left[D_{23}\omega_2 - (D_{23}+D_{33}+D_{34})\,\omega_3 + D_{34}\omega_4 - K_{23}\,(\delta_3-\delta_2) - K_{34}\,(\delta_3-\delta_4) + T_{M_3}\right]$$

$$\frac{d}{dt}\omega_4 = \frac{1}{M_4}\left[D_{34}\,\omega_3 - (D_{34}+D_{44}+D_{45})\,\omega_4 + D_{45}\omega_5 - K_{34}(\delta_4-\delta_3) - K_{45}(\delta_4-\delta_5) + T_{M_4}\right]$$

$$\frac{d}{dt}\omega_5 = \frac{1}{M_5}\left[D_{45}\omega_4 - (D_{45}+D_{55}+D_{56})\,\omega_5 + D_{56}\,\omega_6 - K_{45}\,(\delta_5-\delta_4) - K_{56}(\delta_5-\delta_6) - T_e\right]$$

$$\frac{d}{dt}\omega_6 = \frac{1}{M_6}\left[D_{56}\,\omega_5 - (D_{56}+D_{66})\,\omega_6 - K_{56}\,(\delta_6-\delta_5)\right]$$

$$T_e = -X_d''\,(i_D I_Q - i_Q\, I_D) \tag{4}$$

Where $\delta_{1,}\delta_{2,}\delta_{3,}\delta_{4,}\delta_{5,}\delta_{6,}$ are the angular displacements and $\omega_1,\omega_2,\omega_3,\omega_4,\omega_5,\omega_6$are the angular velocities of different shaft segments as shown in Figure 2.

2.3. Modeling of Excitation System

The IEEE type-1 excitation system [26] is described by the following equations:

$$\begin{aligned} \frac{d}{dt}V_f &= -\frac{(K_E+S_E)}{T_E}V_f+\frac{1}{T_E}V_r \\ \frac{d}{dt}V_S &= -\frac{K_F(K_E+S_E)}{T_ET_F}V_f-\frac{1}{T_E}V_S+\frac{K_F}{T_ET_F}V_r \\ \frac{d}{dt}V_r &= -\frac{K_A}{T_A}V_S-\frac{1}{T_A}V_r-\frac{K_A}{T_A}Vg+\frac{K_A}{T_A}V_{REF} \end{aligned} \tag{5}$$

2.4. Modeling of T Network

The ac transmission line in this study system is adapted from the IEEE first SSR benchmark system [17]. The transmission line is represented by standard lumped parameter T-circuit. The network has been represented by its α–axis equivalent circuit, which is identical with the positive sequence network. The governing equations of the α-axis, T-network representation is derived as follows:

$$\begin{aligned} \frac{di_{1\alpha}}{dt} &= \frac{-R}{L_2}i_{1\alpha}+\frac{1}{L_2}V_{2\alpha}-\frac{1}{L_2}V_{1\alpha} \\ \frac{di_{\alpha}}{dt} &= \frac{1}{L_1}V_{1\alpha}-\frac{R_1}{L_1}i_{\alpha}-\frac{L_d''}{L_1}\frac{di_{\alpha}}{dt}-\frac{1}{4}V_{4\alpha} \\ \frac{dV_2}{dt} &= -\frac{1}{C_n}i_{\alpha}-\frac{1}{c_n}i_{2\alpha}-\frac{1}{C_n}i_{1\alpha} \\ \frac{dV_{4\alpha}}{dt} &= \frac{1}{C_{se}}i_{\alpha} \end{aligned} \tag{6}$$

Where $C_n = C_T + C_{FC}$,$L_1 = L + L_{A,}L_2 = L + L_{T2}$,$L_A = L_{T1} + L''_n$and $R_1 = R + R_a$

Similarly, the equations can be derived for the β- network. The α-β network equations are then transformed to D-Q frame of reference.

2.5. Modeling of Static Var System

The terminal voltage perturbation ΔV and the SVS incremental current weighted by the factor K_D representing current droop are fed to the reference junction. T_M represents the measurement time constant, which for simplicity is assumed to be equal for both voltage and current measurements. The voltage regulator is assumed to be a proportional- integral (PI) controller. Thyristor control action is represented by an average dead time T_D and a firing delay time T_s. ΔB is the variation in TCR susceptance. ΔV_F represents the incremental supplementary control controller [27].

The α-β axes currents entering TCR from the network are expressed as:

$$L_s\frac{di_{2\alpha}}{dt}+R_si_{2\alpha}=V_{2\alpha}$$

$$L_s\frac{di_{2\beta}}{dt}+R_si_{2\beta}=V_{2\beta} \tag{7}$$

Where R_S, L_S represent TCR resistance and inductances respectively. The other equations describing the SVS model are:

$Z_1 = \Delta V_{ref} - Z_2 + \Delta V_F$

$$\dot{Z}_2 = \frac{1}{T_M}(\Delta V_2 - K_D \Delta i_{2)} - \frac{1}{T_M} Z_2 \tag{8}$$

$$\dot{Z}_3 = -\frac{K_I}{T_3} Z_1 + \frac{K_P}{T_S} Z_2 - \frac{1}{T_s} Z_3 - \frac{K_P}{T_S} \Delta V_{ref} - \frac{K_p}{Ts} \Delta V_F$$

$\Delta B = (Z_3 - \Delta B)/ T_D$

Where ΔV2,Δi_2 are incremental magnitudes of SVS voltage and current, respectively, obtained by linearizing.

$$V_2^2 = V_{2D}^2 + V_{2Q}^2 \, , \; i_2^2 = i_{2D}^2 + i_{2Q}^2$$

3. Design of Subsynchronous Damping Controller

The supplementary controller U_C is implemented through a first order supplementary controller transfer function G(s), which is assumed to be:

$$\dot{X}_C = [A_C] X_C + [B_C] U_C$$
$$Y_C = [C_C] X_C + [D_C] U_C$$

3.1. Bus Voltage (BV) Supplementary Controller

The SVS bus voltage can be expressed as:

$$V_2^2 = V_{2D}^2 + V_{2Q}^2 \tag{9}$$

Linearizing (9) gives the deviation in the SVS bus voltage ΔV_2, which is taken as the Supplementary control Controller:

$$\Delta V_2 = (V_{2D0} / V_{20}) \Delta V_{2D} + (V_{2Q0} / V_{20}) \Delta V_{2Q} \tag{10}$$

Where ‘o’ represents operating point or steady state values.

3.2. Line Current (LC) Supplementary Controller

The line current entering to SVS Bus from generator end bus is given by:

$$i_2^2 = i_{2D}^2 + i_{2Q}^2 \tag{11}$$

Linearizing (11) gives the deviation in line current:

$$\Delta i = \frac{i_{Do}}{i_o} \Delta i_D + \frac{i_{Qo}}{i_o} \Delta i_Q \tag{12}$$

Where ‘o’ represents operating point or steady state values.

4. Results and Analysis

The study power system consists of 1110MVA synchronous generator supplying power to an infinite bus over a 400kV, 600km. long series compensated single circuit transmission line. The study system is as per the IEEE first bench mark model. The system data and torsional spring mass system data are given in appendix. The SVS rating for the line has been chosen to be 100MVAR inductive to 300 MVAR capacitive. 40% series compensation is used at the sending end of the transmission line [28-29].

4.1 Eigenvalue Investigation

The eigenvalue investigation has been carried using the linearized system modeling of power system. The natural system damping has been considered to be zero in order to simulate the weakest system conditions. Table 1 shows the eigenvalues without any supplementary controller incorporated in the SVS. Mode 0 is unstable at 800MW. Table 2 shows the system eigenvalues at P = 200, 500 and 800MW with BVLC supplementary controllerare stable. The supplementary controller parameters are selected based on an extensive root locus.All the electrical and electromechanical modes are found to be stable when the proposed supplementary controlleris applied.

Table 1.System Eigenvalues without BVLC Supplementary Controller

Torsional Mode	P =200 MW	P =500 MW	P =800 MW
Mode # 5	-0.0000±298.1i	-0.0000±298.1i	-0.0000±298.1i
Mode # 4	-0.22236±202.88i	-0.27157±202.84i	-0.33712±202.78i
Mode # 3	-.010518±160.52i	-.047052±160.53i	-.096185±160.52i
Mode # 2	-.005104±126.97i	-.010512±126.96i	-.017161±126.95i
Mode # 1	-.026618±98.757i	-.030093±98.665i	-.024943±98.517i
Mode # 0	-0.33922±4.0339i	-.098976±4.2864i	**.078793±4.1284i**
	-13.132±833.01i	-13.133±833i	-13.133±833i
	-532.8±3.3619i	-532.82±4.4606i	-532.83±4.7221i
	-12.767± 442.17i	-12.769±442.15i	-12.769±442.16i
	-5.4252±311.97i	-5.4245±311.97i	-5.4245±311.97i
	-34.282±189.06i	-35.515±187.54i	-35.498±187.12i
	-3.2239±187.16i	-3.2602±188.75i	-3.4007±189.12i
	-57.127±86.317i	-53.469±85.459i	-52.804±85.669i
	-25.634±24.258i	-25.689±24.357i	-25.744±24.309i
	-39.674	-40.643	-40.979
	-27.443	-31.073	-31.573
	-2.5406	-2.8919	-2.9457
	-0.5906±0.74682i	-0.5662±0.79191i	-.66527±0.84667i

Note: Bold values represent unstable mode.

Table 2. System Eigenvalues with BVLC Supplementary Controller

Torsional Mode	P =200 MW	P =500 MW	P =800 MW
Mode # 5	-0.0000±298.1i	-0.0000±298.1i	-0.0000±298.1i
Mode # 4	-0.27644±202.8i	-0.27889±202.82i	-0.32836±202.78i
Mode # 3	-0.00078±160.49i	-0.01263±160.48i	-0.03685±160.47i
Mode # 2	-0.00107±126.97i	-0.00318±126.97i	-0.00752±126.96i
Mode # 1	-0.01376±98.788i	-0.02451±98.724i	-0.05356±98.607i
Mode # 0	-0.32208±4.0334i	-0.7±4.5633i	-1.2374±5.1934i
	-13.631±832.76i	-13.678±833.14i	-13.624±833.27i
	-532.74±22.156i	-532.4±27.532i	-532.33±27.507i
	-11.957±444.13i	-10.874±443.12i	-10.71±442.6i
	-5.4375±311.87i	-5.4377±311.84i	-5.4344±311.85i
	-30.693±201.3i	-33.749± 206.43i	-35.228±206.2i
	-7.0629±196.4i	-3.4775±193.81i	-1.9517±192.73i
	-123.69	-135.66	-130.69
	-10.015±32.411i	-5.7679±35.243i	-8.7622±37.527i
	-27.866±24.192i	-26.712±24.246i	-26.528±24.247i
	-28.713	-31.529	-31.749
	-8.6611	-7.3559	-5.3472
	-3.2366	-3.0933±0.035389i	-3.4477
	-2.5602	-0.42708±0.73451i	-3.0834
	-0.46533±0.70103i		-0.5233±0.79835i

4.2 Time Domain Simulations of SSR Study

A digital computer simulation study, using a nonlinear system model, has been carried out to demonstrate the effectiveness of the BVLC supplementary controller under large disturbance conditions. Applying a pulsed torque of 30% for 0.1 sec simulates a disturbance. The simulation study has been carried out at P=800MW. The natural damping of the mechanical subsystem is assumed to be zero in order to simulate the worst system conditions and to demonstrate the damping effectiveness of the proposed SVS controller alone without considering the already existing natural system damping [30-31]. Figure 3 to Figure 7 shows the response curves of the terminal voltage, SVS bus voltage, SVS susceptance, power angle and angular velocity with BVLC supplementary controller after the disturbance. It can be seen that there is tendency towards stability when BVLC supplementary controller is used in the SVS control system. The torsional oscillations are stabilized and the BVLC SVS supplementary controller attains a significant improvement in the transient performance of the series compensated power system. The control strategy is easily implemental as it utilizes the locally derived controllers from the SVS bus.

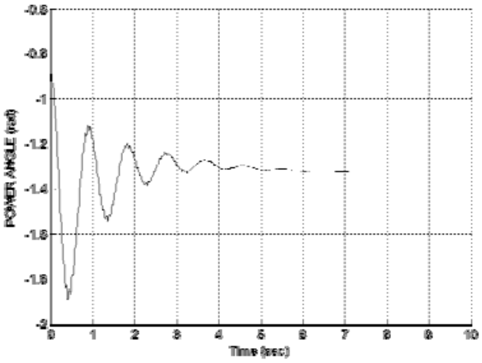

Figure 3. Power Angle Response with BVLC Supplementary Controller

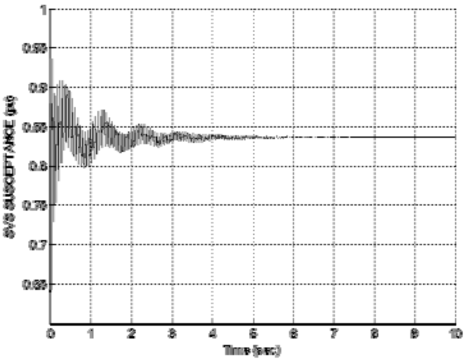

Figure 4. SVS Susceptance Response with BVLC Supplementary Controller

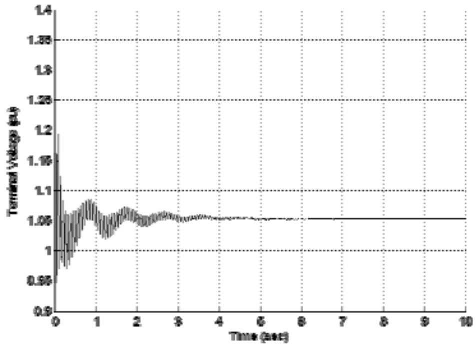

Figure 5. Terminal Voltage Response with BVLC Supplementary Controller

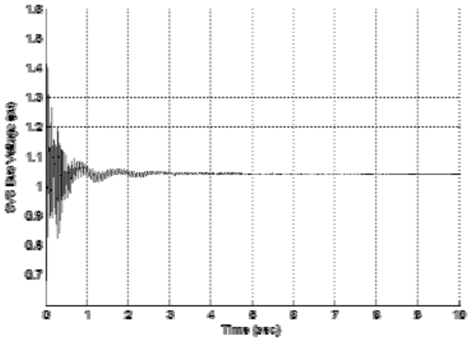

Figure 6. SVS Bus Voltage Response with BVLC Supplementary Controller

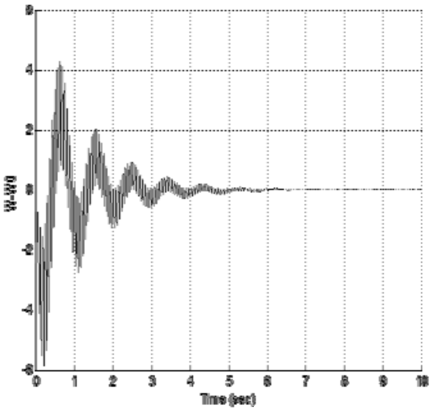

Figure 7. Angular Velocity Response with BVLC Supplementary Controller

5. Conclusion

A combined bus voltage and line current (BVLC) SVS supplementary subsynchronous damping controller (SSDC) has been proposed and designed for improving the transient performance of series compensated power system. The use of supplementary subsynchronous damping controller (SSDC) is to improve torsional characteristics. This location of SSDC is an electrical middle point of the transmission line. Damping of torsional modes is found stable with SSDC for 40% compensation level is presented in Table 1 and Table 2. It can be seen that the presence of the supplementary controller line in the network improves the damping of the lower frequency torsional modes. Eigen value studies and time domain simulations demonstrates that the BVLC supplementary controller improves the damping of the torsional electromechanical oscillations due to sub synchronous resonance (SSR) in the series compensated power system. The power angle ,terminal voltage, SVS bus voltage, SVS susceptance and deviation in angular speed response curves shows poorly damped oscillations or growing oscillations dies out with BVLC supplementary damping controller. It is shown that the use of SVS SSDC in the selected location effectively damps SSR successfully in addition to control the line active power and damping torsional oscillations. Eigenvalues investigation as well as nonlinear time domain simulations in a MATLAB/Simulink environment are carried out.

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Appendix

Table 3. Supplementary Controller Parameters

SVS Supplementary$K_{B1}T_1T_2$ Controller		
Bus Voltage (BV)-0.845	0.008	0.5
K_{B2} T_3T_4		
Line Current (LC)-0.039	0.390.2	

The data for electromechanical system concerning to IEEE FBM is given below. All the data are in per unit (p.u.) on 1110 MVA base.

Generator data:

Power rating=1110 MVA,V_{LL}=22 kV,R_a= 0.0036, X_l = 0.21 pu

Stability data:T_{uo}'=6.66 sec, T_{vo}'=0.44 sec, T_{uo}''=0.032 sec, T_{vo}'' =0.057 sec

X_u = 1.933 pu, X_v = 1.743 pu, X_u' =0.467 pu, X_v' = 1.144 pu, X_u'' = 0.312, X_v'' = 0.312 pu

ω_0 = 314 rad/sec.

IEEE Type 1 Excitation system**:**

T_R=0, T_A=0.02, T_E=1.0, T_F=1.0 sec, K_A=400, K_E=1.0; K_F=0.06 pu

V_{Fmax}=3.9, V_{Fmin} =0, V_{Rmax}=7.3, $V_{R\,min}$= -7.3

Transformer data: R_T = 0, X_T=0.15 pu (Generator base)

Transmission line data**:**

Voltage=400 kV, Length = 600 km, Resistance R=0.034 Ω/km, Reactance X=0.325 Ω/km, Susceptance, B_c=3.7μ mho/km

SVS Data (Six-Pulse Operation)

SVC rating: Q_L = 100 MVAr and Q_C = 350 MVAr.

T_M=2.4, T_S=5, T_D = 1.667ms, K_I= 950, K_P = 0.5, K_D = 0.01.