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Incorporation of SVS CBVLC Supplementary Controller for Damping SSR in Power System

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***Abstract*—**Static VAR System (SVS) is a kind of FACTS device which is used in power system primarily for the purpose of voltage and reactive power control. In this paper presents a systematic approach for designing SVS supplementary controller, which is used to improve the damping of power system oscillation. The combined bus voltage and line current (CBVLC) supplementary controller has been developed and incorporated in the SVS control system located at the middle of the series compensated long transmission line. Damping of torsional stresses due to subsynchronous resonance resulting from series capacitive compensation using CBVLC is investigated in this paper. Simulation results are carried out with MATLAB/Simulink on the IEEE first benchmark model (FBM). The simulation results show that the oscillations are satisfactorily damped out by the SVS supplementary controller. Time domain simulation is performed on power system and the results demonstrate the effectiveness of the proposed controller.

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

I. Introduction

SERIES compensation of long transmission lines is an important approach to improve the power transfer capability of power networks [1]. However, in such compensated networks, the interactions between the electrical modes of the series compensated network and a mechanical mode of a turbine generator shaft can be led to a serious detrimental phenomenon referred to Sub-Synchronous Resonance (SSR) [2]-[4]. In recent years static VAR system (SVS) has been employed to an increasing extent in the modern power systems due to its capability to work as var generation and absorption systems. Besides, voltage control and improvement of transmission capability, SVS in coordination with supplementary controllers can be used for damping of power system oscillations. Damping of power system oscillation plays an important role not only in increasing the power transmission capability but also for stabilization of power system conditions after critical faults, particularly in weakly coupled networks [5]-[9].

The capacitors in series with transmission lines may cause sub-synchronous resonance (SSR) that can lead to turbine-generator shaft failure and electrical instability at oscillation frequencies lower than the normal system frequency. Incidentally, the shaft damage can also occur due to fatigue when the peak torques exceeds a limit [10], [11]. The proposed scheme was able to damp out the torsional modes at wide range of series compensation. However the control scheme was complex as it utilized three different controllers [12]-[14]. This paper introduces a method for reducing the amplitudes of transient torsional torques in series capacitor compensated networks, using supplementary controlled static var system.

In this paper a new SVS control strategy for damping torsional oscillations due to subsynchronous resonance (SSR) in a series compensated power system has been developed. The proposed SVS control strategy utilizes the effectiveness of combined bus voltage and line current (CBVLC) SVS supplementary controller. A digital computer simulation study, using a nonlinear system model, has been carried out to illustrate the performance of the proposed SVS controller under large disturbance. It is found that the torsional oscillations are effectively damped out and the transient performance of the series compensated power system is greatly enhanced. The IEEE First Benchmark (FBM) model is considered for the analysis of SSR [15] 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 and transient simulation. The results show that the suggested controller is satisfactory for damping SSR. This paper is structured as follows. Section II describes the modeling of power system. Section III introduces the development of supplementary controllers. Section IV introduces the eigenvalues and time domain simulations. The major conclusions of the paper are given in Section V.

II. Modeling of the Power System

The Static VAR system is basically a shunt connected variable VAR generator whose output is adjusted to exchange capacitive or inductive current to the system [16-18]. One of the most widely used configurations of the SVS is the FC-TCR type in which a fixed capacitor (FC) is connected in parallel with thyristor controlled reactor (TCR). The studied system is based on the first IEEE benchmark system for subsynchronous resonance [15].

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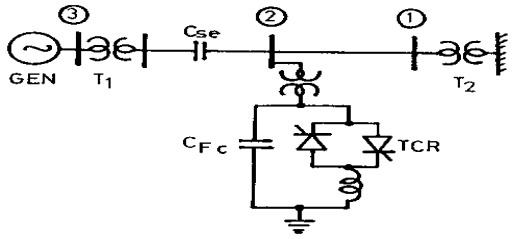


Fig. 1 Study system: IEEE FBM [16]

The considered study system, shown in Fig. 1 consists of one synchronous generator, two transformers T_1& T_2, one series capacitor and a SVS in the middle of line.

A. Generator Model

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 [19]-[21]. The rotor flux linkages 'ψ' associated with different windings are defined by:

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

where V_f is the field excitation voltage. Constants a_1 to a_8 and b_1 to b_6 are defined in [22]. 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:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} i_D \\ i_Q \end{bmatrix} \quad (2)$$

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:

$$\begin{aligned}I_d &= c_1\psi_f + c_2\psi_h\\ I_q &= c_3\psi_g + c_4\psi_k\end{aligned} \quad (3)$$

where constants c_1-c_4 are defined in [16].

B. Mechanical System Modeling

The rotor shaft system of a large turbine generator unit comprises six turbine sections of different sizes, can be lumped together to form a multimass model. In the mechanical model detailed shaft torque dynamics 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 Fig. 2. This shows the electromechanical mass-spring damper system. It consists of Exciter (denoted by EXC), Generator (GEN), Low Pressure of two stages (LPA and LPB respectively), and intermediate pressure stage (IP) and High Pressure stage (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 [23]. The data for electrical and mechanical system is provided in appendix. The equation of motion for shaft sections which are connected to each other is described by:

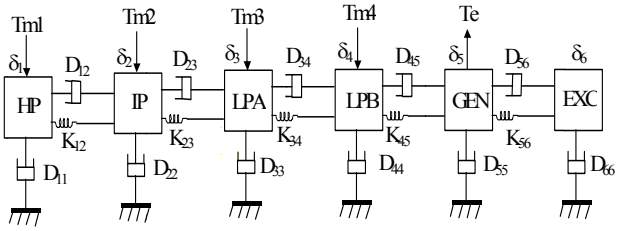


Fig. 2 Six mass spring mechanical system (Typical SSR Studies) [16]

$$\begin{aligned}
&\delta_i = \omega_i,\ i=1,2,3,4,5,6\\
&\dot{\omega}_1 = \frac{1}{M_1}\left[\begin{matrix}-(D_{11}+D_{12})\,\omega_1 + D_{12}\,\omega_2 - \\ K_{12}\,(\delta_1-\delta_2) + T_{M_1}\end{matrix}\right]\\
&\dot{\omega}_2 = \frac{1}{M_2}\left[\begin{matrix}D_{12}\,\omega_1 - (D_{12}+D_{22}+D_{23})\,\omega_2 + D_{23}\omega_3\\ -K_{12}\,(\delta_2-\delta_1) + T_{M2}\end{matrix}\right]\\
&\dot{\omega}_3 = \frac{1}{M_3}\left[\begin{matrix}D_{23}\omega_2 - (D_{23}+D_{33}+D_{34})\,\omega_3 + D_{34}\omega_4\\ -K_{23}\,(\delta_3-\delta_2) - K_{34}\,(\delta_3-\delta_4) + T_{M_3}\end{matrix}\right]\\
&\dot{\omega}_4 = \frac{1}{M_4}\left[\begin{matrix}D_{34}\omega_3 - (D_{34}+D_{44}+D_{45})\,\omega_4 + D_{45}\omega_5\\ -K_{34}\,(\delta_4-\delta_3) - K_{45}\,(\delta_4-\delta_5) + T_{M_4}\end{matrix}\right]\\
&\dot{\omega}_5 = \frac{1}{M_5}\left[\begin{matrix}D_{45}\omega_4 - (D_{45}+D_{55}+D_{56})\,\omega_5\\ +D_{56}\,\omega_6 - K_{45}\,(\delta_5-\delta_4) -\\ K_{56}(\delta_5-\delta_6) - T_e\end{matrix}\right]\\
&\dot{\omega}_6 = \frac{1}{M_6}\left[D_{56}\,\omega_5 - (D_{56}+D_{66})\,\omega_6 - K_{56}\,(\delta_6-\delta_5)\right]\\
&T_e = -X''_d\,(i_D I_Q - i_Q\,I_D)
\end{aligned} \quad (4)$$

where $T_M$is the mechanical torque applied to each mass and $T_e$is the electrical torque produced by the generator. ω is rated speed (rad/s), $\delta_1,\delta_2,\delta_3,\delta_4,\delta_5,\delta_6$, 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 Fig. 2.

C. Excitation System Modeling

The IEEE type-1 excitation system [24] is described by the following equations:

$$\frac{d}{dt}V_f = -\frac{(K_E+S_E)}{T_E}V_f + \frac{1}{T_E}V_r$$

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$$\frac{d}{dt}V_S = -\frac{K_F(K_E+S_E)}{T_E T_F}V_f - \frac{1}{T_E}V_S + \frac{K_F}{T_E T_F}V_r \quad (5)$$

$$\frac{d}{dt}V_r = -\frac{K_A}{T_A}V_S - \frac{1}{T_A}V_r - \frac{K_A}{T_A}Vg + \frac{K_A}{T_A}V_{REF}$$

D. Network System Modeling

The ac transmission line in this study system is adapted from the IEEE first SSR benchmark system [15]. 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:

$$\frac{di_{1\alpha}}{dt} = \frac{-R}{L_2}i_{1\alpha} + \frac{1}{L_2}V_{2\alpha} - \frac{1}{L_2}V_{1\alpha}$$
$$\frac{di_{\alpha}}{dt} = \frac{1}{L_1}V_{1\alpha} - \frac{R_1}{L_1}i_{\alpha} - \frac{L''_d}{L_1}\frac{di_{\alpha}}{dt} - \frac{1}{4}V_4\ \alpha \quad (6)$$
$$\frac{dV_2}{dt} = -\frac{1}{C_n}i_{\alpha} - \frac{1}{c_n}i_{2\alpha} - \frac{1}{C_n}i_{1\alpha}$$
$$\frac{dV_{4\alpha}}{dt} = \frac{1}{C_{se}}i\alpha$$

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.

E. Static VAR System Modeling

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 controller [25]. The α-β axes currents entering TCR from the network are expressed as:

$$L_s\frac{di_{2\alpha}}{dt} + R_s i_{2\alpha} = V_{2\alpha}$$
$$L_s\frac{di_{2\beta}}{dt} + R_s i_{2\beta} = V_{2\beta} \quad (7)$$

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

$$Z_1 = \Delta V_{ref} - Z_2 + \Delta V_F$$
$$\dot{Z}_2 = \frac{1}{T_M}(\Delta V_2 - K_D\Delta i_2) - \frac{1}{T_M}Z_2 \quad (8)$$
$$\dot{Z}_3 = -\frac{K_I}{T_3}Z_1 + \frac{K_P}{T_S}Z_2 - \frac{1}{T_s}Z_3 - \frac{K_P}{T_S}\Delta V_{ref} - \frac{K_p}{Ts}\Delta V_F$$
$$\Delta B = (Z_3 - \Delta B)/\ T_D$$

where $\Delta V2, \Delta i_2$ are incremental magnitudes of SVS voltage and current, respectively, obtained by linearizing

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

III. Development of SVS Supplementary Controller

The supplementary controller U_C is implemented through a first order supplementary controller transfer function.

The state and output equations are given by

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

A. Bus Voltage Supplementary Controller

The SVS bus voltage can be expressed as:

$$V_2^2 = V_{2D}^2 + V_{2Q}^2 \quad (9)$$

Linearizing (9) gives the deviation in the SVS bus voltage ΔV_2, which is taken as the bus voltage supplementary controller:

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

B. Line Current Supplementary Controller

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

$$i_2^2 = i_{2D}^2 + i_{2Q}^2 \quad (11)$$

Linearizing (11) gives the deviation in line current:

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

where 'o' represents operating point or steady state values.

IV. A Case Study

To demonstrate the validity of the proposed scheme, IEEE first benchmark model for time domain simulation is adopted. The system consists of two synchronous generators each of 555 MVA amounting to 1110 MVA equivalent synchronous generator supplying bulk power to an infinite bus over a 400 kV, 600 km. long series compensated single circuit transmission line. The single circuit transmission line has been considered in order to simulate the weakest system conditions. The system data and torsional spring mass system data are given in appendix. The SVS has been considered located at the

middle of the transmission line for its optimal performance. By conducting the load flow study the rating of the SVS has been chosen to be 100 MVAR inductive to 350 MVAR capacitive. About 40% series compensation is used at the sending end side of midpoint located SVS [26]-[29].

V. Time Domain Simulations for SSR Study

A digital computer simulation study, using a nonlinear system model, has been carried out to demonstrate the effectiveness of the proposed supplementary controller under large disturbance conditions. Applying a pulsed torque of 30% for 0.1 s simulates a disturbance. The simulation study has been carried out at P_G=800 MW. Figs. 3-7 show the response curves of the shaft torsional torques with the CBVLC SVS supplementary controller. The torsional oscillations are effectively stabilized and the proposed supplementary controllers attain a significant improvement in the transient performance of the series compensated power system.

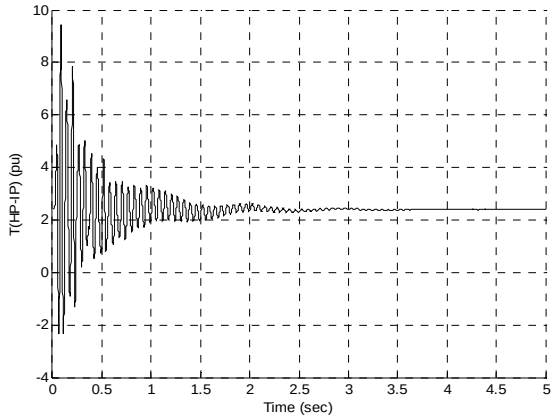


Fig. 3 Variation of shaft torsional torque (HP-IP) with CBVLC

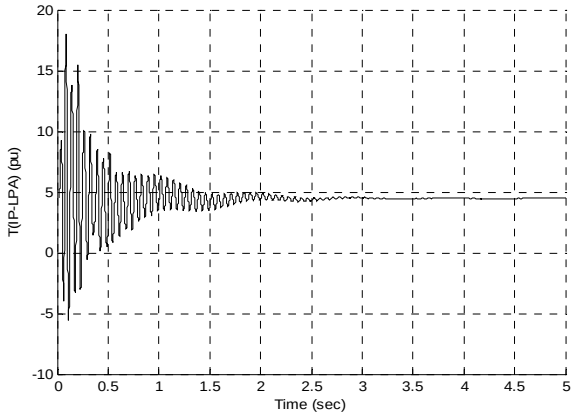


Fig. 4 Variation of shaft torsional torque (IP-LPA) with CBVLC

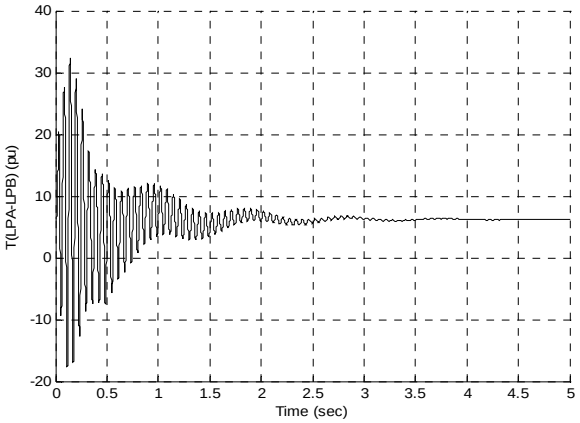


Fig. 5 Variation of shaft torsional torque (LPA-LPB)with CBVLC

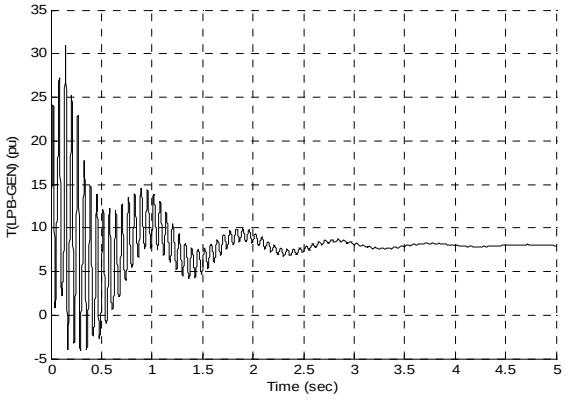


Fig. 6 Variation of shaft torsional torque (LPB-GEN)with CBVLC

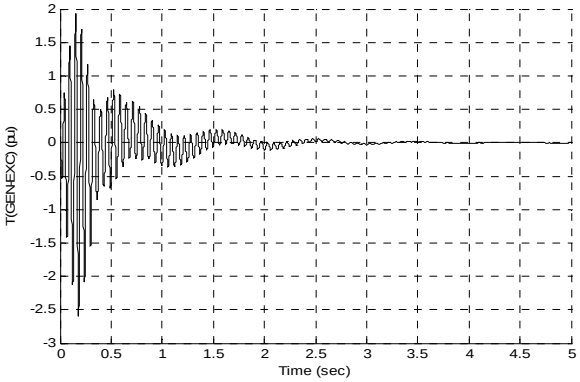


Fig. 7 Variation of shaft torsional torque (GEN-EXC)with CBVLC

VI. Conclusion

In this paper the effectiveness of SVS with supplementary controller have been evaluated for damping the subsynchronous oscillations in a series compensated power system. The existence of sub synchronous conditions and their severity can be verified using MATLAB as a simulation and analytical tool. The effectiveness of combined bus voltage and line current (CBVLC) SVS supplementary controller has been evaluated for damping the electromechanical torsional oscillations in a series compensated power system.

The time domain simulation study demonstrates that the

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combined bus voltage and line current (CBVLC) supplementary controller improve the damping of the torsional electromechanical oscillations due to sub synchronous resonance (SSR) in the series compensated power system.The response curves of shaft torsional torques with the CBVLC SVS supplementary controller show a remarkable improvement and their oscillations die down effectively.

APPENDIX

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.

A. 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 s, T_{vo}=0.44 s, $T_{uo}^{''}$ =0.032 s, $T_{yo}^{''}$ =0.057 s,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/s.

B. IEEE Type-1 Excitation System:

T_R=0, T_A=0.02, T_E=1.0, T_F=1.0 s, 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

C. Transformer Data:

R_T = 0, X_T=0.15 pu (Generator base)

D. 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

E. 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.

TABLE I
SUPPLEMENTARY CONTROLLER PARAMETERS

SVS Supplementary Controller	K_{B1}	T_1	T_2
Bus Voltage (BV)	-0.675	0.006	0.45
	K_{B2}	T_3	T_4
Line Current (LC)	-0.043	0.39	0.02

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