DAMPING TORQUE ANALYSIS OF STATIC VAR SYSTEM CONTROLLERS

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ABSTRACT : This paper is concerned with the application of damping torque technique to examine the efficacy of various control signals for reactive power modulation of a midpoint located Static Var System (SVS) in enhancing the power transfer capability of long transmission lines. A new auxiliary signal designated Computed Internal Frequency (CIF) is proposed which synthesizes internal voltage frequency of the remote generator from electrical measurements at the SVS bus. It is demonstrated that this signal is far superior than other conventional auxiliary control signals in that it allows full utilization of the network transmission capacity. The damping torque results are correlated with those obtained from eigenvalue analysis.

Keywords : Static Var System, Dynamic Stability, Damping Torque Analysis.

1. INTRODUCTION

Static Var System (SVS) is known to extend the stability limit and improve system damping when connected at the midpoint of a long transmission line [1]. While an SVS with pure voltage control may not adequately contribute to system damping, a significant enhancement in the same is achieved when SVS reactive power is modulated in response to auxiliary control signals superimposed over its voltage control loop [1,2]. The various supplementary signals reported in literature for improving system stability include deviation in rotor velocity [2], bus frequency [3], tie line reactive power [4], line active power [5], etc.

A new auxiliary control signal designated Computed Internal Frequency (CIF) is proposed which involves the computation of internal voltage frequency of the remotely stationed generator utilizing locally measurable SVS bus voltage and transmission line current signals. The effectiveness is compared of different locally derivable signals such as bus frequency, line reactive power and CIF in damping the low frequency (zeroth mode) oscillations which are critical in limiting power transfer.

Eigenvalue analysis is the usually employed tool for prediction of system stability. Though this technique is accurate and provides information on the damping and undamping of all the system modes, it suffers

FIG. 1 STUDY SYSTEM

from the disadvantage that matrix size and solution time tend to become excessive with increasing system complexity. Damping Torque method is a computationally simple frequency domain technique originally proposed by Demello et al. [6] for investigating the zeroth mode instability. This method has been extended here to examine the influence of different SVS controllers in the context of electrical damping provided by them at the zeroth mode frequency. The damping torque method relates to small signal stability of a linearized system. The stability results are compared with eigenvalue analysis results [7,8]. The analytical prediction of SVS performance with voltage control based on linearized models is validated on the ASEA's HVDC simulator at Central Power Research Institute (CPRI), Bangalore [9].

2. SYSTEM DESCRIPTION

The study system having configuration shown in Fig. 1 consists of a generator supplying bulk power to an infinite bus over long distance transmission line which is compensated at its midpoint by a Fixed Capacitor - Thyristor Controlled Reactor (FC-TCR) type SVS.

2.1 Generator Model

The synchronous machine model includes a field winding and a damper winding along the d axis and two damper windings on the q axis.

2.1.1 Stator model : The generator stator is represented by a dependent current source I_a in parallel with the subtransient inductance L_d'' [10]. This stator model is directly combined with the transmission network model given in Sec. 2.2.

2.1.2 Rotor model : The rotor flux linkages (ψ) associated with different windings are defined by

$$\begin{aligned}\dot{\psi}_f &= a_1\dot{\psi}_f + a_2\dot{\psi}_h + b_1v_f + b_2i_d \\ \dot{\psi}_h &= a_3\dot{\psi}_f + a_4\dot{\psi}_h + b_3i_d \\ \dot{\psi}_g &= a_5\dot{\psi}_g + a_6\dot{\psi}_k + b_5i_q \\ \dot{\psi}_k &= a_7\dot{\psi}_g + a_8\dot{\psi}_k + b_6i_q\end{aligned}\quad (1)$$

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where v_f is the field excitation voltage. Constants a_1 - a_8 , b_1 - b_6 are defined in [10]. The dot over a symbol indicates time derivative. i_d , i_q are d,q axis components of the machine terminal current, respectively, which are defined with respect to the machine reference frame. However, to have a common axis of representation with the network and SVS, these currents are transformed to D-Q reference frame which is rotating at synchronous speed ω_o , 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 components of machine current along D and Q axes. δ is the angle by which d axis leads the D-axis.

Substituting eqn. (2) in eqn. (1) and linearizing gives the state equation of rotor circuits as

$$\dot{x}_R = [A_R]x_R + [B_R]u_{R1} + [B_R2]u_{R2} + [B_R3]u_{R3} \quad (3)$$

where $x_R = [\Delta\psi_f \Delta\psi_h \Delta\psi_g \Delta\psi_k]^t$, $u_{R1} = [\Delta\delta \Delta\omega]^t$, $u_{R2} = \Delta v_f$, $u_{R3} = [\Delta i_D \Delta i_Q]^t$. Prefix Δ indicates incremental values. I_d , I_q which are the components of dependent current source along d and q axis, respectively, are expressed as

$$I_d = c_1 \psi_f + c_2 \psi_h; \quad I_q = c_3 \psi_g + c_4 \psi_k \quad (4)$$

where constant c_1 - c_4 are defined in [10]. I_d , I_q are transformed to D-Q axis components i_D and i_Q respectively, using the inverse of transformation given in eqn. (2). The linearized output equation of rotor circuits is obtained as

$$Y_{R1} = [C_{R1}]x_R + [D_{R1}]u_{R1} \quad (5)$$

$$Y_{R2} = [C_{R2}]x_R + [D_{R2}]u_{R1} + [D_{R3}]u_{R2} + [D_{R4}]u_{R3}$$

where $Y_{R1} = [\Delta i_D \Delta i_Q]^t$, $Y_{R2} = [\Delta \dot{i}_D \Delta \dot{i}_Q]^t$

2.1.3 Mechanical system : This is described by the following equations

$$\frac{d\omega}{dt} = \frac{\omega_o}{2H} (-D\omega + T_m - T_e) \quad (6)$$

$$T_e = -x_d''(i_d i_q - i_q i_d) \quad (7)$$

where H = generator inertia constant; D = damping torque coefficient; T_m = mechanical torque; T_e = electrical torque; x_d'' = generator subtransient reactance.

Utilizing these basic eqns. (6-7), the state and output equations of mechanical subsystem are derived as

$$\dot{x}_M = [A_M]x_M + [B_{M1}]u_{M1} + [B_{M2}]u_{M2} \quad (8)$$

$$Y_M = [C_M]x_M \quad (9)$$

where $x_M = [\Delta\delta \Delta\omega]^t$, $u_{M1} = [\Delta i_D \Delta i_Q]^t$, $u_{M2} = [\Delta \dot{i}_D \Delta \dot{i}_Q]^t$, $Y_M = [\Delta\delta \Delta\omega]^t$

2.1.4 Excitation system : The excitation system is represented by the IEEE Type I model [11] having configuration shown in Fig. 2. v is the generator terminal voltage and S_E is the saturation function. We have

FIG. 2 BLOCK DIAGRAM OF IEEE TYPE I EXCITATION SYSTEM

$$\begin{aligned} \dot{v}_f &= -\frac{(K_E + S_E)}{T_E} v_f + \frac{1}{T_E} v_r \\ \dot{v}_s &= -\frac{K_F(K_E + S_E)}{T_E T_F} v_f - \frac{1}{T_F} v_s + \frac{K_F}{T_E T_F} v_r \quad (10) \\ \dot{v}_r &= -\frac{K_A}{T_A} v_s - \frac{1}{T_A} v_r - \frac{K_A}{T_A} v_g + \frac{K_A}{T_A} V_{REF} \end{aligned}$$

The state and output equations of the linearized system are derived as

$$\dot{x}_E = [A_E]x_E + [B_E]u_E \quad (11)$$

$$Y_E = [C_E]x_E \quad (12)$$

where $x_E = [\Delta v_f \Delta v_s \Delta v_r]^t$, $u_E = \Delta v_g$, $Y_E = \Delta v_f$

2.2 Network Model

The network model shown in Fig. 3 consists of transformers, transmission line and the fixed capacitor at SVS bus. The transmission line is represented by a single lumped parameter π -circuit on both sides of the SVS. The equivalent circuit of generator stator is also included in the network model. As network components are assumed to be symmetrical the network can be represented by its α -axis equivalent circuit which is identical with the positive sequence network. The equations for α -network are written as

$$\begin{aligned} L_{T2} \frac{di_{1\alpha}}{dt} &= v_{2\alpha} - v_{1\alpha} \\ L \frac{di_{2\alpha}}{dt} + Ri_{2\alpha} &= v_{3\alpha} - v_{2\alpha} \\ L \frac{di_{4\alpha}}{dt} + Ri_{4\alpha} &= v_{4\alpha} - v_{3\alpha} \\ L_A \frac{di_{\alpha}}{dt} &= v_{4\alpha} - R_A i_{\alpha} - L_d' \frac{di_{\alpha}}{dt} \quad (13) \\ C \frac{dv_{2\alpha}}{dt} &= i_{2\alpha} - i_{1\alpha} \\ C_n \frac{dv_{3\alpha}}{dt} &= i_{4\alpha} - i_{3\alpha} - i_{2\alpha} \\ C \frac{dv_{4\alpha}}{dt} &= -i_{4\alpha} - i_{\alpha} \end{aligned}$$

where $L_A = L_{T1} + L_d'$, $C_n = 2C + C_{FC}$.

FIG. 3 : TRANSMISSION NETWORK.

Subscript α denotes α -axis components of corresponding current and voltage variables. Similar equations can be written for the β -network which is identical with the α -network. Since the α -axis components and β -axis components are sinusoidal quantities in steady state they result in a time varying system. To render the system time invariant the α - β components are transformed to D-Q axis components using the relationship

$$\begin{bmatrix} \tilde{x}_\alpha \\ \tilde{x}_\beta \end{bmatrix} = \begin{bmatrix} \cos \Theta_r \tilde{I} & \sin \Theta_r \tilde{I} \\ -\sin \Theta_r \tilde{I} & \cos \Theta_r \tilde{I} \end{bmatrix} \begin{bmatrix} \tilde{x}_D \\ \tilde{x}_Q \end{bmatrix} \quad (14)$$

$$\begin{aligned} \text{where } \mathbf{x}_D &= [i_{1D} \ i_{2D} \ i_{4D} \ i_D \ v_{2D} \ v_{3D} \ v_{4D}]^t \\ \mathbf{x}_Q &= [i_{1Q} \ i_{2Q} \ i_{4Q} \ i_Q \ v_{2Q} \ v_{3Q} \ v_{4Q}]^t \end{aligned}$$

$\underline{x}_\alpha$ and $\underline{x}_\omega$ are similarly defined. $\tilde{\gamma}$ is an identity matrix of proper dimension. $\theta (= \omega_0 t)$ is the angle by which D axis leads α -axis

The linearized state equation of the network model is finally obtained as

$$\dot{\underline{x}}_N = [A_N] \underline{x}_N + [B_{N1}] \underline{u}_{N1} + [B_{N2}] \underline{u}_{N2} + [B_{N3}] \underline{u}_{N3} \quad (15)$$

$$\begin{aligned} \underline{x}_N &= \begin{bmatrix} \Delta \underline{x}_D & \Delta \underline{x}_Q \end{bmatrix}^t, \quad \underline{u}_{N1} = \begin{bmatrix} \Delta i_{3D} & \Delta i_{3Q} \end{bmatrix}^t \\ \underline{u}_{N2} &= \begin{bmatrix} \Delta \underline{i}_D & \Delta \underline{i}_Q \end{bmatrix}^t, \quad \underline{u}_{N3} = \begin{bmatrix} \Delta \underline{i}_D & \Delta \underline{i}_Q \end{bmatrix}^t = \underline{u}_{N2} \end{aligned}$$

The network output equations are given by

$$y_{N1} = [C_{N1}]x_N + [D_{N1}]u_{N1} + [D_{N2}]u_{N2} + [D_{N3}]u_{N3}$$

$$Y_{N2} = [C_{N2}] \underline{x}_N ; \quad Y_{N3} = [C_{N3}] \underline{x}_N \quad (16)$$

where $y_{N1} = \Delta v_g$, $y_{N2} = [\Delta i_D \Delta i_Q]^t$,
 $y_{N3} = [\Delta v_{3D} \Delta v_{3Q}]^t$

2.3 Static Var System

2.3.1 Voltage control :

A small signal model of a general SVS control system is depicted in Fig. 4. 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 auxiliary control signal.

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

FIG. 4 SVS CONTROL SYSTEM WITH AUXILIARY FEEDBACK.

$$L_S \frac{d i_{3a}}{dt} + R_S i_{3a} = v_{3a} \quad (17)$$

$$L_S \frac{di_{3\beta}}{dt} + R_S i_{3\beta} = v_{3\beta}$$

where R_S , L_S represent TCR resistance and inductance, respectively.

Eqn. (17) is transformed to D-Q frame of reference using the transformation given by eqn. (14) and subsequently linearized. The other equations describing the SVS model are

$$\begin{aligned}\dot{z}_1 &= \Delta V_{\text{ref}} - z_2 \\ \dot{z}_2 &= \frac{1}{T_M} (\Delta v_3 - K_D \Delta i_3) - \frac{1}{T_M} z_2 \\ \dot{z}_3 &= \frac{-K_I}{T_S} z_1 + \frac{K_P}{T_S} z_2 - \frac{1}{T_S} z_3 - \frac{K_P}{T_S} \Delta V_{\text{ref}} \\ \Delta \dot{B} &= \frac{1}{T_D} z_3 - \frac{1}{T_D} \Delta B\end{aligned}\quad (18)$$

where Δv_3 , Δi_3 are incremental magnitudes of SVS voltage and current, respectively, obtained by linearizing

$$v_3 = \sqrt{(v_{3D}^2 + v_{3Q}^2)}; \quad i_3 = \sqrt{(i_{3D}^2 + i_{3Q}^2)} \quad (19)$$

The state and output equations of the SVS model are expressed by

$$\dot{\underline{x}}_S = [A_S]\underline{x}_S + [B_{S1}]\underline{u}_{S1} + [B_{S2}]\underline{u}_{S2} + [B_{S3}]\underline{u}_{S3} \quad (20)$$

$$\underline{y}_S = [C_S] \underline{x}_S + [D_S] \underline{u}_{S1} \quad (21)$$

$$\text{where } \underline{x}_S = [\Delta i_{3D} \Delta i_{3Q} z_1 z_2 z_3 \Delta B]^t, \\ \underline{u}_{S1} = [\Delta v_{3D} \Delta v_{3Q}]^t, \quad \underline{u}_{S2} = [\Delta v_{ref}]^t, \\ \underline{u}_{S3} = \Delta v_F, \quad \underline{y}_S = [\Delta i_{3D} \Delta i_{3Q}]^t$$

2.3.2 Auxiliary control :

The effect of any general auxiliary signal u_c is implemented through the auxiliary controller $G(s)$ shown in Fig.5, which is assumed to be

$$G(s) = \Delta v_F / u_C = K_B (1 + sT_1) / (1 + sT_2) \quad (22)$$

The state and output equations are given by

$$\dot{\underline{x}}_C = [A_C] \underline{x}_C + [B_C] u_C \quad (23)$$

$$y_C = [C_C]x_C + [D_C]u_C \quad (24)$$

where $\underline{x}_C = [z_5]$, $y_C = \Delta v_F$.

The different locally derivable signals considered are:

(i) Deviation in SVS bus (bus 3) frequency

The SVS bus frequency is expressed as

$$f_s = \frac{d}{dt} \left[\tan^{-1} \left(\frac{v_{3Q}}{v_{3D}} \right) \right] \quad (25)$$

FIG. 5 :
BLOCK DIAGRAM OF A GENERAL FIRST ORDER AUXILIARY SVS CONTROLLER

Linearizing eqn. (25) and appropriately substituting Δv_{3D} , Δv_{3Q} from the state and output eqns. of the network, generator and SVS voltage controller model results in

$$u_C = [F_{CR}]x_R + [F_{CM}]x_M + [F_{CN}]x_N + [F_{CS}]x_S \quad (26)$$

where $u_C = \Delta f_S$

(ii) Deviation in line reactive power flowing into SVS bus from the generator end (measured at bus 3) :

The line reactive power signal is given as

$$Q_4 = v_{3D} i_{4Q} - v_{3Q} i_{4D} \quad (27)$$

Linearizing eqn. (27) and expressing in general matrix notation

$$u_C = [F_{CN}]x_N \quad (28)$$

where $u_C = \Delta Q_4$

(iii) Computed Internal Frequency (CIF)

As power transfer capability is basically influenced by the low frequency rotor oscillations it is expected that a control signal derived from the generation source frequency will have a more beneficial influence on the dynamic stability limit. However, it is not feasible to obtain this signal by measurement as the generating station and SVS are located far apart from each other. An endeavour is therefore made to compute this signal from parameters which are available at the SVS bus. The quantities which are utilized for this computation are bus voltage, transmission line current at the SVS bus and the reactance between generator internal voltage and SVS terminals. The derivation procedure is as follows :

The system model shown in Fig. 3 is simplified to a form depicted in Fig. 6. Only the section between generator and SVS is considered. The line charging capacitances and resistances of the generator stator and transmission line are neglected. The fixed capacitor is considered as placed on the right of TCR and is hence, ignored in the analysis. The dependent current source representing the generator is transformed to an equivalent voltage source behind subtransient inductance. L_E represents the total inductance between generator and the equivalent voltage source e_1 .

$$L_E = F_M (L_d + L_{T1} + L)$$

where L_{T1} = inductance of the sending end transformer

L = inductance of the transmission line segment between the generator transformer and SVS

F_M = constant representing the tolerance in measurement of the various inductances.

The α, β axes components of the internal voltage e_1 of synchronous generator are

$$\begin{aligned} e_{1\alpha} &= v_{3\alpha} + L_E \frac{di_{4\alpha}}{dt} \\ e_{1\beta} &= v_{3\beta} + L_E \frac{di_{4\beta}}{dt} \end{aligned} \quad (29)$$

FIG. 6 SIMPLIFIED REPRESENTATION OF THE STUDY SYSTEM FOR OBTAINING CIF SIGNAL.

Transforming eqn. (29) to D-Q frame of reference using the transformation given by eqn. (14) results in

$$e_{1D} = v_{3D} + L_E \frac{d}{dt} i_{4D} + \omega_o L_E i_{4Q} \quad (30a)$$

$$e_{1Q} = v_{3Q} + L_E \frac{d}{dt} i_{4Q} - \omega_o L_E i_{4D} \quad (30b)$$

where e_{1D} , e_{1Q} are the D and Q axes components of the internal voltage e_1 , respectively. $(d/dt)i_{4D}$ and $(d/dt)i_{4Q}$ terms are substituted by their corresponding state equations from the network model. The angle δ_1 of the internal voltage e_1 is computed as

$$\delta_1 = \tan^{-1} (e_{1Q} / e_{1D}) \quad (31)$$

Eqn. (31) is linearized and differentiated to give the Computed Internal Frequency (CIF) signal $\Delta \omega_1$ as

$$\Delta \omega_1 = \frac{d}{dt} \delta_1 = \frac{e_{1D0}}{e_{10}^2} \frac{d}{dt} e_{1Q} - \frac{e_{1Q0}}{e_{10}^2} \frac{d}{dt} e_{1D} \quad (32)$$

Subscript 'o' denotes operating point values.

Eqns. (30a) and (30b) are differentiated and substituted in Eqn. (32). This results in an equation having on its right hand side the derivatives of different state variables. Each of these derivative terms are replaced by their corresponding state equations obtained from the generator, network and SVS voltage controller models, finally giving

$$u_C = [F_{CR}]x_R + [F_{CM}]x_M + [F_{CN}]x_N + [F_{CS}]x_S \quad (33)$$

where $u_C = \Delta \omega_1$. Matrices $[F_{CR}]$, $[F_{CM}]$, $[F_{CN}]$ and $[F_{CS}]$ are defined differently for the three different auxiliary control signals considered.

2.4 System Model

The state and output equations of the different constituent subsystems are then suitably combined [7,8] to result in the state equation of overall system as

$$\dot{x} = [A]x + b \Delta V_{ref} \quad (34)$$

where $x = [x_R \ x_M \ x_E \ x_N \ x_S \ x_C]^T$. The various matrices and vectors introduced in eqns. (3), (5), (8-9), (11-12), (15-16), (20-21), (23-24), (26), (28), (33-34) are defined in [8]. The order of system matrix $[A]$ is 29.

3. DERIVATION OF DAMPING AND SYNCHRONIZING TORQUES

The mechanical system is separated from the remaining system and the deviations in generator rotor angle $\Delta \delta$ and rotor velocity

$\Delta\omega$ are treated as input variables. The modified state equation then becomes

$$\dot{\mathbf{x}}_1 = [\mathbf{A}_1]\mathbf{x}_1 + \mathbf{b}_1 \Delta\delta + \mathbf{b}_2 \Delta\omega \quad (35)$$

where $\mathbf{x}_1 = [\mathbf{x}_R \ \mathbf{x}_E \ \mathbf{x}_N \ \mathbf{x}_S \ \mathbf{x}_G]^t$, $\Delta V_{ref} = 0$, $[\mathbf{A}_1]$, $\mathbf{b}_1$ and $\mathbf{b}_2$ are defined in Appendix.

Laplace transforming eqn. (35) results in

$$\mathbf{x}_1(s) = [s\mathbf{I} - [\mathbf{A}_1]]^{-1}[\mathbf{b}_1/s + \mathbf{b}_2]\Delta\omega \quad (36)$$

Substituting eqn. (4) in eqn. (7) and linearizing gives electromagnetic torque as

$$\Delta T_e(s) = [\mathbf{H}_1] \mathbf{x}_1(s) + \mathbf{H}_2 \Delta\omega/s \quad (37)$$

where $[\mathbf{H}_1]$ and $\mathbf{H}_2$ are defined in Appendix. Substituting eqn. (36) in (37)

$$\Delta T_e(s)/\Delta\omega = [\mathbf{H}_1][s\mathbf{I} - [\mathbf{A}_1]]^{-1}[\mathbf{b}_1/s + \mathbf{b}_2] + \mathbf{H}_2/s \quad (38)$$

The electrical damping torque contribution of the SVS compensated system at any complex frequency $s (=j\omega)$ is given by

$$\Delta T_d(s) = \text{Real} [\Delta T_e(s)/\Delta\omega] \quad (39)$$

The 'zeroth' rotor torsional mode will become unstable when the electrical damping contribution T_d at that frequency is negative and exceeds in magnitude the total inherent damping associated with the turbine-generator due to friction, windage, eddy current losses etc. The synchronizing torque is given as

$$\Delta T_s(s) = \text{Real} [s \Delta T_e(s)/\Delta\omega] \quad (40)$$

3. CASE STUDY

The study system shown in Fig. 1 consists of a 1110 MVA synchronous generator supplying power to an infinite bus over a 600 km long line rated at 400 kV. Though a double circuit line would normally be employed to transport the full generator power the studies are conducted for a single circuit line which corresponds to the weakest network state[1]. The dynamic range of SVS is determined on the basis of reactive power requirement at the SVS bus to control voltage under steady state conditions. An optimal load flow routine which minimizes total system real power losses is utilized to select the SVS rating as 300 MVA leading to 200 MVA lagging. The system data is given in Appendix. Machine damping is neglected.

The SVS voltage controller parameters K_I and K_p are determined from step response studies [8] conducted for an operating power level of 500 MW with the auxiliary controller kept inoperative. Time responses are obtained with varying controller gains for a step change in the SVS reference input. It is found that the speed of response depends primarily on the integral gain K_I - the speed improving with increasing gain. However with higher values of gain the peak overshoot also gets increased. The proportional controller helps to reduce the overshoot but increase in proportional gain K_p leads to an oscillatory response. In the present example, zero or a small negative value of gain K_p were found to be satisfactory. However, to achieve minimum rise time and setting time the best values of integral gain and proportional gain have been

obtained as 1200 and -1, respectively. With these SVS voltage controller parameters the maximum power which can be transmitted across the line is determined from eigenvalue studies as 610.2 MW.

As the objective of auxiliary SVS control is to enhance power transfer capacity, the auxiliary controller parameters are determined at an operating generator power level of 800 MW which is close to the network limit of 980 MW. For different auxiliary controllers the loci of critical eigenvalues are obtained with varying controller parameters, each taken at a time [7,8]. Based on these root loci, a range is selected for different parameters (K_p , T_1 and T_2) in which a high degree of stabilization is provided to the critical system modes. Power transfer limits are then evaluated for different sets of parameters in these ranges. The controller parameters which result in maximum power transfer are chosen as optimal for the particular auxiliary controller. A comparison of different auxiliary controllers is presented in Table 1. The CIF auxiliary controller results in the highest power transfer of 980 MW which implies the full utilization of transmission network capacity. This represents a 60% enhancement over the limit attained by pure voltage control of SVS. It was found [7] that even with an error of $\pm 10\%$ in the estimation of equivalent inductance L_e ($0.9 \leq F_M \leq 1.1$) the efficacy of this signal did not get degraded.

As dynamic stability of the study system is predominantly dependent on the low frequency (1-2 Hz) rotor oscillations mode, the electrical torque components are evaluated in the frequency range 0-15 rad/sec. The variation of electrical damping torque with frequency for pure voltage controller (without supplementary control) and different auxiliary SVS controllers are depicted in Fig. 7. The rotor mode eigenvalues for various controllers obtained from Table 1 and the damping torques corresponding to these rotor mode frequencies obtained from Fig. 7 are displayed in Table 2. It is observed that damping torque is positive for line reactive power, bus frequency and CIF auxiliary controllers, all of which exhibit stable rotor modes. Damping torque is however, negative for the voltage controller which has an unstable rotor mode. It is further noticed that the magnitude of damping torque is higher if the rotor mode eigenvalue for any controller has a more negative real part. A correlation is therefore witnessed between damping torque and eigenvalue analyses in respect of the stability of rotor mechanical mode. It is however seen from Fig. 7 that the damping torque is negative at frequencies corresponding to rotor circuits' modes and one of AVR modes which are shown to be stable from Table 1. No pattern is observed between the stability of modes and synchronizing torques of the corresponding mode frequencies. Higher the frequency of rotor mode, higher is the magnitude of synchronizing torque. This torque is positive irrespective of whether the rotor mode is stable or not.

The performance of SVS with voltage controller obtained analytically using linearized models is validated through detailed nonlinear simulation on the ASEA's

FIG. 7 ELECTRICAL DAMPING TORQUE FOR SVS VOLTAGE CONTROLLER AND DIFFERENT AUXILIARY CONTROLLERS IN SYSTEM WITHOUT SERIES COMPENSATION.

TABLE 2 : ELECTRICAL DAMPING AND SYNCHRONIZING TORQUES FOR SVS VOLTAGE CONTROLLER AND DIFFERENT AUXILIARY CONTROLLERS

S. No.	Auxiliary Signal	Rotor Mode Eigenvalue	Electrical Damping Torque (pu)	Synchronizing Torque (pu)
1.	None (Voltage Controller)	$0.19 \pm j4.34$	-0.084	4.28
2.	Line Reactive Power	$-0.044 \pm j5.00$	0.02	5.7
3.	SVS Bus Frequency	$-0.133 \pm j4.31$	0.06	4.2
4.	CIF	$-4.13 \pm j7.53$	1.2	9.4

FIG. 8 POWER TRANSFER LIMIT WITH OPTIMIZED SVS.

HVDC simulator at CPRI, Bangalore. The simulator studies [9] included load flow, determination of the stability range and optimal values of SVS controller gain from time domain responses and evaluation of power transfer limits both with and without the SVS. The machine output power is gradually increased and the simulator signal representing generator real power is monitored. As soon as the generator power exceeds 648 MW it starts oscillating with a continually increasing magnitude at a frequency of 4.7 rad/sec. A stable power level of 500 MW and power oscillations at 649 MW are displayed in Fig. 8. This oscillation frequency compares well with the 4.6 Hz frequency of the generator rotor mode which was seen from eigenvalue analysis to be critical in determining the power limit with SVS voltage controller [8,9]. The analytically obtained power limit of 610.2 MW as given in Table 1 is therefore slightly pessimistic. This can be attributed to the fact that in nonlinear systems even sustained limit cycle oscillations may cause instability in the corresponding linearized model. Fault studies were also conducted [9] to verify that SVS response was fast (2-3 cycles) even under large disturbances. As the HVDC simulator did not have provision of representing SVS auxiliary controllers, their performance could not be verified.

TABLE 1 A COMPARATIVE STUDY OF DIFFERENT AUXILIARY SVS CONTROLLERS

Auxiliary Control Signal	None (Voltage Controller)	Bus Frequency	Line Reactive Power	CIF
Optimal Parameters	K_B T_1 T_2	- - -	-0.065 0.0 0.03	-0.035 0.044 0.02
Generator	$0.186 \pm j4.34$ $-32.0 \pm j0.874$ -2.89 $-0.893 \pm j0.97$	$-0.132 \pm j4.31$ $-36.9 - 2.89$ $-27.7 - j10.0$ $-0.9 \pm j0.97$	$-0.046 \pm j5.0$ $-32.3 - 28.6$ -3.02 $-0.62 \pm j0.85$	$-4.131 \pm j7.52$ $-30.9 - 1.29$ -3.3 $-0.584 \pm j1.25$
Eigen-Values	$-0.893 - j0.97$ $-26.0 \pm j24.1$	$-0.9 - j0.97$ $-26.3 \pm j22.72$	$-0.62 - j0.85$ $-26.1 \pm j24.3$	$-0.584 - j1.25$ $-25.9 \pm j22.9$
With Optimal Parameters	$-3.2 \pm j3496$ $-13.2 \pm j2470$ $-3.2 \pm j2868$ $-14.9 \pm j1841$ $-12.9 \pm j1000$ $-23.8 \pm j369$ $-23.5 \pm j313.5$	$-3.2 \pm j3496$ $-13.2 \pm j2470$ $-3.2 \pm j2868$ $-14.9 \pm j1841$ $-12.91 \pm j1003$ $-1.16 \pm j362$ $-23.3 \pm j314.1$	$-3.2 \pm j3496$ $-13.2 \pm j2470$ $-3.2 \pm j2868$ $-14.9 \pm j1842$ $-13.0 \pm j1000$ $-26.8 \pm j379$ $-24.9 \pm j313$	$-3.2 \pm j3496$ $-13.2 \pm j2469$ $-3.2 \pm j2868$ $-14.0 \pm j1842$ $-13.3 \pm j1002$ $-23.1 \pm j355$ $-25.0 \pm j316$
for $P_g = 800$ MW	$-544.3 \pm j65.8$ $-5.63 \pm j313.2$ $-49.5 \pm j99.8$	$-540.3 \pm j87.8$ $-5.66 \pm j307$ $-78.0 \pm j95.0$ $-27.7 \pm j10.0$	$-544.0 \pm j73.3$ $-0.32 \pm j323.0$ $-8.0 \pm j55.9$ -138.1	$-539.0 \pm j80.1$ $-7.7 \pm j293$ $-26.7 \pm j159$ -108.3
Power Limit (MW)	610.2	911.0	868.5	980.0
Time constants T_1 and T_2 are in seconds.				

4. DISCUSSIONS

The damping torque method accurately predicts the stability of rotor mechanical mode corresponding to all SVS controllers. Moreover, the electrical damping is related to real parts of the corresponding eigenvalues. This method however does not correctly assess the stability of other system modes i.e. those corresponding to rotor circuits and AVR, which is not quite unexpected. As this method involves computation of damping torque contributions of the power system after isolating the mechanical system, it is essentially expected to predict the stability of mechanical mode and not of any other system modes.

Auxiliary signals based on frequency, such as bus frequency or CIF, lead to higher power transfers compared to other signals. CIF provides maximum damping to the rotor mode at the considered operating point and results in the highest power transfer in relation to all other signals investigated.

5. CONCLUSIONS

In this paper, the damping torque method is utilized to investigate the influence of different SVS control signals in achieving improved power transfer in long transmission lines. The results obtained on application of damping torque method are correlated with those of eigenvalue analysis. The analytical prediction of SVS performance with voltage controller based on linearized models is validated through detailed nonlinear simulation on a physical simulator. The following inferences are made :

(1) The damping torque method accurately predicts the stability of rotor mechanical mode in SVS compensated systems both with and without the auxiliary SVS controller. Unlike eigenvalue analysis this method does not predict stability of all the system modes.

(2) The choice of control signals to damp the critical rotor mode can be based on the amount of electrical damping they provide at that mode frequency.

(3) A new auxiliary control signal CIF is proposed, which synthesizes the internal voltage frequency of the remotely located generator from locally measurable bus voltage, transmission line current and knowledge of the total inductance between the generator internal voltage and SVS terminals. This signal is far superior than other control signals as it permits the full utilization of network power transmission capacity.

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APPENDIX

The various matrices defined in eqns. (34), (35) and (37) are expressed as follows. The '~' over a symbol indicates a submatrix.

$$[A] = \begin{bmatrix} \tilde{A}_{RR} & \tilde{A}_{RM} & \tilde{A}_{RE} & \tilde{A}_{RN} & \tilde{A}_{RS} & \tilde{A}_{RC} \\ \tilde{A}_{MR} & \tilde{A}_{MM} & \tilde{A}_{ME} & \tilde{A}_{MN} & \tilde{A}_{MS} & \tilde{A}_{MC} \\ \tilde{A}_{ER} & \tilde{A}_{EM} & \tilde{A}_{EE} & \tilde{A}_{EN} & \tilde{A}_{ES} & \tilde{A}_{EC} \\ \tilde{A}_{NR} & \tilde{A}_{NM} & \tilde{A}_{NE} & \tilde{A}_{NN} & \tilde{A}_{NS} & \tilde{A}_{NC} \\ \tilde{A}_{SR} & \tilde{A}_{SM} & \tilde{A}_{SE} & \tilde{A}_{SN} & \tilde{A}_{SS} & \tilde{A}_{SC} \\ \tilde{A}_{CR} & \tilde{A}_{CM} & \tilde{A}_{CE} & \tilde{A}_{CN} & \tilde{A}_{CS} & \tilde{A}_{CC} \end{bmatrix}$$

$$[A_1] = \begin{bmatrix} \tilde{A}_{RR} & \tilde{A}_{RE} & \tilde{A}_{RN} & \tilde{A}_{RS} & \tilde{A}_{RC} \\ \tilde{A}_{ER} & \tilde{A}_{EE} & \tilde{A}_{EN} & \tilde{A}_{ES} & \tilde{A}_{EC} \\ \tilde{A}_{NR} & \tilde{A}_{NE} & \tilde{A}_{NN} & \tilde{A}_{NS} & \tilde{A}_{NC} \\ \tilde{A}_{SR} & \tilde{A}_{SE} & \tilde{A}_{SN} & \tilde{A}_{SS} & \tilde{A}_{SC} \\ \tilde{A}_{CR} & \tilde{A}_{CE} & \tilde{A}_{CN} & \tilde{A}_{CS} & \tilde{A}_{CC} \end{bmatrix}, [B_1] = \begin{bmatrix} \tilde{A}_{RM} \\ \tilde{A}_{EM} \\ \tilde{A}_{NM} \\ \tilde{A}_{SM} \\ \tilde{A}_{CM} \end{bmatrix} = [B_1 B_2]$$

The nonzero elements of matrix $[H_1]$ and H_2 are:

$$\begin{aligned} H_1(1,1) &= c_1 i_{qo} x_d'', H_1(1,2) = c_2 i_{qo} x_d'', H_1(1,3) = -c_3 i_{do} x_d'' \\ H_1(1,4) &= c_4 i_{do} x_d'', H_1(1,11) = -x_d'' (I_{qo} \cos \delta_o - I_{do} \sin \delta_o) \\ H_1(1,18) &= x_d'' (I_{qo} \sin \delta_o + I_{do} \cos \delta_o), H_2 = x_d'' (I_{qo} i_{qo} + I_{do} i_{do}) \end{aligned}$$

SYSTEM DATA

Base Quantities: 400 kV, 100 MVA, 50 Hz.
 Generator (on its own base): $S_n = 1110$ MVA, $V_n = 22$ kV, p.f. = 0.9, $R_a = 0.0036$ pu, $x_1 = 0.21$ pu, $R_d = 0$, $x_o = 0.195$ pu, $T_{do} = 6.66$ sec, $T_{qo} = 0.44$ sec, $T_{d0}' = 0.032$ sec, $T_{qo}' = 0.057$ sec, $x_d = 1.933$ pu, $x_q = 1.743$ pu, $x_d' = 0.467$ pu, $x_q' = 1.144$ pu, $x_d'' = 0.312$ pu, $x_q'' = 0.312$ pu.
 Transformers: $R_T = 0.0$ pu, $X_T = 0.15$ pu.
 IEEE type I Excitation System: $T_R = 0$ sec, $K_A = 400$ pu, $I_A = 0.02$ sec, $K_E = 1.0$ pu, $T_E = 1.0$ sec, $K_F = 0.06$ pu, $T_F = 1.0$ sec, $S'_E = 0$.
 Transmission Line:
 Resistance (R): 0.055 ohm per phase per mile
 Resistance (X_L): 0.52 ohm per phase per mile
 Susceptance (B_C): 5.92×10^{-6} mho per phase per mile
 Static VAR System: (6 pulse operation)
 $T_M = 2.4$ msec, $T_S = 5$ msec, $T_D = 1.667$ msec, $K_I = 1200$, $K_p = -1$, $K_D = 0.01$ pu (3%).

BIOGRAPHY

K.R. Padiyar received the BE degree in Electrical Engg. from Poona University in 1962, ME and Ph.D. from Indian Institute of Science, Bangalore, and University of Waterloo in 1964 and 1972, respectively. He is currently Professor of Electrical Engineering at IISc. Bangalore. His teaching and research interests include HVDC Transmission, Reliability, System Stability and Control.

R.K. Varma received B.Tech. and Ph.D. degrees from Indian Institute of Technology, Kanpur in 1980 and 1989, respectively. At present he is working as Research Associate in the Elect. Engg. Dept., IIT Kanpur. His teaching and research interests include Static Var Systems, Power System Analysis and Real Time Control.

Discussion

M. A. Pai (University of Illinois, Urbana, IL 61801): The paper contains a very interesting idea that the damping of electro-mechanical modes can be improved by modulation in the SVS at the middle of the line. It is also interesting to note that unlike in PSS both the damping and synchronizing torques get affected. I have the following comments and questions to make

1. Is it necessary to have such a detailed model which includes the network high frequency transient also? From Table 1 the network frequencies and their damping remain almost unaffected.
2. In Table 2 what value of ω is used to compute the damping and synchronizing torques? If the eigenvalues are used, it contradicts the statement in paragraph two of the introduction where computation of eigenvalues is considered disadvantageous for computing $T_d(s)$ and $T_s(s)$. As in PSS calculations, knowing K_1 (one of the DeMello-Concordia constants) an approximate value of damped frequency can be obtained which in turn can be used to compute $T_d(s)$. With a huge model size, there may be no easy method of computing the equivalent of K_1 in this case. Can the authors comment on this? Alternatively, the authors can use algorithm of AESOPS and PEALS (explained theoretically and in a generalized manner in Ref [A]) to compute the damped frequency from equations (6), (36) and (37) of the paper. Either a fixed point iterative or Newton scheme can be used.
3. Finally it would have been helpful if the stator and rotor model were in terms of standard variables such as E'_d , E'_q , etc.
4. The concept of CIF is a new one and obviously the parameters T_1 and T_2 have to be adjusted along with the PSS lead-lag time constants. It would be nice if the work is extended to include PSS action also.
5. The value of the inertia constant H seems to be missing.

The authors are to be commended for proposing a new idea in SVS control.

Reference

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T. Smed and G. Andersson (Dep of Electric Power Systems, Royal Institute of Technology, Stockholm Sweden): The authors have presented an interesting paper on an important problem.

The damping action of an SVC is accomplished by a modulation of the reactive power with an appropriate phase with regard to the power oscillations. This phase depends on several parameters, e.g. machine ratings, power flow conditions, and mode shape, and in our view the purpose of the feedback signal is to identify this phase. It appears that the bus frequency can be used to identify the modulation phase, since the eigenvalue is shifted straight into the left half plane for this feedback signal, as seen from Table 2 in the paper. Therefore, the higher damping achieved by using CIF as feedback signal could be due to the higher gain applied for that case, cf. Table 1. We appreciate if the authors indicated the amplitude of the modulating signal for the different cases.

In the studied case, only *one* generator is modelled and it is therefore clear that the rotor frequency of this generator should be utilized. *If more generators are present, it is not obvious which rotor frequency should be used. Could the authors comment on this?*

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K.R.PADIYAR AND R.K.VARMA : We thank the discussors for their comments and the interest shown in our paper.

In response to the queries raised by Dr. M.A.Pai we answer as follows :

1. For the analysis of low frequency rotor oscillation mode, it is generally not

necessary to include a detailed model of the system including the network transients. However, for ensuring an accurate determination of the stability of the SVS operation, we have found it necessary to model the network and TCR transients also along with the measurement delays [1]. Also, if higher frequency oscillations of the rotor (torsional modes) are to be considered, the inclusion of the network transients is necessary.

2. The comments regarding the computation of the frequency of oscillation in a large scale system, are well taken. However, we are considering in this paper, a specific configuration of a generator supplying power over a long transmission line with SVS connected at the midpoint. The emphasis in the paper is mainly on the comparative study of different SVS controllers using damping torque analysis.

3. As the synchronous machine model described in reference [10] of the paper is used, the rotor flux-linkages are directly used as state-variables. It is to be noted that the 'standard' variables E'_d , E'_q are useful mainly when the stator (along with the network) transients are neglected. If more than one rotor circuit per axis is to be considered, rotor flux-linkages which are the 'basic' state variables are convenient to use rather than the 'derived' variables such as E'_d , E'_q etc.

4. The coordination of PSS design with the SVS auxiliary control is an interesting concept and needs to be studied further. We are looking into this aspect.

5. The value of the inertia constant (H) used in the study is 3.22.

Drs. T. Smed and G. Andersson have raised some pertinent points. The limitation on the gain with bus frequency signal is imposed by the destabilization of higher frequency modes (checked from a root locus study not reported in this paper). The major advantage with CIF signal is that it permitted a higher gain to be used without destabilizing other modes. By the way, we have not carried out simulation studies with auxiliary controllers and hence cannot comment about the amplitudes of the modulating signal.

It is true that the CIF signal can be used in specific situations where a generating plant is connected to a large load centre through long radial transmission lines. We have represented all the generating units in a plant by a single equivalent machine. We think this is adequate. In situations where a SVS is connected to a tie line, the choice of the control signal has to be examined afresh.

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