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 [1,2,2]. The various auxiliary control 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 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 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 in parallel with the subtransient inductance Ls* [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 (\(\Psi\)) associated with different windings are defined by:

\[
\begin{align*}
\dot{\Psi}_f &= s_f \Psi_f + s_y \Psi_y + b_y \Psi_y + b_{2f} \\
\dot{\Psi}_h &= s_h \Psi_h + s_y \Psi_y + b_y \Psi_y + b_{2h} \\
\dot{\Psi}_y &= s_y \Psi_y + s_h \Psi_h + b_y \Psi_y + b_{2y} \\
\dot{\Psi}_x &= s_x \Psi_x + s_h \Psi_h + b_y \Psi_y + b_{2x}
\end{align*}
\]
where \( v_f \) is the field excitation voltage. Constants \( a_{1-a}, b_{1-b} \) 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 \( \omega_s \), using the following transformation

\[
\begin{bmatrix}
0
1
\end{bmatrix}
= \begin{bmatrix}
\cos \delta & -\sin \delta \\
\sin \delta & \cos \delta
\end{bmatrix}
\begin{bmatrix}
i_D
i_Q
\end{bmatrix}
\]

(2)

where \( i_D, i_Q \) are the respective components of machine current along \( D \) and \( Q \) axes. \( \delta \) 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

\[
\begin{bmatrix}
\dot{i}_R
\end{bmatrix}
= \begin{bmatrix}
A_R & B_R & C_R
\end{bmatrix}
\begin{bmatrix}
i_R
\end{bmatrix}
= \begin{bmatrix}
\dot{i}_D
\dot{i}_Q
\end{bmatrix}
\]

(3)

where \( A_R, B_R, C_R \) are defined in [10].

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

\[
\begin{bmatrix}
\dot{i}_E
\end{bmatrix}
= \begin{bmatrix}
A_E & B_E & C_E
\end{bmatrix}
\begin{bmatrix}
i_E
\end{bmatrix}
= \begin{bmatrix}
\dot{v}_E
\end{bmatrix}
\]

(11)

\[
\begin{bmatrix}
\dot{i}_E
\end{bmatrix}
= \begin{bmatrix}
A_E & B_E & C_E
\end{bmatrix}
\begin{bmatrix}
i_E
\end{bmatrix}
= \begin{bmatrix}
\dot{v}_E
\end{bmatrix}
\]

(12)

where \( A_E, B_E, C_E \) are defined in [10].

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

\[
\begin{bmatrix}
\dot{i}_E
\end{bmatrix}
= \begin{bmatrix}
A_E & B_E & C_E
\end{bmatrix}
\begin{bmatrix}
i_E
\end{bmatrix}
= \begin{bmatrix}
\dot{v}_E
\end{bmatrix}
\]

(11)

\[
\begin{bmatrix}
\dot{v}_E
\end{bmatrix}
= \begin{bmatrix}
A_E & B_E & C_E
\end{bmatrix}
\begin{bmatrix}
i_E
\end{bmatrix}
= \begin{bmatrix}
\dot{v}_E
\end{bmatrix}
\]

(12)

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

\[
\begin{bmatrix}
\dot{v}_E
\end{bmatrix}
= \begin{bmatrix}
A_E & B_E & C_E
\end{bmatrix}
\begin{bmatrix}
i_E
\end{bmatrix}
= \begin{bmatrix}
\dot{v}_E
\end{bmatrix}
\]

(11)

\[
\begin{bmatrix}
\dot{v}_E
\end{bmatrix}
= \begin{bmatrix}
A_E & B_E & C_E
\end{bmatrix}
\begin{bmatrix}
i_E
\end{bmatrix}
= \begin{bmatrix}
\dot{v}_E
\end{bmatrix}
\]

(12)

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 \( t \)-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 \( \sigma \)-axis equivalent circuit which is identical with the positive sequence network. The equations for \( \sigma \)-network are written as

\[
\begin{bmatrix}
\dot{v}_E
\end{bmatrix}
= \begin{bmatrix}
A_E & B_E & C_E
\end{bmatrix}
\begin{bmatrix}
i_E
\end{bmatrix}
= \begin{bmatrix}
\dot{v}_E
\end{bmatrix}
\]

(11)

\[
\begin{bmatrix}
\dot{v}_E
\end{bmatrix}
= \begin{bmatrix}
A_E & B_E & C_E
\end{bmatrix}
\begin{bmatrix}
i_E
\end{bmatrix}
= \begin{bmatrix}
\dot{v}_E
\end{bmatrix}
\]

(12)
Subscript \( a \) denotes \( a \)-axis components of corresponding current and voltage variables. Similar equations can be written for the \( \beta \)-network which is identical with the \( a \)-network. Since the \( a \)-axis components and \( \beta \)-axis components are sinusoidal quantities in steady state they result in a time varying system. To render the system time invariant the \( a-\beta \) components are transformed to \( D-Q \) axis components using the relationship

\[
\begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
x_a \\
x_\beta
\end{pmatrix}
= 
\begin{pmatrix}
x_D \\
x_Q
\end{pmatrix}
\]

where \( x_D \) and \( x_Q \) are similarly defined. \( \theta \) is the angle by which \( D \) axis leads \( a \)-axis.

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

\[
\begin{pmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3 \\
\dot{x}_4 \\
\dot{x}_5 \\
\dot{x}_6
\end{pmatrix}
= 
\begin{pmatrix}
A_1 & A_2 & A_3 & A_4 & A_5 & A_6 \\
B_1 & B_2 & B_3 & B_4 & B_5 & B_6 \\
C_1 & C_2 & C_3 & C_4 & C_5 & C_6 \\
D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\
E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \\
F_1 & F_2 & F_3 & F_4 & F_5 & F_6
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4 \\
x_5 \\
x_6
\end{pmatrix}
+ 
\begin{pmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
1
\end{pmatrix}
\]

\[
\begin{pmatrix}
y_1 \\
y_2 \\
y_3
\end{pmatrix}
= 
\begin{pmatrix}
D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\
E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \\
F_1 & F_2 & F_3 & F_4 & F_5 & F_6
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4 \\
x_5 \\
x_6
\end{pmatrix}
+ 
\begin{pmatrix}
0 \\
0 \\
1
\end{pmatrix}
\]

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 \( \Delta V \) and the SVS incremental current weighted by the factor \( K \) 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 delay time \( T_d \) and a firing delay time \( T_s \). \( \Delta B \) is the variation in TCR susceptance. \( \Delta V_f \) represents the incremental auxiliary control signal.

The \( a, \beta \) axes currents entering TCR from the network are expressed as

\[
\begin{pmatrix}
I_a \\
I_\beta
\end{pmatrix}
= 
\begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
I_D \\
I_Q
\end{pmatrix}
\]

\[
\begin{pmatrix}
x_a \\
x_\beta
\end{pmatrix}
= 
\begin{pmatrix}
x_D \\
x_Q
\end{pmatrix}
\]

FIG. 4 SVS CONTROL SYSTEM WITH AUXILIARY FEEDBACK.
Linearizing eqn. (25) and appropriately substituting \( \Delta V_{g0} \) from the state and output eqns. of the network, generator and SVS voltage controller model results in

\[
 u_C = [F_{CM}] R_S + [F_{CM}] N + [F_{CM}] N^T [F_{CS}] S
\]

(26)

where \( u_C = A f_S \)

(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

\[
 Q_4 = V_3 Q - V_3 Q_4
\]

(27)

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

\[
 u_C = [F_{CM}] x_N
\]

(28)

where \( u_C = A f_4 \)

(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 SVS and the equivalent voltage source el.

\[
 L_E = F_M \left( L_d + L_{T1} + L \right)
\]

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 \( a, b \) axes components of the internal voltage \( e_1 \) of synchronous generator are

\[
 e_{1a} = \frac{v_{3a} + L \frac{d}{dt} e_{1b}}{L}
\]

\[
 e_{1b} = \frac{v_{3b} + L \frac{d}{dt} e_{1a}}{L}
\]

(29)

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

\[
 e_{1D} = \frac{v_{3D} + \frac{L}{L_d} \frac{d}{dt} e_{1Q}}{L_d}
\]

\[
 e_{1Q} = \frac{v_{3Q} + \frac{L}{L_d} \frac{d}{dt} e_{1D}}{L_d}
\]

(30a)

\[
 e_{10D} = \frac{v_{30D} + \frac{L}{L_d} \frac{d}{dt} e_{1Q}}{L_d}
\]

\[
 e_{10Q} = \frac{v_{30Q} + \frac{L}{L_d} \frac{d}{dt} e_{1D}}{L_d}
\]

(30b)

where \( e_{1D}, e_{1Q} \) are the D and Q axes components of the internal voltage \( e_1 \), respectively. \( (d/dt)_{10} \) and \( (d/dt)_{10} \) terms are substituted by their corresponding state equations from the network model. The angle \( \delta_1 \) of the internal voltage \( e_1 \) is computed as

\[
 \delta_1 = \tan^{-1} \left( \frac{e_{1Q}}{e_{1D}} \right)
\]

(31)

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

\[
 \Delta \omega_1 = \frac{\frac{d}{dt} e_{1Q}}{e_{1D}} - \frac{e_{1Q} \frac{d}{dt} e_{1D}}{e_{1D}^2}
\]

(32)

Subscript 'o' denotes operating point values.

Egnrs. (30a) and (30b) are differentiated and substituted in Egn. (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

\[
 u_C = [F_{CM}] x_N + [F_{CM}] N + [F_{CM}] N^T [F_{CS}] S
\]

(33)

where \( u_C = \Delta \omega_1 \)

Matrices \([F_{CM}], [F_{CM}], [F_{CM}] \) and \([F_{CM}] \) 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

\[
 \dot{x} = [A] x + [B] \Delta V_{ref}
\]

(34)

where \( x = [x_1, x_2, x_3, x_4, x_5]^T \)

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
\[ \Delta \omega \text{ are treated as input variables. The modified state equation then becomes} \]
\[ \dot{x}_1 = [A_1] x_1 + [b_1] \Delta \delta + [b_2] \Delta \omega \]
\[ \text{where } x_1 = [x_p \, x_Q \, x_F \, x_M]^T, \quad \Delta \omega \text{ is an input variable.} \]

Laplace transforming eqn. (35) results in
\[ X_1(s) = [s I - [A_1]]^{-1}[b_1]/s + b_2 \Delta \omega \]

Substituting eqn. (4) in eqn. (7) and linearizing gives electromagnetic torque as
\[ \Delta T_e(s) = [H_1] X_1(s) + H_2 \Delta \omega \]

where \([H_1]\) and \(H_2\) are given in Appendix. Substituting eqn. (36) in (37)
\[ \Delta T_e(s)/\Delta \omega = [H_1] X_1(s) - [A_1]^{-1}[b_1]/s + b_2 H_2/s \]

The electrical damping torque contribution of the SVS compensated system at any complex frequency \(s=j\omega\) is given by
\[ \Delta T_d(s) = \text{Real} \{s \Delta T_e(s)/\Delta \omega \} \]

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

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 inactive. 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 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 \(K_V\) and \(T_a\) 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 that even with an error of \(\pm 10\%\) in the estimation of equivalent inductance \(L_e\) (0.9 \(\leq F_e \leq 1.1\)) 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 expected 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...
were also conducted monitored.

was seen from eigenvalue analysis to be corresponding linearized model. Fault studies continually increasing magnitude at a not be verified.

auxiliary controllers, their performance could of electrical damping they provide at that mode frequency.

The machine output power is gradually

increase in determining the power limit with SVS voltage controller [3,9,11]. The analytically obtained power limit of 1.02 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.

4. DISCUSSIONS

The damping torque method accurately predicts the stability of rotor mechanical mode in 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.

TABLE 1 A COMPARATIVE STUDY OF DIFFERENT AUXILIARY SVS CONTROLLERS

<table>
<thead>
<tr>
<th>Auxiliary Signal</th>
<th>Bus Frequency (Hz)</th>
<th>SVS Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Controller</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>CIF</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Bus Frequency</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Generator</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

4. DISCUSSIONS

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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 to other control signals as it permits the full utilization of network power transmission capacity.

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REFERENCES


APPENDIX

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

\[
[A] = \begin{pmatrix}
    r & x & x & x & x \\
    x & r & x & x & x \\
    x & x & r & x & x \\
    x & x & x & r & x \\
    x & x & x & x & r
\end{pmatrix}
\]

The nonzero elements of matrix \( H_1 \) and \( H_2 \) are:

\[
H_1(1,1) = c_1 \\
H_1(1,2) = c_2 \\
H_1(1,3) = c_3 \\
H_1(1,4) = c_4
\]

\[
H_2 = \begin{pmatrix}
    r & x & x & x & x \\
    x & r & x & x & x \\
    x & x & r & x & x \\
    x & x & x & r & x \\
    x & x & x & x & r
\end{pmatrix}
\]

SYSTEM DATA

Base quantities: 400 kV, 100 kVA, 50 Hz.

generating unit (1.0 pu base) : \( V_g = 22 \) kV, \( f = 0.057 \) pu, \( X_g = 0.030 \) pu, \( T_F = 0.095 \) pu, \( X_T = 0.21 \) pu, \( T_T = 0.057 \) pu, \( T_A = 0.057 \) pu, \( T_A = 0.030 \) pu.

Transmission line: \( I_T = 0.05 \) pu, \( X_T = 0.057 \) pu, \( T_T = 0.057 \) pu, \( T_A = 0.057 \) pu, \( T_A = 0.030 \) pu.

Transmission line: \( R_A = 0.05 \) pu, \( X_A = 0.057 \) pu, \( T_A = 0.057 \) pu, \( T_A = 0.030 \) pu.

Static VAR System: (6 pulse operation)

\( I_g = 0.05 \) pu, \( X_g = 0.030 \) pu, \( T_g = 0.057 \) pu, \( T_A = 0.057 \) pu, \( T_A = 0.030 \) pu.

BIography

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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 \( \omega \) 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 \( T_f(s) \) and \( T_i(s) \). 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 \( T_f(s) \). 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 algorithms 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 \( E_p^c, E_q^c \), 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. Anderson (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 lower 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 would 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 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. 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 SVC connected at the midpoint. The emphasis in the paper is mainly on the comparative study of different SVS controllers during 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 \( E'_q, E'_g \) 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 \( E'_q, E'_g \), 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.

Dr. T. Smed and G. Anderson 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 SVC is connected to a tie line, the choice of the control signal has to be examined afresh.

References


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