Determination of Study Zone for Sub-Synchronous Oscillation Analysis in Large Power Systems

Elizabeth P. Cheriyan, A. M. Kulkarni

***Abstract*— In this paper, we address the issue of identification of a reduced study zone to carry out torsional interaction studies. The generators which could be adversely affected by interaction with a series compensated network, are selected based on approximate damping torque analysis. This does not require complete frequency scanning of damping torque, but evaluates only the residues corresponding to the sub-synchronous network modes. We formulate a differential algebraic model of the network for SSR analysis for this purpose. This formulation is easy to implement and is suitable for selective generalized eigen analysis using widely available tools. A case study on a large power system, with multiple series compensated lines is presented to illustrate the methodology.**

***Index Terms*— SSR, Torsional Interaction, Series Compensation, Selective Generalized Eigen Analysis**

I. Introduction

POWER transfer capability of long transmission lines is often limited by stability considerations. Reducing the effective reactance of lines by series capacitors is a direct approach to increase transmission capability. This generally provides the most economical solution. Turbo-generators connected to series compensated lines lead to adverse interactions between the compensated electrical network and the turbine-generator mechanical system. This phenomenon is termed as Sub-Synchronous Resonance (SSR) [1], [10] - [12]. Moreover, HVDC , FACTS and other network based controllers may also adversely interact with torsional modes.

While, inter-area low frequency oscillations (power swings: 0.2-1 Hz), may propagate almost throughout the entire interconnected network, SSR phenomena is usually experienced in a limited part of the network. This limited part of the network needs to be represented in sufficient amount of detail for simulation studies. However, the identification of study zone is often based on engineering judgment [2].

It can be argued that the issue of finding a reduced study zone for torsional studies is no longer relevant, given the computational power available today. This is indeed true for the off-line studies of slower phenomena like power swings and transient stability. Selective eigen analysis of a large (un-reduced) linearized power system model which includes network transients and torsional dynamics *is feasible* with large and sparse matrix computation techniques. However, the motivation for identification of a reduced study zone to carry out torsional interaction studies still exists because:

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1) Real Time Digital Simulation studies are an important part of testing of protection relays and controllers like FACTS and HVDC. These simulators are not able to handle large systems since computation has to be done in real time with a limited number of processors. Although linearized state space discrete or continuous time models of FACTS controllers like TCSC and HVDC are available, validation using digital simulation is considered necessary due to the approximations made in deriving any analytical model.
2) An EMTP offline digital simulation of a very large system is conceivable, given the computational power available today. However, it is tedious to represent a large system with detailed component models in such programs.
3) Obtaining detailed and accurate mechanical data for a large number of turbine-generator systems can be difficult and time consuming task. If one can reduce the system to include only the generators which can potentially be affected, focus could be on obtaining accurate data for these turbine-generators only.

If all torsional and network data are available *a priori*, obtaining a study zone (if required for simulation studies) is not difficult, and can be based on linearized analysis. If torsional data of all units are not available, then a possible way of identifying the generators to be included in a study zone is to evaluate the electrical damping torque [3] or the equivalent system impedance [4] seen from the generator internal buses at different frequencies. Using electrical damping torque data and worst case estimates of modal inertia, one can evaluate the worst-case change in the decrement factor (related to the decay of subsynchronous oscillations) at a generator [10]. However, damping torque for a large number of generators and frequency points may be necessary if the entire system is considered.

A pragmatic approach is outlined in this paper wherein, we screen generators based on selective eigen-analysis of the subsynchronous modes of the network (for series compensated lines).This does not require complete frequency scanning of damping torque, but evaluates only the residues corresponding to the sub-synchronous network modes. This approach can be extended to controller modes associated with FACTS and HVDC controllers as well. We use a differential-algebraic formulation, similar to [5], that is convenient to incorporate in computer program and that does not require tedious preprocessing for removal of redundant states.

A case study is carried out on a large system adapted from a practical Indian grid illustrating identification of study zone for SSR analysis.

II. Analysis of Torsional Oscillations in Multi-machine Systems

In this section we present a few analytical results which motivate us to use the methodology given later in the paper. To conserve space, we only state the important results.

A. Electrical Damping Torque Analysis

Electrical damping torque is obtained by neglecting the mechanical system dynamical equations and treating the generator rotor angle (δ) and corresponding slip (S_m) as "inputs" to the linearized electrical system. The electrical torque (T_e) is the "output". The transfer function between torque and speed is computed at various frequencies (by setting $s = j\Omega$); the real part of this is called electrical damping torque (T_{De}) [10].

$$\Delta T_{De}(j\Omega) = \Re\left[\frac{\Delta T_e(j\Omega)}{\Delta S_m(j\Omega)}\right] \tag{1}$$

The change in decrement factor ($\Delta\sigma_e$) of the torsional modes can then be related to the damping torque in various situations.

1) Torsional mode of a turbine-generator system having a torsional frequency distinct from other torsional frequencies in the system [3]:

$$\Delta\sigma_e \approx \frac{1}{4H_m}.\Delta T_{De}(j\Omega) \tag{2}$$

where,

$$\begin{aligned} \Omega &: Torsional\ frequency\ in\ rad/s \\ H_m &: Modal\ inertia\ corresponding\ to \\ &\ the\ torsional\ mode \end{aligned}$$

2) Torsional modes of turbine-generator systems having identical torsional frequencies and modal inertias:

$$\underline{\Delta\sigma_e} \approx \frac{1}{4H_m}.\Re\left[eig\{[\mathbf{\Delta T}(j\Omega)]\}\right] \tag{3}$$

The matrix $[\mathbf{\Delta T}(j\Omega)]$ has elements $\frac{\Delta T_{ei}(j\Omega)}{\Delta S_{mj}(j\Omega)}$ where i and j indicate generators belonging to the set of units having identical torsional frequencies and modal inertias. Note that the mode shapes are determined by the eigen-vectors of $[\mathbf{\Delta T}(j\Omega)]$. Typically, this situation occurs in a plant having identical units. The torsional modes include common (or in-phase) modes of torsional oscillations and antiphase modes [6]. Since only the common modes are affected by the external network, it is convenient to club the identical units to form common mode equivalent unit rather than use (3).

3) Torsional modes of turbine-generators which have identical torsional frequencies but different corresponding modal inertias:

$$\underline{\Delta\sigma_e} \approx \frac{1}{4}.\Re\left[eig\{[\mathbf{H}]^{-1}[\mathbf{\Delta T}(j\Omega)]\}\right]. \tag{4}$$

Here $\mathbf{H}$ is a diagonal matrix of modal inertias corresponding to the torsional modes. This situation can occur if different numbers of identical units in different plants are clubbed together to form equivalents as shown in Figs. 1 and 2. When analyzed on a common base, modal inertias of the equivalent units GA and GB will be different while their torsional frequencies will be equal.

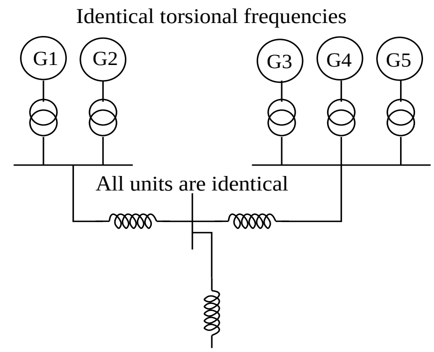

Fig. 1. Turbine-generator systems with identical torsional frequencies

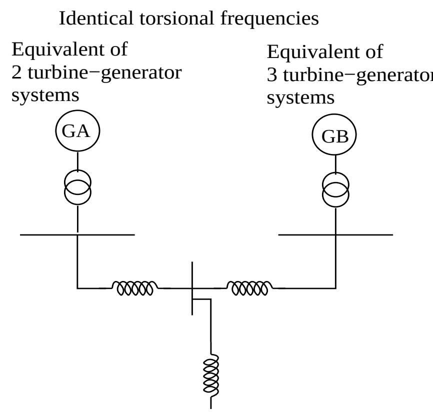

Fig. 2. Turbine-generator systems with identical torsional frequencies but different modal inertias

Note:

a) In general, it is required to compute the matrix $\left[\frac{\Delta T_{ei}(j\Omega)}{\Delta S_{mj}(j\Omega)}\right]$ for many frequency points in the torsional range for all units
b) $\left[\frac{\Delta T_{ei}(j\Omega)}{\Delta S_{mj}(j\Omega)}\right]$ can be obtained by the knowledge of the network, the generator rating and typical dynamical data.
c) Computation of modal inertia, H_m requires the knowledge of the turbine-generator system. However, $H_m \geq H_g$ where H_g is the generator rotor inertia. Therefore we can obtain <u>worst case</u> estimates of $\Delta\sigma_e$ using H_g. For thermal units, H_g can be about $1/3^{rd}$ of the total H for a plant. For hydro units, H_m is quite large and the electrical system does not have much effect on damping of torsional oscillations.

Therefore it appears that electrical damping torque analysis is feasible for getting worst case quantitative estimate of torsional un-damping, without complete turbine-generator mechanical data.

B. Approximated Electrical Damping Torque by Selective Eigen Analysis

Since the frequency response of transfer function, $\left[\frac{\Delta T_{ei}(j\Omega)}{\Delta S_{mj}(j\Omega)}\right]$ is likely to have peaks or troughs near network oscillatory modes, a modal approach involving computing only the right and left eigenvectors corresponding the network subsynchronous modes is attractive. The corresponding residues of the transfer function are then computed using these left and right eigenvectors [7]. Note that the transfer function may be written as follows in terms of the residues and eigenvalues.

$$\Delta T(s) = \frac{\Delta T_{ei}(s)}{\Delta S_{mj}(s)} = \sum_{i=1}^{n} \frac{R_i}{s - \lambda_i} \tag{5}$$

In the subsynchronous range of frequencies, the approximate expression given below may be used:

$$\Delta \tilde{T}(s) = \sum_{i \ \epsilon \ k} \frac{R_i}{s - \lambda_i}, \quad \Delta \tilde{T}_{De}(s) = \Re[\Delta \tilde{T}(s)] \tag{6}$$

where k are the subsynchronous network modes. A worst case scenario can be obtained by evaluating $\Delta \tilde{T}(s)$ only at the subsynchronous network modal frequencies. This can be used to screen generators which can be affected by the selected network modes. Computational effort is limited to selective generalized eigen-analysis which is more efficient than evaluating the frequency response of $\Delta T(s)$ at many frequencies for all generators.

III. Formulation of System Model

A. General Formulation [14]

In general, for a network, we can write equations as follows:

$$M_N \dot{X}_N = A_N X_N + B_N U_N \tag{7}$$

where,

- $A_N = \begin{bmatrix} A_{11} & [0] & [0] & A_L \\ [0] & A_{22} & [I] & [0] \\ [0] & [I] & [0] & -A_C \\ A_L^T & [0] & A_C^T & [G] \end{bmatrix}$
  $[I]$ represents an identity matrix, while $[0]$ represents a null matrix of appropriate dimensions.
- $M_N = \begin{bmatrix} [L] & [0] & [0] & [0] \\ [0] & [C] & [0] & [0] \\ [0] & [0] & [0] & [0] \\ [0] & [0] & [0] & [0] \end{bmatrix}$.
  Note that M_N matrix is diagonal and positive semi-definite.
- $A_{11} = \begin{bmatrix} -[R] & -\omega_b[L] \\ \omega_b[L] & -[R] \end{bmatrix}$
- $A_{22} = \begin{bmatrix} [0] & -\omega_b[C] \\ \omega_b[C] & [0] \end{bmatrix}$
- $[G]$ is a diagonal matrix with nonzero elements corresponding to conductances from a node to the reference node.
- A_C and A_L are the incidence matrices relating capacitor and inductor branch voltages respectively, to the node voltages.
- The vector $X_N = [i_{LDQ}^T \quad V_{CDQ}^T \quad i_{CDQ}^T \quad V_{nDQ}^T]^T]$, i.e., it is made up of the inductive branch current vector, capacitive branch voltage vector, capacitive branch current vector and node voltage vector in D-Q frame of reference.
- U_N denotes the voltage and/or current injections into the network by other sub-systems like generators, HVDC links etc.

Note that in the above formulation, the choice of states are the inductor currents and capacitor voltages. The "auxiliary variables", i.e., i_{CDQ} amd V_{nDQ} can be eliminated if the submatrix

$$A_{aux} = \begin{bmatrix} [0] & -A_C \\ A_C^T & [G] \end{bmatrix}$$

is invertible. However, this may not be possible always. This interesting situation arises when only inductors are incident on a node or a loop is formed only of capacitors. In such a case, the actual number of states is lesser than number of inductors and capacitors. In these circumstances, it is not possible to directly eliminate auxiliary variables i_{CDQ} amd V_{nDQ}. Therefore, one of the following may be done:

1) Connect fictitious small capacitors to ground at all nodes where only inductors are incident. Connect fictitious small inductors in series in a loop which has only capacitors.
2) Eliminate redundant states by simplification, e.g., parallel capacitors are combined to a single equivalent capacitor.
3) Do not explicitly eliminate the algebraic states or carry out the simplifications given above. Instead, analyze the complete differential algebraic equations (DAE).

The first two approaches may be tedious since they involve pre-processing to find out all-inductor-incident nodes and all-capacitor loops. In [5], the first two steps are proposed although the DAE form is retained. Actually generalized eigen-analysis can be used easily in these circumstances without recourse to the pre-processing steps 1 and 2 above. The above formulation and analysis have been exclusively for a network. Network equations have to be interfaced with other equations corresponding to generator-turbine-excitation system, HVDC and FACTS devices as given in [10].

B. Generalized Eigen Analysis

The DAE formulation is amenable for study using generalized eigenvalue-eigenvector analysis. Note that generalized eigenvalues are defined by the equation:

$$A_N v = \lambda M_N v \tag{8}$$

where λ and v represent the generalized eigenvalue and corresponding right eigenvector. A left eigenvector is defined by:

$$u^T A_N = u^T \lambda M_N \tag{9}$$

The *finite* generalized eigenvalues and corresponding eigenvectors give us information regarding physically meaningful modes of the system. The number of finite eigenvalues equals the number of capacitor and inductor branch states, excluding those which are redundant due to all-inductor-incident nodes and all-capacitor loops.

Consider the overall system equations which can be written as follows:

$$M\Delta x = A\Delta x + B_\delta \Delta\delta + B_{S_m}\Delta S_m \tag{10}$$

$$\Delta T_e = C\Delta x \tag{11}$$

The residues [7] can be written as:

$$R_{i\delta} = \frac{Cv_i u_i' B_\delta}{u_i' M v_i} \quad and \quad R_{iS_m} = \frac{Cv_i u_i' B_{S_m}}{u_i' M v_i} \tag{12}$$

Since ΔS_m and $\Delta\delta$ are related by $\Delta S_m = \frac{s\Delta\delta}{w_B}$, w_B being the base frequency, a modified frequency dependent residue is used.

$$R_i = R_{i S_m} + \frac{R_{i\delta}}{s}.w_B \tag{13}$$

C. Large Scale Eigen-Analysis Tools

While the computational issues concerning large scale generalized eigen-analysis are beyond the scope of the paper, we briefly note the commonly available tools which can be used for *selective* generalized eigen-analysis for sparse matrix.

1) `eigs` tool of MATLAB [15] based on ARPACK [13] routines.
2) `eigen` tool [16] also based on ARPACK which can be used along with SCILAB [17].

Both tools can compute a few generalized eigenvalues closest to a scalar value. This feature is especially suitable for modal analysis of network sub-synchronous modes since they are few and caused by series capacitive compensation. The results shown in this paper are obtained using the MATLAB tool.

IV. Case Study

Consider the case of a large power system (adapted from the central Indian grid), the details of which are given in Table I. Fig. 3 shows a part of this system which has six series capacitor compensated lines of which two pairs are identically compensated parallel lines. The generator electrical system is represented by a detailed model with excitation system included. An idea of the size of the system model can be inferred from the dimensions of matrices given in Table I.

TABLE I
DETAILS OF LARGE POWER SYSTEM

Components	**Nos.**
Generators / plants	353 / 130
Buses	1021
PI line sections	1158
Short lines	14
Interconnecting transformers	236
Series capacitive compensation	6
System Models	**Matrices [size]**
Generator electrical & excitation control systems	A_G [3883 × 3883]
Electric Network using DAE model	A_N [16502 × 16502]
Combining the above two systems	A_{sys} [20385 × 20385]

A. Analysis with Detailed and Simplified Generator Models

The subsynchronous network modes, which are due to series capacitive compensation, are listed in Table II. These were obtained using the `eigs` tool by scanning for six eigenvalues closest to $j140$. The first two network modes are intra-parallel line modes corresponding to the identically compensated parallel lines. Generators with significant $\Delta\tilde{T}_{De}(s)$ and $\Delta T_{De}(s)$ are screened and highly ranked ones are shown in Table II.

TABLE II
SUBSYNCHRONOUS NETWORK MODES WITH DETAILED GENERATOR MODEL

Subsynchronous Network Modes, λ_i	**Generators with relatively high $\Delta T_{De}(s)$ at $s = j\Im(\lambda_i)$**	**Generators with relatively high $\Delta\tilde{T}_{De}(s)$ at $s = j\Im(\lambda_i)$**
(1) -14.19 ± j97.876	Not observable at generators	
(2) -12.992 ± j108.68	Not observable at generators	
(3) -14.087 ± j131.18	G12 (-0.3869)	G8 (-3.3081) G12 (-0.6391)
(4) -13.145 ± j142.51	G15 (-1.5385) G8 (-1.5856)	G15 (-12.280) G8 (-5.6232)
(5) -12.871 ± j174.63	G15 (-9.3094) G12 (-5.5247) G10 (-2.8167) G11 (-1.5475)	G15 (-18.997) G12 (-5.9300) G10 (-2.8200) G11 (-1.7600)
(6) -8.0685 ± j261.5	Low observability at generators	

$\Delta\tilde{T}_{De}(s)$ and $\Delta T_{De}(s)$ are also given in brackets against each generator. These generators need to be included in a study zone. Note that the overall set of generators screened is identical when $\Delta\tilde{T}_{De}(s)$ and $\Delta T_{De}(s)$ are used, although the values of $\Delta\tilde{T}_{De}(s)$ and $\Delta T_{De}(s)$ are different.

SSR analysis of the large system is repeated with generator electrical system represented using simplified model. In this case, generator is modelled as a voltage source behind a sub-transient reactance, x''. Note that the subsynchronous network modes and screened generators are not affected by the detail of model (refer Table III).

TABLE III
SUBSYNCHRONOUS NETWORK MODES WITH SIMPLIFIED MACHINE MODEL

Subsynchronous Network Modes, λ_i	**Generators with relatively high $\Delta T_{De}(s)$ at $s = j\Im(\lambda_i)$**	**Generators with relatively high $\Delta\tilde{T}_{De}(s)$ at $s = j\Im(\lambda_i)$**
(1) -14.19 ± j97.876	Not observable at generators	
(2) -12.992 ± j108.68	Not observable at generators	
(3) -14.095 ± j131.16	G8 (-3.0419) G12 (-0.7879)	G8 (-3.6900) G12 (-0.7650)
(4) -13.361 ± j142.22	G15 (-5.4476) G8 (-5.2362)	G15 (-13.500) G8 (-5.8745)
(5) -13.197 ± j173.71	G15 (-12.108) G12 (-5.8819) G10 (-2.7432) G11 (-2.2781)	G15 (-20.100) G12 (-6.1400) G10 (-2.500) G11 (-2.2100)
(6) -8.105 ± j261.43	Low observability at generators	

B. Formation of Study Zone

A study zone is formed by retaining the screened generators which have significant $\Delta\tilde{T}_{De}(s)$ as well as associated network branches which have a significant participation in the subsynchronous network modes. At the border nodes of the study zone, we connect voltage sources whose values are equal to those obtained from the load flow of the complete system. A comparison of $\Delta T_{De}(s)$ at the subsynchronous network

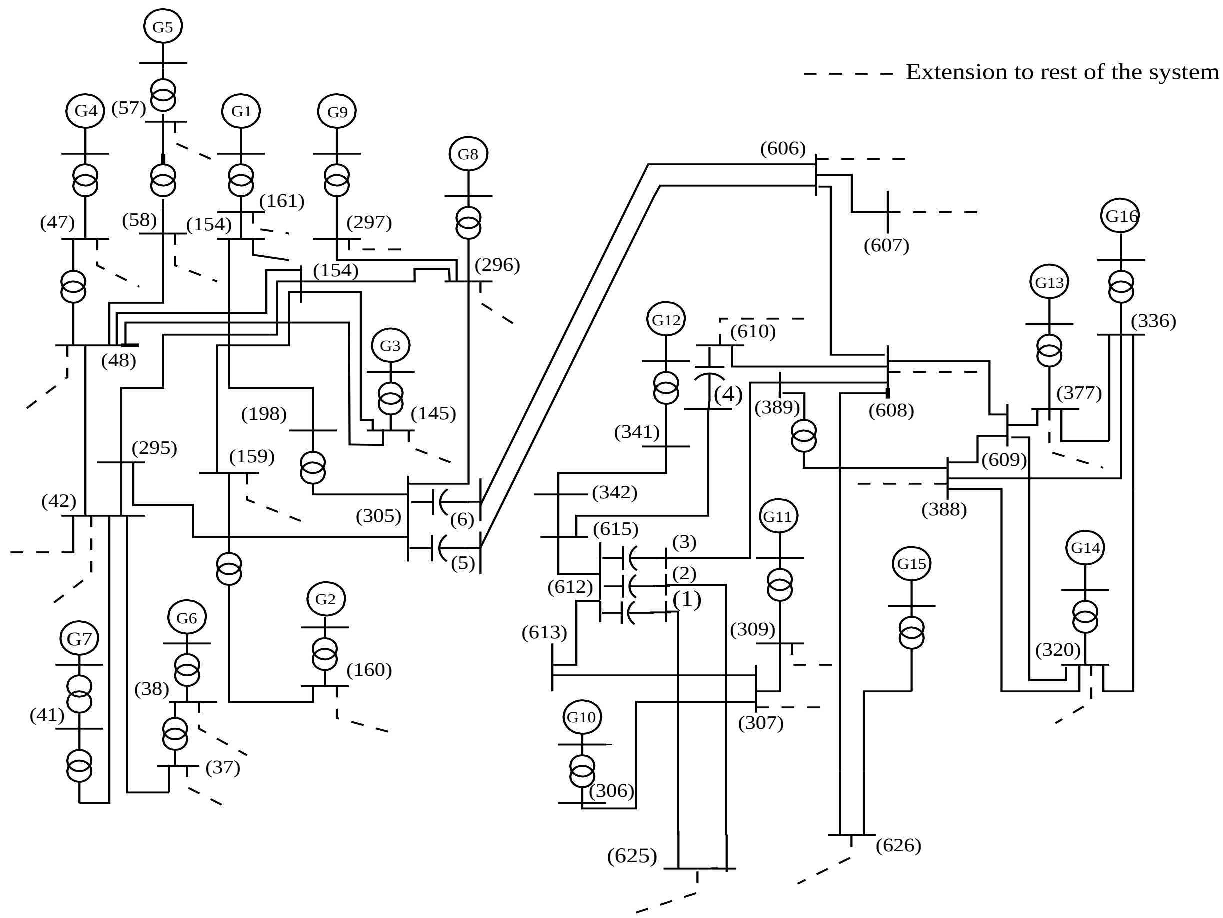

Fig. 3. A subnetwork of the large system containing series compensated lines

modes for the full system and the reduced study zone shown in Table IV. Note that the $\Delta T_{De}(s)$ for the reduced study zone is almost identical to that for the entire system. If required further reduction is possible in the number of non-generator nodes by selective modal analysis techniques [8], but it is not pursued here.

TABLE IV

COMPARISON OF $\Delta T_{De}(s)$ AT GENERATORS OF FULL SYSTEM AND OF STUDY ZONE

Subsynchronous network modes	**Plants**	**$\mathbf{\Delta T_{De}(s)}$ at generators of study zone**	**$\mathbf{\Delta T_{De}(s)}$ at generators of full system**
(1)	Not observable at generators		
(2)	Not observable at generators		
(3)	G8	-3.8921	-3.0419
	G12	-0.7917	-0.7879
(4)	G15	-6.7034	-5.4476
	G8	-5.699	-5.2362
(5)	G15	-13.546	-12.108
	G12	-5.9856	-5.8819
	G10	-2.7464	-2.7432
	G11	-2.3329	-2.2440
(6)	Low observability at generators		

C. Evaluation of σ_e of Generators Outside the Study Zone

The worst case expected change in σ_e of generators outside the study zone is shown in Table V. The insignificant values indicate that these generators are unlikely to be affected by the subsynchronous network modes, therefore validating their exclusion.

TABLE V

WORST CASE σ_e OF GENERATORS OUTSIDE THE STUDY ZONE
$(H_m \approx H_g \approx \frac{H}{3})$

Subsynchronous network modes, λ_k	**Generators having worst case change in σ_e in external system**	**Worst case expected change in σ_e**
(1)	Not observable at generators	
(2)	Not observable at generators	
(3)	G126	0.00006
(4)	G111	0.00061
	G122	0.00046
(5)	G122	0.00011
	G111	0.00009
(6)	Low observability at generators	

D. HVDC and FACTS Controllers

The present study concentrated on subsynchronous oscillatory modes of network due to series compensation. This can be extended to analyze modes associated with HVDC and FACTS devices. The main issues related to this are:

a) Use of appropriate modular linearized state space models [9], [10]

b) Modes associated with fixed series compensation are easy to obtain using selective eigen-analysis, since the modal frequencies are known to lie in the sub-synchronous range. However, the modes in which HVDC and FACTS states participate significantly have to be separately identified in order to be included in the approximate damping torque calculation.

V. Conclusion

In this paper, we have screened generators for the study zone based on approximate damping torque using selective generalized eigen analysis. This approach is computationally more efficient than evaluating the frequency response of $\Delta T(s)$ at many frequencies for all generators. It is also found to be relatively insensitive to the detail of the generator model. Therefore it is useful when complete generator data are not available *a priori*. A case study of a large system is used to validate the methodology.

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