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ABSTRACT

Damping of torsional oscillations using coordinated control through power system stabilizer (PSS) and thyristor controlled reactor(TCR) is presented in this paper.The PSS has modal speed deviations as its feedback signal.The reactive power control is achieved through thyristor controlled reactor (TCR) at the machine terminals. Generator speed deviation is used as auxiliary signal and terminal voltage feedback signal as main control signal for TCR. The following control strategies have been analysed :

a PSS with modal speed control

b PSS with modal speeds plus TCR with terminal voltage control

c PSS with modal speeds plus TCR with complete controls (voltage feed back signal and generator speed deviation signal)

The main objective of this paper is to discuss the modelling aspects and analyse different control strategies for damping torsional oscillations in series compensated ac transmission system. The control parameters like gains and time constants have been obtained by performing repeated eigenvalue analysis. IEEE First Benchmark Model is considered for illustration.

1.0 INTRODUCTION

The adequate operation of power systems demands many times, transmission of large bulk power over longer distances.In order to improve the power transfer capability of an EHV transmission system,lines are frequently series compensated to reduce the line reactance.Series capacitor compensation in power system has been an economic and practical method for providing better power transfer capability and stability. However, the presence of series capacitors has given rise to the phenomena of subsynchronous resonance.Subsynchronous resonance induces shaft fatigue in turbine-generator assemblies which reduces the life time of the turbine shaft.

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Subsynchronous resonance occurs when a natural frequency of a series compensated electrical system interacts with torsional mode of the turbine-generator set.A component of subsynchronous torque in phase with rotor velocity deviation is produced.This torque aids rotor oscillations and makes the oscillations grow exponentially with time.References [35-38] provide complete bibliography for the study of subsynchronous resonance between rotating machines and power systems.

Many countermeasures to subsynchronous resonance (SSR) problem have been reported in the literature to increase the torsional mode damping, such as block filters, excitation controls, static reactive power compensators, HVDC, static phase shifter, bypass filter and the shunt reactor. Conventionally power system stabilizer is used for damping the inertial oscillatory modes of T - G sets. Modulation of generator excitation via PSS has been proposed as a supplementary damper for torsional oscillations [2,3]. Saito et.al[4] have examined signals derived from reactive power, active power and field current in the excitation control to suppress subsynchronous resonance and have found the reactive power signal to be most effective. Wasynczuk [5] suggested that to successfully damp all the SSR modes in the IEEE system, composite speed stabilizing signals in conjunction with a torsional monitor device can be used. But this strategy is complex as it involves measurements of a number of variables. Hingorani et.al [6,7] have suggested the use of a linear resistor in series with back-to-back thyristors connected across the series capacitor. The proposed NGH-SSR damping scheme consists of dissipating the charge on the capacitor whenever its period of half cycle voltage exceeds the desired half cycle period. Andrew Yan et al [9] presented an output feedback excitation control.Design is based on an equivalent mass-spring model,eigenvalue sensitivity analysis. Putman et al [10] proposed dynamic stabilizer for damping torsional oscillations. Lahoud et al [11] investigated the use of an optimal controller using state variable feedback to supress SSR. Hammad et al [12] introduced a novel control concept which enables the SVC units to damp torsional oscillations and meanwhile maintain the conventional voltage regulation functions. The control concept is based on utilizing the generator speed deviation signal as the auxiliary stabilizing signal of SVC unit. Harely R G and Balda [13] analysed the possibility of enhancing the damping of a turbogenerator with SSR problems by proposing an HVDC link in parallel with the existing series compensated ac line and adding auxiliary damping controls to the HVDC rectifier end control circuitry. Ooi et.al [14] have suggested a scheme based on the connection of a passive device at the generator terminals. Iravani et al [15] proposed a thyristor controlled phase shifter to modulate the generator active power by injecting a quadrature phase voltage in the system.The rotor speed deviation from the synchronous speed is used as the control signal. Iravani et.al [16,17] have described the use of the point on wave controlled and discrete step controlled thyristorised static phase shifters for preventing the occurrance of SSR.

Chen et al [19,20] proposed a method which involves the measurement of the transmission system currents from which the subsynchronous components which produce torsional interactions are extracted. These signals are subsequently amplified by a controllable current source and injected into the generator bus so as to cancel the original subsynchronous components which would otherwise produce torsional interactions. Hamouda et.al[21] reported the technical advantages of coordinating SVC and PSS for damping inertial and torsional modes of steam turbine generators. Modal speeds as the auxiliary feedback stabilizing signals for SVC is proposed. Comparison is made between the cases where either modal speeds or generator speed deviations are used as the stabilizing signals of SVC. Li Wang et al [22] presented a comparative study on the application of two counter measures i.e. the excitation controller and SVC for the damping of SSR.Unified approach based on modal control theory is proposed for the design of excitation controller and the SVC which are essentially dynamic output feedback compensators. Hsu et al [23] presented a static var compensator with a PID controller.The parameters of the PID controller are determined by shifting SSR mode eigenvalue to desired location. Eitelberg et.al [24] show how large plant parameter uncertainities can be taken into account in the design of controller for power systems by applying frequency domain technique based upon Horowitz's quantitative feedback theory.They presented the design of a controller for a shunt reactor to eliminate torsional shaft oscillations. Kai Xiang et.al [25] proposed, thyristor controlled-phase shifter, to damp SSR. The control approach aims to use generator speed and/or modal speed deviations as control signals for the phase shifters. Hsu and Wang [26] presented a systematic approach based on modal control theory for the design of a supplementary subsynchronous damping controller equipped at the rectifier end of an HVDC link connected in parallel with an AC line. Hamdan et al [27] demonstrated that the participation factors of the selective modal analysis (SMA),originally used for modal reduction,can also be used for the design of excitation controllers .It is shown that a current signal is strongly coupled to the instability modes of hunting and subsynchronous resonance. Hsu and Chen [28] proposed SVC for damping electromechanical oscillations. The parameters for both the feedforward controller and the feedback controller of the SVC are determined using eigenvalue assignment. Lee and Wu [29] proposed controller for superconducting magnetic energy storage(SMES) unit to improve the torsional modes.A PID controller is employed to modulate the power input output of the SMES unit according to generator speed deviation.The gains of the PID controller are determined by the pole assignment method. Lee and Wu [30] designed an SVC to improve the damping of a synchronous generator.The pole assignment method is used to determine the gains of PI controller by placing the electromechanical mode at the pre-specified position.SVC is placed at the generator bus terminals with the speed deviation as the feedback signal for the PI controller. The authors have studied the effect of two PSS with modal speed deviation feedback [31].

In this case the phase compensation provided to each PSS is different which depends on the input signals to PSS.This control strategy provides much better damping to torsional modes when compared to damping with only one PSS.The authors have also studied the damping of torsional oscillations using reactive power control [32].The reactive power control is achieved through thyristor controlled reactor (TCR) at the machine terminal.The different control strategies analysed are (i) TCR with voltage feedback signal (ii) TCR with complete controls (i.e. TCR with voltage feedback signal and generator speed deviation signal) (iii) TCR with complete controls,with weightages to either speed deviation signal or voltage signal. Analysis with various control signals provided the following information : (i) the voltage controller of TCR type compensator can enhance the damping provided by auxiliary signal derived from the generator rotor speed. It is effective in damping all the unstable torsional modes and stabilizing the system at all compensation levels.TCR with complete controls with weighted speed or voltage feedback signal control is effective in enhancing the overall stability,in comparision to that of no weightage to either speed or voltage feedback signals .The authors also have studied [33] the effect of damping torsional oscillations using a co-ordinated approach with PSS (generator speed deviation feedback) and TCR (voltage and generator speed deviation feedback).It is seen that TCR provides maximum damping to the torsional modes,whereas the PSS with generator speed signal acts as a supplementary stabilizer. PSS plus TCR with complete controls stabilizes the system at all levels of compensation.This highlights the necessity of having auxiliary speed feedback signal for TCR. The voltage feedback on the other hand enhances the system stability by preventing modal interaction. Keeping in view , the performance of different control schemes the aim of this paper is to investigate the performance of (i) PSS with modal speeds (ii) PSS with modal speeds plus TCR with terminal voltage control ,and (iii) PSS with modal speed plus TCR with complete controls (here the auxiliary signal to TCR is generator speed deviation and the main control signal is the terminal voltage) in damping the torsional oscillations. However,the effectiveness of SVC with only terminal voltage feedback in preventing the modal interactions that occur when PSS with modal speed deviation feedback is used has not been reported . This paper attempts to highlight the effectiveness of coordinating TCR (terminal voltage feed back) with PSS (Modal speed deviation feedback) in damping the unstable torsional modes and preventing modal interactions. In this paper eigenvalue analysis has been presented.It gives information regarding both the natural frequencies of oscillations of a system and the damping of each frequency.It is relatively easy,therefore,to determine those torsional frequencies that are not damped,and would therefore result in growing oscillations and almost certain damage to the affected turbine generator shaft.

The IEEE First Benchmark Model (FBM) [1] was created by the IEEE working group on subsynchronous resonance in 1977 for use in 'computer programme comparision and development'.

This system provides a useful test bed for the SSR analytical methods. The FBM network consists of a single series-capacitor compensated transmission line connecting a synchronous generator to large system. As a result of small signal disturbances in the series compensated power system the turbine-generator (T-G) set experiences oscillatory modes in the subsynchronous frequency range (1 to 47.5 Hz).The oscillatory mode with the lowest frequency (1 to 2.2 Hz) represents the inertial mode of oscillation (mode zero).The oscillatory modes with frequencies ranging from 15 Hz to 47.5 Hz represents the torsional modes. The number of torsional modes is equal to (N-1) where N represents the number of masses on the shaft. The turbine-generator mechanical damping coefficients are generally too small to have any impact on the torsional frequencies.This is equivalent to asserting that the damped and undamped natural frequencies are equal or are very close to being equal.

In the following section, a detailed modelling of system representation is discussed.

2.0 POWER SYSTEM MODELLING

The basic electro-mechanical system considered is shown in Fig (1). The electrical system is represented as a single machine connected to an infinite bus through a series- compensated AC transmission system. Ref [34], gives a nice exposure to get system state space matrix from system differential and algebraic equations in a form amenable for digital simulation. In this paper, this approach has been extended to the case of series compensated transmission system, and the mechanical system comprising of six masses. A detailed machine model is considered for analysis. The state variables chosen for the basic system are angular displacements, angular speeds of the rotating masses, machine currents and voltage across series capacitor. The linearized equations of the system used in the analysis are given below.

2.1 Linearized Equations of the Mechanical System (2.1.1 to 2.1.12)

$$\frac{1}{\omega_o} p\Delta\delta_i = \Delta\omega_i \quad i = 1, 2....6 \qquad (2.1.1 \text{ to } 2.1.6)$$

$$2H_1 p\Delta\omega_1 = -d_1\Delta\omega_1 - K_{12}(\Delta\delta_1 - \Delta\delta_2) + \Delta T_{m1} \qquad (2.1.7)$$

$$2H_2 p\Delta\omega_2 = -d_2\Delta\omega_2 - K_{12}(\Delta\delta_2 - \Delta\delta_1) - K_{23}(\Delta\delta_2 - \Delta\delta_3) + \Delta T_{m2} \qquad (2.1.8)$$

$$2H_3 p\Delta\omega_3 = -d_3\Delta\omega_3 - K_{23}(\Delta\delta_3 - \Delta\delta_2) - K_{34}(\Delta\delta_3 - \Delta\delta_4) + \Delta T_{m3} \qquad (2.1.9)$$

$$2H_4 p\Delta\omega_4 = -d_4\Delta\omega_4 - K_{34}(\Delta\delta_4 - \Delta\delta_3) - K_{45}(\Delta\delta_4 - \Delta\delta_5) + \Delta T_{m4} \qquad (2.1.10)$$

$$\Delta T_u + 2H_5 p\Delta\omega_5 = -d_5\Delta\omega_5 - K_{45}(\Delta\delta_5 - \Delta\delta_4) - K_{56}(\Delta\delta_5 - \Delta\delta_6) \qquad (2.1.11)$$

$$2H_6 p\Delta\omega_6 = -d_6\Delta\omega_6 - K_{56}(\Delta\delta_6 - \Delta\delta_5) \qquad (2.1.12)$$

2.2 Machine Equations (2.2.1 to 2.2.5

$$(X_d p\Delta_{id} - X_{afd} p\Delta i_{fd} - X_{akd} p\Delta i_{kd})/\omega_o + \Delta V_d = -r_a \Delta i_d + X_q \Delta i_q - X_{akq} \Delta i_{kq} + [(X_q i_q - X_{akq} i_{kq})/\omega_o]\Delta\omega \quad (2.2.1)$$

$$(X_q p\Delta i_q - X_{akq} p\Delta i_{kq}/\omega_o + \Delta V_q = -r_a \Delta i_q - X_d \Delta i_d + X_{afd} \Delta i_{fd} + X_{akd} \Delta i_{kd} + [(-X_d i_d + X_{akd} i_{kd} + X_{afd} i_{fd})/\omega_o]\Delta\omega \quad (2.2.2)$$

$$(-X_{afd} p\Delta i_d + X_{ffd} p\Delta i_{fd} + X_{fkd} p\Delta i_{kd})/\omega_o = -r_{fd}\Delta i_{fd} + \Delta V_{fd} \quad (2.2.3)$$

$$(-X_{akd} p\Delta i_d + X_{fkd} p\Delta i_{fd} + X_{kdkd} p\Delta i_{kd})/\omega_o = -r_{kd}\Delta i_{kd} \quad (2.2.4)$$

$$(-X_{akq} p\Delta i_q + X_{kqkq} p\Delta i_{kq})/\omega_o = -r_{kq}\Delta i_{kq} \quad (2.2.5)$$

2.3 Network Equations (2.3.1 to 2.3.2)

$$-(x_t/\omega_o)p\Delta i_d + \Delta V_d - \Delta V_{bd} = r_t \Delta i_d - x_t \Delta i_q + \Delta V_{cd} - (x_t/\omega_o) i_q \Delta\omega \quad (2.3.1)$$

$$-(x_t/\omega_o)p\Delta i_q + \Delta V_q - \Delta V_{bq} = r_t \Delta i_q + x_t \Delta i_d + \Delta V_{cq} + (x_t/\omega_o) i_d \Delta\omega \quad (2.3.2)$$

2.4 Linearized Equations representing rate of change of voltage across series capacitor along the d and q axes (2.4.1 to 2.4.2)

$$1/\omega_o p\Delta V_{cd} = X_c \Delta i_d + V_{cq}/\omega_o \Delta\omega + \Delta V_{cq} \quad (2.4.1)$$

$$1/\omega_o p\Delta V_{cq} = X_c \Delta i_q - V_{cd}/\omega_o \Delta\omega - \Delta V_{cd} \quad (2.4.2)$$

2.5 Algebraic Equations connecting state variables and output variables (2.5.1 to 2.5.10)

$$\Delta V_{bd} = V_\infty cos\delta\Delta\delta \quad (2.5.1)$$

$$\Delta V_{bq} = -V_\infty sin\delta\Delta\delta \quad (2.5.2)$$

$$-i_d \Delta V_d - i_q \Delta V_q + \Delta P_o = V_d \Delta i_d + V_q \Delta i_q \quad (2.5.3)$$

$$-(V_d/V_t)\Delta V_d - (V_q/V_t)\Delta V_q + \Delta V_t = 0 \quad (2.5.4)$$

$$\Delta T_u - i_q \Delta\psi_d + i_d \Delta\psi_q = -\psi_q \Delta i_d + \psi_d \Delta i_q \quad (2.5.5)$$

$$\Delta\psi_d = -x_d \Delta i_d + x_{afd}\Delta i_{fd} + x_{akd}\Delta i_{kd} \quad (2.5.6)$$

$$\Delta\psi_{fd} = -x_{afd}\Delta i_d + x_{ffd}\Delta i_{fd} + x_{fkd}\Delta i_{kd} \quad (2.5.7)$$

$$\Delta\psi_{kd} = -x_{akd}\Delta i_d + x_{fkd}\Delta i_{fd} + x_{kdkd}\Delta i_{kd} \quad (2.5.8)$$

$$\Delta\psi_q = -x_q \Delta i_q + x_{akq}\Delta i_{kq} \quad (2.5.9)$$

$$\Delta\psi_{kq} = -x_{akq}\Delta i_q + x_{kqkq}\Delta i_{kq} \quad (2.5.10)$$

The set of equations listed under sections 2.1 to 2.5 are when represented in state space form results in the following vectors;

state vector $X_1 = [\Delta i_d \Delta i_q \Delta i_{fd} \Delta i_{kd} \Delta i_{kq} \Delta V_{cd} \Delta V_{cq} \Delta\delta_1 ... \Delta\delta_6, \Delta\omega_1 ... \Delta\omega_6]^T$

output vector $Z = [\Delta V_d, \Delta V_q, \Delta V_{bd}, \Delta V_{bq}, \Delta P_o, \Delta V_t, \Delta T_u, \Delta\psi_d, \psi_q,$

$\Delta\psi f_d, \Delta\psi k_d, \Delta\psi k_q]^T$

control vector

$U_1 = [\Delta V_{fd}, \Delta T_{m1}, ... \Delta T_{m4}, \Delta V_\infty]^T$

3.0 MODELLING OF EXCITATION SYSTEM AND POWER SYSTEM STABILIZER

3.1 Modelling of Excitation System(3.1.1 to 3.1.4)

In SSR studies the excitation system is not always represented, in which case the field voltage is taken to be constant. In the present analysis IEEE Type I excitation system (with saturation) (Fig.2) which is simple to represent and most commonly used in simulation studies, is considered to study the effect of supplementary signal derived from power system stabilizer. The linearized equations around an operating point are expressed in state variable form as follows;

$$p\Delta E_{fd} = -[(\Delta S_{ei} + K_E)/T_E]\Delta E_{fd} + (1/T_E)\Delta V_R \quad (3.1.1)$$

where $S_{ei} = A.Be^{B}.^{Efd}$

The relation between E_{fd} and the field voltage V_{fd} is given by

$$E_{fd} = (X_{afd}/r_{fd})V_{fd}$$

$$p\Delta V_1 = -1/T_R \Delta V_1 + (K_R/T_R)\Delta V_t \quad (3.1.2)$$

$$p\Delta V_3 = -[K_F(\Delta S_{ei} + K_E)]/(T_E T_F)\Delta E_{fd} - (1/T_F)\Delta V_3$$
$$+ (K_F/T_E T_F)\Delta V_R \quad (3.1.3)$$

$$p\Delta V_R = -(K_A/T_A)\Delta V_1 - (K_A/T_A)\Delta V_3 - (1/T_A)\Delta V_R + K_A/T_A \Delta V_{ref} \quad (3.1.4)$$

State vector $X_{21} = [E_{fd} \Delta V_1 \Delta V_3 \Delta V_R]^T$

Control vector $U_{21} = [\Delta V_t(\Delta V_{ref} - \Omega_s)]^T$

Here $\Delta\Omega_s$ refers to supplementary signal such as feedback from the power system stabilizer.

3.2 Modelling Aspects of PSS

In the study of negative damping situations in power systems, a stabilizing signal is introduced in the excitation system to enhance the system damping. This signal is derived from the speed deviation of the synchronous machine and is fedback to the input of the excitation system through a power system stabilizer.This control circuit is designed to dampout unstable modes of torsional oscillations,instead of damping out the inertial mode (mode 0) as does the conventional PSS.

The following state equations are derived referring to Fig.(3a). The transfer function is given by:

$$\frac{\Omega_s(s)}{\omega_5(s)} = \frac{K_{ps}\ sT_{p5}(1+sT_{p1})(1+sT_{p2})}{(1+sT_{p3})(1+sT_{p4})(1+sT_{p6})} \tag{3.2.1}$$

$$\frac{\Omega_s(s)}{\omega_5(s)} = \frac{K_{ps}T_{c6}\ (s^3T_{c1}+s^2T_{c2}+sT_{c3})}{(S^3+s^2T_{c4}+sT_{c5}+T_{c6})} \tag{3.2.2}$$

where

$T_{c1} = T_{p1}T_{p2}T_{p5}$

$T_{c2} = T_{p1}T_{p5} + T_{p2}T_{p5}$

$T_{c3} = T_{p5}$; $\quad T_{c4} = 1/T_{p6} + 1/T_{p4} + 1/T_{p3}$

$T_{c5} = 1/T_{p4}T_{p6} + 1/T_{p3}T_{p6} + 1/T_{p3}T_{p4}$

$T_{c6} = 1/T_{p3}T_{p4}T_{p6}$

From the above transfer function the following state equations that describe the PSS for small disturbances analysis are obtianed:

$$p\Delta s_1 = \Delta\omega_5 - T_{c4}\Delta s_1 - T_{c5}\Delta s_2 - T_{c6}\Delta s_3 \tag{3.2.3}$$

$$p\Delta s_2 = \Delta s_1 \tag{3.2.4}$$

$$p\Delta s_3 = \Delta s_2 \tag{3.2.5}$$

$$\Delta\Omega_s = K_{ps}T_{c6}[T_{c1}\Delta\omega_5 + (T_{c2} - T_{c1}T_{c4})\Delta s_1 + (T_{c3} - T_{c1}T_{c5})\Delta s_2 - T_{c1}T_{c6}\Delta s_3] \tag{3.2.6}$$

where $\Delta\omega_5 = (K_{ps1}\Delta\omega_{m1} - K_{ps2}\Delta\omega_{m2} + K_{ps3}\Delta\omega_{m3} - K_{ps4}\Delta\omega_{m4})$

3.3 Modal Speed Deviations as Input to PSS (3.3.1 to 3.3.4)

There is a separate gain adjustment for each modal speed deviation feedback as shown in Fig.(3b). The phase adjustment is common for all the modes.

The equations describing the PSS with modal speed deviation signal can be obtained as follows by substituting for $\Delta\omega_5$ in equations (3.2.3) and (3.2.6)

$$p\Delta s_1 = [K_{ps1}\Delta\omega_{m1} - K_{ps2}\Delta\omega_{m2} + K_{ps3}\Delta\omega_{m3} - K_{ps4}\Delta\omega_{m4}] - T_{c4}\Delta s_1 - T_{c5}\Delta s_2 - T_{c6}\Delta s_3 \quad (3.3.1)$$

$$p\Delta s_2 = \Delta s_1 \quad (3.3.2)$$

$$p\Delta s_3 = \Delta s_2 \quad (3.3.3)$$

$$\Delta\Omega_s = T_{c6}[T_{c1}\{K_{ps1}\Delta\omega_{m1} - K_{ps2}\Delta\omega_{m2} + K_{ps3}\Delta\omega_{m3} - K_{ps4}\Delta\omega_{m4}\} + (T_{c2} - T_{c1}T_{c4})\Delta s_1 + (T_{c3} - T_{c1}T_{c5})\Delta s_2 - (T_{c1}T_{c6})\Delta s_3] \quad (3.3.4)$$

The modal speeds are linearly related to the shaft speed deviations by the matrix relation (3.3.5)

$$\Delta\omega_m = [QM]^{-1}\Delta\omega \quad (3.3.5)$$

where $\Delta\omega_m = [\Delta\omega_{mo}.....\Delta\omega_{m5}]^T$

$\Delta\omega = [\Delta\omega_1......\Delta\omega_6]$

The QM matrix which represents the mode shapes is given in Appendix-I. The transformation is defined by the above equation decouples various modes and is an orthogonal vector of modal speeds. The modal speed deviations in equation(3.3.1 and 3.3.4) are expressed in terms of the actual speeds by the matrix relation given in equation (3.3.5). The modal speeds can be obtained in terms of the actual speeds using torsional monitor device [5]. The excitation system equations (3.1.1 to 3.1.4) are combined with PSS equations (3.3.1 to 3.3.3). The combined state vector is X_{22} and control vector is U_{22}

state vector $X_{22} = [\Delta E_{fd}\Delta V_1\Delta V_3\Delta V_R\Delta s_1\Delta s_2\Delta s_3]^T$

control vector $U_{22} = [\Delta V_t\Delta V_{ref}\Delta\omega_1...\Delta\omega_6]^T$

4.0 STATIC REACTIVE POWER COMPENSATOR MODEL

The thyristor phase controlled reactor is represented (Fig.4) by an inertia less voltage source E_s behind the fixed reactance X_s. Since, the static compensator provides only reactive power and has negligible MW power loss, E_s of the SVS model is always in phase with the voltage V_t.

$E_s = X_{c4}V_t$
where $X_{c4} = [(2\alpha - sin2\alpha)/\pi - 1]/(1 + T_s)$
α = Firing angle of the thyristor (remains constant)

T_s represents the delay time of thyristor circuits. The magnitude of the admittance of the SVC is obtained as $B_s = (1 - X_{c4})/X_s$. Where X_s is the full reactance of the SVC, and the relation with MVA rating Q_s is given by $Q_s = V_t^2/X_s$

4.1 Modelling Aspects of TCR

i) Modelling of TCR with compelte controls (4.1.1 to 4.1.6)

The linearized equations representing the TCR model referring to block diagram given in Fig.4 are given below:

TCR current is in the d- q axis:

$$p\Delta i_{sd} - (\omega_o/X_s)(1 - X_{c4})\Delta V_d = -(\omega_o/X_s)V_d\Delta X_{c4} + i_{sq}\Delta\omega_5 + \omega_o\Delta i_{sq} \quad (4.1.1)$$

$$p\Delta i_{sq} - (\omega_o/X_s)(1 - X_{c4})\Delta V_q = -(\omega_o/X_s)V_q\Delta X_{c4} - i_{sd}\Delta\omega_5 - \omega_o\Delta i_{sd} \quad (4.1.2)$$

Voltage measurement

$$-(1/T_m)\Delta V_t + p\Delta X_{c1} = -(1/T_m)\Delta X_{c1} \quad (4.1.3)$$

Voltage regulator:

$$p\Delta X_{c22} = \Delta X_{c21} \quad (4.1.4)$$

$$p\Delta X_{c21} = -\Delta X_{c1} - e\Delta X_{c22} - f\Delta X_{c21} \quad (4.1.5)$$

Thyristor

$$p\Delta X_{c4} = SCK_w\Delta\omega_5 - SCa\Delta X_{c1} + SCa(c - e)\Delta X_{c22} + SCa(d - f)\Delta X_{c21} - (1/T_s)\Delta X_{c4} \quad (4.1.6)$$

where $SC = (1/T_s)\, 2/\pi\, (1 - \cos 2\alpha)$

State vector is $X_{31} = [\Delta i_{sd}\Delta i_{sq}\Delta X_{c1}\Delta X_{c22}\Delta X_{c21}\Delta X_{c4}]^T$

4.2 Modelling of TCR with terminal voltage feed-back only

The TCR is controlled by terminal voltage feedback. The same set of equations as for TCR with complete controls is applicable for this case study also, except that in equation (4.1.6), the term [SC $K_w\Delta\omega_5$] will not be present, as speed feedback is not considered. The state vector remains same as in the case of TCR with complete controls.

State vector is $X_{32} = [\Delta i_{sd}\Delta i_{sq}\Delta X_{c1}\Delta X_{c22}\Delta X_{c21}\Delta X_{c4}]^T$

5.0 ANALYSIS

The analysis is carried out based on the folloiwng initial operating conditions and assumptions:

* The generator delivers 0.9pu power to the system. This operating has been considered for the study as this is the most likely operaitng point for the Indian power system.

* The steady state voltage at the sending and receiving end are 1.05 and 1.0 pu respectively.

* To consider the worst condition regarding system oscillations, the mechanical damping of the T-G shaft is assumed to be zero.

* The dynamics of the governor systems are neglected and the input mechanical power to the turbine is assumed to be constant.

The following cases are studied to analyse the effectiveness of different control strategies in damping the torsional oscillations.

Case 1: Analysis of basic system without any controls.For this case study the state vector is $X = [\ X_1\ X_{21}\ ]^T$

Case 2: Analysis with PSS (using modal speed deviations).In this case the state vector is $X = [\ X_1\ X_{22}\ ]^T$

Case 3: PSS with modal speeds plus TCR with terminal voltage control.For this case the state vector is $X = [\ X_1\ X_{22}\ X_{32}]^T$.

Case 4: PSS with modal speeds plus TCR with complete controls.The state vector for this case is given by $X = [\ X_1\ X_{22}\ X_{31}]^T$.

The system equations depending upon the type of case study under investigation are formulated in the following state variable form.

$$\begin{bmatrix} \dot{X}t \\ \\ Z_t \end{bmatrix} = [P^{-1}Q]X_t + [P^{-1}R]U_t \tag{5.1}$$

where the elements of P matrix are the co-efficients of the derivatives of state variables and output variables. The Q matrix elements are the co-efficients of state variables and R matrix contains the co-efficients of control elements. Here, the state vector X varies depending upon the type of case study. The output vector Z_t is given under section 2. The significance of the vector Z_t is that the output variables can be expressed in terms of state variables. Equation (5.1) is partitioned and expressed as follows:

$$\dot{X}_t = AX_t + BU_t \tag{5.2}$$
$$Z_t = CX_t + DU_t \tag{5.3}$$

The eigenvalues of system matrix A are obtained for analysis. This analysis gives information concerning the decrement factors i.e. the rate of growth of decay of all the modes of oscillations along with their respective frequency.

Case 1: Analysis of basic system without controls

The basic system without any controls is analysed to identified the unstable modes of oscillations. For this study, at the specified operating point the level of series compensation is varied in steps and the eigenvalues are computed. From these eigenvalues variation of decrement factor with respect to variation in compensation level is plotted as shown in Fig.5. The peak of these mode shapes gives an indication, of the maximum negative damping experienced by these modes at the corresponding percentage of compensation level, as shown in Table 1. It is ensured that the decrement factor of the electrical mode at all levels of compensation is in stable region. (Fig.6 Case:1)

Table:1

Operating point Vt = 1.05 p.u Pf = 0.9, Pg=0.9

Mode	Frequency (Hz)	% Compensation	Decrement factor
4	32.28	33.25	1.49
3	25.55	51.5	1.49
2	20.21	68.0	0.78
1	15.71	85.0	5.23

It is also observed that mode 5 has negligible decrement factor which indicates it is always stable. Mode 0 is stable. Once the unstable modes (4,3,2,and 1) are identified, the objective is to dampout these oscillations using proper control strategy.

Case 2 : PSS with modal speed control

The PSS time constants have been selected by repeated eigenvalue analysis so as to provide proper phase adjustment to damp effectively the torsional oscillations of mode 1 at 85% compensation.The gains Kps4,Kps3,Kps2 and Kps1 have been selected so as to provide effective damping for these respective modes (4,3,2,and 1) at 33.25%,51.5%,68% and 85% compensation respectively. The results are given in Fig.7 and Table 2 (Case 2)

* The system is effectively stabilized at compensation levels corresponding to the maximum negative damping of modes 3,2 and 1.

* At 33.25% compensation level (which corresponds to the maximum negative damping of mode 4) the negative damping of mode 4 is reduced to a considerable extent. The system is marginally stable.

* Mode 4 could be effectively stabilized by providing more phase lead but this will result in mode 1 instability at 85% compensation.

* Modes 4, 3 and 1 become unstable over other compensation levels which do not correspond to the peak negative damping of these modes.This sort of instability is due to the presence of modal interaction.

* Mode 0 remains stable over the entire range of compensation.

* The electrical mode is in the stable region over the entire range of compensation. (Fig.6 Case:2)

Case 3 : PSS with modal speeds plus TCR with terminal voltage control

The results are given in Fig 8 and Table 2 (Case 3)

* The system is effectively stabilized at all levels of compensation.

* The instability due to modal interaction is eliminated.

* Mode 0 remains stable over the entire range of compensation.

* The electrical mode is in the stable region over the entire range of compensation (Fig 6 Case 3).

Case 4 : PSS with modal speeds plus TCR with complete controls

The results are given in Fig 9 and Table 2 (Case 4)

* The auxiliary speed feedback signal for TCR enhances the system stability as compared to PSS plus TCR with voltage control only.

* Mode 0 remains stable over the entire range of compensation.

* The electrical mode is in the stable region over the entire range of compensation (Fig.6 Case:4)

Table 2 Maximum Decrement factors of torsional modes

Operating point Vt = 1.05 pu PF =0.9 Pg=0.9

Mode	frequency (HZ)	% compensation	Decrement factors			
			case1	case2	case3	case4
4	32.28	33.25	1.49	0.1647	-2.817	-2.4686
3	25.55	51.5	1.49	-0.0988	-0.6352	-2.05
2	20.21	68.0	0.78	-0.5	-0.0132	-0.5503
1	15.71	85.0	5.23	-0.0714	-0.666	-1.56

CONCLUSIONS

* Effective damping of torsional oscillations using coordinated control is established.
* PSS with modal speed deviation feedback is able to effectively damp the torsional oscillations at 51.5%, 68% and 85% compensation levels. At 33.25% compensation the negative damping of mode 4 is considerably reduced.
* Coordinated control using PSS plus TCR with voltage control establishes the effectiveness of terminal voltage feedback in eliminating the modal interactions and effectively stabilizing the system
* Coordinated control using PSS plus TCR with complete controls enhances the system stability as compared to PSS plus TCR with voltage control only.

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APPENDIX I

Modes of oscillation and mode shapes

Consider an unforced and undamped mechanical system.This system can be described by set of second order differential equations that can be written in matrix form as follows :

$(1/w_o)$ H $p^2\delta$ + K δ = 0 (1)
All quantities are in pu δ in radians and time in seconds
H = Diag [$2H_1$ $2H_2$ $2H_3$ $2H_4$ $2H_5$ $2H_6]^T$
δ = Col [$\delta_1\delta_2\delta_3\delta_4\delta_5\delta_6]^T$
K = Tridiagonal matrix of shaft stiffness constants.
At resonance all masses oscillate at the same frequency, such that
$\delta_i = X_i \sin(\omega_m t + \alpha)$; i = 1,2,.....,6 (2)
Substituting equation(2) in (1) we get λ_m X = M X
where M = $H^{-1}K$; $\lambda_m = (\omega_m^2 / \omega_o)$; $\omega_m = [\lambda_m\omega_o]^{\frac{1}{2}}$, m = 0,1,....5

1	-0.777	0.1099	1.0	0.6638	-0.7874
1	-0.5837	0.0646	0.3422	-0.0437	1.0
1	-0.3424	0.015	-0.2297	-0.5027	-0.1133
1	0.1117	-0.0395	-0.0954	1.0	0.0211
1	0.373	-0.0374	0.166	-0.6205	-0.0045
1	1.0	1.0	-0.2525	0.3768	0.0009

= QM

Each column of QM corresponds to a mode shape.

APPENDIX II

System data

The data for the electro mechanical system pertains to the first IEEE benchmark system [1].

Electrical system

The electrical system consists of an 892.4 MVA generator connected to a 500 Kv transmission system.

(All data are in pu on 892.4 MVA base)

Machine data

$X_d = 1.79$ $X_q = 1.71$ Transformer data $r_{tt} = 0.0$ $X_{tt} = 0.14$

$X_{ffd} = 1.722$ $X_{kdkd} = 1.6655$

$X_{kqkq} = 1.675$ $X_{afd} = 1.66$ Line data $r_e = 0.02$ $X_e = 0.56$

$X_{akd} = 1.66$ $X_{akq} = 1.58$

$X_{fkd} = 1.66$ $X''_d = 0.135$

$r_a = 0.0$ $r_{fd} = 0.001406$

$r_{kd} = 0.004085$ $r_{kq} = 0.008223$

Mechanical system

Mass	Inertia H(sec)	Shaft sections	Spring constant (pu torque/rad)
(HP)H1	0.092897	(HP-IP)K12	19.303
(IP)H2	0.155589	(IP-LPA)K23	34.929
(LPA)H3	0.85867	(LPA-LPB)K34	52.038
(LPB)H4	0.884215	(LPB-GEN)K45	70.858
(GEN)H5	0.868495	(GEN-EXC)K56	2.822
(EXC)H6	0.0342165		

Mechanical damping D is taken as zero.
(synchronous speed Wo = 377 rad/sec)

IEEE Type1 Excitation		Power system stabilizer (PSS)	
KA = 20	KE = -0.05	Tp1 = 0.285 sec	Tp2 =0.0709sec
KF = 0.04	KR = 1.0	Tp3 = 0.0021 sec	Tp4 =0.0102sec
TA = 0.05 sec	TE = 0.55sec	Tp5 = 1.0 sec	Tp6 =0.0058sec
TF = 0.715 sec	TR = 0.01 sec	Kps = 8.0	Kps1=4.1
A = 0.0039	B = 1.555	Kps2 = 0.35 $K_{ps4} = 17.5$	Kps3=2.5

TCR data used in the present analysis.
Qs (rated) = 0.1 pu $\alpha = 2.0$ radians
Xs = 10.0 pu a = 60, c = 460 d=60
e=300 f=201 Tm =0.04 Ts=0.0015

Nomenclature

V_d,V_q d and q axes stator voltages
V_t terminal voltage
V_∞ voltage at infinite bus
V_{bd},V_{bq} components of infinite bus voltage along d and q axes
V_{fd} field voltage
E_{fd} field voltage referred to armature side
V_{cd},V_{cq} d and q axes components of the voltage across series capacitor
ψ_d,ψ_q d and q axes stator flux linkages
ψ_{fd}, ψ_{kd},ψ_{kq} flux linkages of field winding,d and q axes damper circuits
i_d, i_q d and q axes stator currents
i_{fd},i_{kd},i_{kq} currents in field winding, d and q axes damper windings
ω_o synchronous speed in rad/sec
P_g generator power output
P_f power factor at generator terminals.
δ_i angular deviation of rotor i with respect to synchronous reference frame
ω_i velocity of mass i
ω_{mi} modal velocity corresponding to mode i
H_i inertia constant of mass i
K_{ij} spring constant of shaft between mass i and j
D_i mechanical damping coefficient of mass i
T input torque vector
T_{mi} mechanical torque applied on mass i
T_u electrical torque developed
p denoting time derivative
Δ operator prefix denoting incremental value of a variable
X_s Full reactance of TCR
T_m measuring circuit time constant
T_s delay time of thyristor circuits
a,c,d,e & f voltage regulator constants.

Excitation system (IEEE type 1 system)

K_A amplifier gain
K_E exciter constant related to self exciter field
K_F stabilizing circuit gain
K_R regulator gain
S_E exciter saturation function

T_A amplifier time constant
T_E exciter time constant
T_F stabilizing circuit time constant
T_R regulator time constant

Power system stabilizer (PSS)

T_{p3}, T_{p5} washout time constants
$T_{p1}; T_{p2}$ phase compensation time constants
$T_{p4}; T_{p6}$
K_{ps1}, K_{ps2} pss gains for modal speed deviation signals
K_{ps3}, K_{ps4} of modes 1,2,3,and 4 respectively

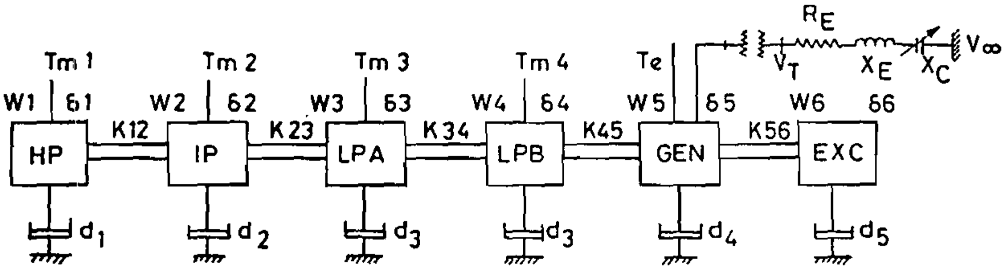

Fig.1: Schematic Representation of Electromechanical System

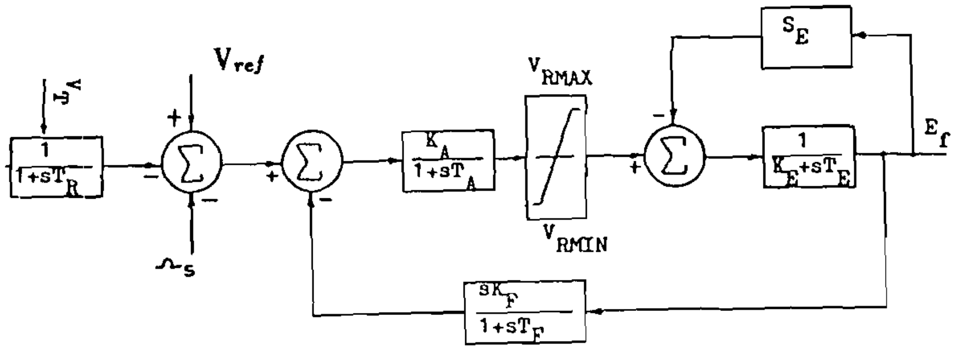

Fig.2: IEEE Type 1 Excitation System

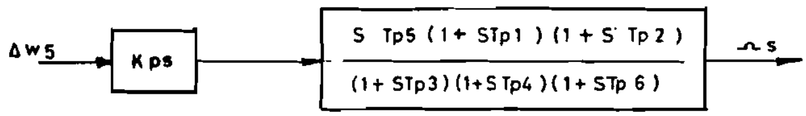

Fig.3a: Block Diagram of Power System Stabilizer(Generator Speed Deviation Signal)

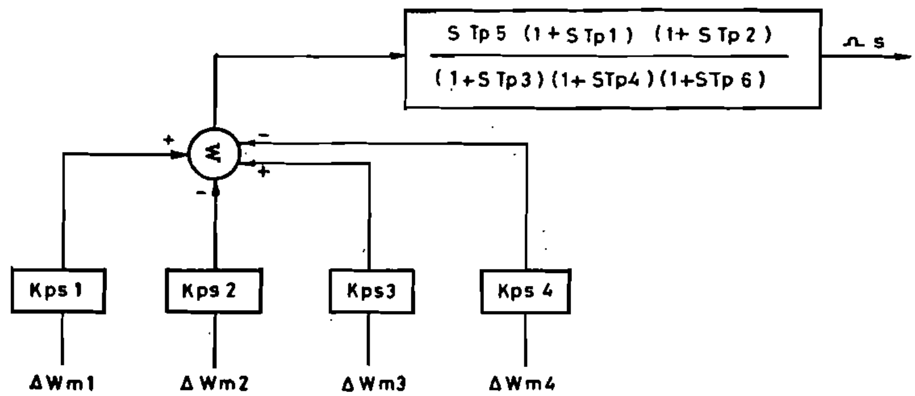

Fig.3b: Block Diagarm of Power System Stabilizer(Modal Speed Deviation Signals)

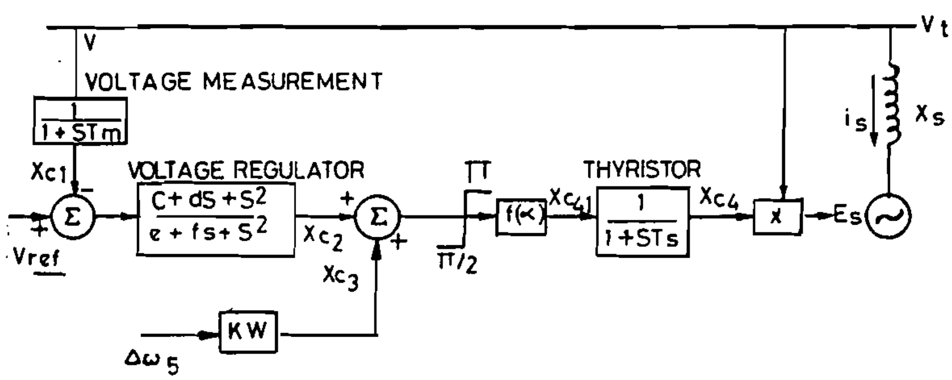

Fig.4: Block Diagram of Thyristor Controlled Reactor

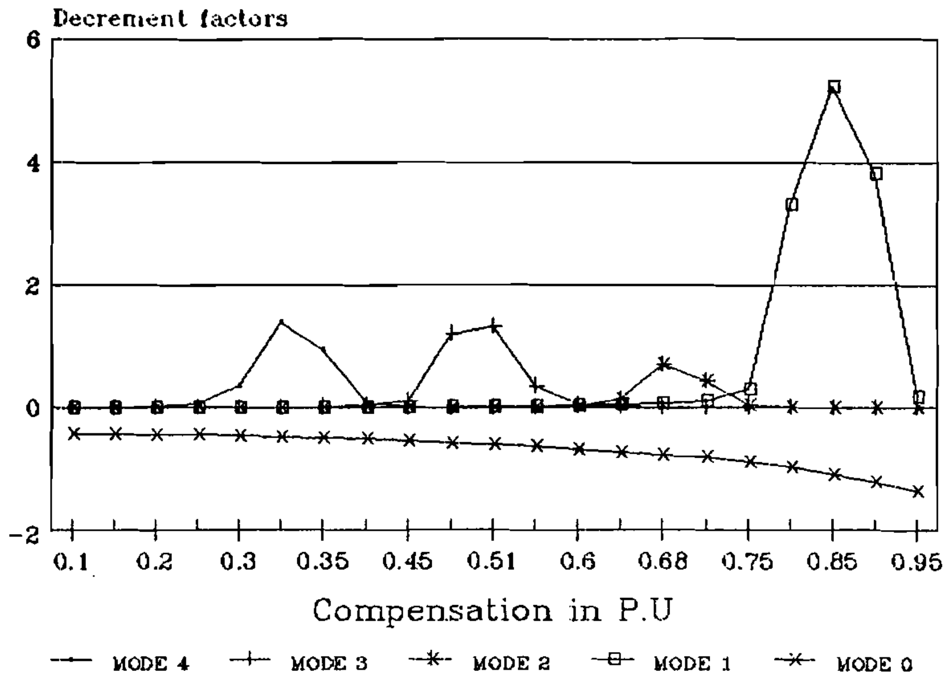

Fig.5: Decrement Factors of Torsional Modes without SSR Damping Control

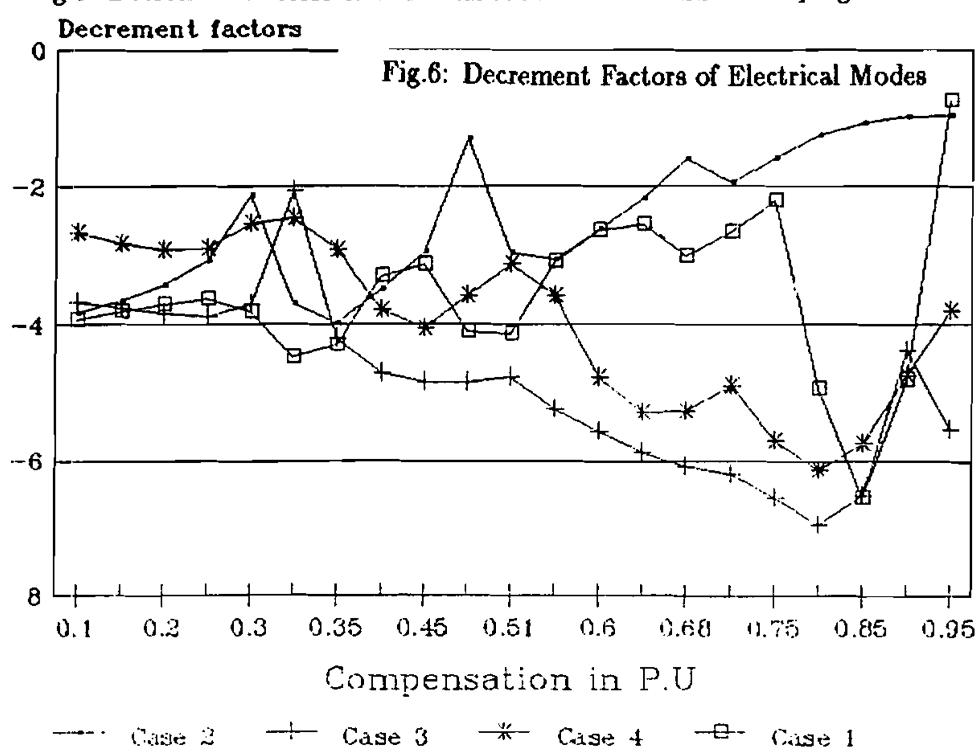

Fig.6: Decrement Factors of Electrical Modes

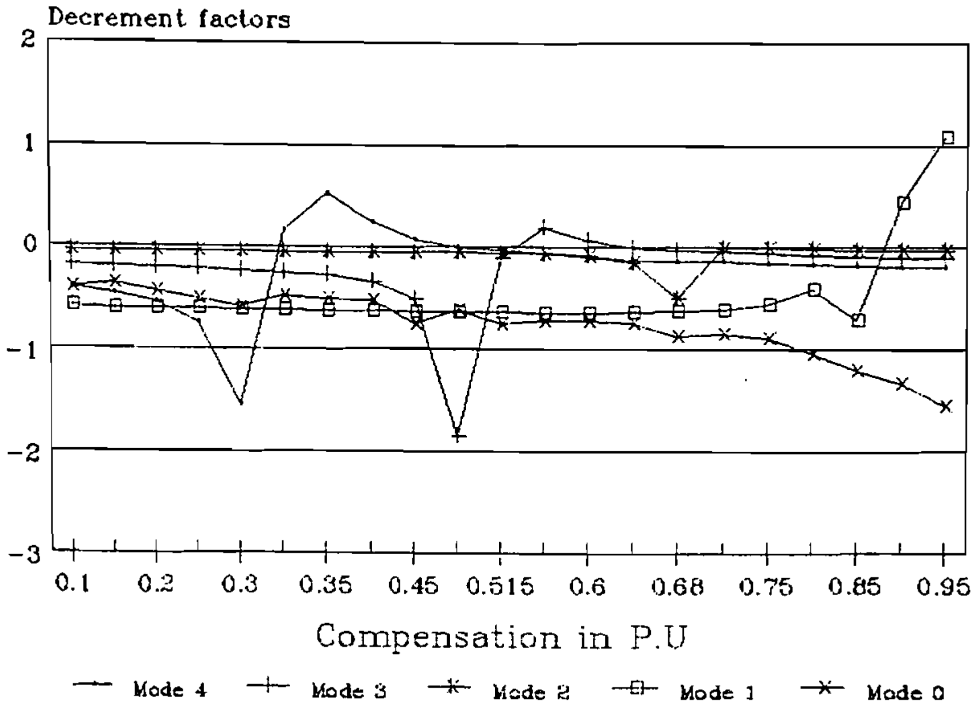

Fig.7: Decrement Factors of Torsional Modes. PSS with Modal Speed Control

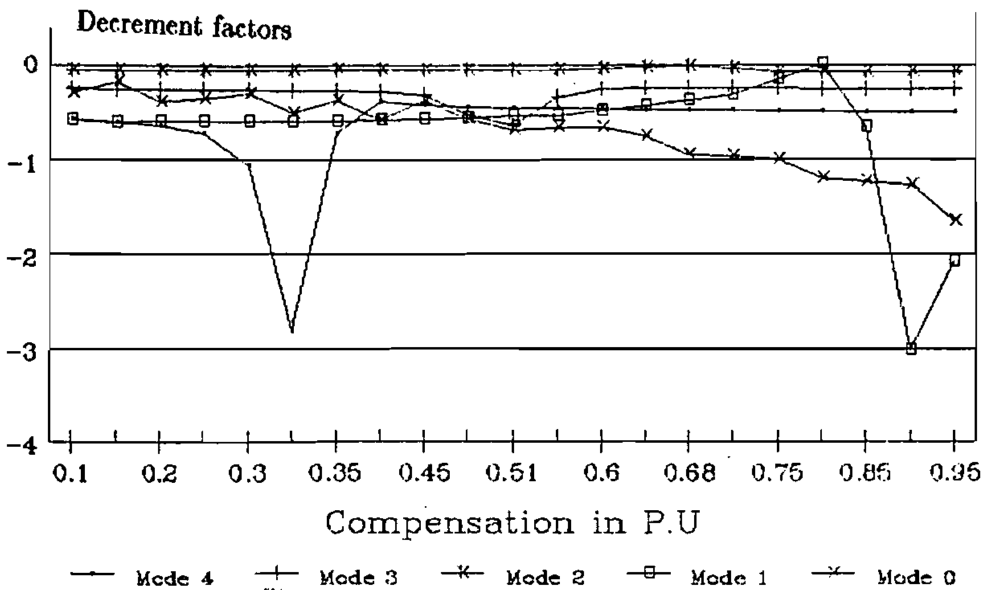

Fig.8: Decrement Factors of Torsional Modes. PSS with Modal Speeds plus TCR with Terminal Voltage Control

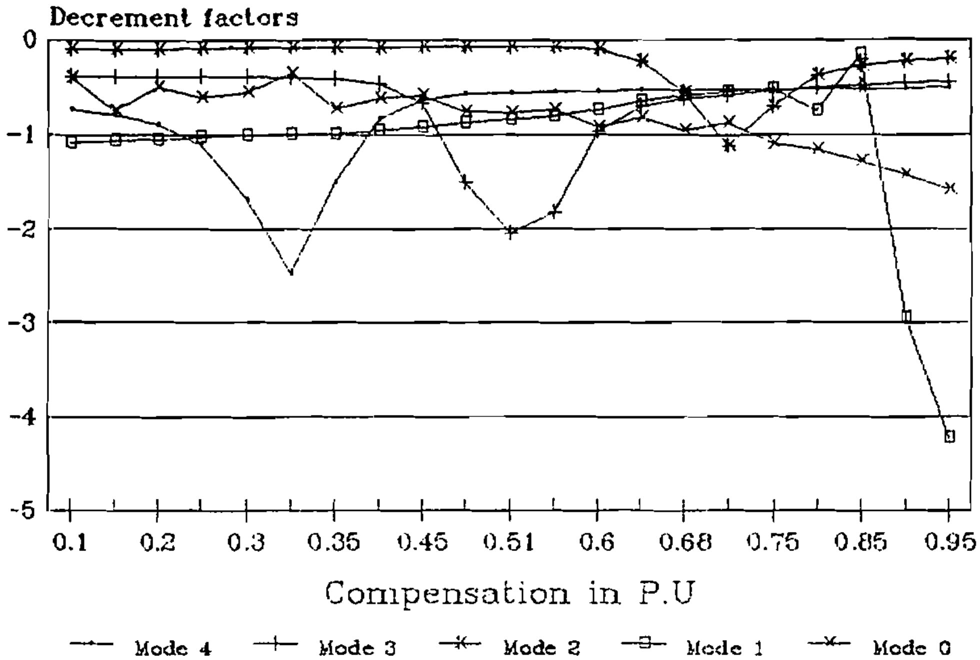

Fig.9: Decrement Factors of Torsional Modes. PSS with Modal Speed plus TCR with complete controls