

CRITICAL ANALYTICAL IMPACT OF AVR AND PSS ON STABILITY OF POWER SYSTEMS

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Abstract

In a power system network, electrical loads are always dynamically changing. This variation may be as a result of load demands or faults on the network. The result of these changes gives rise to instability in the terminal voltage and frequency. This paper examines the impact of Automatic voltage regulator (AVR) and Power system stabilizer (PSS) on a typical power system network. The result shows that AVR alone may stabilize the terminal voltage but brings instability to rotor angles and speed. The inclusion of PSS stabilizes the system within the linearized region.

Keywords: Automatic voltage regulator, Power system stabilizer, synchronizing and damping torque. Excitation system.

1.0 Introduction

The stability of single-machine infinite bus system under disturbed conditions has been centered on its synchronizing torque and damping torque parameters as view from its classical generator model [1]. The analysis is based on looking at its eigenvalue, eigenvector and participation factors [2, 3]. This has led to development of many types of controllers for both terminal voltage regulation, and rotor/speed oscillation. Automatic voltage regulators (AVR) have been generally recommended for excitation system control and power system stabilizer (PSS) for rotor angle and speed regulation [4, 5].

To achieve global transient and voltage regulation for power system within an operating region, there must be a good balance between the properties of AVR used and the power system stabilizer [6, 7]. This will in turn provide the necessary synchronizing torque and damping torque for the stability in question. Many attempts have been made in this direction. Linear controllers have been made to coordinate the various requirements for stabilization and voltage regulations. An approach [8] based on the advanced robust control tries to effect a trade-off between voltage regulation and small signal power system stabilizer (PSS). Other practical approach called

discontinuous excitation control (DEC) [1] uses switching of a transient stability control models to augment the usual PSS. The DEC assumes linearized configuration but uses different controller structure for different operating conditions. Power system has in general been observed as nonlinear in nature and for such, many nonlinear techniques has been developed. The idea is based on gain scheduling and more recently is the use of multi-model control. These ideas usually referred to as global control uses combined technique of both qualitative and quantitative knowledge through some hierarchy [9]. Fuzzy logic and neural network has been the two practical approaches utilizing the qualitative knowledge to design the controller.

This paper explores and outlays the significance of AVR and PSS in the power system stability studies of single generator connected to infinite bus under normal and abnormal operating conditions. A case study is considered and a model structure is developed based on its state space model. The eigenvalue, eigenvector and participation factors were obtained. The result revealed important effects of the AVR and PSS on the overall stability analysis.

2.0 Dynamic Model of Power System

Like pointed out earlier, this paper considers a single machine infinite bus power system (SMIB). It is observed in general that SMIB system qualitatively exhibits important aspects of the behaviour of a multi-machine system and is relatively easier to study. The paper considers SMIB power system arrangement shown in Fig 1.

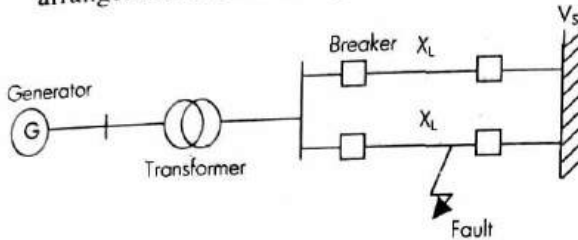


Fig. 1: A single machine infinite bus power system

The dynamic behavior of this machine will be considered under the following headings.

2.1 Generator Represented by the Classical Model

When the system is represented with the classical model, all resistances are neglected as shown in fig. 2 below.

In this equivalent circuit, E' is the voltage behind X'_d . Its value is constant at the pre-disturbance value. δ is the angle by which E' leads the infinite bus voltage V_s . As the rotor oscillates during a disturbance, δ changes.

Let E' be reference phasor,

$$\tilde{I}_t = \frac{E' \angle 0 - V_s \angle -\delta}{jX_T} = \frac{E' - V_s (\cos \delta - j \sin \delta)}{jX_T}$$

$$\tilde{E}' = \tilde{E}_{to} + jX'_d I'_{to}$$

Then the state space representation becomes

$$\frac{d}{dt} \begin{bmatrix} \Delta \omega_r \\ \Delta \delta \end{bmatrix} = \begin{bmatrix} -k_D & -k_s \\ \omega_b & 0 \end{bmatrix} \begin{bmatrix} \Delta \omega_r \\ \Delta \delta \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \frac{\Delta T_m}{2H}$$

2.2 Dynamic Model of Synchronous Machine with Field Circuit

With the effect of field flux variation included in the system performance and

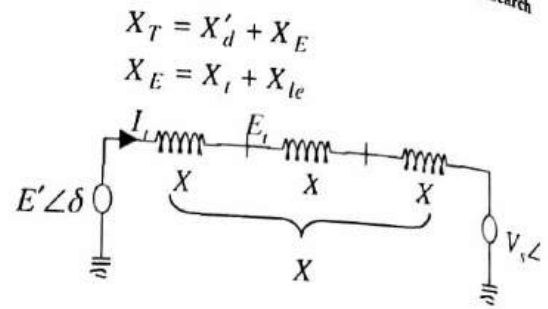


Fig. 2: Equivalent circuit of generator classical model

The complex power behind X'_d is given by

$$S' = P + jQ' = \tilde{E}' \tilde{I}_t^* = \frac{E' V_s \sin \delta}{X_T} + \frac{j E' (E' - V_s \cos \delta)}{X_T}$$

When the stator resistance is neglected, the air-gap power P_e is equal to the terminal power P and in per unit, the air-gap torque is equal to air-gap power or

$$T_e = P = \frac{E' V_s \sin \delta}{X_T}$$

When linearized about initial operating point given by $\delta = \delta_0$ yields

$$\Delta T_e = \frac{\partial T_e}{\partial \delta} \Delta \delta = \frac{E' V_s}{X_T} \cos \delta_0 (\Delta \delta)$$

The equation of motion in p.u is

$$d/d_t (\Delta \omega_r) = \frac{1}{2H} (T_m - T_e - K_D \Delta \omega_r)$$

$$\frac{\partial}{\partial t} (\delta) = \omega_0 \Delta \omega_r$$

$$\text{Let } K_s = \frac{E' V_s}{X_T} \cos \delta_0$$

assuming constant field voltage, the state space model [1] shown below is obtained.

$$\begin{bmatrix} \Delta \dot{\phi} \\ \Delta \dot{\delta} \\ \Delta \dot{\phi}_{fd} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & 0 & 0 \\ 0 & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} \Delta \phi \\ \Delta \delta \\ \Delta \phi_{fd} \end{bmatrix} + \begin{bmatrix} b_{11} & 0 \\ 0 & 0 \\ 0 & b_{32} \end{bmatrix} \begin{bmatrix} \Delta T_m \\ \Delta E_{fd} \end{bmatrix}$$

Where

$$a_{11} = \frac{-K_D}{2H}, \quad a_{12} = \frac{-K_1}{2H}, \quad a_{13} = \frac{-K_2}{2H}$$

$$a_{21} = w_0 = 2\pi f_0, \quad f_0 = 50\text{Hz}$$

$$a_{32} = \frac{-w_0 R_{fd}}{L_{fd}} m_1 L'_{ads}$$

$$a_{33} = \frac{-w_0 R_{fd}}{L_{fd}} \left[1 - \frac{L'_{ads}}{L_{fd}} + M_2 L'_{ads} \right]$$

$$b_{11} = \frac{1}{2H}$$

$$b_{32} = \frac{w_0 R_{fd}}{L_{adu}}$$

$$M_1 = \frac{V_s (X_{Tq} \sin \delta_0 - R_T \cos \delta_0)}{D}$$

$$M_2 = \frac{X_{Tq} L_{ads}}{D(L_{ads} + L_{fd})}$$

$$n_1 = \frac{V_s (R_T \sin \delta_0 + X_{Td} \cos \delta_0)}{D}$$

$$n_2 = \frac{R_T L_{ads}}{D(L_{ads} + L_{fd})}$$

$$\begin{bmatrix} \Delta \dot{\omega}_r \\ \Delta \dot{\delta} \\ \Delta \dot{\varphi}_{fd} \\ \Delta \dot{V}_1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 \\ a_{21} & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} \Delta \omega_r \\ \Delta \delta \\ \Delta \varphi_{fd} \\ \Delta V_1 \end{bmatrix} + \begin{bmatrix} b_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \Delta T_m$$

$$= \frac{1}{L_{fd}} - M_2$$

$$a_{34} = -b_{32} K_A = \frac{-w_0 R_{fd}}{L_{adu}} K_A$$

Where

$$a_{41} = 0, \quad a_{42} = \frac{K_5}{T_R}, \quad a_{43} = \frac{K_6}{T_R}, \quad a_{44} = \frac{-1}{T_R}$$

$$K_5 = \frac{e_{d0}}{E_{i0}} [-R_a M_1 + L_1 n_1 + L_{aq} n_1] + \frac{e_{q0}}{E_{i0}} [-R_a n_1 - L_1 M_1 - L'_{qds} M_1]$$

$$K_6 = \frac{e_{d0}}{E_{i0}} [-R_a M_2 + L_1 n_2 + L_{aq} n_2] + \frac{e_{q0}}{E_{i0}} [-R_a n_2 - L_1 M_2 + L'_{qds}]$$

If the mechanical input torque is constant, then $\Delta T_m = 0$.

$$K_1 = n_1 (\varphi_{ado} + L_{aq} i_{d0}) - M_1 (\varphi_{aq0} + L'_{ads} i_{q0})$$

$$K_2 = n_2 (\varphi_{ado} + L_{aq} i_{d0}) - M_2 (\varphi_{aq0} + L'_{ads} i_{q0}) + \frac{L'_{qds}}{L_{fd}} i_{q0}$$

$$R_T = R_a + R_E$$

$$X_{Tq} = X_E + (L_{aq} + L_1) = X_E + X_{qs}$$

$$X_{Td} = X_E + (L'_{qds} L_1) = X_E + X'_{ds}$$

$$D = R_T^2 + X_{Tq} X_{Td}$$

2.3 System with Excitation System

Now, the excitation system is included in the state space model by expressing the terminal voltage E_t in terms of the state variables Δw_r , $\Delta \delta$ and $\Delta \varphi_{fd}$. The resulting state space equation is given below (eqn. 13).

2.4 System Model with Power System Stabilizer

During the analysis, we will observe that the primary effect of power system stabilizer (PSS) is to add damping to the generator rotors oscillation by controlling its excitation using auxiliary stabilizing signals. The stabilizer usually produces a component of electrical torque in phase with the rotor speed deviations. The state space model of the system with PSS is given in equation (14), while the complete block diagram with AVR and PSS is shown in fig. 3. Figure 4 shows thyristor excitation system with AVR and PSS.

In the state space model,

$$a_{51} = K_{STAB} a_{11}, \quad a_{52} = K_{STAB} a_{12},$$

$$a_{53} = K_{STAB} a_{13},$$

$$a_{55} = \frac{-1}{T_w}, \quad a_{56} = \frac{w_0 R_{fd}}{L_{adu}} K_A, \quad a_{61} = \frac{T_1}{T_2} a_{51},$$

$$a_{62} = \frac{T_1}{T_2} a_{52}, \quad a_{63} = \frac{T_1}{T_2} a_{53},$$

$$a_{65} = \frac{T_1}{T_2} a_{55} + \frac{1}{T_2}, \quad a_{66} = \frac{-1}{T_2}$$

The complete state-space model, including the PSS with $\Delta T_m = 0$ is shown below.

$$\begin{bmatrix} \Delta \dot{\omega} \\ \Delta \dot{\delta} \\ \Delta \dot{\varphi}_{fd} \\ \Delta \dot{V}_1 \\ \Delta \dot{V}_2 \\ \Delta \dot{V}_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 & 0 \\ a_{21} & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & a_{34} & 0 & a_{36} \\ 0 & a_{42} & a_{43} & a_{44} & 0 & 0 \\ a_{51} & a_{52} & a_{53} & 0 & a_{55} & 0 \\ a_{61} & a_{62} & a_{63} & 0 & a_{65} & a_{66} \end{bmatrix} \begin{bmatrix} \Delta \omega \\ \Delta \delta \\ \Delta \varphi_{fd} \\ \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \end{bmatrix}$$

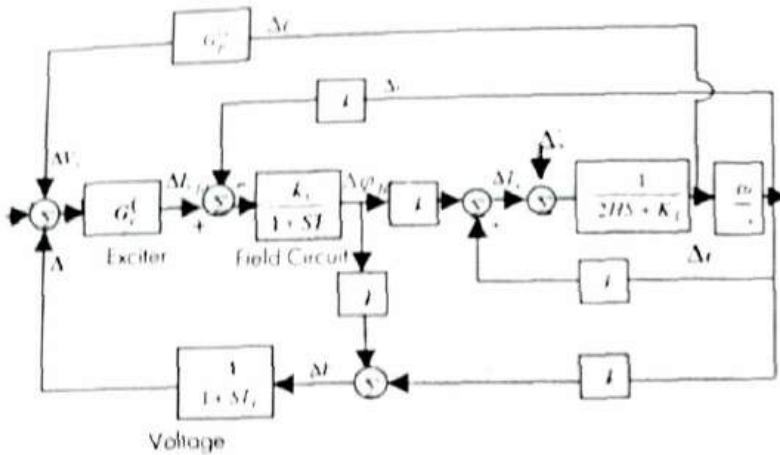


Fig.3: Block diagram representation with AVR and PSS

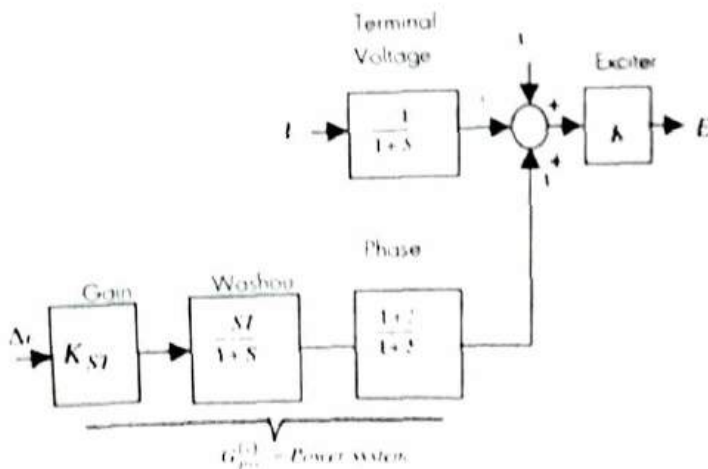


Fig. 4: Thyristor excitation system with AVR and PSS

3.0 Analytical and Simulation of Effect of Avr and Pss on Stability of Thermal Generating Station

The analytical and simulation study is based on upon three cases.

3.1 Case 1

The thermal generating station under study is shown in figure 5, with the equivalent circuit after an open circuit fault knocked out CCT₂ line shown in figure 6.

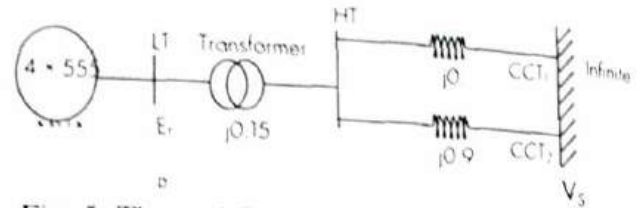


Fig. 5: Thermal Generating Station

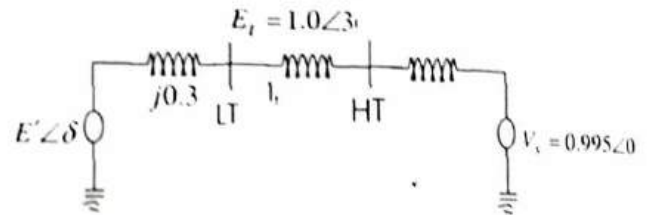


Fig. 6: Equivalent circuit

The rating and parameters of the generator are four 555MVA, 24kV, and 50Hz units.

$$P = 0.9, \quad Q = 0.3, \quad E_t = 1.0 \angle 36^\circ,$$

$V_t = 0.995 \angle 0^\circ$, on 2220 MVA and 24 kV base.

$$X'_d = 0.3 \quad \text{and} \quad H = 3.5 \text{ MW} \cdot \text{S} / \text{MVA}.$$

The study investigates the effect of damping coefficient (K_D) on damping of local oscillation after the fault occurred on the CCT₂ line using the classical model.

Procedure:

Based on the equations derived earlier, the A matrix

$$\begin{aligned} A &= \begin{bmatrix} -k_p/2H & -k_s/2H \\ \omega_0 & 0 \end{bmatrix} \\ &= \begin{bmatrix} -k_p/7 & -0.757/7 \\ 314.2 & 0 \end{bmatrix} \\ &= \begin{bmatrix} -0.143k_p & -0.108 \\ 314.2 & 0 \end{bmatrix} \end{aligned}$$

So we have

$$\begin{bmatrix} \Delta \dot{\omega}_t \\ \Delta \dot{\delta} \end{bmatrix} = \begin{bmatrix} -0.143k_p & -0.108 \\ 314.2 & 0 \end{bmatrix} \begin{bmatrix} \Delta \omega_t \\ \Delta \delta \end{bmatrix} + \begin{bmatrix} 0.143 \\ 0 \end{bmatrix} \Delta T_m$$

The Eigenvalue λ , damped frequency ω_d , Damping Ratio ξ and undamped natural

frequency ω_n for $k_D = 0, 10$ and -10 are tabulated below.

Table 1: The Eigenvalue λ , damped frequency ω_d , Damping Ratio ξ and undamped natural frequency ω_n for $k_D = 0, 10$ and -10

k_D	0	+10	-10
Eigenvalue λ	$\pm j5.83e \times 000$	$-7.02/10 \pm 5.78i$	$7.15 \times 10^{-1} \pm 5.78i$
Damping ratio ξ	0	1.2×10^{-1}	-1.23×10^{-1}
Damped freq. ω_d	0.98Hz	0.92Hz	-0.92Hz
Underdamped natural freq. ω_n	5.83rad/s	5.83 r/s	-5.83 rad/s

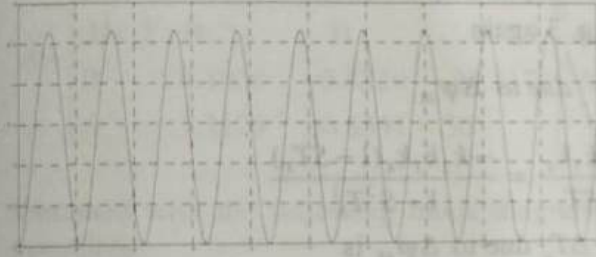


Fig. 6a: Plot of ω_r for step change of T_m and damping torque constant $K_D = 0$.

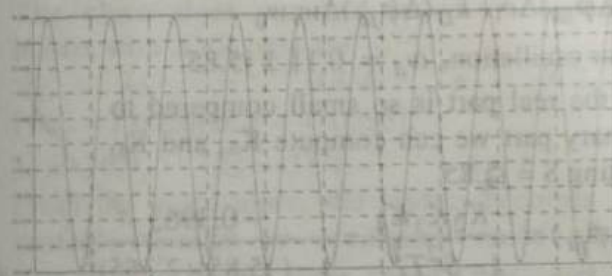


Fig. 6b: Plot of δ for step change of T_m and damping torque constant $K_D = 0$.

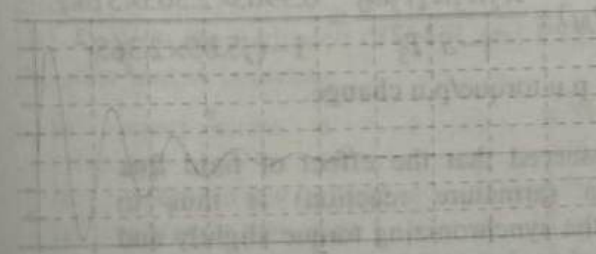


Fig. 7a: Plot of ω_r (rotor speed) for step change of T_m and $K_D = +10$.

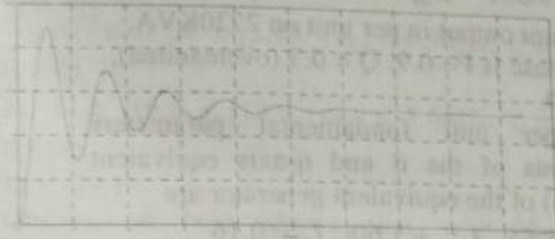


Fig. 7b: Plot of δ_r (rotor angle) for step change of T_m and $K_D = +10$.

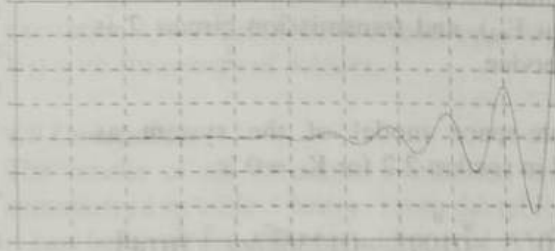


Fig. 8a: Plot of ω_r for step change T_m and $K_D = -10$.



Fig. 8b: Plot of δ for step change of T_m and $K_D = -10$.

Observation: For case of $K_D = 0$, the damping ratio $\xi = 0$ and both the change in rotor frequency $\Delta\omega_r$ and rotor angle $\Delta\delta$ oscillates to infinity. For both $K_D = +10$ and -10 , the damped frequency is 5.83rad/s (0.98Hz) and the oscillation delays with time constant of $1/0.715S$ corresponding to damping ratio of 0.12.

3.2 Case 2:

In this study case, the effect of field flux variation in the dynamic performance of the system is considered. The plant is as in case 1 with the following parameters or ratings

$$X_d = 1.81, X_q = 1.76, X'_d = 0.3, X_L = 0.16$$

$$R_a = 0.003, T'_{d0} = 8.0S, H = 3.5, K_D = 0$$

The saturation parameters are

$$A_{sat} = 0.031 \quad B_{sat} = 6.93 \quad \phi_{T1} = 0.8$$

The plant output in per unit on 2220KVA, 24kV base is $P = 0.9$, $Q = 0.3$ (overexcited), $E_t = 1.0$.

The per unit fundamental parameters (elements of the d and q-axis equivalent circuits) of the equivalent generator are

$$L_{adu} = 1.65, L_{aqu} = 1.60, L_1 = 0.16$$

$$R_a = 0.003, R_{fd} = 0.0006, L_{fd} = 0.153$$

The excitation system is on manual control (constant E_{fd}), and transmission circuit 2 is out of service.

The state-space model of the system as outlined in section 2.2 for $K_D = 0$ is

$$\begin{bmatrix} \Delta \dot{\omega}_r \\ \Delta \dot{\delta} \\ \Delta \dot{\psi}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & -0.1092 & -0.1236 \\ 3142 & 0 & 0 \\ 0 & -0.1938 & -0.4229 \end{bmatrix} \begin{bmatrix} \Delta \omega_r \\ \Delta \delta \\ \Delta \psi_{fd} \end{bmatrix} + \begin{bmatrix} 0.143 \\ 0 \\ 0 \end{bmatrix} \Delta T_m, \quad \Delta E_{fd} = 0$$

Table 2: Table of eigenvalue, damping ratio and frequency with zero K_D

Eigenvalue λ	Damping factor ξ	Damped frequency ω_r
$-1.10 \times 10^{-001} \pm 5.85$	1.87×10^{-2}	5.85 rad/s (0.93Hz)
-2.04×10^{-1}	1.000	(0.32Hz) 2.04 $\times 10^{-1}$ rad/sec.

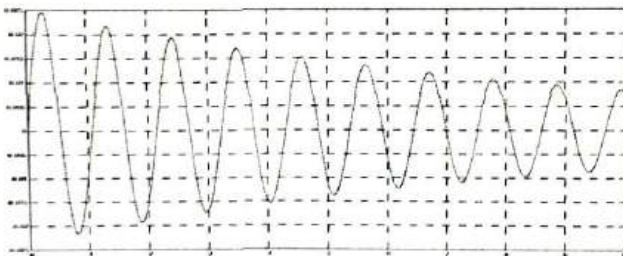


Fig. 9(a): Response of rotor frequency ω_r for field flux variation

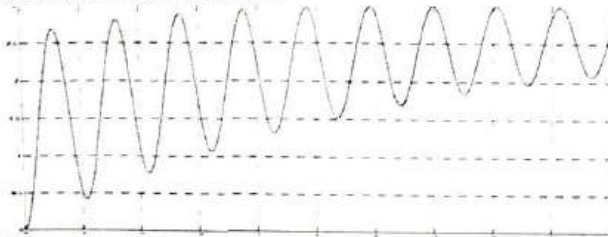


Fig. 9b: Response of rotor angle for field flux variation

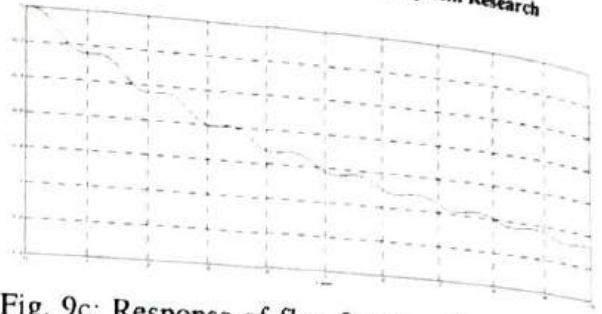


Fig. 9c: Response of flux for step change of torque.

Observation: From earlier analysis, the steady-state synchronizing torque coefficient due to $\Delta \phi_{fd}$ (see fig. 3) is

$$-k_1 k_2 k_3 = -0.8649 \times 0.323 \times 1.4187 = -0.3963$$

Then total steady-state synchronizing torque coefficient is

$$k_s \approx k_1 - k_2 k_3 k_4 = 0.7643 - 0.3963 = 0.3679 \text{ p.u torque/rad.}$$

From fig. 3 again

$$\frac{\Delta T_e(s)}{\Delta \delta(s)} \bigg/ \text{due to } \Delta \psi_{fd} = \frac{-k_2 k_3 k_4}{1 + ST_3} = \frac{-k_2 k_3 k_4 (1 - ST_3)}{1 - S^2 T_3^2}$$

So that ΔT_e due to $\Delta \phi_{fd}$ is

$$\frac{\Delta T_e}{\Delta \phi_{fd}} = \frac{-k_2 k_3 k_4}{1 - S^2 T_3^2} \Delta \delta + \frac{k_2 k_3 k_4 T_3 s \Delta \delta}{1 - S^2 T_3^2} = k_S (\Delta \phi_{fd}) \Delta \delta + k_D (\Delta \phi_{fd}) \Delta \omega_r / \omega_0$$

At rotor oscillation, $\omega_d = 0.11 \pm j5.85$

Since the real part is so small compared to imaginary part we can compute K_S and K_D by setting $S = j5.85$

$$K_S (\Delta \phi_{fd}) = \frac{-K_2 K_3 K_4}{1 - S^2 T_3^2} = \frac{-0.3963}{1 - (j5.85 \times 2.365)^2}$$

$$= 0.002 \text{ p.u torque/rad.}$$

$$K_D (\Delta \phi_{fd}) = \frac{K_2 K_3 K_4 T_3 \omega_0}{1 - S^2 T_3^2} = \frac{0.3963 \times 2.365 \times 3142}{1 - (j5.85 \times 2.365)^2} = 1.53 \text{ p.u torque/p.u change.}$$

It is observed that the effect of field flux variation (armature reaction) is thus to reduce the synchronizing torque slightly and to add a damping torque component.

3.3 Case 3: Effect of AVR and PSS on the system stability

This is the extension of the problem of the other case studies. In this study, the effect of two alternative types of excitation control is considered.

[A] A thyristor exciter with AVR with $K_A = 200$ and $T_R = 0.02s$.

[B] The above excitation system with PSS included as shown in fig. 3.

The parameters and saturation data are as given in case 2. The transmission circuit 2 is out of service and the plant output in per unit on 2220 MVA and 24kV base is given below.

$$P = 0.9, \quad Q = 0.3, \quad E_f = 1.0 \angle 36^\circ,$$

$$E_B = V_S = 0.995 \angle 0^\circ$$

[A] The state matrix with only AVR is

$$A = \begin{bmatrix} 0 & -0.1092 & -0.1236 & 0 \\ 314.2 & 0 & 0 & 0 \\ 0 & -0.1938 & -0.4229 & -27.3172 \\ 0 & -7.3125 & 20.8391 & -50 \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\phi_{fd} \\ \Delta V_1 \end{bmatrix}$$

Obtained with the following block diagram constants.

$$K_1 = 0.7643, \quad K_2 = 0.8649, \quad K_3 = 0.3230, \quad K_4 = 1.4187, \quad K_5 = -0.1463, \quad K_6 = 0.4168, \quad T_3 = 2.365, \quad T_R = 0.02, \quad G_{ex}(s) = 200.0.$$

The eigenvalues obtained based on state matrix with AVR only are

$$\lambda_1, \lambda_2 = 0.436 \pm j6.3, \quad (\omega_d = 1.0026\text{Hz}, \zeta = -0.0656),$$

$$\lambda_3 = -19.9, \quad \lambda_4 = -31.4, \quad \varepsilon = 1$$

From the eigenvalues, the system becomes unstable through an oscillatory mode of 1.06Hz due to the rotor speed, $\Delta\omega_r$ and angle $\Delta\delta$. The none oscillatory mode which delay specially are due to AVR and the field circuit.

[B] With the inclusion of AVR and PSS, the state matrix becomes

$$A = \begin{bmatrix} 0 & -0.1092 & -0.1236 & 0 & 0 & 0 \\ 314.2 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.1938 & -0.4229 & -27.3172 & 0 & 27.3172 \\ 0 & -7.3125 & 20.8391 & -50.0 & 0 & 0 \\ 0 & -1.0372 & -1.1738 & 0 & -0.7143 & 0 \\ 0 & -4.8404 & -5.4777 & 0 & 26.9697 & -30.380 \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\phi_{fd} \\ \Delta V_1 \\ \Delta V_2 \\ \Delta V_S \end{bmatrix}$$

The eigenvalues are

$$\lambda_1 = -0.744,$$

$$\lambda_2, \lambda_3 = -1.01 \pm j5.99, \quad (\omega_d = 0.95\text{Hz}, \zeta = 0.166),$$

$$\lambda_4, \lambda_5 = -19.8 \pm j12.9 \quad (\omega_d = 3.66\text{Hz}, \zeta = 0.838),$$

$$\lambda_6 = -39.1$$

Observation here shows that with the inclusion of PSS, that the system has become very stable. The oscillatory modes are due to rotor angle with frequency of 1.095Hz and excitation system and field circuit (ϕ_{fd} , V_1 , V_2) with frequency of 3.66Hz.

4.0 Conclusion

The results of all the cases considered are summarized in table 3 below. From the table, it can be observed that the addition of AVR and PSS increases the damping constant K_D and reduces the synchronizing torque constant K_S . Also, the frequency of oscillation reduces with the inclusion of AVR and PSS. So it can now be properly understood that when the parameters of the AVR and PSS are properly tuned using numerous auto tuning methods (example fuzzy control, neural network, adaptive control etc) that oscillation of the power system can be totally and completely eliminated.

Table 3: Summary of Results

Model	Classical mode $K_D = 0$	Constant E_{fd}	AVR only	AVR + PSS
ω_d	0.92Hz	0.97Hz	1.00Hz	0.95Hz
ζ	0	0.00187	-0.065	0.166
K_S	-0.757	0.763	0.976	0.829
K_D	0	1.53	-7.06	14.08

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