# Manual For A Multi-machine Transient Stability Programme

(Version 1.0)

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# Chapter 1

# Generator Modelling

## 1.1 Introduction

A 3 phase synchronous machine is modelled in the rotor frame of reference as shown in Figure 1.1. The figure shows 2 fictitious $d$ and $q$ stator windings representing three phase armature windings on the stator. The figure also depicts 2 rotor windings, including the field winding 'f' along d-axis and 2 rotor coils along q-axis. The short circuited coils, one along d-axis ('h') and two along q-axis ('g' and 'k') represent the effect of damper windings and eddy currents induced in the rotor mass. This representation of the rotor circuits is normally referred to as 2.2 model [1].

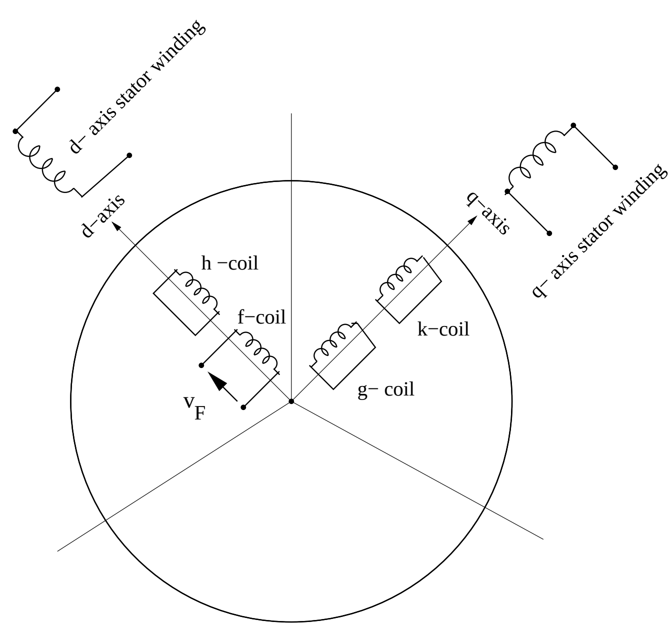


Figure 1.1: 2.2 model of a Synchronous Machine.

## 1.2 Generator Parameters

The generator parameters that are usually specified are tabulated in Table 1.1.

| **Parameters** | **Notation** |
|---|---|
| d-axis synchronous reactance | $x_d$ |
| q-axis synchronous reactance | $x_q$ |
| d-axis transient reactance | $x_d^{'}$ |
| q-axis transient reactance | $x_q^{'}$ |
| d-axis subtransient reactance | $x_d^{''}$ |
| q-axis subtransient reactance | $x_q^{''}$ |
| d-axis transient open circuit time constant | $T_{do}^{'}$ |
| q-axis transient open circuit time constant | $T_{qo}^{'}$ |
| d-axis transient short circuit time constant | $T_d^{'}$ |
| q-axis transient short circuit time constant | $T_q^{'}$ |
| d-axis subtransient open circuit time constant | $T_{do}^{''}$ |
| q-axis subtransient open circuit time constant | $T_{qo}^{''}$ |
| d-axis subtransient short circuit time constant | $T_d^{''}$ |
| q-axis subtransient short circuit time constant | $T_q^{''}$ |
| Stator resistance per phase | $R_a$ |
| Stator leakage reactance per phase | $x_l$ |

Table 1.1: Generator parameters.

NOTE:

1. The reactance values are in per unit on the stator base values equal to the machine ratings. In per unit representation, p.u. reactance is equal to p.u. inductance.

2. The leakage reactance of the stator is not treated separately as saturation is not considered.

3. The time constants are in seconds.

4. The following relationship holds with respect to parameters:

$$x_d \geq x_q > x_q^{'} \geq x_d^{'} > x_q^{''} \geq x_d^{''} \tag{1.1}$$

$$T_{do}^{'} > T_d^{'} > T_{do}^{''} > T_d^{''} \tag{1.2}$$

$$T_{qo}^{'} > T_q^{'} > T_{qo}^{''} > T_q^{''} \tag{1.3}$$

## 1.3 Rotor Equations:

### 1.3.1 d-axis Equations:

In terms of operational impedance, the Laplace transform of the d-axis stator flux linkages is given by [2]

$$\psi_d(s) = X_d(s)i_d(s) + G(s)E_{fd}(s) \tag{1.4}$$

where

$$X_d(s) = x_d \frac{(1+sT_d^{'})(1+sT_d^{''})}{(1+sT_{do}^{'})(1+sT_{do}^{''})} \tag{1.5}$$

$G(s)$ is approximated as

$$G(s) = \frac{(1+sT_d^{''})}{(1+sT_{do}^{'})(1+sT_{do}^{''})}$$

$i_d(s)$ represents d-axis stator current.
$E_{fd}$ represents the exciter output voltage. It is proportional to the generator field voltage, $v_f$. Note that though exciter output voltage and generator field voltage are physically the same, the notation $E_{fd}$ is preferred since in steady state the open circuit per unit line-to-line terminal voltage of a synchronous machine is equal to $E_{fd}$ in per unit.

The operational impedance $X_d(s)$ can also be written in a classical form as

$$\frac{1}{X_d(s)} = \frac{1}{x_d} + \left(\frac{1}{x_d^{'}} - \frac{1}{x_d}\right)\frac{sT_d^{'}}{1+sT_d^{'}} + \left(\frac{1}{x_d^{''}} - \frac{1}{x_d^{'}}\right)\frac{sT_d^{''}}{1+sT_d^{''}} \tag{1.6}$$

Note that the inverse of (1.5) is equal to (1.6) satisfying the following relationship between the open and short circuit time constants of d-axis:

$$T_{do}^{'} + T_{do}^{''} = \left(\frac{x_d}{x_d^{'}}\right)T_d^{'} + \left(1 - \frac{x_d}{x_d^{'}} + \frac{x_d}{x_d^{''}}\right)T_d^{''} \tag{1.7}$$

$$T_{do}^{'}T_{do}^{''} = T_d^{'}T_d^{''}\left(\frac{x_d}{x_d^{''}}\right) \tag{1.8}$$

### 1.3.2 d-axis Equivalent Circuit

To develop an equivalent circuit for d-axis the following procedure is employed [2]:

From (1.4), an expression for $i_d(s)$ can be written as

$$i_d(s) = \frac{\psi_d(s)}{X_d(s)} - \frac{G(s)}{X_d(s)} E_{fd}(s)$$

Simplifying the above expression using either (1.5) or (1.6), the following equivalent circuit can be developed (see Figure 1.2).

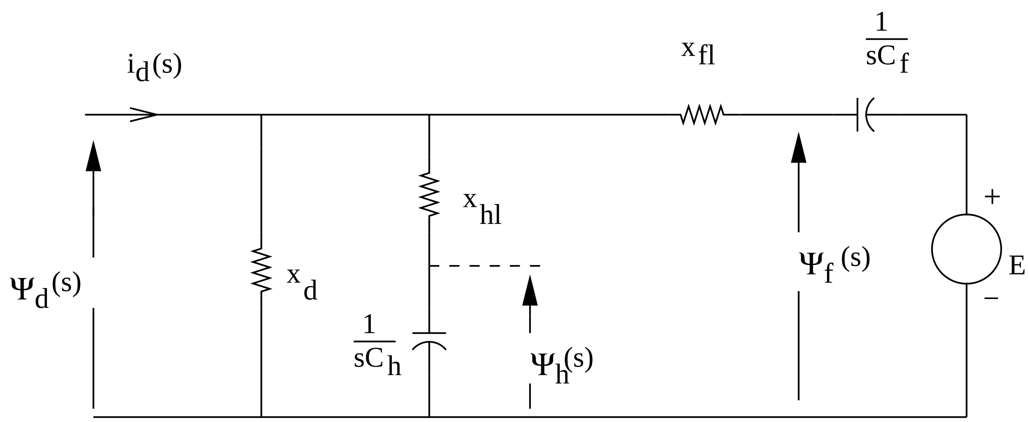


Figure 1.2: d-axis equivalent circuit

The parameters in the figure are defined as follows:

$$x_{fl} = \frac{x_d x_d^{'}}{x_d - x_d^{'}} \tag{1.9}$$

$$x_{hl} = \frac{x_d^{'} x_d^{''}}{x_d^{'} - x_d^{''}} \tag{1.10}$$

$$E = \frac{x_{fl} E_{fd}(s)}{x_d \; sT_d^{'}} \tag{1.11}$$

$$C_f = \frac{T_d^{'}}{x_{fl}} \tag{1.12}$$

$$C_h = \frac{T_d^{''}}{x_{hl}} \tag{1.13}$$

From the equivalent, choosing appropriate state variables, the differential equations are written in the state-space form as follows:

$$\frac{d\psi_h}{dt} = \frac{1}{T_d^{''}} \left[ -\psi_h + \psi_d \right] \tag{1.14}$$

$$\frac{d\psi_f}{dt} = \frac{1}{T_d^{'}} \left[ -\psi_f + \psi_d + \frac{x_d^{'} E_{fd}}{(x_d - x_d^{'})} \right] \tag{1.15}$$

where

$\psi_h$ represents flux linkages of 'h'- damper coil.

$\psi_f$ represents flux linkage of field coil.

Note that the short circuit time constants, $T_d^{'}$ and $T_d^{''}$ are solved by using (1.7) and (1.8), and satisfying the relationship (1.2).

Solving for $\psi_h$ and $\psi_f$ from (1.14) and (1.15), we can calculate d-axis flux linkages as:

$$\psi_d = x_d^{''} i_d + E_q^{''} \tag{1.16}$$

where $E_q^{''}$ represents q-axis subtransient voltage and are related to $\psi_h$ and $\psi_f$ as:

$$E_q^{''} = \left[ \frac{\left(x_d^{'} - x_d^{''}\right) \psi_h}{x_d^{'}} + \frac{\left(x_d - x_d^{'}\right)}{x_d x_d^{'}} x_d^{''} \psi_f \right] \tag{1.17}$$

### 1.3.3 q-axis Equations:

In terms of operational impedance, the Laplace transform of the q-axis stator flux linkages is given by

$$\psi_q(s) = X_q(s) i_q(s) \tag{1.18}$$

where

$$X_q(s) = x_q \frac{(1 + sT_q^{'})(1 + sT_q^{''})}{(1 + sT_{qo}^{'})(1 + sT_{qo}^{''})} \tag{1.19}$$

$i_q(s)$ represents q-axis stator current.

The operational impedance $X_q(s)$ can also be written in a classical form as

$$\frac{1}{X_q(s)} = \frac{1}{x_q} + \left(\frac{1}{x_q^{'}} - \frac{1}{x_q}\right) \frac{sT_q^{'}}{1 + sT_q^{'}} + \left(\frac{1}{x_q^{''}} - \frac{1}{x_q^{'}}\right) \frac{sT_q^{''}}{1 + sT_q^{''}} \tag{1.20}$$

Note that the inverse of (1.19) is equal to (1.20) satisfying the following relationship between the open and short circuit time constants of q-axis:

$$T_{qo}^{'} + T_{qo}^{''} = \left(\frac{x_q}{x_q^{'}}\right) T_q^{'} + \left(1 - \frac{x_q}{x_q^{'}} + \frac{x_q}{x_q^{''}}\right) T_q^{''} \tag{1.21}$$

$$T_{qo}^{'} T_{qo}^{''} = T_q^{'} T_q^{''} \left(\frac{x_q}{x_q^{''}}\right) \tag{1.22}$$

### 1.3.4 q-axis Equivalent Circuit

To develop an equivalent circuit for q-axis the following procedure is employed [2]:

From (1.18), an expression for $i_q(s)$ can be written as

$$i_q(s) = \frac{\psi_q(s)}{X_q(s)}$$

Using the above expression in addition to (1.20), the following equivalent circuit can be developed (see Figure 1.3).

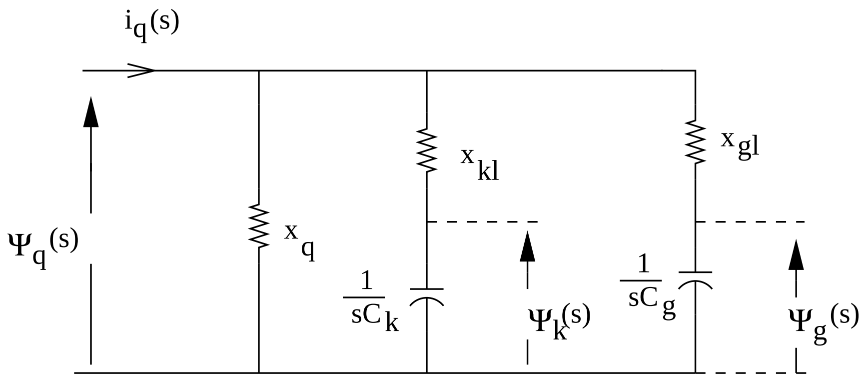


Figure 1.3: q-axis equivalent circuit

The parameters in the figure are defined as follows:

$$x_{gl} = \frac{x_q x_q^{'}}{x_q - x_q^{'}} \tag{1.23}$$

$$x_{kl} = \frac{x_q^{'} x_q^{''}}{x_q^{'} - x_q^{''}} \tag{1.24}$$

$$C_g = \frac{T_q^{'}}{x_{gl}} \tag{1.25}$$

$$C_k = \frac{T_q^{''}}{x_{kl}} \tag{1.26}$$

From the equivalent, choosing appropriate state variables, the differential equations are written in the state-space form as follows:

$$\frac{d\psi_g}{dt} = \frac{1}{T_q^{'}}\left[-\psi_g + \psi_q\right] \tag{1.27}$$

$$\frac{d\psi_k}{dt} = \frac{1}{T_q^{''}}\left[-\psi_k + \psi_q\right] \tag{1.28}$$

where

$\psi_g$ represents flux linkages of 'g'- damper coil.

$\psi_k$ represents flux linkage of 'k'- damper coil.

Note that the short circuit time constants, $T_q^{'}$ and $T_q^{''}$ are solved by using (1.21) and (1.22), and satisfying the relationship (1.3).

Solving for $\psi_g$ and $\psi_k$ from (1.27) and (1.28), we can calculate q-axis flux linkages as:

$$\psi_q = x_q^{''} i_q - E_d^{''} \tag{1.29}$$

where $E_d^{''}$ represents d-axis subtransient voltage and are related to $\psi_g$ and $\psi_k$ as:

$$E_d^{''} = -\left[ \frac{\left(x_q^{'} - x_q^{''}\right)\psi_k}{x_q^{'}} + \frac{\left(x_q - x_q^{'}\right)}{x_q x_q^{'}} x_q^{''} \psi_g \right] \tag{1.30}$$

## 1.4 Stator Equations

Neglecting stator transients and ignoring speed variations, the stator d- and q-axes voltage equations are given by

$$\begin{aligned} v_d &= -i_d R_a - \psi_q && (1.31) \\ v_q &= -i_q R_a + \psi_d && (1.32) \end{aligned}$$

where $v_d$ and $v_q$ represent d- and q- axis generator terminal voltages respectively. Using (1.16) and (1.29) in (1.31) and (1.32), we have

$$\begin{aligned} v_d &= -i_d R_a - x_q^{''} i_q + E_d^{''} && (1.33) \\ v_q &= -i_q R_a + x_d^{''} i_d + E_q^{''} && (1.34) \end{aligned}$$

## 1.5 Interfacing Generator to Network

Note that the generator is modelled in the 'rotor or machine-frame' of reference and all the variables and parameters indicated above are with respect to the 'machine-frame' of reference. For interfacing the generator to the network for performing system studies, one has to transform these variables to the 'synchronous-frame' of reference. The relationship between the 'machine-frame' and the 'synchronous-frame' of references is shown in Figure 1.4.

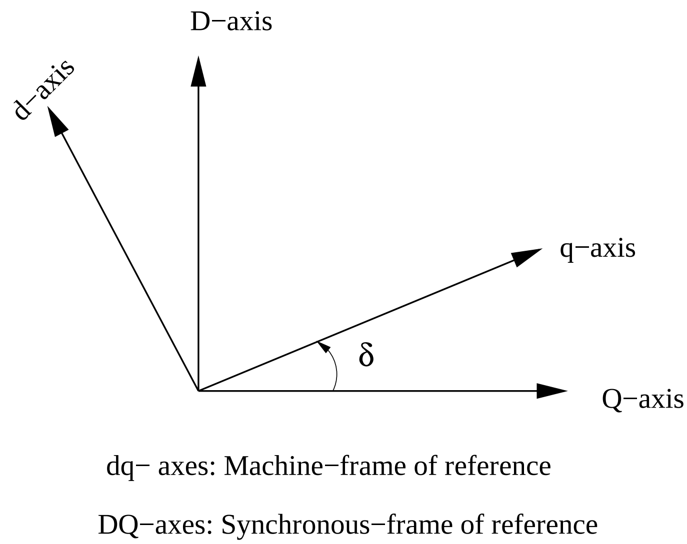


Figure 1.4: Relationship between reference frames.

The relationship depicted in the above figure can be mathematically expressed as [1]:

$$(F_q + jF_d) = (F_Q + jF_D)e^{-j\delta}$$

where $\delta$ represents machine rotor angle.
The above equation can be written in matrix notation as:

$$\begin{bmatrix} F_q \\ F_d \end{bmatrix} = \begin{bmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} F_Q \\ F_D \end{bmatrix} \tag{1.35}$$

Note that in (1.35), $F$ -represents voltages/currents.

From (1.33) and (1.34), it is clear that the generator winding currents are a function of generator terminal voltage and in turn depend on the network conditions. Writing the stator voltage equations in matrix form we get,

$$\begin{bmatrix} R_a & -x''_d \\ x''_q & R_a \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} E''_q - v_q \\ E''_d - v_d \end{bmatrix} \tag{1.36}$$

The currents $i_q$ and $i_d$ can be obtained as

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \frac{1}{R_a^2 + x''_d x''_q} \begin{bmatrix} R_a & x''_d \\ -x''_q & R_a \end{bmatrix} \begin{bmatrix} E''_q - v_q \\ E''_d - v_d \end{bmatrix} \tag{1.37}$$

Now writing the above equation in 'synchronous-frame' of reference, we get $i_Q$ and $i_D$ as

$$\begin{aligned}\begin{bmatrix} i_Q \\ i_D \end{bmatrix} &= y_{gDQ}(t)\begin{bmatrix} E_Q^{''} - v_Q \\ E_D^{''} - v_D \end{bmatrix} \\ &= y_{gDQ}(t)\begin{bmatrix} E_Q^{''} \\ E_D^{''} \end{bmatrix} - y_{gDQ}(t)\begin{bmatrix} v_Q \\ v_D \end{bmatrix} \\ &= I_{DQS}(t) - y_{gDQ}(t)\begin{bmatrix} v_Q \\ v_D \end{bmatrix} \end{aligned} \tag{1.38}$$

where

$$y_{gDQ}(t) = \frac{1}{R_a^2 + x_d^{''}x_q^{''}}\begin{bmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{bmatrix}\begin{bmatrix} R_a & x_d^{''} \\ -x_q^{''} & R_a \end{bmatrix}\begin{bmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix}$$

and $I_{DQS}(t)$ represents $Q$ and $D$ components of generator source current.
When we solve for $i_Q$ and $i_D$, the following difficulties are encountered if $x_d^{''} \neq x_q^{''}$:

1. The stator cannot be represented by an equivalent circuit on single phase basis.
2. The evaluation of $i_Q$ and $i_D$ requires the solution of a *time varying* algebraic equation.

In (1.38), $y_{gDQ}(t)$ is a function of $\delta$, and as $\delta$ varies with time, is a time varying matrix. While solving for $i_Q$ and $i_D$, one has to deal with the overall network matrix including $y_{gDQ}(t)$, which is not a constant matrix. This implies that the network matrix has to be factored at every time step, which increases the computational complexity.

In order to eliminate the solution of time varying algebraic equations and to develop an approximate equivalent circuit, the following approach is employed [1]:

### 1.5.1 Dummy Coil Approach

From (1.33), we have

$$E_d^{''} - x_q^{''}i_q - i_dR_a = v_d$$

Add and subtract $x_d^{''}i_q$ from the LHS of the above equation, we get

$$\begin{aligned} E_d^{''} - x_q^{''}i_q + x_d^{''}i_q - x_d^{''}i_q - i_dR_a &= v_d \\ E_d^{''} - (x_q^{''} - x_d^{''})i_q - x_d^{''}i_q - i_dR_a &= v_d \end{aligned}$$

Now, using (1.34) and the above equation, we can write the stator voltage equations in a compact form as,

$$(E_q^{''} + jE_d^{''}) - j(x_q^{''} - x_d^{''})i_q - jx_d^{''}(i_q + ji_d) - R_a(i_q + ji_d) = (v_q + jv_d) \tag{1.39}$$

Let $E_{dummy}^{''} = -(x_q^{''} - x_d^{''})i_q$
The stator voltage equations now appear as

$$E_q^{''} + j(E_d^{''} + E_{dummy}^{''}) - (R_a + jx_d^{''})(i_q + ji_d) = (v_q + jv_d) \tag{1.40}$$

Note that $E_{dummy}^{''}$ is a function of $i_q$ and it requires the solution of network equations. This difficulty of calculating $E_{dummy}^{''}$ is handled in the following approximate way:

$E_{dummy}^{''}$ is considered as a fictitious voltage source proportional to a flux linkage of a dummy coil in the q-axis of the armature, which has no coupling with other coils. The differential equation, considering $E_{dummy}^{''}$ as a state variable, is given by

$$\frac{dE_{dummy}^{''}}{dt} = \frac{1}{T_{dummy}}\left[-E_{dummy}^{''} - \left(x_q^{''} - x_d^{''}\right) i_q\right] \tag{1.41}$$

where $T_{dummy}$ is the open circuit time constant of the dummy coil, usually set to 0.01 s.

### 1.5.2 Generator Source Current Calculations:

Treating the generator as a current source, we have in the 'machine-frame' of reference,

$$\bar{I}_{dqS} = (i_{qS} + ji_{dS}) = \frac{E_q^{''} + j(E_d^{''} + E_{dummy}^{''})}{(R_a + jx_d^{''})} \tag{1.42}$$

where $E_{dummy}^{''}$ is obtained as a solution of (1.41).
Using (1.42) in (1.40), we have

$$(i_{qS} + ji_{dS}) - (i_q + ji_d) = \frac{(v_q + jv_d)}{(R_a + jx_d^{''})}$$

In the 'synchronous-frame' of reference, we have,

$$(i_{qS} + ji_{dS})e^{j\delta} - (i_q + ji_d)e^{j\delta} = \frac{(v_q + jv_d)}{(R_a + jx_d^{''})}e^{j\delta}$$

$$(i_{QS} + ji_{DS}) - (i_Q + ji_D) = \frac{(v_Q + jv_D)}{(R_a + jx_d^{''})} \tag{1.43}$$

The circuit representation of (1.43) is shown in Figure 1.5. In the figure, $(R_a + jx''_d)$ has been absorbed into bus admittance matrix.

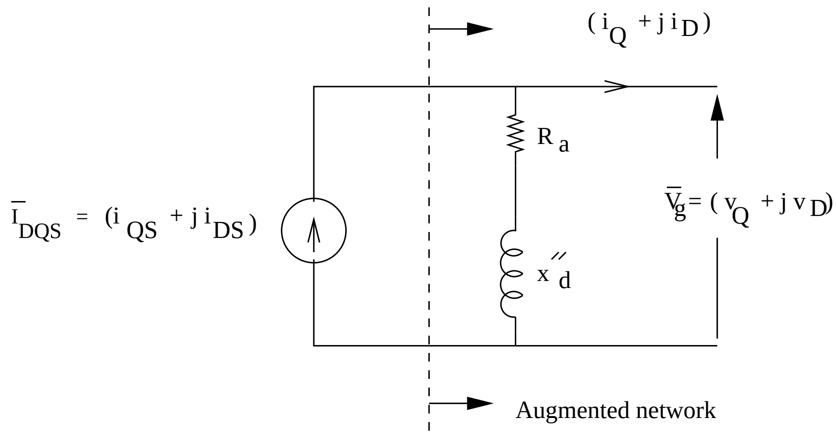


Figure 1.5: Current source representation of generator.

Note that $\bar{I}_g = (i_Q + ji_D)$ is the generator winding current in the 'synchronous-frame' of reference.

If armature resistance, $R_a$ is neglected one may calculate $i_q$ and $i_d$ in the following manner:
From (1.42), comparing real and imaginary parts, we have

$$\begin{aligned} i_{qS} &= \frac{(E''_d + E''_{dummy})}{x''_d} \\ i_{dS} &= -\frac{E''_q}{x''_d} \end{aligned}$$

The above components are transformed into the 'synchronous-frame' of reference as shown in Figure 1.6.

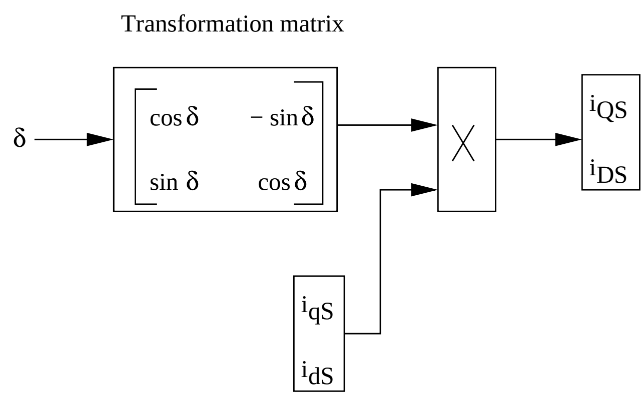


Figure 1.6: Calculation of $i_{QS}$ and $i_{DS}$ from $i_{qS}$ and $i_{dS}$.

Now, from (1.43), $i_Q$ and $i_D$ can be evaluated as

$$
\begin{aligned}
i_Q &= i_{QS} - \frac{v_D}{x_d''} \\
i_D &= i_{DS} + \frac{v_Q}{x_d''}
\end{aligned}
$$

Since machine parameters are defined in the 'rotor-frame' of reference, the above components of generator winding currents are transformed into the 'rotor-frame' of reference as shown in Figure 1.7.

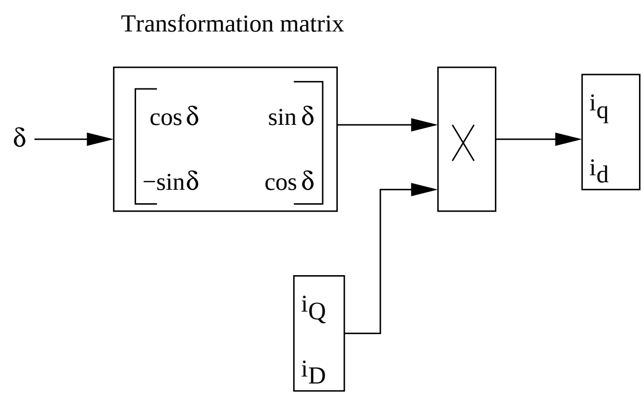


Figure 1.7: Calculation of $i_q$ and $i_d$ from $i_Q$ and $i_D$

## 1.6 Expression for Electromagnetic Torque:

In terms of flux linkages and generator winding currents, the electromagnetic torque is given by

$$T_e = (\psi_d i_q - \psi_q i_d) \tag{1.44}$$

Using (1.16) and (1.29), the expression for torque can be rewritten as

$$T_e = E_q'' i_q + E_d'' i_d + \left(x_d'' - x_q''\right) i_d \; i_q \tag{1.45}$$

## 1.7 Swing Equations

Rotor mechanical equations are given by

$$\frac{d\delta}{dt} = \omega_B \; S_m \tag{1.46}$$

$$2H \frac{dS_m}{dt} = T_m - T_e - DS_m \tag{1.47}$$

where

$T_m$ = mechanical input torque in per unit
$H$ = inertia constant of a generator (MJ/MVA)
$S_m$ = per unit slip, $D$ = per unit mechanical damping
$\omega_B$ = base speed in rad/s ($= 2\pi f_o$), $f_o$= nominal frequency in Hz.

## 1.8 Initial Condition Calculations

From the load-flow analysis, the following end results are noted:

1. Real power output of generator, $P_{g0}$
2. Reactive power output of generator, $Q_{g0}$
3. Terminal bus voltage, $V_{g0}\angle\theta_0$

Using these values, the initial conditions of states variables are calculated as follows [2]:

1. Compute

$$\bar{V}_{g0} = V_{g0}(\cos\theta_0 + j\sin\theta_0) \tag{1.48}$$
$$\bar{I}_{g0} = \left(\frac{P_{g0} + jQ_{g0}}{\bar{V}_{g0}}\right)^* = I_{g0}\angle\phi_0 \tag{1.49}$$

$$\bar{E}_{q0} = \bar{V}_{g0} + jx_q\bar{I}_{g0} \tag{1.50}$$
$$\delta_0 = \angle\bar{E}_{q0} \tag{1.51}$$

2. Compute

$$\begin{aligned} i_{q0} + ji_{d0} &= \bar{I}_{g0}\ e^{-j\delta_0} \\ &= I_{g0}\angle(\phi_0 - \delta_0) \end{aligned}$$

$$i_{q0} = I_{g0}\cos(\phi_0 - \delta_0) \tag{1.52}$$
$$i_{d0} = I_{g0}\sin(\phi_0 - \delta_0) \tag{1.53}$$

3. Compute

$$\begin{aligned} v_{q0} + jv_{d0} &= \bar{V}_{g0}e^{-j\delta_0} \\ &= V_{g0}\angle(\theta_0 - \delta_0) \end{aligned}$$

$$v_{q0} = V_{g0} \cos(\theta_0 - \delta_0) \quad (1.54)$$
$$v_{d0} = V_{g0} \sin(\theta_0 - \delta_0) \quad (1.55)$$

4. Compute

$$E_{fd0} = E_{q0} - (x_d - x_q) i_{d0} \quad (1.56)$$

5. Compute

$$\psi_{d0} = v_{q0} \quad (1.57)$$
$$\psi_{q0} = -v_{d0} \quad (1.58)$$

6. Compute

$$\psi_{h0} = \psi_{d0} \quad (1.59)$$
$$\psi_{f0} = \psi_{d0} + \frac{x_d^{'}}{x_d - x_d^{'}} E_{fd0} \quad (1.60)$$
$$\psi_{k0} = \psi_{q0} \quad (1.61)$$
$$\psi_{g0} = \psi_{q0} \quad (1.62)$$

7. Compute

$$T_{m0} = P_{g0} \quad (1.63)$$

8. Compute

   The generator field current,

$$i_{f0} = \frac{(\psi_{f0} - \psi_{d0})}{x_{fl}} \quad (1.64)$$

   The exciter current,

$$I_{FD0} = x_d \; i_{f0} \quad (1.65)$$

NOTE: In the above calculations, the armature resistance, $R_a$ has been neglected.

## 1.9 Modification of 2.2 Model

Modifications to be made in 2.2 model to get various other simple models [1] are tabulated in Table 1.2.

| Model | Basic Modifications | Settings for No dynamic Saliency |
|---|---|---|
| 2.2 | - | $x_q^{''} = x_d^{''}$ |
| 2.1 | $x_q^{''} = x_q^{'}$ and $T_{qo}^{''} \neq 0$ | $x_q^{'} = x_d^{''}$ |
| 1.1 | $x_d^{''} = x_d^{'}$ and $T_{do}^{''} \neq 0$<br>$x_q^{''} = x_q^{'}$ and $T_{qo}^{''} \neq 0$ | $x_q^{'} = x_d^{'}$ |
| 1.0 | $x_d^{''} = x_d^{'}$ and $T_{do}^{''} \neq 0$<br>$x_q^{''} = x_q^{'} = x_q$ and $T_{qo}^{''} \neq 0$<br>$T_{qo}^{'} \neq 0$ | $x_q = x_d^{'}$ |
| 0.0 (classical) | $x_d^{''} = x_d^{'}$ and $T_{do}^{''} \neq 0$<br>$T_{do}^{'} = 10000$ (say)<br>$x_q^{''} = x_q^{'} = x_q = x_d^{'}$ and<br>$T_{qo}^{''} \neq 0$, $T_{qo}^{'} \neq 0$ | - |

Table 1.2: Simplifications in 2.2 Model.

NOTE:
For classical model, the q-axis transient voltage, $E_q^{'} = E_q^{''}$ is assumed to be a constant. To achieve this in 2.2 model, one may require to disable exciter in addition to choosing an appropriate value for $x_d$ relative to $x_d^{'}$. For example, one may set $x_d = 6x_d^{'}$.

## 1.10 Center Of Inertia Reference

Like, the distance to 'center of gravity' in mechanics, the distance to center of inertia (COI) is defined in terms of rotor angles as follows [5]:

$$\delta_{COI} = \frac{1}{H_T} \sum_{i=1}^{n_g} H_i \delta_i \tag{1.66}$$

where
$n_g$ = number of generator

$H_T = \sum_{i=1}^{n_g} H_i$
$H_i$ = inertia constant (in MJ/MVA) of $i^{th}$ generator.
$\delta_i$ = rotor angle of $i^{th}$ generator in radians.

Similarly, the distance to center of inertia in terms of rotor speed deviations is defined as follows:

$$\omega_{COI} = \frac{1}{H_T} \sum_{i=1}^{n_g} H_i \omega_i \tag{1.67}$$

where, $\omega_i$ = rotor speed deviation ($S_m \omega_B$) of $i^{th}$ generator in radian per second.

It is usually preferred to refer the rotor angle and rotor speed deviation of a generator with respect to the above said time-varying COI-reference. This is achieved by defining the following variables.

$$\tilde{\delta}_i = \delta_i - \delta_{COI} \tag{1.68}$$

$$\tilde{\omega}_i = \omega_i - \omega_{COI} \tag{1.69}$$

In the time-domain simulation, the stability of a system is inferred by plotting $\tilde{\delta}_i$ against time.

# Chapter 2

# Exciter Modelling

## 2.1 Introduction

The basic function of an excitation system is to provide dc power to the field winding of a synchronous generator. In addition, the excitation system performs control functions such as control of voltage and reactive power shared by the generator, and provides means to improve dynamic and transient stability performance of the power systems by controlling the field voltage and thereby the field current.

### 2.1.1 Elements of Excitation System

The functional block schematic of a typical excitation control system is shown in Figure 2.1.

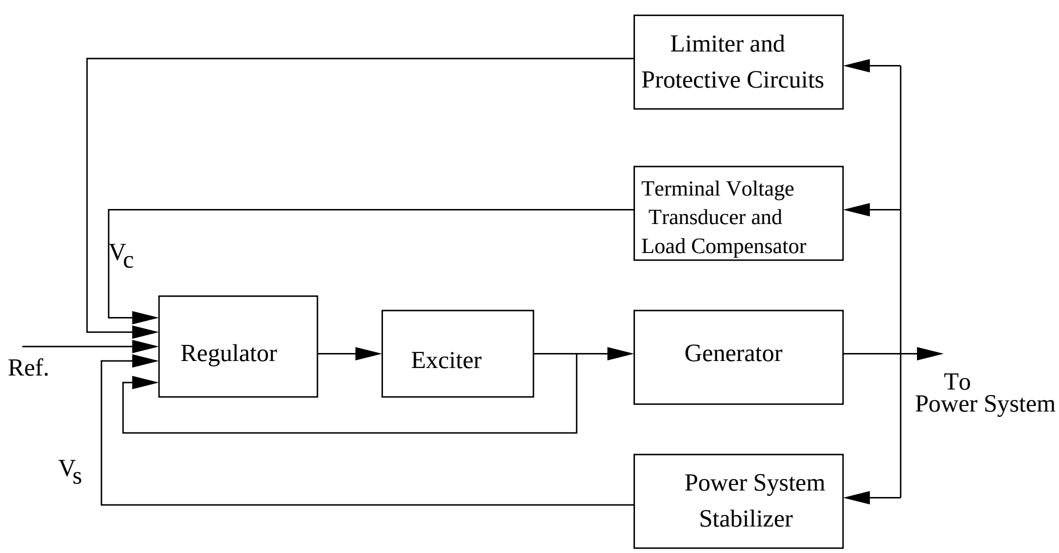


Figure 2.1: Functional Block Diagram of an Excitation System

The functions of each of the block have been highlighted below [4]:

1. *Exciter:* Exciter constitutes the power stage of the excitation system and it provides dc power to the synchronous machine field winding.

2. *Regulator:* Regulator process and amplifies input control signals to a level and form appropriate for control of the exciter. This includes both regulating and excitation system stabilizing functions.

3. *Terminal voltage transducer and load compensator:* Senses generator terminal voltage, rectifies and filters it to dc quantity, and compares it with a reference which represents the desired terminal voltage. In addition, load compensation may be provided.

4. *Power System Stabilizers:* Power System Stabilizers provides an additional input signal to the regulator to damp power system oscillations.

5. *Limiters and Protective Circuits:* These include a wide array of control and protective functions which ensure that the capability limits of the exciter and synchronous generator are not exceeded. Some of the commonly used functions are the field-current limiter, maximum excitation limiter, terminal voltage limiter, volts-per-hertz regulator and protection, and underexcitation limiter. These are normally distinct circuits and their output signals may be applied to the excitation system at various locations as a summing input or a gated input.

## 2.2 Types of Excitation System

The excitation system are classified into the following three broad categories based on the excitation power source [4, 6]:

1. DC Excitation System

2. AC Excitation System

3. Static Excitation System

## 2.3 DC Excitation Systems

The block diagram of a typical DC type excitation system is shown in Figure 2.2.

The excitation systems of this type utilize dc generators as sources of excitation power and provide current to the rotor of the synchronous machine through slip rings. The

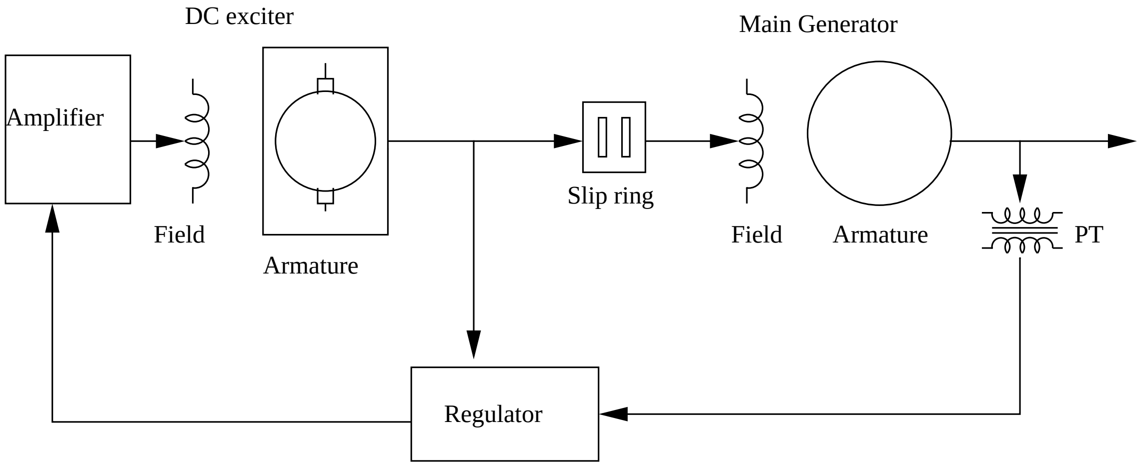


Figure 2.2: Field controlled DC excitation system.

exciter may be driven by a motor or the shaft of the generator. It may be either self-excited or separately excited. When separately excited, the exciter field is supplied by a pilot exciter comprising a permanent magnet generator.

Type DC1A exciter model represents field-controlled DC commutator exciters, with continuously acting voltage regulators. The structure of IEEE-type DC1A excitation model is shown in Figure 2.3.

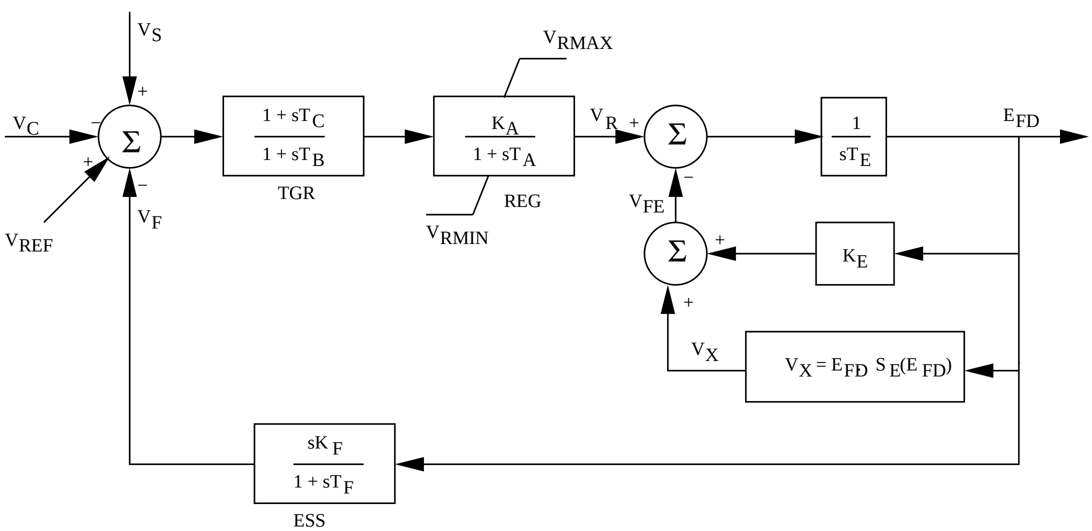


Figure 2.3: IEEE-type DC1A excitation system.

In the above figure,

TGR - represents transient gain reduction block

ESS - represents excitation system stabilizer block

$S_E$ - represents exciter saturation function given by $A\ e^{B\ E_{fd}}$, where $A$ and $B$ are to be determined from two sample points.

Typical values of the parameters of DC1A -excitation system are tabulated in Table 2.1.

| | | | | |
|---|---|---|---|---|
| $K_A$ = 200 | $T_A$ = 0.02 s | $T_C$ = 1.0 | $T_B$ = 10.0 s | $K_E$ = -0.0485 |
| $T_E$ = 0.25 s | $K_F$ = 0.04 | $T_F$ = 0.56 s | $V_{RMAX}$ = 6.0 | $V_{RMIN}$ = -6.0 |
| $E_1$ = 3.5461 | $S_{E1}$ = 0.08 | $E_2$ = 4.7281 | $S_{E2}$ = 0.260 | |

Table 2.1: Typical values of DC1A excitation system parameters.

The time constant of the bus voltage measuring transducer can be taken as 0.02 s.

## 2.4 AC Excitation Systems

The excitation systems of this type utilize alternators (ac machines) as sources of the main generator excitation power. Usually, the exciter is on the same shaft as the turbine generator. The ac output of the exciter is rectified by either controlled or non-controlled rectifiers to produce the direct current needed for the generator field. AC exciters can be classified as follows:

1. Field-controlled alternator with non-controlled rectifiers
   (a) Rotating rectifier arrangements- Brushless excitation system.
   (b) Stationary rectifier arrangements.
2. Alternator-supplied controlled-rectifier excitation systems.

Two typical types of AC excitation systems are discussed in the following sections.

### 2.4.1 Field-Controlled Alternator with Non-controlled Rectifiers: Brushless Excitation Systems

With rotating rectifiers, the need for slip rings and brushes is eliminated, and the dc output is directly fed to the main generator field. The armature of the ac exciter and the diode rectifiers rotate with the main generator field. A small ac pilot exciter, with a permanent magnet rotor, rotates with the exciter armature and the diode rectifiers. The rectified output of the pilot exciter stator energizes the stationary field of the ac exciter. The voltage regulator controls the ac exciter field, which in turn controls the field of the main generator.

The functional block schematic of a typical brushless excitation system is shown in Figure 2.4.

The structure of IEEE-type AC1A excitation model is shown in Figure 2.5.

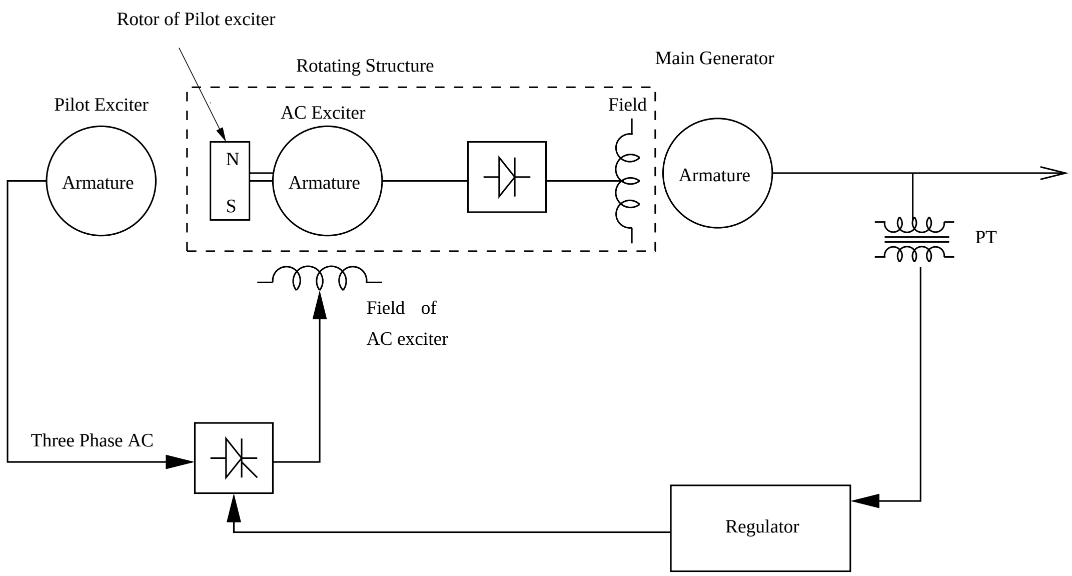


Figure 2.4: Brushless excitation system

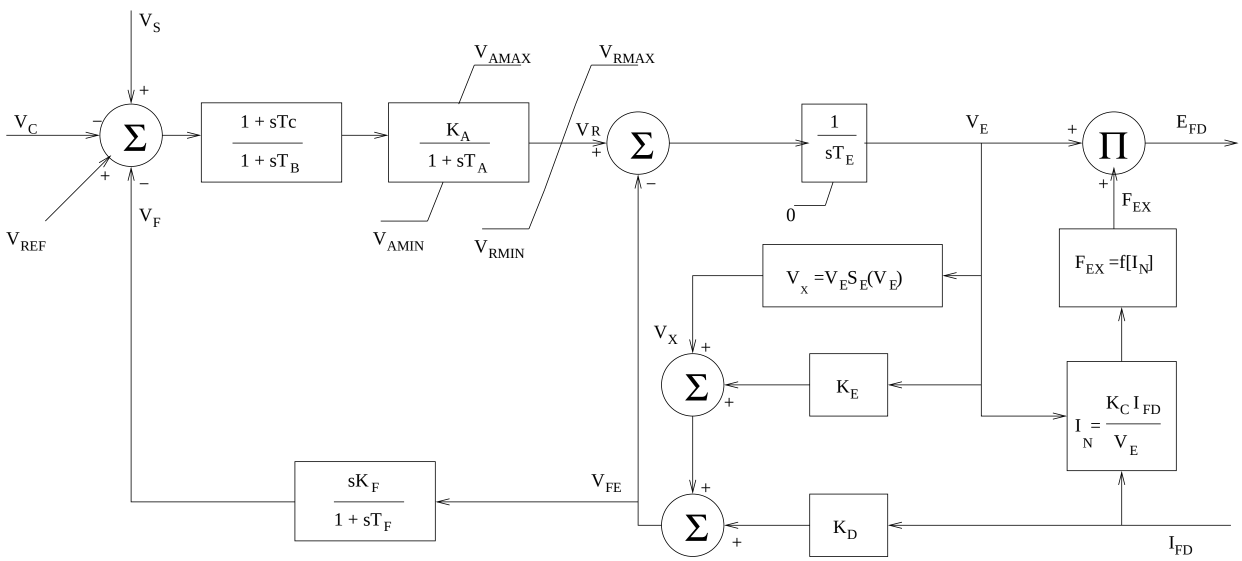


Figure 2.5: IEEE-type AC1A excitation system.

This exciter, also includes the rectifier regulation characteristics which is given by the following set of equations:

$$f(I_N) = 1.0 - 0.577 I_N \quad \text{if} \quad I_N \leq 0.433 \tag{2.1}$$
$$f(I_N) = \sqrt{0.75 - I_N^2} \quad \text{if} \quad 0.433 < I_N < 0.75 \tag{2.2}$$
$$f(I_N) = 1.732\,(1.0 - I_N) \quad \text{if} \quad 0.75 \leq I_N \leq 1.0 \tag{2.3}$$
$$f(I_N) = 0 \quad \text{if} \quad I_N > 1.0 \tag{2.4}$$

The above set of equations introduces non-linearity and hence it requires iterative steps to evaluate the initial conditions of the states pertaining to the exciter.

Typical values of the parameters of AC1A -excitation system are tabulated in Table 2.2.

| | | | | |
|---|---|---|---|---|
| $K_A$ = 100 | $T_A$ = 0.02 s | $T_C$ = 1.0 s | $T_B$ = 1.0 s | $V_{AMAX}$ = 14.5 |
| $V_{AMIN}$ = -14.5 | $V_{RMAX}$ = 6.03 | $V_{RMIN}$ = -5.43 | $K_E$ = 1.0 | $T_E$ = 0.8 s |
| $K_F$ = 0.03 | $T_F$ = 1.0 s | $K_D$ = 0.38 | $K_C$ = 0.2 | $E_1$ = 3.14 |
| $S_{E1}$ = 0.03 | $E_2$ = 4.18 | $S_{E2}$ = 0.1 | | |

Table 2.2: Typical values of AC1A excitation system parameters.

The time constant of the bus voltage measuring transducer can be taken as 0.02 s.

### 2.4.2 Alternator-Supplied Controlled-rectifier Excitation Systems

In this case, the dc output is fed to the field winding of the main generator through brushes and slip-ring arrangements. The AC output of the exciter is rectified using controlled rectifiers. The regulator directly controls the dc input to the main field winding by adjusting the firing angle of the controlled rectifiers. Hence, this system inherently provides high initial response. The AC exciter is a self-excited type and it uses an independent static voltage regulator to maintain its output voltage.

The functional block schematic of a typical alternator-supplied controlled-rectifier excitation system is shown in Figure 2.6.

The IEEE-type AC4A excitation model is an example to this kind of excitation systems. The transfer function level block schematic of this model is shown in Figure 2.7.

Typical values of the parameters of IEEE-type AC4A excitation system are tabulated in Table 2.3.

The time constant of the bus voltage measuring transducer can be taken as 0.02 s.

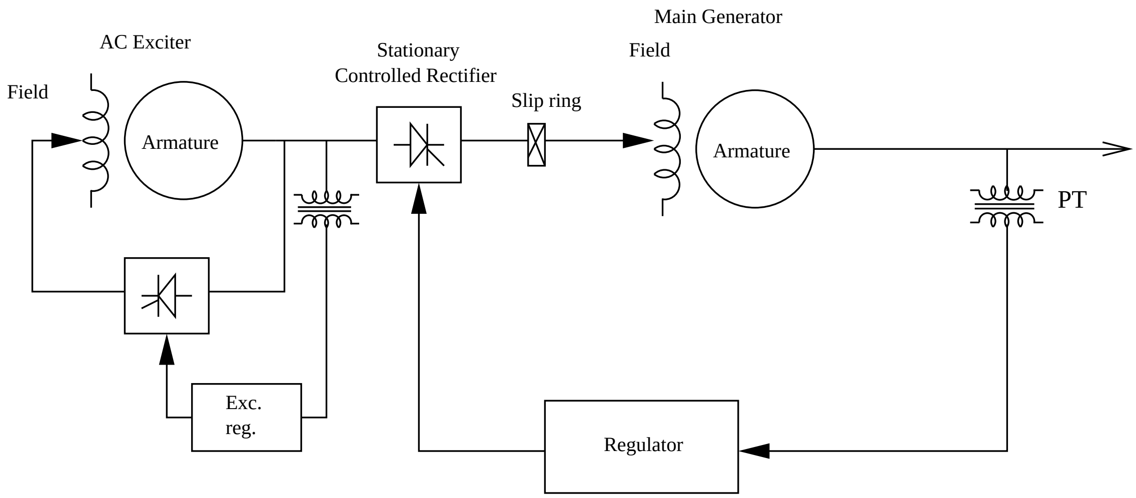


Figure 2.6: Alternator-supplied controlled-rectifier excitation system.

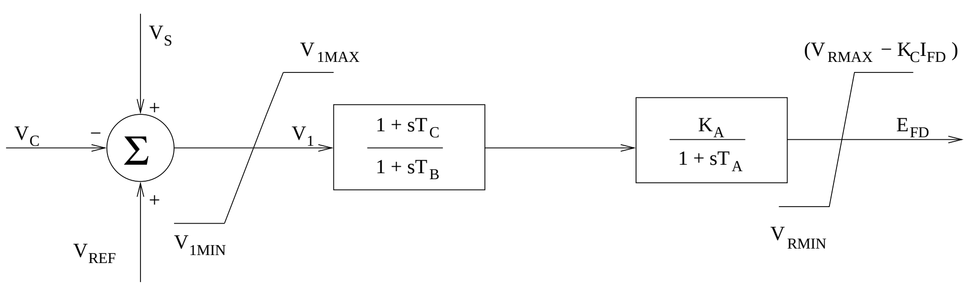


Figure 2.7: IEEE-type AC4A excitation system.

| | | |
|---|---|---|
| $K_A$ = 200 | $T_A$ = 0.015 s | $T_C$ = 1.0 s |
| $T_B$ = 12.0 s | $V_{IMAX}$ = 10.0 | $V_{IMIN}$ = -10.0 |
| $V_{RMAX}$ = 5.64 | $V_{RMIN}$ = -4.53 | $K_C$ = 0 |

Table 2.3: Typical values of AC4A excitation system parameters.

## 2.5 Static Excitation Systems

All components in these systems are static or stationary. Static rectifiers, controlled or uncontrolled, supply the excitation current directly to the field of the main synchronous generator through slip rings. The supply of power to the rectifiers is from the main generator (or the station auxiliary bus) through a transformer to step down the voltage to an appropriate level, or in some cases from auxiliary windings in the generator.

Following are the two major types of static excitation systems:

1. Potential-source controlled rectifier systems.
2. Compound-source rectifier systems.

### 2.5.1 Potential-Source Controlled Rectifier Systems

In this system, the excitation power is supplied through a transformer from the generator terminals or the station auxiliary bus, and is regulated by a controlled rectifier. This type of excitation system is also called as a bus-fed or transformer-fed static system. A functional block schematic of this type exciter is shown in Figure 2.8.

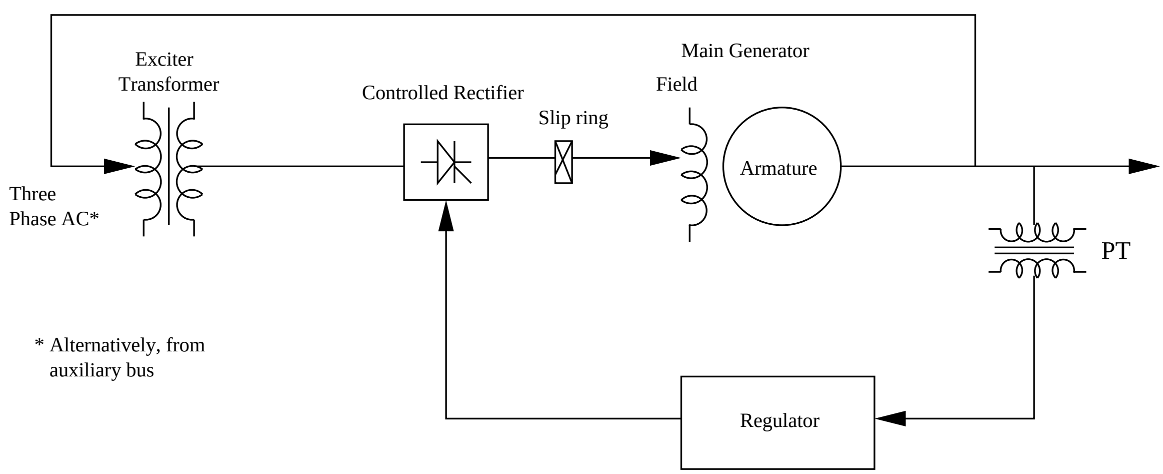


Figure 2.8: Potential-source controlled rectifier excitation system

The IEEE-type ST1A exciter model (see Figure 2.9) represents a potential-source controlled rectifier systems.

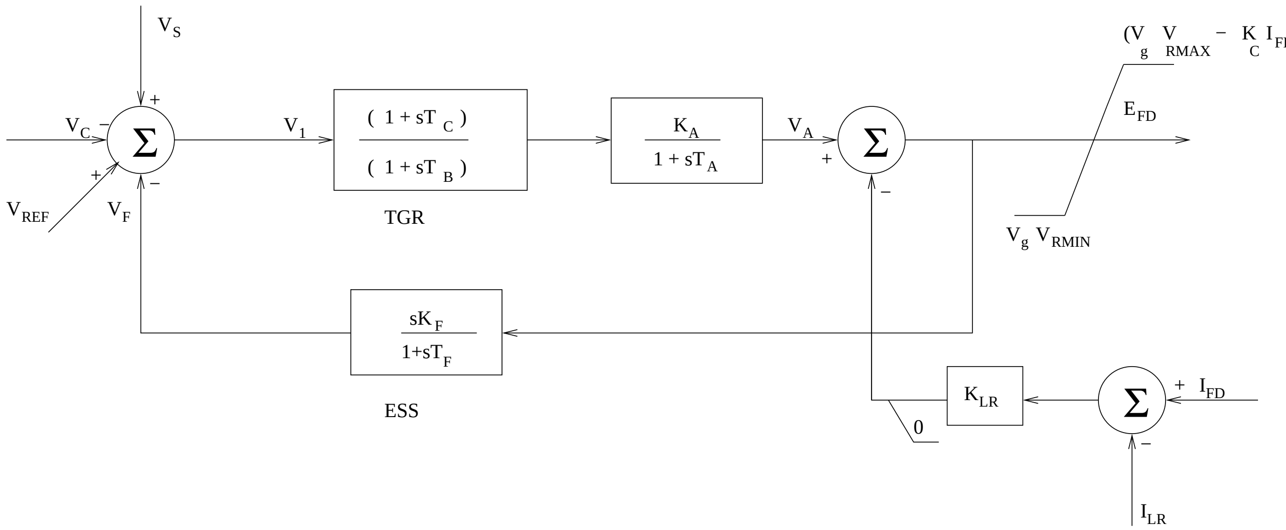


Figure 2.9: IEEE-type ST1A excitation system.

Note:

1. $K_{LR}$ and $I_{LR}$ represent the field current limiter parameters. These are used to protect the exciter and field circuit as the exciter ceiling voltage tends to be high in static exciters.

2. Since the excitation power is supplied through a transformer from the generator terminals, the exciter ceiling voltage is directly proportional to the generator terminal voltage. This is accounted by $V_g$ in the limiter.

3. The effect of rectifier regulation on ceiling voltage is represented by $K_C$. For transformer fed system $K_C$ is usually small.

Typical values of the parameters of IEEE-type ST1A excitation system are tabulated in Table 2.4.

| | | | |
|---|---|---|---|
| $K_A = 200$ | $T_A = 0.02$ s | $T_C = 1.0$ s | $T_B = 1.0$ s |
| $K_F = 0$ | $T_F = 1.0$ s | $K_C = 0.04$ | $K_{LR} = 4.54$ |
| $I_{LR} = 5$ | $V_{RMAX} = 7.0$ | $V_{RMIN} =$ -6.4 | |

Table 2.4: Typical values of IEEE-type ST1A excitation system parameters.

The time constant of the bus voltage measuring transducer can be taken as 0.02 s.

NOTE:

If TGR, ESS, the effect of terminal voltage and rectifier regulation on the ceiling voltage, and the field current limiters are neglected, it results in a simple single-time constant, fast acting and high gain static exciters [1]. The block schematic of such an exciter is shown in Figure 2.10.

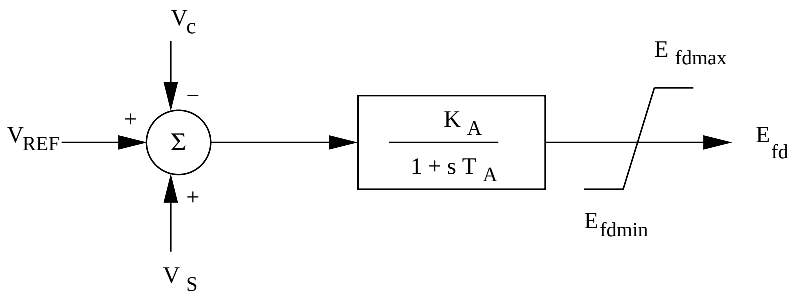


Figure 2.10: Single time constant static excitation system.

The time delay associated with the bus voltage measuring transducer is neglected.

### 2.5.2 Compound-Source Rectifier Systems

In this case, the power to the excitation system is formed by utilizing the current as well as the voltage of the main generator. This may be achieved by means of a power potential transformer and a saturable current transformer as depicted in Figure 2.11.

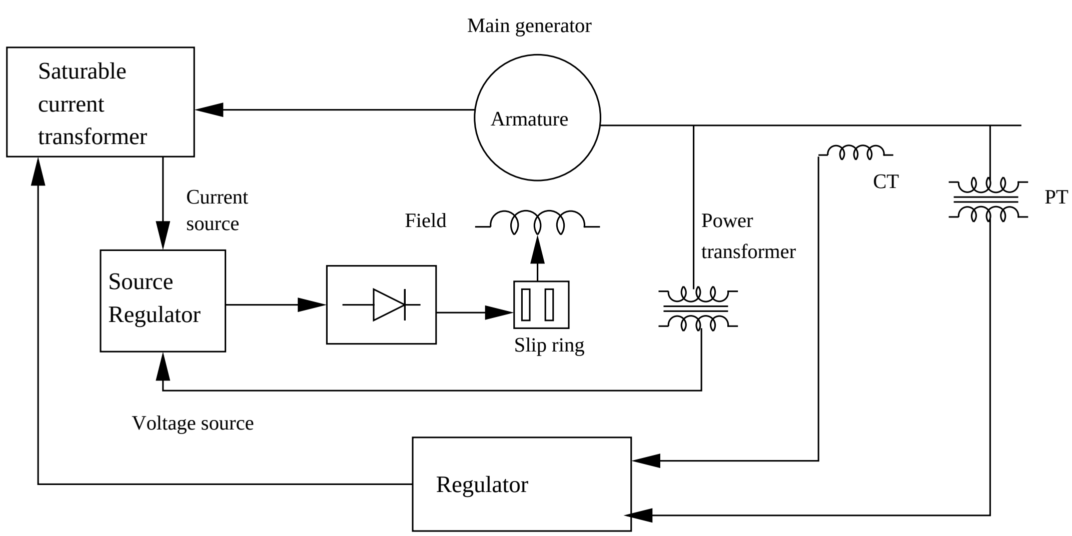


Figure 2.11: Compound-source rectifier excitation system.

The IEEE-type ST2A exciter model (see Figure 2.12) represents a compound-source rectifier excitation system.

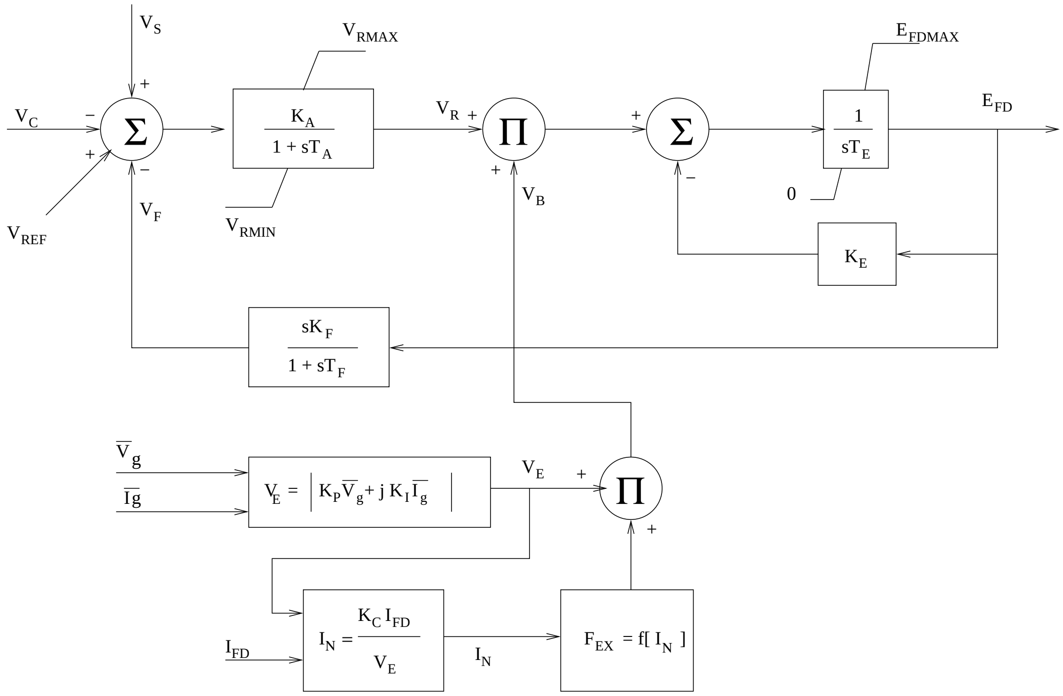


Figure 2.12: IEEE-type ST2A excitation system.

This exciter also includes the rectifier regulation characteristics as given in (2.1)-(2.4). Typical values of the parameters of IEEE-type ST2A excitation system are tabulated in Table 2.5.

| | | | |
|---|---|---|---|
| $K_A = 120$ | $T_A = 0.15$ s | $K_E = 1.0$ | $T_E = 0.5$ s |
| $K_C = 0.65$ | $K_F = 0.05$ | $T_F = 1.0$ s | $V_{RMAX} = 4.20$ |
| $V_{RMIN} =$ -4.20 | $K_P = 1.19$ | $K_I = 1.62$ | $E_{FDMAX} = 3.55$ |

Table 2.5: Typical values of IEEE-type ST2A excitation system parameters.

The time delay associated with the bus voltage measuring transducer is neglected.

# Chapter 3

# Modelling of Power System Stabilizers

## 3.1 Introduction

The function of a power system stabilizer (PSS) is to add damping to the generator rotor oscillations. This is achieved by modulating the generator excitation so as to develop a component of electrical torque in phase with the rotor speed deviations. Such a way of producing damping torque is the most cost-effective method of enhancing the small signal stability of power systems, when fast acting high gain excitation systems are used.

## 3.2 Types of Power System Stabilizers

As per IEEE standards 421.5 - 1992 [6], the following are the two main categories of PSS:

1. Single input power system stabilizer (PSS1A)
2. Dual input power system stabilizer (PSS2A)

## 3.3 Single Input PSS

For this kind of PSS, shaft speed, terminal bus frequency and electrical power output are the commonly used input signals. In the following lines, PSS with each of this type of input signal, is briefly discussed.

### 3.3.1 Speed Input Signal PSS

The block schematic of a speed input type PSS is shown in Figure 3.1. The functions of each of the block have been explained in reference [1].

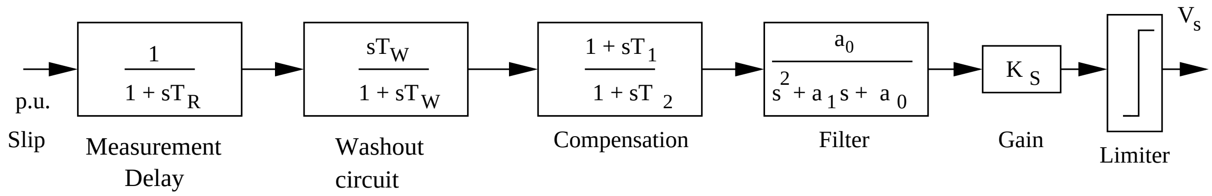


Figure 3.1: Speed input signal PSS.

The typical values of the parameters are tabulated in Table 3.1.

| | | |
|---|---|---|
| $K_S = 5$ | $T_R = 0.02$ s | $T_W = 10$ s |
| $T_1 = 0.1$ s | $T_2 = 0.05$ s | $V_{SMAX} = 0.1$ |
| $V_{SMIN} =$ -0.1 | $a_1 = 35$ | $a_0 = 570$ |

Table 3.1: Typical values of speed -input type PSS parameters.

### 3.3.2 Frequency Input Signal PSS

The block schematic of a frequency input type PSS is shown in Figure 3.2. Note that though a frequency input type PSS is less sensitive to torsional oscillations, its structure is assumed to be the same as that of a speed input type PSS.

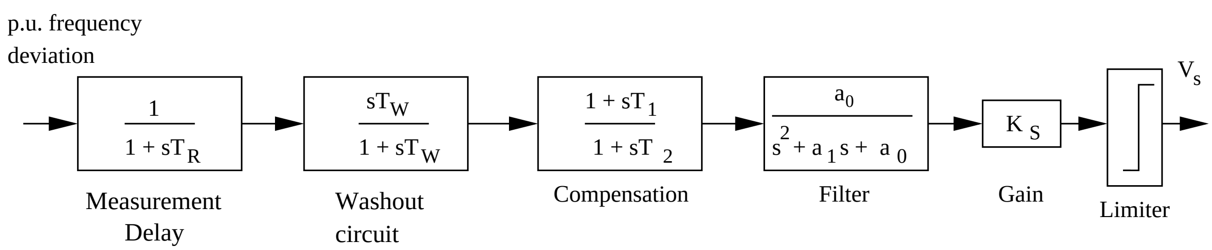


Figure 3.2: Frequency input signal PSS.

See Table 3.1 for typical values of the parameters of a frequency input type PSS.

### 3.3.3 Power Input Signal PSS

The block schematic of a power input type PSS is shown in Figure 3.3. Since $\Delta T_e$ signal has a high degree of torsional attenuation, generally there is no need for a torsional filter.

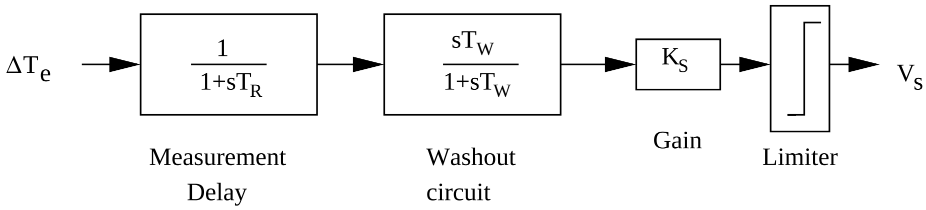


Figure 3.3: Power input signal PSS.

The typical values of the parameters are tabulated in Table 3.2.

| | | |
|---|---|---|
| $K_S$ = 0.07 | $T_R$ = 0.05 s | $T_W$ = 10 s |
| $V_{SMAX}$ = 0.1 | $V_{SMIN}$ = -0.1 | |

Table 3.2: Typical values of power input signal PSS parameters.

## 3.4 Dual Input PSS

Here, one input is speed and the other input is electrical power. This type of PSS is referred to as Delta-P-Omega PSS.

In this type of PSS, the speed signal is synthesized by using shaft speed signal and electrical power. This permits the selection of a higher stabilizer gain that results in better damping of system oscillations, without causing the destabilization of exciter mods [4]. The block schematic of a Delta-P-Omega type PSS is shown in Figure 3.4.

The typical values of the parameters are tabulated in Table 3.3. Note that $H$ is the inertia constant of a machine.

| | | | |
|---|---|---|---|
| $T_{W1}$ = 10 s | $T_{W2}$ = 10 s | $T_{W3}$ = 10 s | $T_{W4}$ = 10 s |
| $T_6$ = 0.01 s | $T_7$ = 10 s | $K_{S3}$ = 1 | $T_8$ = 0 |
| $T_9$ = 0.1 s | $T_1$ = 0.1 s | $T_2$ = 0.05 s | $K_{S1}$ =10 |
| $V_{SMAX}$ = 0.1 | $V_{SMIN}$ = -0.1 | M = 2 | N = 4 |

Table 3.3: Typical values of Delta-P-Omega PSS parameters.

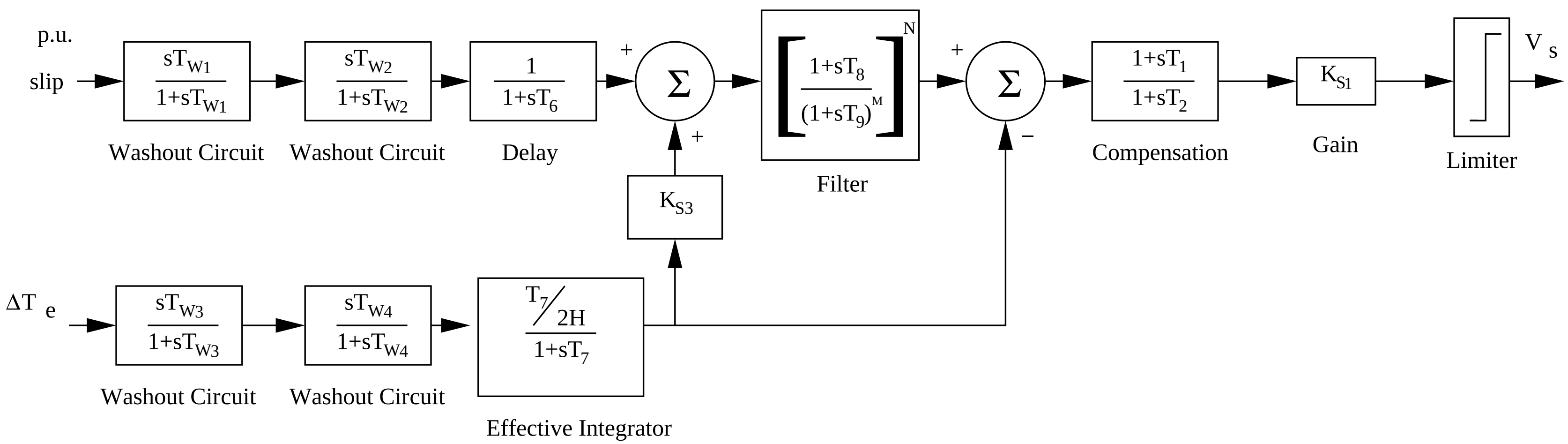


Figure 3.4: Delta-P-Omega PSS.

# Chapter 4

# Speed-Governor and Turbine Modelling

## 4.1 Introduction

A typical block schematic of a speed-governor and turbine system is shown in Figure 4.1. In stability studies, only speed-governor (primary) control systems are represented including turbine systems.

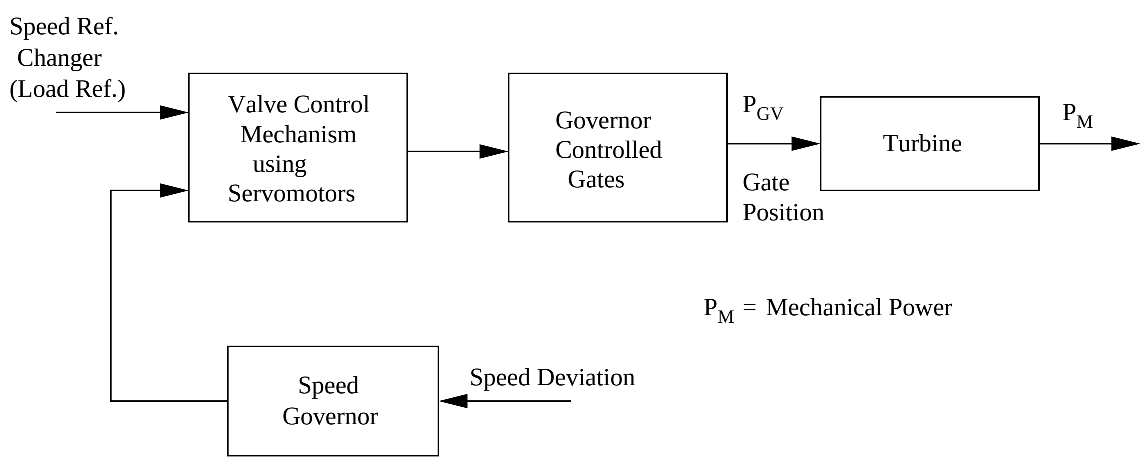


Figure 4.1: Block schematic of speed-governor and turbine systems.

## 4.2 Modelling of Turbines

As per the IEEE committee report [7], the following are the typical types of turbines employed in stability studies:

### 4.2.1 Hydraulic Turbines

The hydraulic turbine is approximately represented as shown in Figure 4.2.

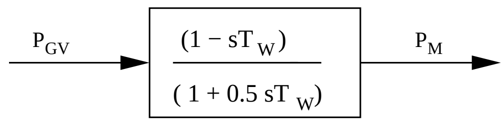


Figure 4.2: Hydraulic turbine model.

The time constant $T_W$ is called water starting time or water time constant. Values for $T_W$ lie in the range of 0.5 to 5 s with the typical value around 1.0 s. It is to be noted that, since hydraulic turbine has non-minimum phase characteristic, it requires some dashpot arrangements in the speed governor systems to improve its response.

### 4.2.2 Steam Turbines

Following are the two major types of steam turbines:

1. Tandem Compounded, Single Reheat Type (see Figure 4.3):

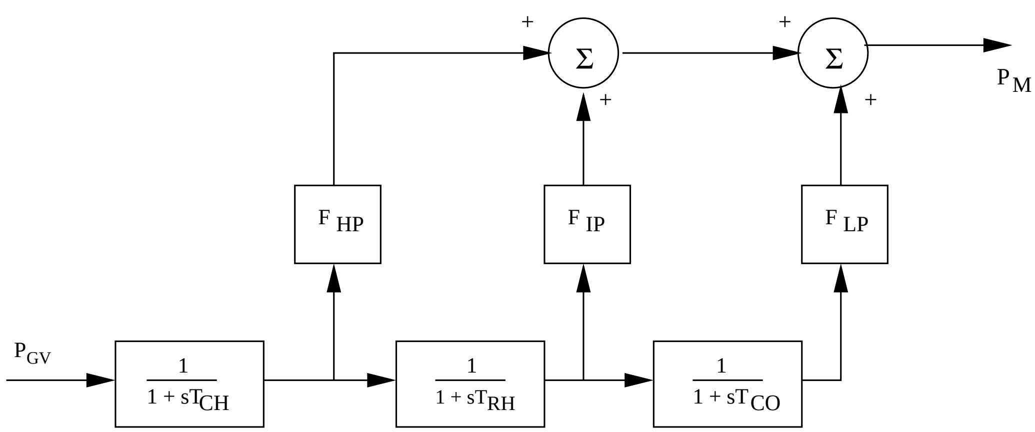


Figure 4.3: Tandem compounded, single reheat type steam turbine model.

The typical values of the parameters are tabulated in Table 4.1

| | | |
|---|---|---|
| $T_{CH} = 0.1\text{-}0.4$ s | $T_{RH} = 4\text{-}11$ s | $T_{CO} = 0.3\text{-}0.5$ s |
| $F_{HP} = 0.3$ | $F_{IP} = 0.3$ | $F_{LP} = 0.4$ |

Table 4.1: Typical values of tandem compounded, single reheat type steam turbine parameters.

2. Non-Reheat Type (see Figure 4.4):

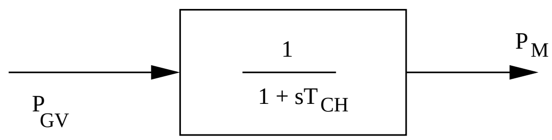


Figure 4.4: Non-reheat type steam turbine.

The typical value of $T_{CH}$ is 0.1-0.4 s.

## 4.3 Modelling of Speed-Governing Systems

Typically, there are two types of speed-governing systems [1], namely

### 4.3.1 Speed-Governing Systems for Hydraulic Turbines

An approximate non-linear model for the hydro-speed-governing system is shown in Figure 4.5.

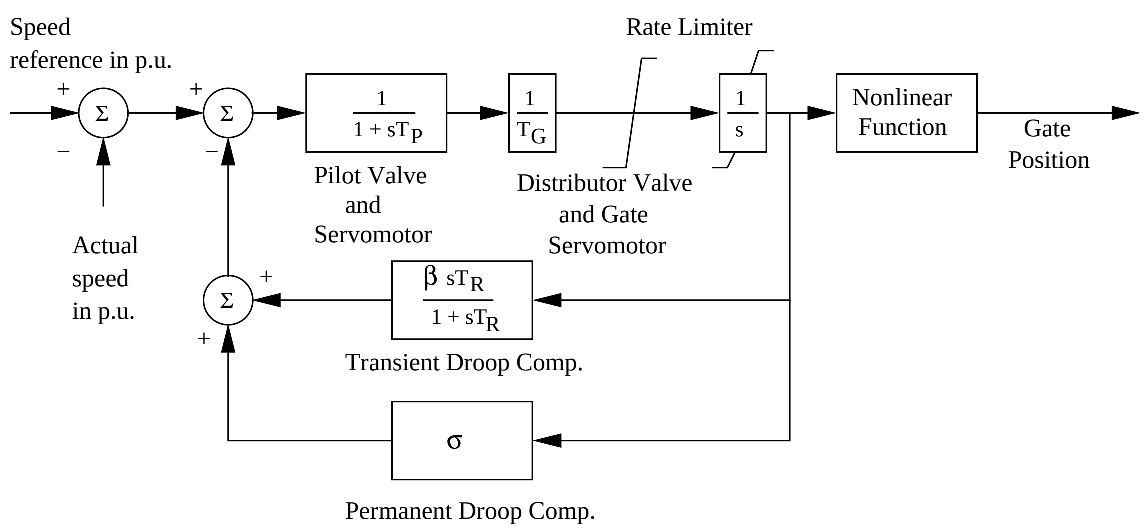


Figure 4.5: Speed-governing system for hydro turbines.

In the above figure, $T_R$ and $\beta$ are calculated as

$$T_R = 5T_W, \qquad \beta = \frac{1.25T_W}{H}$$

where

$T_W$ = water time constant.
$H$ = inertia constant of a machine.

A simplified block schematic that can be employed in stability studies which is derived from the above figure, is as shown in Figure 4.6.

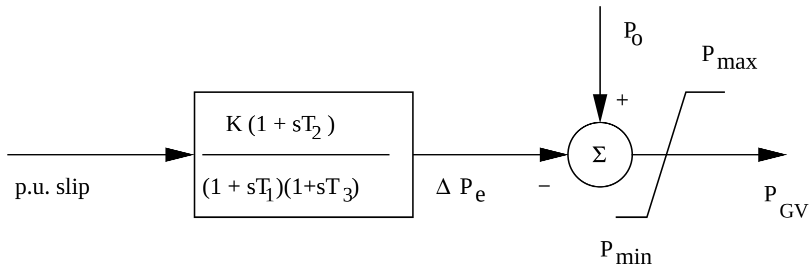


Figure 4.6: General model for speed-governor for hydro turbines.

The various parameters and time constants shown in the simplified block can be obtained using the following expressions [1].

$$T_1, T_3 = \frac{T_B}{2} \pm \sqrt{\frac{T_B^2}{4} - T_A} \tag{4.1}$$

where

$$T_A = \left(\frac{1}{\sigma}\right) T_R T_G, \qquad T_B = \left(\frac{1}{\sigma}\right) \left[(\sigma + \beta)\, T_R + T_G\right]$$

and

$$K = \frac{1}{\sigma}$$

Typical values of parameters for speed-governor of hydro turbines are tabulated in Table 4.2.

| | | |
|---|---|---|
| $T_W = 1.0$ s | $T_G = 0.2$ s | $T_2 = 0$ |
| $\sigma = 0.05$ | | |

Table 4.2: Typical values of parameters for speed-governor of hydro turbines.

In the above figure, $P_o$ represents the nominal value of the mechanical input $P_M$. Limits on $P_{GV}$ can be selected as $P_{max} = 1.1\ P_o$ and $P_{min} = 0.1\ P_o$.

### 4.3.2 Speed-Governing System for Steam Turbines

A simplified, general model for the speed-governing system for steam turbine is shown in Figure 4.7.

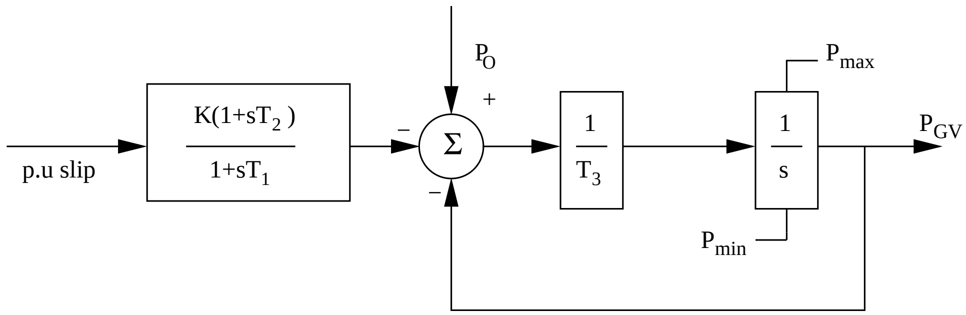


Figure 4.7: General model for speed-governor for steam turbines.

Typical values of parameters for speed-governor of steam turbines are tabulated in Table 4.3.

| | | |
|---|---|---|
| $T_1 = 0.2$ s | $T_2 = 0$ | $T_3 = 0.1$ s |
| $P_{max} = 1.1\ P_o$ | $P_{min} = 0.1\ P_o$ | |

Table 4.3: Typical values of parameters for speed-governor of steam turbines.

# Chapter 5

# Network Modelling

## 5.1 Introduction

Transmission network mainly consists of transmission lines and transformers. Since the time constants of these elements are relatively small compared to the mechanical time constants, the network transients are neglected and the network is assumed to be in sinusoidal steady state. The modelling of these components are briefly discussed in the following sections:

## 5.2 Transmission Lines

Transmission Lines are modelled as a nominal $\pi$ circuit [3] as shown in Figure 5.1.

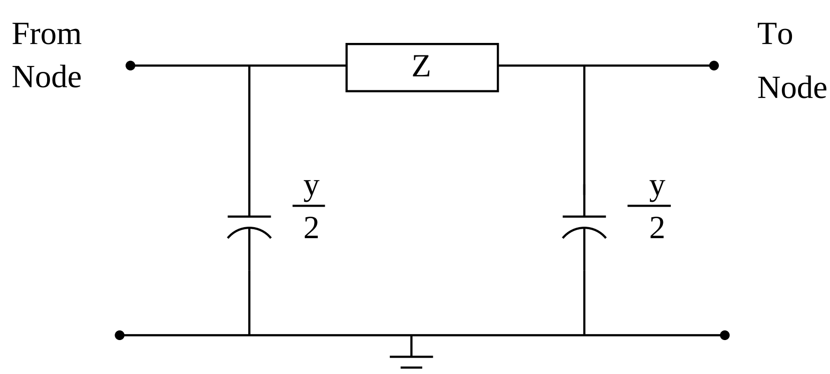


Figure 5.1: Nominal $\pi$ Model of transmission lines.

where,

$Z$: represents the series impedance of the line.

$\frac{y}{2}$: represents half of the total line charging $y$, at each node.

## 5.3 Transformers

The transformers are generally used as inter-connecting (IC) transformers and generator transformers. These transformers are usually with off-nominal-turns-ratio and are modelled as equivalent $\pi$ circuit [3] as shown in Figure 5.2.

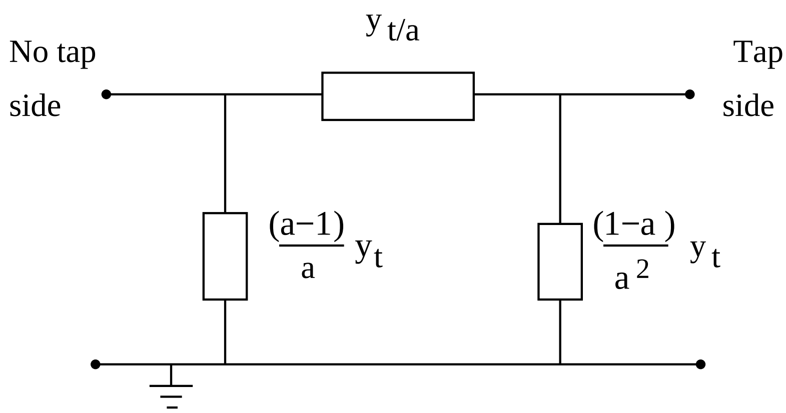


Figure 5.2: Transformer Model

where,

$y_t = \frac{1}{z_t}$

$z_t$: represents the series impedance at nominal-turns-ratio.

$a$: represents per unit off-nominal tap position.

The transmission network is represented by an algebraic equation given by

$$Y_{BUS}\underline{\bar{V}} = \underline{\bar{I}} \tag{5.1}$$

where

$Y_{BUS}$ = Bus admittance matrix

$\underline{\bar{V}}$ = Vector of bus voltages

$\underline{\bar{I}}$ = Vector of injected bus currents

The above equation is obtained by writing the network equations in the node-frame of reference taking ground as the reference.

## 5.4 Simulation of Fault

A 3-phase bolted fault is applied at a bus (named as $fbus$) by setting

$$Y_{BUS}(fbus, fbus) = 10^5 \quad \text{(a large conductance.)}$$

The fault clearing is simulated by using $Y_{BUS}$ corresponding to the post-fault system. The fault clearing, may or may not involve tripping of a line(s) .

1. If a line is tripped, then the respective line is removed from the pre-fault $Y_{BUS}$.
2. If no line is tripped, then the pre-fault $Y_{BUS}$ itself is used as the post-fault $Y_{BUS}$.

# Chapter 6

# Load Modelling

## 6.1 Introduction:

The modelling equations of power system are in the form of a set of differential-algebraic equations (DAEs) given by

$$\begin{aligned}\underline{\dot{x}} &= f(\underline{x}, \underline{\bar{V}}, \underline{u}) && (6.1)\\ Y_{BUS}\ \underline{\bar{V}} &= \bar{I}(\underline{x}, \underline{\bar{V}}, \underline{S}_L) && (6.2)\end{aligned}$$

where $\underline{x}$ represents the state variables.
$\underline{u}$ represents input vector $= [\underline{u}_1^t, \ldots, \underline{u}_{n_g}^t]^t$ with $\underline{u}_i = [\omega_B, V_{REFi}]^t$

In (6.2), the vector of injected bus currents, $\bar{I}$ in general, represents a combination of generators source currents, $\bar{I}_{DQS}$ and load currents, $\bar{I}_L$. If dynamic saliency is neglected or accounted using dummy coil approach, $\bar{I}_{DQS}$ is a function of only state variables. Whereas, $\bar{I}_L$ is related to load power, $S_L$ and bus voltage, $\bar{V}$ as given by the following expression.

$$\bar{I}_L = -\left(\frac{S_L}{\bar{V}}\right)^* \tag{6.3}$$

Loads are modelled as aggregate static loads, employing polynomial representation. This method of modelling loads is briefly explained in the following section.

## 6.2 Polynomial Load Representation

The active and reactive components of load powers are represented separately as static voltage dependent models, as given below [1]:

$$
\begin{aligned}
P_L &= a_1\ P_{Lo} + a_2 \left(\frac{P_{Lo}}{V_o}\right) V + a_3 \left(\frac{P_{Lo}}{V_o^2}\right) V^2 \\
Q_L &= b_1\ Q_{Lo} + b_2 \left(\frac{Q_{Lo}}{V_o}\right) V + b_3 \left(\frac{Q_{Lo}}{V_o^2}\right) V^2 \qquad (6.4)
\end{aligned}
$$

where $P_{Lo}$ and $Q_{Lo}$ are nominal values of active and reactive components of load powers at nominal voltage, $\bar{V}_o$.

The coefficients $a_1$, $a_2$ and $a_3$ are the fractions of the constant power, constant current and constant impedance components in the active load powers, respectively. similarly, the coefficients $b_1$, $b_2$ and $b_3$ are defined for reactive load powers. While selecting these fractions, it should be noted that

$$
\begin{aligned}
a_1 + a_2 + a_3 &= 1 \\
b_1 + b_2 + b_3 &= 1
\end{aligned}
$$

From (6.4), the load power is given by

$$
S_L = P_L + jQ_L \qquad (6.5)
$$

Remarks:

1. If both active and reactive components are modelled as constant impedance type i.e. by setting $a_1 = a_2 = 0$ and $a_3 = 1$, $b_1 = b_2 = 0$ and $b_3 = 1$, then the load admittance $Y_L$ is given by

$$
Y_L = \frac{P_{Lo} - jQ_{Lo}}{V_o^2} \qquad (6.6)
$$

   Now, the load admittance $Y_L$ can be absorbed into $Y_{BUS}$, to make the algebraic equation (6.2) linear.

2. Modelling of active and/or reactive components as constant power/current type.(i.e., by having $a_1$ and/or $a_2$,and $b_1$ and/or $b_2$ non-zero), makes the algebraic equation (6.2) non-linear. This calls for iterative solution within each time step of numerical integration.

## 6.3 Frequency Dependent Load Models

In addition to voltage dependency, the effect of frequency variations on the active and reactive components of loads is accounted as follows:

$$\begin{aligned} P_L &= P_{Lo}\left\{a_1 + a_2\left(\frac{V}{V_o}\right) + a_3\left(\frac{V}{V_o}\right)^2\right\}\left[1 + k_{pf}\frac{\Delta f}{f_o}\right] \\ Q_L &= Q_{Lo}\left\{b_1 + b_2\left(\frac{V}{V_o}\right) + b_3\left(\frac{V}{V_o}\right)^2\right\}\left[1 - k_{qf}\frac{\Delta f}{f_o}\right] \end{aligned} \tag{6.7}$$

where,

$k_{pf}$, $k_{qf}$ = frequency sensitivity coefficients
$\Delta f$ = deviation in bus frequency in Hz
$f_o$ = nominal frequency in Hz

NOTE:

Frequency deviation is calculated using the rate of change of respective bus angles. The bus frequency deviation in rad/s at bus $i$ is given by

$$\begin{aligned} \frac{d\phi}{dt} &= \frac{d}{dt}\left[\tan^{-1}\left(\frac{v_{Di}}{v_{Qi}}\right)\right] \\ &= \left(\frac{v_{Qi}\frac{dv_{Di}}{dt} - v_{Di}\frac{dv_{Qi}}{dt}}{V_i^2}\right) \end{aligned}$$

The derivatives of $v_{Qi}$ and $v_{Di}$ are obtained approximately by using the following transfer function

$$\frac{s}{(1 + s\ T)}$$

where $T$ is set to 0.02 s.

## 6.4 Load Equivalent Circuit

The load at a bus is represented by an equivalent circuit as shown in Figure 6.1.

In the figure above, the load admittance $Y_L$ has been absorbed into $Y_{BUS}$. Therefore, the net equivalent load current to be injected at a load bus is given by

$$\begin{aligned} \hat{\bar{I}}_L &= -\left(\frac{S_L}{\bar{V}}\right)^* - \left(-Y_L\bar{V}\right) \\ &= -\left(\frac{S_L}{\bar{V}}\right)^* + Y_L\bar{V} \\ &= g(\bar{V}, f) \end{aligned} \tag{6.8}$$

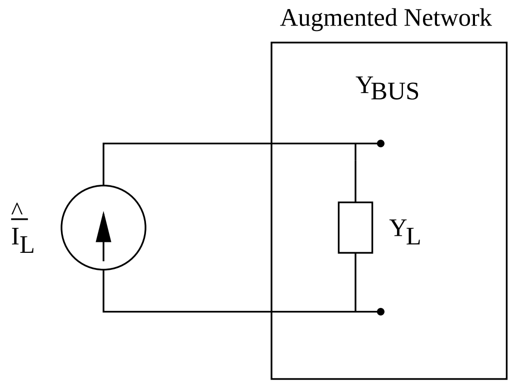


Figure 6.1: Equivalent circuit of load.

NOTE:

If both active and reactive load components are modelled as constant impedance type without any frequency dependency, then $\hat{\bar{I}}_L$ is identically equal to zero. Otherwise, $\hat{\bar{I}}_L$ is zero only at the operating point.

## 6.5 Modification of Constant Power type Load Characteristics

It is found that, when the active load power component is represented as constant power type, the programme encounters numerical convergence problem. This is true especially when there is a severe dip in the bus voltage. This problem is overcome by adopting the following characteristic [8]:

1. When the voltage magnitude at $i^{th}$ load bus drops below $V_c$ (=0.6), change the active load power component at that bus as

$$P_{L_i} = P_{Lo_i} \left( \frac{V_i}{V_c} \right)^2 \tag{6.9}$$

2. Otherwise, the active load power component is held at $P_{Lo_i}$

In general, the types of load models used are summarized in Figure 6.2.

## 6.6 An Approach to Avoid Iterative Solution of Algebraic Equations

It is known that when loads are modelled as constant power/current type and/or frequency dependent, it calls for iterative solution within a time step. A procedure similar to dummy

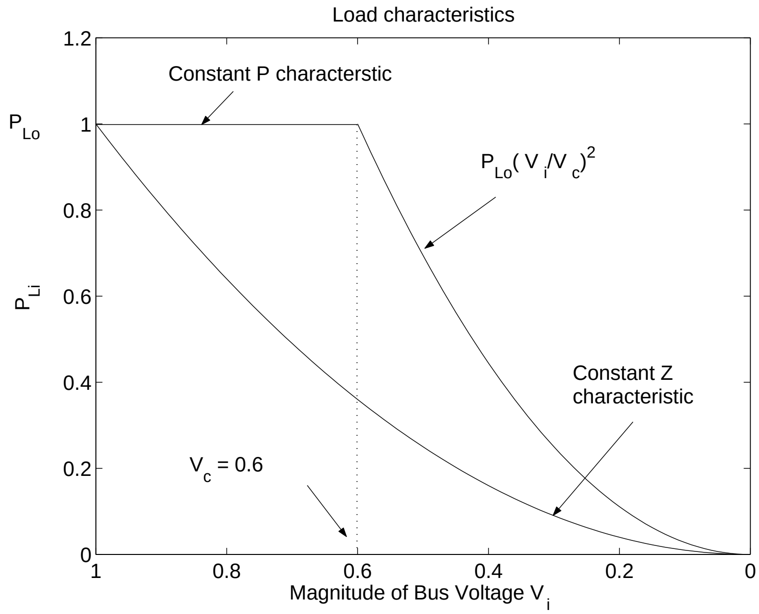


Figure 6.2: Summary of load models

coil approach that is used to account dynamic saliency [1], has been employed here also to avoid iterative solution.

The non-linear algebraic equations are converted into a combination of fast acting differential equations and linear algebraic equations. The algebraic equations are made functions of the 'dummy' states of the fast acting differential equations.
The non-linear algebraic equation (6.8), is modified as follows:

$$\begin{aligned} \frac{d\bar{I}_{Ld}}{dt} &= \frac{1}{T_L}\left\{-\bar{I}_{Ld} + g(\bar{V}, f)\right\} \\ \hat{\bar{I}}_L &= \bar{I}_{Ld} \end{aligned} \tag{6.10}$$

The time constant $T_L$ is chosen to be small, which implies that $\bar{I}_{Ld} \approx g(\bar{V}, f)$, except for a short while after a disturbance. This is an approximate treatment, but the degree of approximation can be controlled directly by choosing $T_L$ appropriately. It is found that reasonable accuracy can be obtained if $T_L$ is about 0.01 s. The main advantage of this method is its simplicity and modularity.

NOTE:
Since $\bar{I}_{Ld}$ is a complex number, the above strategy is realized for real and imaginary components separately.

# Chapter 7

# Implementation Issues

## 7.1 Introduction

The component models discussed in the previous chapters are interconnected as shown in Figure 7.1 to obtain the complete power system model for carrying out transient stability studies.

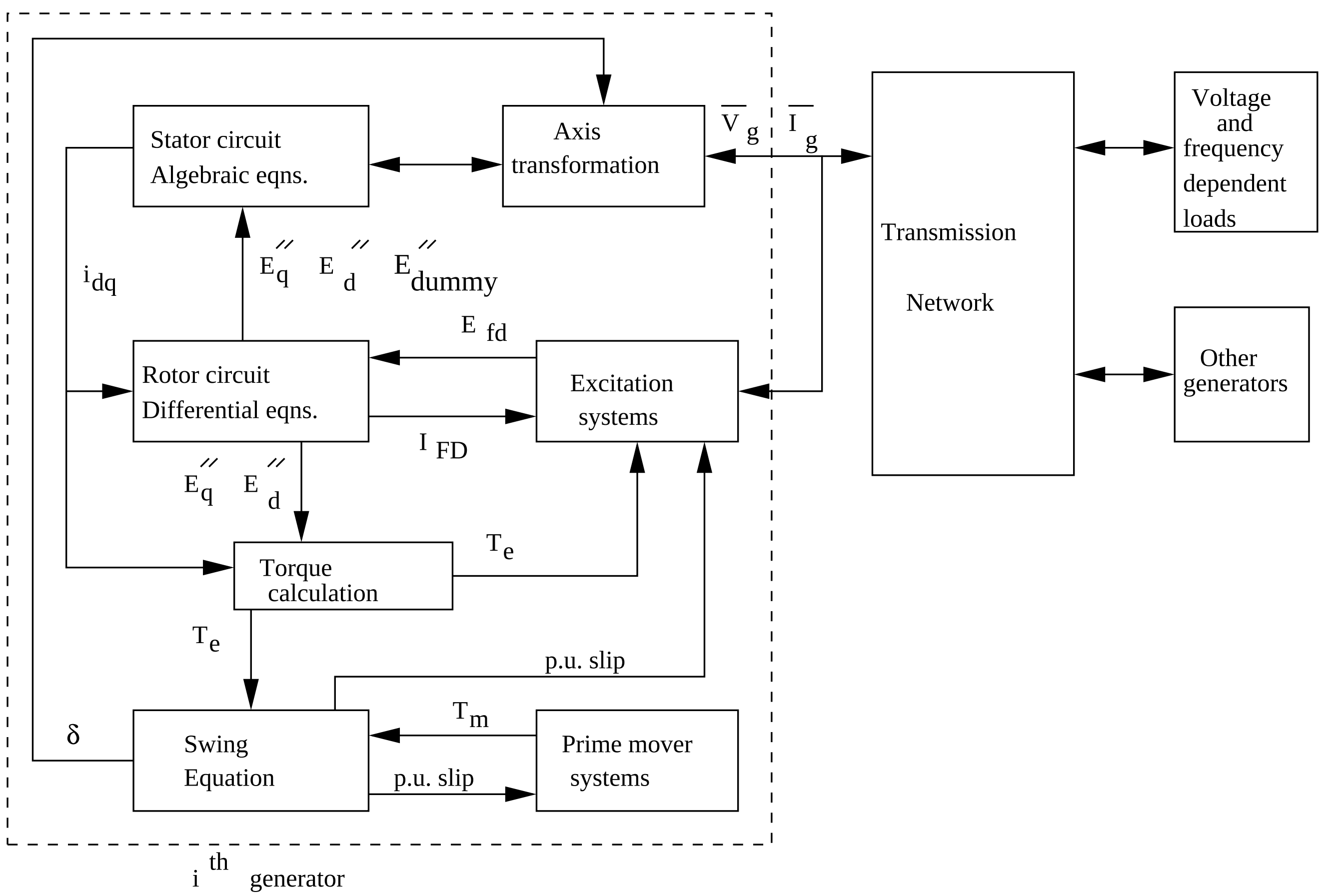


Figure 7.1: The structure of the complete power system model.

The multi-machine transient stability programme has been implemented on MATLAB-5.3/SIMULINK-3 platform. The initial condition calculations have been performed by writing script files (.m files). Whereas the differential-algebraic equations (DAEs) have been solved in the SIMULINK platform.

## 7.2 Introduction to MATLAB

MATLAB is a command interpreting language written in C++. It provides an extensive function support for performing matrix calculations [9]. In addition, by treating variables as vectors and using 'period operators', we have the following advantages:

1. The use of for-loops can be avoided.
2. For systems having similar state-model structure, the duplication of SIMULINK blocks can be avoided.

Thus the above approach, not only simplifies the task of programming repetitive calculations, it also improves the speed of execution. This is demonstrated in the following example.

Let $v$ be a vector of voltages across 5 different resistors in a circuit. The values of the resistors are defined in a vector $r$. It is required to compute the power consumed by each of the resistor. This is achieved by the following Matlab statements without using for-loops:

```
>>v=[1 2 3 4 5];
>>r=[2 4 6 8 10];
>>i=v./r
i =
  0.50000  0.50000  0.50000  0.50000  0.50000

>>p=i.*v
p =
  0.50000  1.00000  1.50000  2.00000  2.50000
```

Alternatively, the above task can be accomplished by the following single Matlab statement:

```
>>p=v.^2./r
p =
  0.50000  1.00000  1.50000  2.00000  2.50000
```

NOTE: While using the 'period operators', care must be taken to see that the vectors are of the same dimension.

## 7.3 Introduction to SIMULINK

SIMULINK is a toolbox of MATLAB, which provides facility to obtain time-domain solution of differential equations [10]. To achieve this, the basic steps to be followed are:

1. Obtain the state-space model of a system.
2. Construct an analog block schematic to realize the state-model.
3. Select a suitable numerical-integration algorithm from the available list.

The above steps are illustrated in the following example. Further, the advantage of treating variables as vectors and using them with 'period operators', is demonstrated. Consider an RLC series circuit excited by an unit step, $v$ (see Figure 7.2).

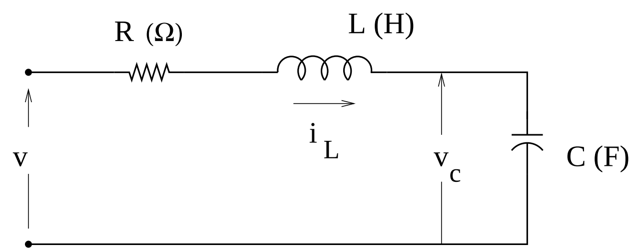


Figure 7.2: Series RLC Circuit.

The state-space equations are given by

$$\begin{aligned} \frac{di_L}{dt} &= -\frac{R}{L}i_L - \frac{v_c}{L} + \frac{v}{L} \\ \frac{dv_c}{dt} &= \frac{i_L}{C} \end{aligned} \tag{7.1}$$

with $i_L(0) = 0$ and $v_c(0) = 0.5$.
The corresponding SIMULINK model is shown in Figure 7.3.
In the MATLAB Command Window, set
R=[1, 0.1, 10];
L=[0.5, 0.1, 0.8];
C=[0.5, 1, 0.1];
The above statements show that the RLC series circuit needs to be analyzed for 3 sets of values for R, L and C.

Using RK $4^{th}$ order numerical-integration method (ODE-4, fixed-step version), the solution is obtained for (7.1). The flow of state variables (i.e., the output at the scope points) is depicted in Figure 7.4. Note that the time-domain solution is obtained simultaneously for each of the set R(j) L(j) C(j), j=1,2,3 in a single run of the simulation.

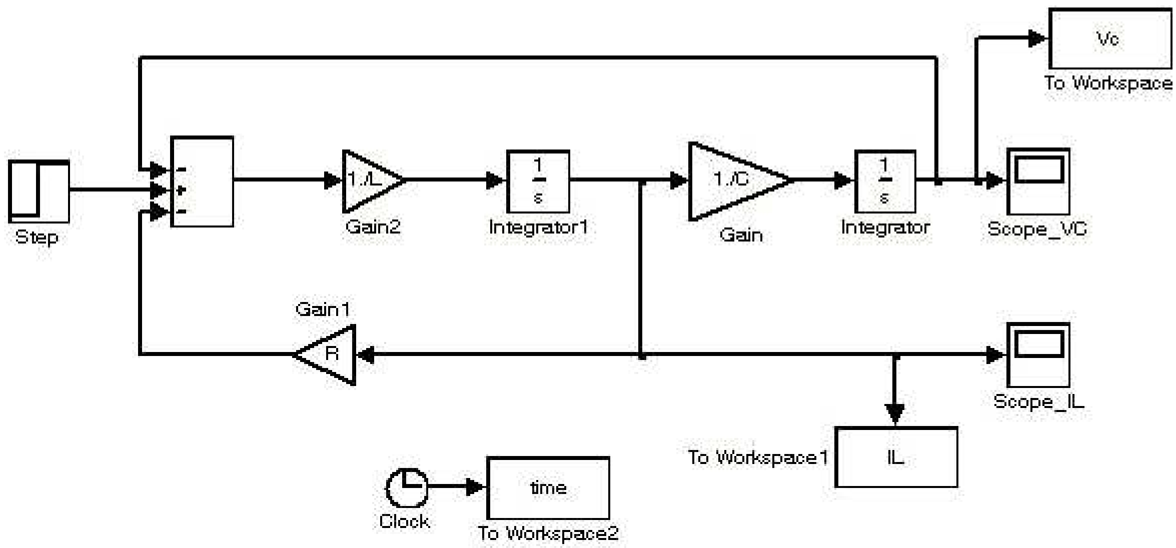


Figure 7.3: SIMULINK model for RLC series circuit.

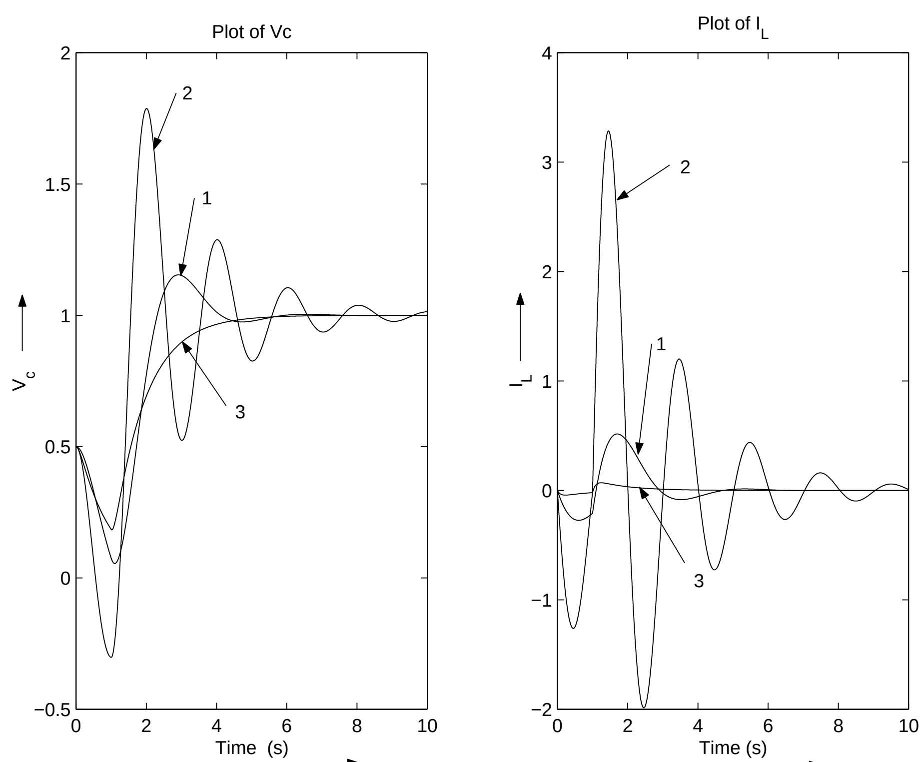


Figure 7.4: Plots of $v_c(t)$ and $i_L(t)$ for RLC series circuit.

## 7.4 A Scheme for Solving DAEs

The solution of DAE is obtained by employing partitioned solution technique [1]. In this approach, the differential equations and algebraic equations are solved separately, in a partitioned manner. The differential equations may be solved either by using implicit or explicit integration method. While doing this, the values of the algebraic variables known in the previous time step are used. Though, it may introduce 'interface-errors', the partitioned solution technique is generally followed in large-scale system studies.

Further, for large systems, partitioned solutions with explicit integration method is normally employed [4]. In SIMULINK, one can choose, fixed-step methods, which are explicit type. It is found that in this category, ODE-4 (RK $4^{th}$ order) or ODE-5 (Dormand Prince) method are best suited. However, knowing the limitations of fixed-step methods (long simulation time), it is always recommended to use variable step methods of explicit kind, e.g., ODE-45, ODE-13 etc. By appropriately choosing the Relative and Absolute error parameters, one can achieve the desired accuracy of the solution and improved speed of simulation [10].

In addition to exploiting *vectorization*, the programme uses the *sparsity solution techniques* inherent to MATLAB. The solution for bus voltages is obtained by declaring $Y_{BUS}$ as sparse and employing *back slash* command: $\underline{\bar{V}} = Y_{BUS} \backslash \underline{\bar{I}}$. This procedure reduces the number of flops considerably.

# Chapter 8

# Case Studies with Test Systems

## 8.1 Four Machine System

The single line diagram of a 4 machine power system is shown in Figure 8.1. The system details are adopted from [1].

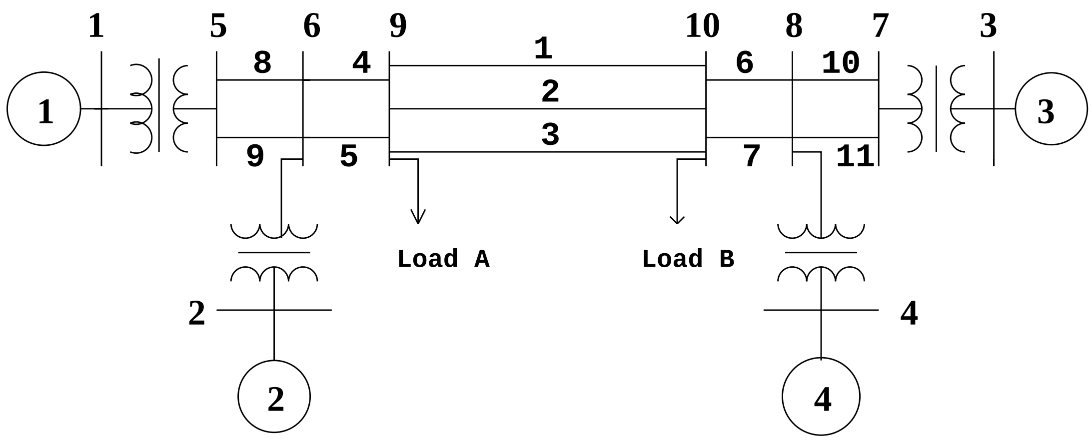


Figure 8.1: Four machine power system.

To run the transient stability programme, the steps to be followed are :

1. Perform the power flow studies by running: `fdlf_loadflow.m` file. It requires the following `.m` and data files:
   (a) `B_bus_form.m`, `fdlf_jacob_form.m`, `powerflow.m` and `lfl_result.m`.
   (b) `busno.dat` : System details- number of lines, buses, transformers, etc
   (c) `nt.dat` : Transmission line and transformer data
   (d) `pvpq.dat` : Generation data and load data.
   (e) `shunt.dat` : Shunt data

On successful run, it generates two output files: `lfl.dat` and `report.dat`. The converged loadflow results are available in `lfl.dat`.

2. Execute the main file: `simpre.m` . This file in turn calls the following two files:

   (a) `initcond.m` : It calculates the initial conditions.

   (b) `yform.m`: It constructs the $Y_{BUS}$.

   The above `.m` files require the following data files:

   (i) `lfl.dat` : Converged loadflow results.
   (ii) `nt.dat` : Transmission line and transformer data.
   (iii) `ld.dat` : Load data.
   (iv) `shunt.dat` : Shunt data.
   (v) `gen.dat` : Generator data.
   (vi) `busno.dat` : System details- number of lines, buses, transformers, etc.
   (vii) `exc_static.dat` : Single-time constant static exciter data .
   (viii) `exc_ST1A.dat` : IEEE ST1A type static exciter data.
   (ix) `exc_ST2A.dat` : IEEE ST2A type static exciter data.
   (x) `exc_AC4A.dat` : IEEE AC4A type AC exciter data.
   (xi) `exc_AC1A.dat` : IEEE AC1A type AC exciter data.
   (xii) `exc_DC1A.dat` : IEEE DC1A type DC commutator exciter data.
   (xiii) `turb_hydro.dat` : Simplified hydro-turbine data.
   (xiv) `turb_nrst.dat` : Non-reheat type steam turbine data.
   (xv) `turb_rhst.dat` : Reheat type steam turbine data.
   (xvi) `slip_pss.dat` : Slip-signal-based PSS data.
   (xvii) `power_pss.dat` : Power-signal-based PSS data.
   (xviii) `freq_pss.dat` : Bus-frequency-signal-based PSS data
   (xix) `delPw_pss.dat` : Delta-P-Omega type PSS data.

3. Then run `transtability.mdl` to perform the transient stability simulation.

### 8.1.1 Format of Data Files

In the following lines the format of each of the data file has been given using 4 machine power system data:

System details:

File name: busno.dat

```
----------------------------------------------------------------------
 3          ---> Slack bus number.
 0.001      ---> Loadflow convergence tolerance.
10          ---> Number of buses in the system.
11          ---> Number of lines.
 4          ---> Number of transformers.
 3          ---> Number of PV buses = (Number of generators - 1).
 0          ---> Q-bit (please set this bit to zero only).
 2          ---> Number of load buses (including loads at PV and slack buses).
 2          ---> Number of shunts.
 1.03       ---> Slack bus voltage magnitude.
 50         ---> Nominal frequency in Hz.
-----------------------------------------------------------------------
```

Network data:

File name:  nt.dat

```
------------------------------------------------------------------------
 From    To        R          X    B (total)/Tap ratio      Remarks
------------------------------------------------------------------------
  9      10      0.022      0.220    0.330                ---Line 1
  9      10      0.022      0.220    0.330                ---Line 2
  9      10      0.022      0.220    0.330                ---Line 3
  9       6      0.002      0.020    0.030                ---Line 4
  9       6      0.002      0.020    0.030                ---Line 5
 10       8      0.002      0.020    0.030                ---Line 6
 10       8      0.002      0.020    0.030                ---Line 7
  5       6      0.005      0.050    0.075                ---Line 8
  5       6      0.005      0.050    0.075                ---Line 9
  7       8      0.005      0.050    0.075                ---Line 10
  7       8      0.005      0.050    0.075                ---Line 11
  1       5      0.001      0.012    1.000 ---> Transformer data starts here.
  2       6      0.001      0.012    1.000
  3       7      0.001      0.012    1.000
  4       8      0.001      0.012    1.000
-------------------------------------------------------------------------
```

Generation and load data:

```
File name:  pvpq.dat
---------------------------------------------------------------------------
Bus No.     Vg/PL0        Pg0/QL0                  Remarks
---------------------------------------------------------------------------
  1          1.03        7.00    ---> Generator buses other than the slack bus
  2          1.01        7.00                are specified as PV buses
  4          1.01        7.00
  9          11.59       2.12    ---> Load data starts here (including loads at
 10          15.75       2.88             PV and slack buses)
---------------------------------------------------------------------------
```

Shunt admittances:

```
File name: shunt.dat
--------------------
Bus No.    G      B
--------------------
  9       0.0    3.0
 10       0.0    4.0
--------------------
```

Converged load flow results:

```
File name: lfl.dat
----------------------------------------------------------------------------------
Bus No.   Vb0           theta0          Pg0            Qg0       PL0     QL0
----------------------------------------------------------------------------------
 1      1.030000       8.215523      7.000000     1.338523     0.00     0.00
 2      1.010000      -1.503809      7.000000     1.591791     0.00     0.00
 3      1.030000       0.000000      7.217178     1.446427     0.00     0.00
 4      1.010000     -10.204916      7.000000     1.807834     0.00     0.00
 5      1.010800       3.661654      0.000000     0.000000     0.00     0.00
 6      0.987533      -6.243121      0.000000     0.000000     0.00     0.00
 7      1.009533      -4.697706      0.000000     0.000000     0.00     0.00
 8      0.984958     -14.944164      0.000000     0.000000     0.00     0.00
 9      0.976120     -14.419101      0.000000     0.000000    11.59     2.12
10      0.971659     -23.291847      0.000000     0.000000    15.75     2.88

-----------------------------------------------------------------------------------
```

Load data:

File name: ld.dat

| Load Bus No. | PL0 | QL0 |
|---|---|---|
| 9 | 11.59 | 2.12 |
| 10 | 15.75 | 2.88 |

Generator data (2.2 model):

File name: gen.dat

| Gen.No. | xd | xdd | xddd | Td0d | Td0dd | xq | xqd | xqdd | Tq0d | Tq0dd | H | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.2 | 0.033 | 0.0264 | 8.0 | 0.05 | 0.190 | 0.061 | 0.03 | 0.4 | 0.04 | 54 | 0 |
| 2 | 0.2 | 0.033 | 0.0264 | 8.0 | 0.05 | 0.190 | 0.061 | 0.03 | 0.4 | 0.04 | 54 | 0 |
| 3 | 0.2 | 0.033 | 0.0264 | 8.0 | 0.05 | 0.190 | 0.061 | 0.03 | 0.4 | 0.04 | 63 | 0 |
| 4 | 0.2 | 0.033 | 0.0264 | 8.0 | 0.05 | 0.190 | 0.061 | 0.03 | 0.4 | 0.04 | 63 | 0 |

NOTE: Armature resistance, $R_a$ is neglected. Generators are identified by their bus numbers to which they are connected.

Single time constant static exciter:

File name: exc_static.dat

| Gen.no. | KA | TA | EFDMIN | EFDMAX |
|---|---|---|---|---|
| 1 | 200 | 0.02 | -6.0 | 6.0 |
| 2 | 200 | 0.02 | -6.0 | 6.0 |
| 3 | 200 | 0.02 | -6.0 | 6.0 |
| 4 | 200 | 0.02 | -6.0 | 6.0 |

IEEE ST1A type exciter:

File name: exc_ST1A.dat

| Gen.no. | Tr | TC | TB | KA | TA | KF | TF | VRMAX | VRMIN | KC | KLR | ILR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.02 | 1.0 | 1.0 | 200 | 0.02 | 0 | 1.0 | 7 | -6.4 | 0.04 | 4.54 | 5 |
| 2 | 0.02 | 1.0 | 1.0 | 200 | 0.02 | 0 | 1.0 | 7 | -6.4 | 0.04 | 4.54 | 5 |
| 3 | 0.02 | 1.0 | 1.0 | 200 | 0.02 | 0 | 1.0 | 7 | -6.4 | 0.04 | 4.54 | 5 |
| 4 | 0.02 | 1.0 | 1.0 | 200 | 0.02 | 0 | 1.0 | 7 | -6.4 | 0.04 | 4.54 | 5 |

IEEE ST2A type exciter:

File name: exc_ST2A.dat

| Gen.no. | KA | TA | KE | TE | KC | KF | TF | VRMAX | VRMIN | KP | KI | EFDMAX |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 120 | 0.15 | 1.0 | 0.5 | 0.65 | 0.05 | 1.0 | 1.2 | -1.2 | 1.19 | 1.62 | 3.55 |
| 2 | 120 | 0.15 | 1.0 | 0.5 | 0.65 | 0.05 | 1.0 | 1.2 | -1.2 | 1.19 | 1.62 | 3.55 |
| 3 | 120 | 0.15 | 1.0 | 0.5 | 0.65 | 0.05 | 1.0 | 1.2 | -1.2 | 1.19 | 1.62 | 3.55 |
| 4 | 120 | 0.15 | 1.0 | 0.5 | 0.65 | 0.05 | 1.0 | 1.2 | -1.2 | 1.19 | 1.62 | 3.55 |

IEEE AC4A type exciter:

File name: exc_AC4A.dat

| Gen.no. | Tr | KA | TA | TC | TB | VIMAX | VIMIN | VRMIN | VRMAX | KC |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.02 | 200 | 0.02 | 1.0 | 10 | 10 | -10 | -4.53 | 5.64 | 0 |
| 2 | 0.02 | 200 | 0.02 | 1.0 | 10 | 10 | -10 | -4.53 | 5.64 | 0 |
| 3 | 0.02 | 200 | 0.02 | 1.0 | 10 | 10 | -10 | -4.53 | 5.64 | 0 |
| 4 | 0.02 | 200 | 0.02 | 1.0 | 10 | 10 | -10 | -4.53 | 5.64 | 0 |

IEEE AC1A type exciter:

```
File name: exc_AC1A.dat
-------------------------------------------------------------------------
Gen. no. Tr    KA   TA   TC TB VAMAX VAMIN VRMAX VRMIN KE  TE   E1  SE1
--------------------------------------------------------------------------
 1     0.02   100 0.02  1  1  14.5 -14.5  6.03 -5.43  1  0.8  3.14  0.03
 2     0.02   100 0.02  1  1  14.5 -14.5  6.03 -5.43  1  0.8  3.14  0.03
 3     0.02   100 0.02  1  1  14.5 -14.5  6.03 -5.43  1  0.8  3.14  0.03
 4     0.02   100 0.02  1  1  14.5 -14.5  6.03 -5.43  1  0.8  3.14  0.03
--------------------------------------------------------------------------
---------------------------------
  E2     SE2    KF   TF  KD    KC
---------------------------------
  4.18   0.1   0.03  1  0.38  0.2
  4.18   0.1   0.03  1  0.38  0.2
  4.18   0.1   0.03  1  0.38  0.2
  4.18   0.1   0.03  1  0.38  0.2
----------------------------------
```

IEEE DC1A type exciter:

```
File name: exc_DC1A.dat
--------------------------------------------------------------------------
 Gen. no. Tr   KA     TA   TC TB VRMAX VRMIN   KE    TE      E1    SE1
---------------------------------------------------------------------------
  1     0.02   20    0.06  1  1   6.0  -6.0 -0.0485  0.250  3.5461  0.08
  2     0.02   20    0.06  1  1   6.0  -6.0 -0.0633  0.405  0.9183  0.66
  3     0.02   20    0.06  1  1   6.0  -6.0 -0.0198  0.500  2.3423  0.13
  4     0.02   20    0.06  1  1   6.0  -6.0 -0.0525  0.500  2.8681  0.08
---------------------------------------------------------------------------
--------------------------
     E2    SE2   KF   TF
--------------------------
  4.7281 0.260 0.040 1.0
  1.2244 0.880 0.057 0.5
  3.1230 0.340 0.080 1.0
  3.8241 0.314 0.080 1.0
---------------------------
```

Speed-governor for hydro-turbine:

```
File name: turb_hydro.dat
----------------------------------------------------
 Gen. no. TW    TG   SIGMA  T2   PMAX_fac   PMIN_fac
 ---------------------------------------------------
   1       1    0.2   0.05   0      1.1       0.1
   2       1    0.2   0.05   0      1.1       0.1
   3       1    0.2   0.05   0      1.1       0.1
   4       1    0.2   0.05   0      1.1       0.1
----------------------------------------------------
```

Speed-governor for steam turbine- non reheat type:

```
File name: turb_nrst.dat
----------------------------------------------------
 Gen.no. TCH  SIGMA   T1   T2  T3  PMAX_fac  PMIN_fac
-----------------------------------------------------
   1     0.2  0.05   0.2  0.0  0.1    1.1     0.1
   2     0.2  0.05   0.2  0.0  0.1    1.1     0.1
   3     0.2  0.05   0.2  0.0  0.1    1.1     0.1
   4     0.2  0.05   0.2  0.0  0.1    1.1     0.1
-----------------------------------------------------
```

Speed-governor for steam turbine- reheat type:

```
File name: turb_rhst.dat
-----------------------------------------------------------------------------
Gen.no. T1  T2   T3   SIGMA  PMAX_fac  PMIN_fac  TCH  TRH  TCO  FHP  FIP  FLP
-----------------------------------------------------------------------------
  1    0.2  0.0  0.1  0.05    1.1        0.1      0.3   10  0.4  0.3  0.3  0.4
  2    0.2  0.0  0.1  0.05    1.1        0.1      0.3   10  0.4  0.3  0.3  0.4
  3    0.2  0.0  0.1  0.05    1.1        0.1      0.3   10  0.4  0.3  0.3  0.4
  4    0.2  0.0  0.1  0.05    1.1        0.1      0.3   10  0.4  0.3  0.3  0.4
-----------------------------------------------------------------------------
```

NOTE: The data files `turb_hydro.dat, turb_nrst.dat` and `turb_rhst.dat` should not contain any entries for generators whose `Pg0` = 0.

Slip-signal PSS:

```
File name: slip_pss.dat
--------------------------------------------
Gen.no. KS   TR   TW   T1   T2  VSMAX  VSMIN
--------------------------------------------
  1      5  0.05  10  0.1  0.05  0.1   -0.1
  2      5  0.05  10  0.1  0.05  0.1   -0.1
  3      5  0.05  10  0.1  0.05  0.1   -0.1
  4      5  0.05  10  0.1  0.05  0.1   -0.1
--------------------------------------------
```

Power-signal PSS:

```
File name: power_pss.dat
-------------------------------------
Gen.No.  TW   TR    KS  VSMAX  VSMIN
-------------------------------------
  1      10  0.05  0.07  0.1   -0.1
  2      10  0.05  0.07  0.1   -0.1
  3      10  0.05  0.07  0.1   -0.1
  4      10  0.05  0.07  0.1   -0.1
-------------------------------------
```

Bus frequency-signal PSS:

```
File name: freq_pss.dat
--------------------------------------------
Gen.no. TW   TR   KS   T1   T2  VSMAX  VSMIN
--------------------------------------------
  1     10  0.02  5   0.1  0.05  0.1    0
  2     10  0.02  5   0.1  0.05  0.1    0
  3     10  0.02  5   0.1  0.05  0.1    0
  4     10  0.02  5   0.1  0.05  0.1    0
--------------------------------------------
```

Delta-omega PSS:

File name: delPw_pss.dat

| Gen.No. | Tw1 | Tw2 | Tw3 | Tw4 | T6 | T7 | H | KS3 | T8 | T9 | T1 | T2 | KS1 | VSMAX | VSMIN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 10 | 10 | 10 | 0.01 | 10 | 54 | 1 | 0 | 0.1 | 0.1 | 0.05 | 10 | 0.1 | -0.1 |
| 2 | 10 | 10 | 10 | 10 | 0.01 | 10 | 54 | 1 | 0 | 0.1 | 0.1 | 0.05 | 10 | 0.1 | -0.1 |
| 3 | 10 | 10 | 10 | 10 | 0.01 | 10 | 63 | 1 | 0 | 0.1 | 0.1 | 0.05 | 10 | 0.1 | -0.1 |
| 4 | 10 | 10 | 10 | 10 | 0.01 | 10 | 63 | 1 | 0 | 0.1 | 0.1 | 0.05 | 10 | 0.1 | -0.1 |

NOTE:

The parameters of all PSS have been selected for providing adequate damping with single-time constant static/IEEE ST1A type exciters with constant impedance type loads.

### 8.1.2 Component Selectors:

To perform transient stability studies with a variety of exciters, power system stabilizers and turbines, the following kinds of selectors are used:

1. Main Selectors.
2. Individual Selectors.

These selectors permit us to choose a specific type of exciter/PSS/turbine for a given generator. For example, if one wants to select any one type of exciter for a given generator out of 6 different IEEE-type exciters (for which data files have been prepared), it can be carried out by using Individual Selectors without altering the data files. Whereas, the Main Selectors can be used to disable an exciter on a generator without modifying the Individual Selectors.

The Main Selectors are as follows:

| Variable name | Component | Enable | Disable |
|---|---|---|---|
| `AVR` | Exciters | 0 | 1 |
| `TURB` | Turbines | 0 | 1 |
| `PSS` | Power System Stabilizers | 0 | 1 |

NOTE:

These selectors have been provided in file `initcond.m`. The vector size of these variables is equal to the number of buses in a system.

The Individual Selectors are as follows:

1. Individual Selectors for exciters:

```
ng_static   ---> Single-time constant static type exciter.
ng_ST1A     ---> IEEE ST1A type exciter.
ng_ST2A     ---> IEEE ST2A type exciter.
ng_AC4A     ---> IEEE AC4A type exciter.
ng_AC1A     ---> IEEE AC1A type exciter.
ng_DC1A     ---> IEEE DC1A type exciter.
```

Indicate the generator number on which a specific type of exciter is present, otherwise null. For example, if generators 3 and 4 are with single-time constant static type, and generators 1 and 2 are with IEEE ST1A type exciter, then the selectors are initialized as follows:

```
ng_static=[3,4]
ng_ST1A=[1,2]
ng_ST2A=[]
ng_AC4A=[]
ng_AC1A=[]
ng_DC1A=[]
```

The Main Selector, `AVR` is enabled for all exciters as: `AVR = zeros(1,nb)`, where `nb` denotes the number of buses in the system.
NOTE:

(a) Since all the variables used in the SIMULINK file `transtability.mdl` are to be initialized, it is necessary to prepare the data file for IEEE ST2A, IEEE AC4A, IEEE AC1A and IEEE DC1A type exciters atleast for one machine. One may use typical data for the same. However, the respective exciter output is not used in the programme.

(b) If it is required to enter a large set of generator numbers to initialize the Individual Selectors, one can list the generator numbers in a file `ng_****.dat` and use the `load ng_****.dat` command. This has to be done after commenting out the corresponding initialization command as `%ng_**** = [...]` in file `initcond.m`.

(c) If classical model is used for a machine, then it is better to disable the exciter of that machine by using the Main Selector, `AVR`.

2. Individual Selectors for turbines:

```
ng_hydro   ---> Hydro-turbines.
  ng_nrt   ---> Non-reheat type steam turbines.
  ng_rht   ---> Reheat type steam turbines.
```

The procedure to initialize these selectors is the same as that described for the exciters. For example, if generators 1 and 2 are with hydro-turbines, and generator 3 is with reheat type steam turbine, and no prime-mover control on generator 4, then the selectors are initialized as follows:

```
ng_hydro =[1,2]
  ng_nrt =[]
  ng_rht =[3]
```

In addition, by using the Main Selector, `TURB` the turbine on machine 4 is disabled. NOTE:

(a) To initialize the variables pertaining to non-reheat type steam turbines, it is necessary to prepare the data file using typical data for any one machine. However, the respective turbine output is not used in the programme.

(b) If it is required to enter a large set of generator numbers to initialize the Individual Selectors, one can list the generator numbers in a file `ng_****.dat` and use the `load ng_****.dat` command. This has to be done after commenting out the corresponding initialization command as `%ng_**** = [...]` in file `initcond.m`.

3. Individual Selectors for power system stabilizers:

```
 ng_slip_pss   ---> Slip signal based PSS.
ng_power_pss   ---> Power signal based PSS.
 ng_freq_pss   ---> Frequency signal based PSS.
ng_delPw_pss   ---> Delta-P-Omega signal based PSS.
```

The procedure to initialize these selectors is the same as that described for the exciters. For example, if generator 2 alone is with slip-signal based PSS, then the selectors are initialized as follows:

```
 ng_slip_pss=[2]
ng_power_pss=[]
 ng_freq_pss=[]
ng_delPw_pss=[]
```

The Main Selector, `PSS` may be set to enable the PSS only on machine 2 or it may be set as `PSS = zeros(1,nb)`.
NOTE:

(a) To initialize the variables pertaining to power, frequency and delta-P-omega signal based PSS, it is necessary to prepare the data files using typical data for any one machine. However, the respective PSS outputs are not used in the programme.

(b) If it is required to enter a large set of generator numbers to initialize the Individual Selectors, one can list the generator numbers in a file `ng_****.dat` and use the `load ng_****.dat` command. This has to be done after commenting out the corresponding initialization command as `%ng_**** = [...]` in file `initcond.m`.

(c) The Main Selector, `PSS` is normally used to disable any PSS without changing the Individual Selectors.

### 8.1.3 Load Modelling

Both real and reactive components of loads are modelled following polynomial approach. The composition of real and reactive components can be specified in a file `load_zip_model.m` as follows:

1. Real component of load:

```
p1 ---> fraction for constant power.
p2 ---> fraction for constant current.
p3 ---> fraction for constant impedance.
```

   For example, if real power component is to be modelled as 30% constant power, 30% constant current and 40% constant impedance type, then the fractions are set as follows:

```
p1 = 0.3;
p2 = 0.3;
p3 = 0.4;
```

2. Reactive component of load:

```
r1 ---> fraction for constant power.
r2 ---> fraction for constant current.
r3 ---> fraction for constant impedance.
```

For example, if reactive power component is to be modelled as constant impedance type, then the fractions are set as follows:

```
r1 = 0;
r2 = 0;
r3 = 1;
```

The frequency dependency of loads are accounted by specifying the following variables in file `yform.m`:

```
kpf = 1.5;
kqf = 2.0;
```

### 8.1.4 A Sample Run

Consider the following case:

A 3-phase bolted fault is applied at time $t = 0.5$ s at bus 9. This fault persists for a duration of 0.1 s and is cleared by tripping line 1 (9-10) (see file `nt.dat`).

The above case is simulated by using the following steps:

1. Prepare the data files as indicated in the previous sections.

2. Initialize the Main and Individual Selectors in file `initcond.m`

3. Execute `simpre.m`. The statements displayed in the MATLAB Command Window and the respective inputs are shown below:

```
If NO action is to be taken, PRESS ENTER for every prompt.

Fault initiation time (s), Tfault = 0.5
Fault Duration,(s) Tclear= 0.1
Faulted Bus: 9
Line(s) to be tripped, [ , ]= 1
```

4. Open `transtability.mdl` and start the simulation.

After the simulation stops, the following variables are available in the Command Window for plotting:

```
COI          ---> COI reference.
delta_COI    ---> Rotor angles wrt to COI reference.
Efd_var      ---> Variation of Efd.
```

```
Vbus        ---> Bus voltages.
Vs          ---> PSS output.
Tm_out      ---> Turbine output.
If_var      ---> Generator field currents.
time        ---> Time coordinates.
```

Following figures display the variation of different variables with respect to time.

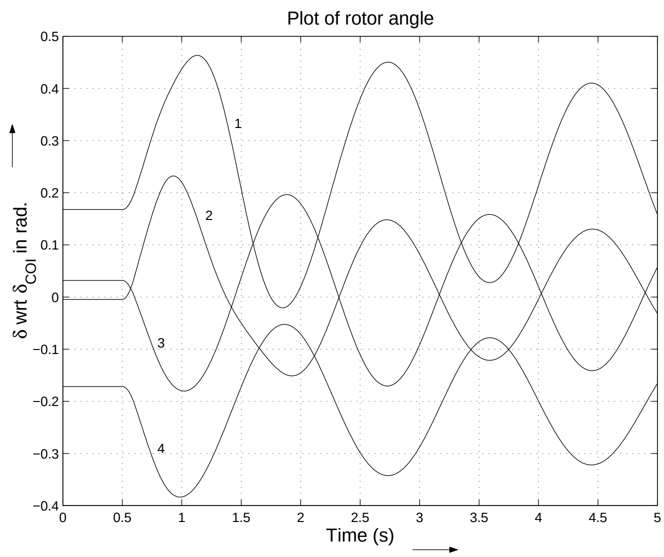


Figure 8.2: Variation of rotor angles with respect to COI reference (4 m/c system).

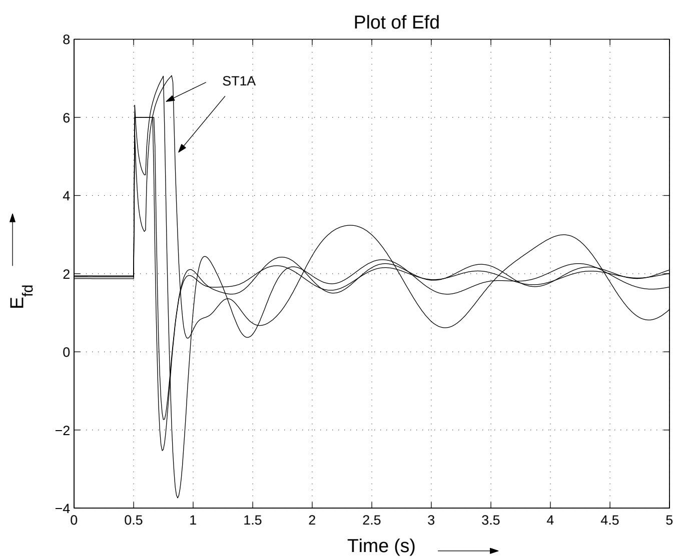


Figure 8.3: Variation of $E_{fd}$ (4 m/c system).

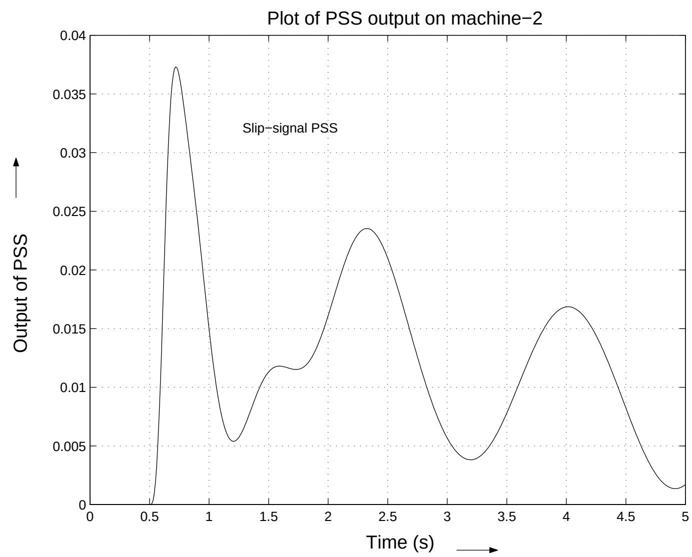


Figure 8.4: Variation of PSS output (4 m/c system).

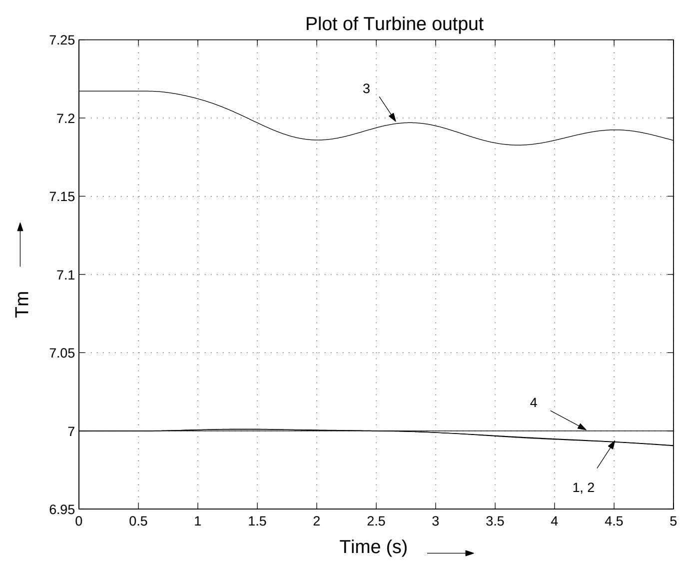


Figure 8.5: Variation of Turbine output (4 m/c system).

## 8.2 Single Machine Infinite System

The single line diagram of SMIB power system is shown in Figure 8.6. The system details are adopted from Example 6.6 in [1].

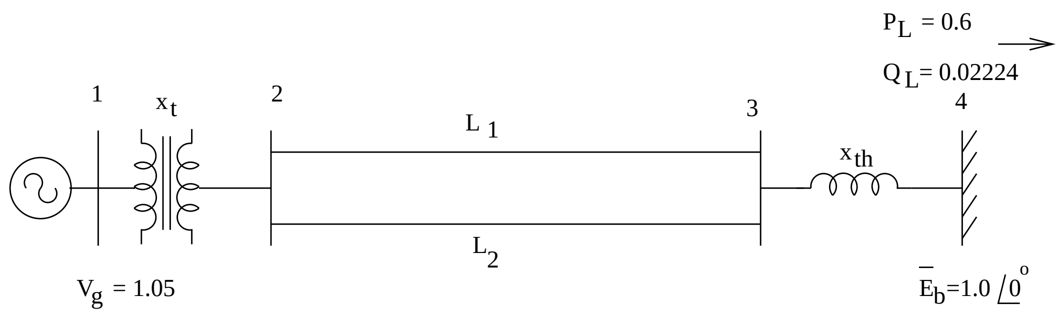


Figure 8.6: SMIB power system.

The system details are as follows:

Generator: $x_d = 1.7572$, $x_d^{'} = 0.4245$, $T_{do}^{'} = 6.66$ s, $x_q = 1.5845$, $x_q^{'} = 1.0400$,
$T_{qo}^{'} = 0.44$ s, $H = 3.542$, $f_o = 50$ Hz, $D = 0$

Exciter : Single-time constant static exciter, $K_A = 400$, $T_A$ =0.025 s, $Efd_{limits} = \pm\ 6$

Transformer: $x_t = 0.1364$

Lines: $R = 0.08593$, $x_L = 0.81250$ and $B_c = 0.1184$, $x_{th} = 0.13636$

Loads: Constant impedance type.

A three phase fault is applied at bus 2 at time $t = 1$ s and is cleared by tripping the line $L_1$. For a fault clearing time of 0.08 s, the variation of the rotor angle is as shown in Figure 8.7. It can be seen from the figure that the post fault system is small signal unstable.

For the above case, a slip-signal-based PSS has been used (with the typical data) to make the post fault system stable. The respective rotor angle plot is depicted in Figure 8.8.

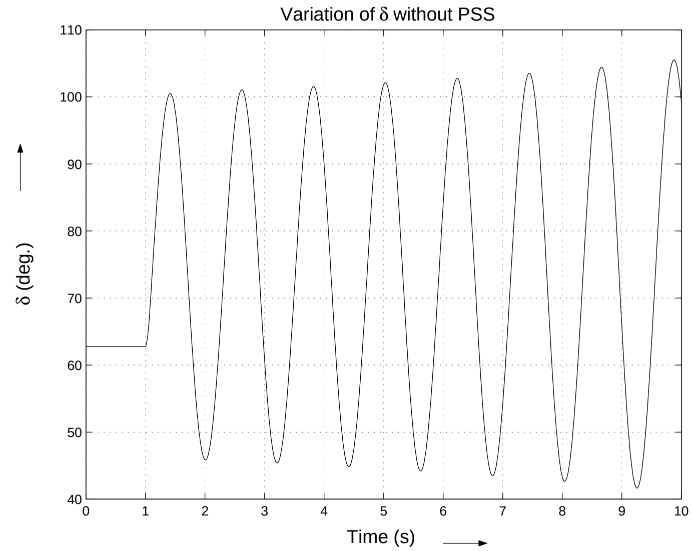


Figure 8.7: Variation of rotor angle without PSS (SMIB system).

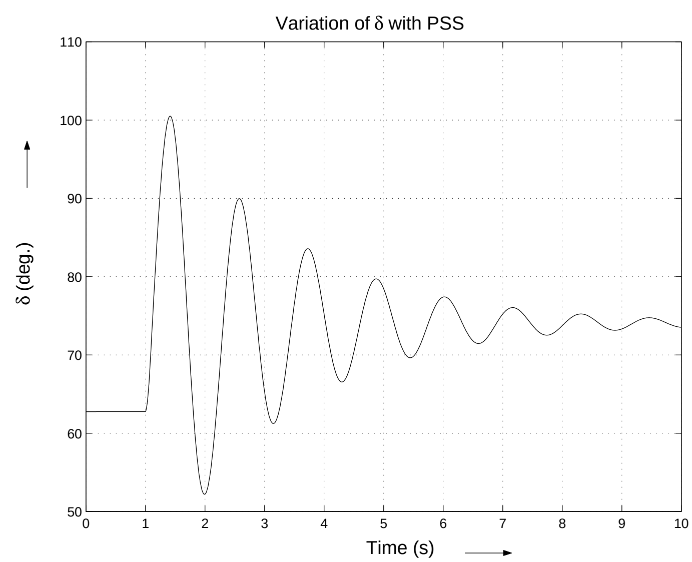


Figure 8.8: Variation of rotor angle with PSS (SMIB system).

## 8.3 50 Machine IEEE System:

The data for a 50 machine IEEE system has been obtained following the web link [11]. This system has 145 buses, 401 lines, 52 transformers, 64 loads and 97 shunts. Out of 50 generators, 44 generators are with classical model and the rest 6 generators are with 1.1 model. These 6 generators are provided with IEEE-type AC4A exciters. To demonstrate the applicability of the developed programme, a three phase fault is applied at time $t = 0.5$ s at bus 7 and is cleared by tripping line 6-7 ($8^{th}$ entry in file `nt.dat`). The loads are modelled as constant impedance type. For a fault clearing time of 0.143 s (Tcr), the rotor angle plots are shown in Figure 8.9.

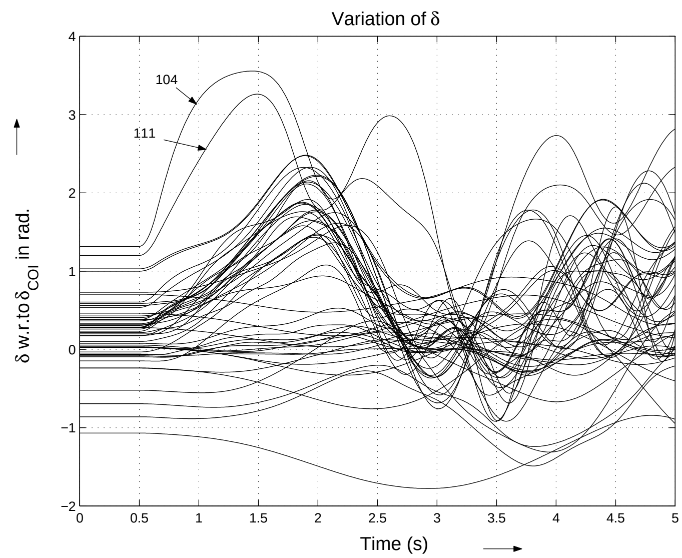


Figure 8.9: Variation of rotor angle (50 m/c system).

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