System Stability of Synchronous Machine with Small Signal Representation including Rotor Circuit Dynamics

S.Padhi[1], B.P.Mishra[2]

[1]Assistant Professor, Dept. of Electrical Engg.,OEC, Bhubaneswar

[2]Associate Professor, Dept. of Electronics Engg., DRIEMS, Cuttack

ABSTRACT

In an interconnected power system, continuously growing in size and extending over vast geographical regions it becomes very difficult to maintain synchronism between various parts of power system. In this paper, the focus is made on small signal performance of a synchronous machine connected to a large system through transmission lines. The model detail is gradually increased by accounting for the effects of the dynamics of the field circuit. By using Eigen value, analysis has been made about the small signal performance.

Keywords:- Stability, Field Circuit Dynamics, Synchronous Machine, State Matrix, Field Flux Linkage etc.

1. INTRODUCTION

Successful operation of a power system depends on the ability to provide reliable and uninterrupted service to the loads. The first requirement is to keep the synchronous generators running in parallel and with adequate capacity. Synchronous machines do not easily fall out of step under normal conditions. Conditions do arise, however, such as a fault on the network, failure in a piece of equipment, sudden application of a major load may not be adequate, and small impacts in the system may cause these machines to lose synchronism. A second requirement is to maintain the integrity of the power network. Interruptions in the transmission system may hinder the flow of power to the load. This usually requires a study of large geographical areas since almost all power systems are interconnected with neighboring systems.

2. SMALL SIGNAL STABILITY

Small signal stability is the ability of the power system to maintain synchronism when subjected to small disturbances. Here we study the small-signal performance of a machine connected to a large system through transmission lines. A equivalent system configuration is shown below in Fig.1 which is equivalent of the transmission network external to the machine and adjacent transmission.

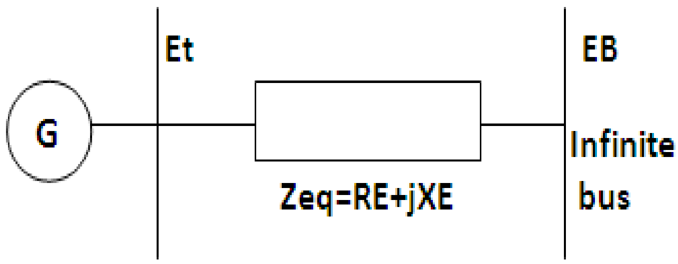

Figure 1: Small Signal Studies of equivalent system

By gradually increasing the model detail by accounting for the effects of the dynamics of the field circuit and excitation systems, the development of the expressions for the elements of the state matrix as explicit functions of system parameters. It is useful in gaining a physical insight into the effects of field circuit dynamics and in establishing the basis for methods of enhancing stability through excitation control.

3. EFFECT OF FIELD CIRCUIT DYNAMICS

The system performance is considered including the effect of the field flux variations. The field voltage is assumed constant (manual excitation control). The state-space model of the system is developed by first reducing the synchronous machine equations to an appropriate form and then combining them with the network equations. Time is expressed in seconds, angles in electrical radians and all other variables in per unit.

3.1 Equations for Synchronous Machine

The rotor angle δ is the angle (in electrical radian) by which the q-axis leads the reference EB. The equivalent circuits relating the machine flux linkages and current are as shown min Fig. 2.

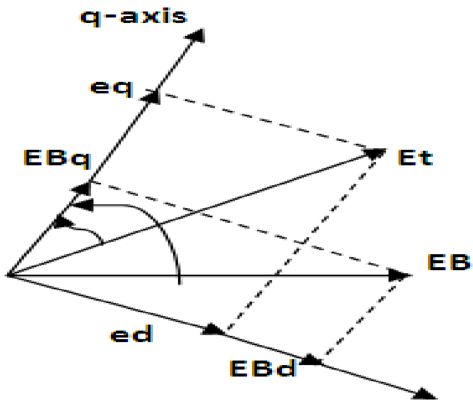

Figure 2: Rotor angle & EB representation

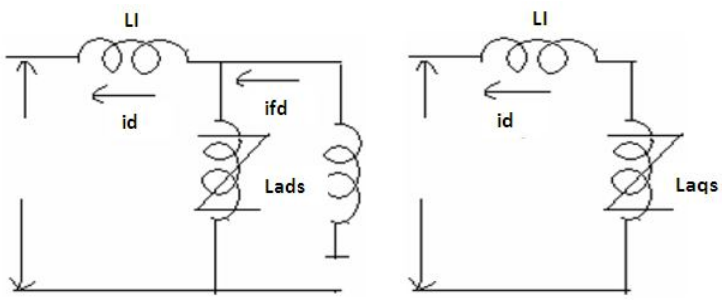

Figure 3: Equivalent circuit for Machine Flux Linkages & Current

The Stator and Rotor flux linkage are given by:

$$\Psi_d = -L_1 i_d + \Psi_{ad} \qquad (1)$$

$$\Psi_q = -L_1 i_q + \Psi_{aq} \qquad (2)$$

$$\Psi_{fd} = L_{fd} i_{fd} + \Psi_{ad} \qquad (3)$$

In the above equations Ψ_{ad} and Ψ_{aq} are the air-gap (mutual) flux linkages and L_{fd} is the saturated value of mutual inductance.

The field current:

$$i_{fd} = (\Psi_{fd} - \Psi_{ad})/L_{fd} \qquad (4)$$

The d-axis mutual flux linkage in terms of Ψ_{fd} and i_d is,

$$\Psi_{ad} = L'_{ads}(-i_d + \Psi_{fd})/L_{fd} \qquad (5)$$ Where

$$L'_{ads} = 1/(1/L_{ads} + 1/L_{fd}) \qquad (6)$$

Since there is no rotor circuit considered in the q-axis, the mutual flux linkage is given by,

$$\Psi_{aq} = -L_{aqs} * i_q) \qquad (7)$$

The air-gap torque is,

$$T_e = \Psi_{ad} * i_q - \Psi_{aq} * i_d \qquad (8)$$

With $p\Psi$ terms and speed variations neglected the stator voltage equations become,

$$e_d = -R_a i_d + (L_1 i_q - \Psi_{aq}) \qquad (9)$$

$$e_q = -R_a i_d + (L_1 i_d - \Psi_{ad}) \qquad (10)$$

3.2 Network Equations

Since there is only one machine, the machine as well as network equations can be expressed in terms of one reference frame, ie. d-q reference frame of the machine. Referring to Figure, the machine terminal and infinite bus voltages in terms of the d and q components are:

$$E_t = e_d + je_q \quad (11)$$
$$E_B = E_{BD} + jE_{bq} \quad (12)$$
$$E_t = E_B + (R_E + jX_E)I_t \quad (13)$$
$$e_d + je_q = (E_{BD} + jE_{bq}) + (R_E + jX_E)(i_d + ji_q) \quad (14)$$
$$e_d = R_E i_d - X_E i_q + E_{Bd} \quad (15)$$
$$e_q = R_E i_d - X_E i_d + E_{Bq} \quad (16)$$

Where

$$E_{Bd} = E_B sin\delta \quad (17)$$
$$E_{Bq} = E_B cos\delta \quad (18)$$

Using equations and to eliminate e_d , e_q in equations and using the expressions for Ψ_{ad} and Ψ_{aq} given by equations and the following expressions are obtained for i_d and i_q in terms of state variables Ψ_{fd} and δ.

$$i_d = (X_{tq}[\Psi_{fd}\left(\frac{L_{ads}}{L_{ads}+L_{fd}} - E_B cos\delta\right] - R_T E_B sin\delta)/D \quad (19)$$
$$i_q = (R_T[\Psi_{fd}\left(\frac{L_{ads}}{L_{ads}+L_{fd}} - E_B cos\delta\right] - X_{Td} E_B sin\delta)/D \quad (20)$$

The reactance is saturated values and in per unit they are equal to the corresponding inductances.

3.3 Linearized System Equations

Expressing equations and in terms of perturbed values, we may write,

$$\Delta_{id} = m_1\Delta\delta + m_2\Delta\Psi_{fd} \quad (21)$$
$$\Delta_{iq} = n_1\Delta\delta + n_2\Delta\Psi_{fd} \quad (22)$$

Where,

$$m_1 = E_B(X_{T0} sin\delta_0 - R_T cos\delta_0)/D \quad (23)$$
$$n_1 = E_B(R_T sin\delta_0 - X_{Td} cos\delta_0)/D \quad (24)$$
$$m_2 = \left(\frac{X_{Tq}}{D}\right) * \frac{L_{ads}}{L_{ads}+L_{fd}} \quad (25)$$
$$n_2 = \left(\frac{R_T}{D}\right) * \frac{L_{ads}}{L_{ads}+L_{fd}} \quad (26)$$

By linearizing equations (5) & (7) and substituting them in the above expressions for Δ_{id} and Δ_{iq} we get,

$$\Delta\Psi_{ad} = \left(\frac{1}{L_{fd}} - m_2\right)L'_{ads}\Delta\Psi_{fd} - m_2 L'_{ads}\Delta\delta \quad (27)$$
$$\Delta\Psi_{aq} = -n_2 L_{ads}\Delta\Psi_{fd} - n_1 L_{ads}\Delta\delta \quad (28)$$

Linearizing equation (4) and substituting for $\Delta\Psi_{ad}$ from equation (27) gives,

$$\Delta i_{fd} = \left(1 - \frac{L'_{ads}}{L_{fd}} + mL'_{ads}\right)\Delta\Psi_{fd}/L_{fd} \quad (29)$$

The Linearized form of equation (8) is,

$$\Delta T_e = \Psi_{ad0}\Delta i_q + i_{q0}\Delta\Psi_{ad} - \Psi_{aq0}\Delta i_d + i_{d0}\Delta\Psi_{aq} \quad (30)$$

Substituting for Δ_{id}, Δ_{iq}, $\Delta\Psi_{ad}$ and Ψ_{aq} from equations (21) to (28), we obtain

$$\Delta T_e = K_1\Delta\delta + K_2\Delta\Psi_{fd} \quad (31)$$

Where,

$$K_1 = n_1(\Psi_{ad0} + L_{aqs}i_{d0}) - m_1(\Psi_{aq0} + L'_{ads}i_{q0}) \quad (32)$$
$$K_2 = n_2(\Psi_{ad0} + L_{aqs}i_{d0}) - m_2(\Psi_{aq0} + L'_{ads}i_{q0}) + L'_{ads}/L_{fd}i_{q0} \quad (33)$$

By using the expressions for Δi_{fd} and ΔT_e given by equations (29) and (31), we obtain the system equations in the desired final form:

$$a_{11} = \frac{-K_D}{2H}, a_{12} = \frac{-K_1}{2H}, a_{13} = \frac{-K_2}{2H} \quad (34)$$

$$a_{21} = \omega_0 = 2\pi f_0, a_{32} = -(\omega_0 R_{fd}/L_{fd}) m_1 L'_{ads} \quad (35)$$

$$a_{33} = -\omega_0 R_{fd}/L_{fd}[1 - \frac{L'_{ads}}{L_{fd}} + L_{fd} L'_{ads} \quad (36)$$

$$b_{11} = \frac{1}{2H}, b_{32} = \omega_0 R_{fd}/L_{ad0} \quad (37)$$

and ΔT_m and ΔE_{fd} depends on prime-mover and excitation controls. With constant mechanical input $t\Delta T_m = 0;$ with constant exciter output voltage $\Delta E_{fd} = 0$. The mutual inductances in the above equations are saturated values.

3.4 Representation of Saturation in Small Signal Studies

Total saturation is associated with total values of flux linkages and currents. Incremental saturation is associated with perturbed values of flux linkages and currents. Therefore, the incremental slope of the saturation curve is used in computing the incremental saturation as shown in figure. Denoting the incremental saturation factor $K_{sd(incr)}$, we have

$$L_{ads(incr)} = K_{sd(incr)} L_{adu} \quad (38)$$

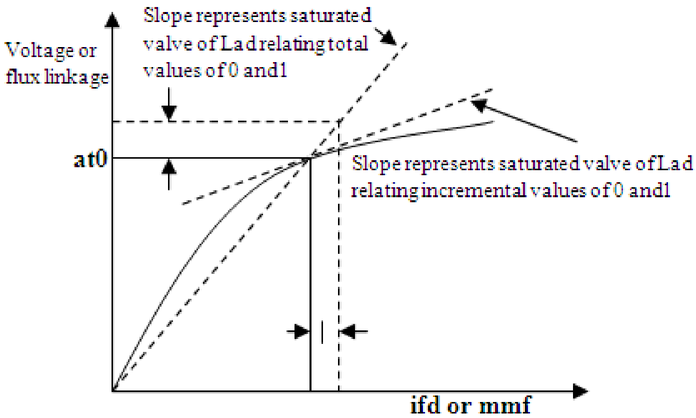

Figure 4: Distinction between incremental & total saturation

3.5 Formulating the State Matrix

a) The following steady-state operating conditions, machine parameters and network parameters are given:
Pt Qt Et RE XE
Ld Lq Ll Ra Lfd Rfd Asat Bsat ΨT1
Alternatively E_B may be specified instead of Q_t or E_t.

b) The first step is to compute the initial steady-state values of system variables:
It, power factor angle Φ, Total saturation factors Ksd and Ksq
Xds = Lds = Ksd Ladu + Ll
Xqs = Lqs = Ksq Laqu + Ll
δi = tan-1((It Xqs cosΦ – It Ra sinΦ)/(Et + It Ra cosΦ – It Xqs sinΦ))
ed0 = Et sinδi
eq0 = Et cosδi
id0 = It sin(δi+Φ)
iq0 = It cos(δi+Φ)
EBd0 = ed0 – REid0+XEiq0
EBq0 = eq0 – REiq0+XEid0
δ0 = tan-1(EBd0/ EBq0)
$EB = (EBd0^2 + EBq0^2)^{1/2}$
ifd0 = (eq0 + Raiq0 + Ldsido)/Lads
Efd0 = Ladu ifd0

Ψad0 = Lads(-id0+ifd0)
Ψaq0 = -Laqsiq0

c) The next step is to compute incremental saturation factors and the corresponding Saturated values of Lads, Laqs, L'ads and then,
RT, XTq, XTd, D
m1, m2, n1, n2
K1, K2

d) Finally, compute the elements of matrix A from equation (34-37).

4. BLOCK DIAGRAM REPRESENTATION

Figure.5 shows the block diagram representation of the small-signal performance of the system. In this representation, the dynamic characteristics of the system are expressed in terms of the so-called K constants. The basis for the block diagram and the expressions for the associated constants are developed below.

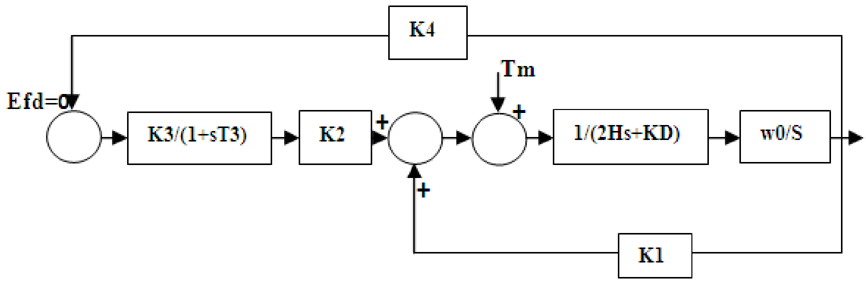

Figure 5: Block Diagram Representation of Small Signal Performance

From equation (32) we may express the change in air-gap torque as a function of Δδ and ΔΨfd as follows:

$$\Delta T_e = K_1 \Delta\delta + K_2 \Delta\Psi_{fd}$$

Where K1= ΔTe/ Δδ with constant Ψfd
K2= ΔTe/ ΔΨfd with constant rotor angle δ

The component of torque given by K1 Δδ is in phase with Δδ and hence represents a synchronizing torque component. The component of torque resulting from variations in field flux linkage is given by K2ΔΨfd. The variation of Ψfd is determined by the field circuit dynamic equation.

$$p\Delta\Psi_{fd} = a_{32}\Delta\delta + a_{33}\Delta\Psi_{fd} + b_{32}\Delta E_{fd}$$

By grouping terms involving ΔΨfd and rearranging, we get

$$\Delta\Psi_{fd} = K_3(\Delta E_{fd} - K_4\Delta\delta)/(1 + pT_3)$$

4.1 K-constants in the expanded form

Expression for K constants in terms of the elements of matrix A is made. In the literature, they are usually expressed explicitly in terms of the various system parameters. The constants can be computed are :

$$K_1, K_2, K_3, K_4, a_{32}, a_{33} \,\&\, T_3$$

If the elements of matrix A are available, the K constants may be computed directly from them. The expanded forms are derived here to illustrate the form of expressions used in the literature. An advantage of these expanded forms is that the dependence of the K constants on the various system parameters is more readily apparent. A disadvantage, however, is that some inconsistencies appear in representing saturation effects.

4.2 Effect of field flux linkage variation on system stability

It was seen from the block diagram of figures that, with constant field voltage (ΔEfd =0), the field flux variations are caused only by feedback of Δδ through the coefficient K4. This represents the demagnetizing effect of the armature reaction. The change in air-gap torque due to field flux variations caused by rotor angle changes is given by:

$$(\Delta T_e/\Delta\delta)\, due\ to\ \Delta\Psi_{fd} = -K_2K_3K_4/(1 + sT_3)$$

The constants K2, K3 and K4 are usually positive. The condition of ΔΨd to synchronizing and damping torque components depends on the oscillating frequency as discussed below.

(a) In the steady state and at very low oscillating frequencies (s = jω→0):

ΔTe due to ΔΨfd = -K2K3K4 Δδ

The field flux variation due to Δδ feedback (i.e. , due to armature reaction) introduces a negative synchronizing torque component. The system becomes monotonically unstable when this exceeds K1 Δδ. The steady state stability limit is reached when

$$K2K3K4 = K1$$

(b) At oscillating frequencies much higher than 1/T3

$$\Delta Te \approx -K2K3K4\ \Delta\delta / j\omega T3$$
$$= K2K3K4\ j\ \Delta\delta / \omega T3$$

Thus, the component of air-gap torque due to $\Delta\Psi fd$ is 90o ahead of $\Delta\delta$ or in phase with $\Delta\omega$. Hence, $\Delta\Psi fd$ results in a positive damping torque component.

(c) At typical machine oscillating frequencies of about 1 Hz (2 rad/s), $\Delta\Psi fd$ results in a positive damping torque component and a negative synchronizing torque component. The net effect is to reduce slightly the synchronizing torque component and increase the damping torque component.

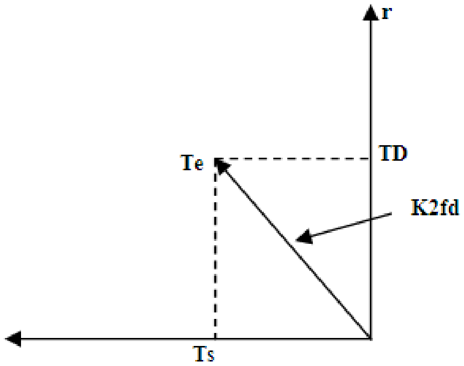

Figure 6: Positive damping torque and negative synchronizing torque due to K2ΔΨfd

4.3 Special situations with K4 negative

The coefficient K4 is normally positive. As long as it is positive, the effect of field flux variation due to armature reaction ($\Delta\Psi fd$ with constant Efd) is to introduce a positive torque component. However, there can be situations where K4 is negative. From the expression given by Equation:

K4 is negative when $(XE+XQ)\sin\delta 0 - (Ra + RE)\cos\delta 0$ is negative.

This is the situation when a hydraulic generator without damper windings is operated at light load and is connected by a line of relatively high resistance to reactance ratio to a large system Also K4 can be negative when a machine is connected to a large local load, supplied partly by the generator and partly by the remote large system. Under such conditions, the torques produced by induced currents in the field due to armature reaction have components out of phase with $\Delta\ \omega$, and produce negative damping.

5. STEPS TAKEN FOR SIMULATION

The analysis of small-signal stability of the system can be carried out for the figure.7 , Thermal Generating Station. Including the effects of the generator field circuit dynamics. The parameters of each of the four generators of the plant in pu on its rating.

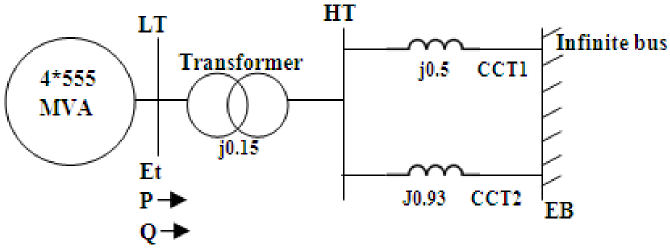

Figure 7: Thermal generating station

The elements of the state matrix A representing the small signal performance of the system. The constants K1 to K4 and T3 associated with the block diagram representation of figure. Eigen values of A and the corresponding Eigen vectors and participation matrix; frequency and damping ratio of the oscillatory mode. Steady state synchronizing torque coefficient, damping and synchronizing torque coefficients at the rotor oscillating frequency.

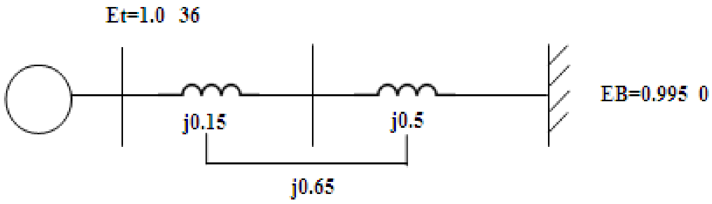

Figure 8: Equivalent Circuit model of the System

6.RESULT ANALYSIS

State matrix A

A =

0	-0.1094	-0.1236
376.9911	0	0
0	-0.1942	-0.4229

Eigen vectors matrix

V =

-0.0003 + 0.0170i	-0.0003 - 0.0170i	0.0004
0.9994	0.9994	-0.7485
-0.0015 + 0.0302i	-0.0015 - 0.0302i	0.6631

Participation matrix

P =

0.5005 - 0.0085i	0.5005 + 0.0085i	-0.0011 - 0.0000i
0.5005 - 0.0085i	0.5005 + 0.0085i	-0.0011 - 0.0000i
-0.0011 + 0.0171i	-0.0011 - 0.0171i	1.0022 + 0.0000i

Steady-state synchronizing torque coefficient Ks = 0.368
Synchronizing torque coefficient at rotor oscillating frequency Ksrf = 0.764
Damping coefficient at rotor oscillating frequency Kdrf = 1.531
Undamped natural frequency of the oscillatory mode Wn = 6.413
Damping ratio of the oscillatory mode Ep = 0.017

7. CONCLUSIONS

For a given clearing angle, as the maximum power limit of the various power angles is raised, it adds to the transient stability limit of the system. The maximum steady power of a system can be increased by raising the voltage profile of a system and by reducing the transfer reactance. Thus it was observed that by considering the effect of rotor circuit dynamics, the study of model in greater details. The expressions were developed for the elements of the state matrix as explicit functions of system parameters. In addition to the state-space representation, block diagram representation was taken into consideration to analyze the system stability characteristics. While this approach is not suited for a detailed study of large systems, it is useful in gaining a physical insight into the effects of field circuit dynamics and in establishing the basis for methods of enhancing stability through excitation control.

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