ESTIMATION OF EXACT EQUIVALENT PARAMETERS OF SYNCHRONOUS MACHINES FOR POWER SYSTEM STUDIES

A Project Report Submitted in partial fulfillment of the

requirements for the degree of

Bachelor of Technology in Electrical Engineering

By

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<u>CERTIFICATE</u>

This is to certify that the project entitled "**ESTIMATION OF EXACT EQUIVALENT PARAMETERS OF SYNCHRONOUS MACHINES FOR POWER SYSTEM STUDIES**" submitted by **Ms. Garima Gupta (Roll No. 10602068) and Mr. Alok Ranjan Dhara (Roll No. 10602037)** was in partial fulfillment of the requirements for the award of **Bachelor of Technology Degree** in **Electrical Engineering** at **NIT Rourkela** is an authentic work carried out by them under my supervision and guidance.

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ACKNOWLEDGEMENT

We would like to thank NIT Rourkela for giving us the opportunity to use their resources and work in such a challenging environment. .

We would like to articulate our profound gratitude and indebtedness to our project guide **Prof. Dr. P.C. Panda** *who has always been a constant motivation and guiding factor throughout the project time. It has been a great pleasure for us to get an opportunity to work under him and progress with the project.*

We would also like to extend our gratitude to friends and senior students of the department who have always encouraged and supported us in the progress of the project.

Last but not the least we would like to thank all the staff members of the Department of Electrical Engineering who have been very cooperative with us.

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ABSTRACT

Synchronous generators form the principal source of electrical energy in power system. Many large loads are driven by synchronous motors. For stability studies of large power systems, accurate representation of the synchronous machine is required. The synchronous machine equations have the inductances and resistances of the stator and rotor circuits as parameters. These are referred to as *fundamental parameters* or *basic parameters.* While the fundamental parameters completely specify the machine electrical characteristics, they cannot be directly determined from measured responses of the machine. Therefore, the traditional approach to assigning machine data has been to express them in terms of derived parameters that are related to observed behavior as viewed from the terminals under suitable test conditions. This project is aimed at modeling and analyzing different models of synchronous machine. Models with different number of damper windings are analyzed and fundamental parameters of the machine are obtained using manufacturer's data. Newton Raphson method is used to solve the rotor and stator equations for the equivalent circuits of models and simulated in MATLAB. An experimental data is used to simulate the models and results are studied. Frequency domain analysis is performed to obtain transient time constants and compared with those obtained from computer simulation.

Chapter 1

INTRODUCTION

**Synchronous Machine
Theory**

Introduction

Synchronous generators form the principal source of electrical energy in power systems. Many large loads are driven by synchronous motors. Synchronous condensers are sometimes used as a means of providing reactive power compensation and controlling voltage. These devices operate on the same principle and are collectively referred to as synchronous machines. The power system stability problem is largely one of keeping interconnected synchronous machines in synchronism. Therefore, an understanding of their characteristics and accurate modeling of their dynamic performance are of fundamental importance in the study of power system stability.

The synchronous machine equations have the inductances and resistances of the stator and rotor circuits as parameters. These are referred to as fundamental or basic parameters and are identified by the elements of the d- and q- axis equivalent circuits. While the fundamental parameters completely specify the machine electrical characteristics, they cannot be directly determined from measured responses of the machine. Therefore the traditional approach to assigning machine data has been to express them in terms of derived parameters that are related to observed behavior as viewed from the terminals under suitable test conditions. This project will define these derived parameters and develop their relationships to the fundamental parameters.

Chapter 2

Physical Description of

Synchronous Machine

2.1 Physical Description
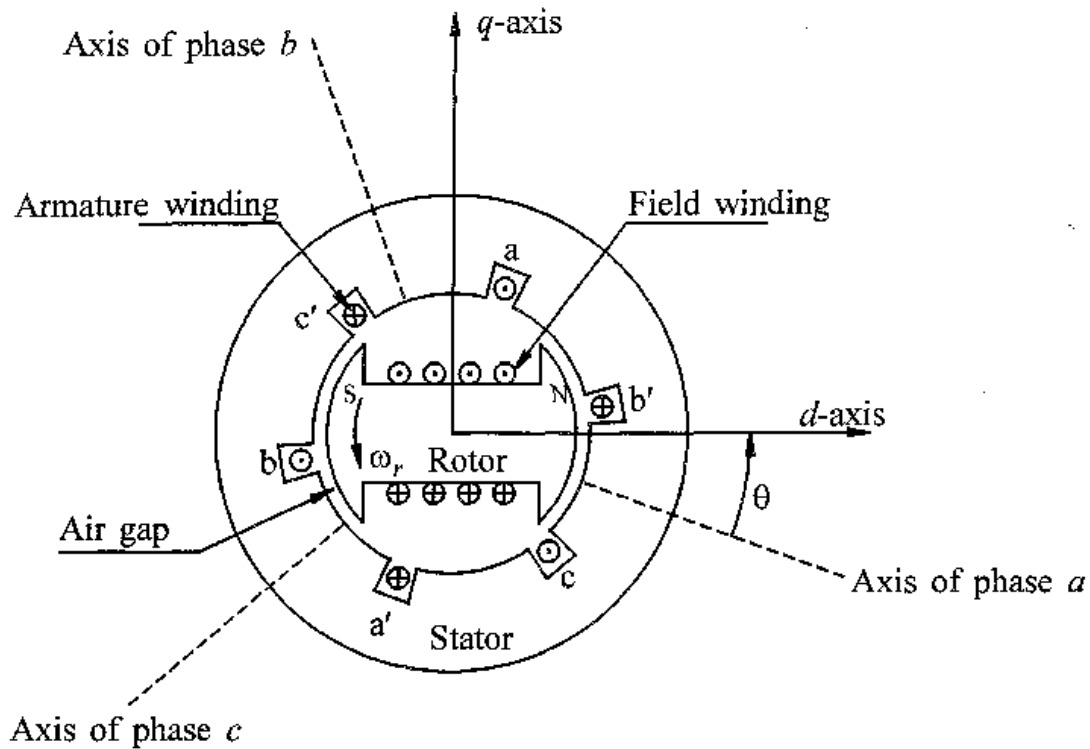
Figure 2.1 Schematic diagram of a three-phase synchronous machine

Figure 2.1 shows the schematic of the cross section of a three-phase synchronous machine with one pair of field poles. The machine consists of two essential elements: the field and the armature. The field winding carries direct current and produces a magnetic field which induces alternating voltages in the armature windings.

2.2 Armature and Field Structure

The armature windings usually operate at a voltage that is considerably higher than that of the field and thus they require most space for insulation. They are also subjected to high transient currents and must have adequate mechanical strength. Therefore normal practice is to have the armature on stator. The three-phase windings of the armature are distributed 120 degrees in time space so that, with uniform rotation of the magnetic field, voltages displaced by 120 degrees in time phase will be produced in the windings. Because the armature is subjected to a varying magnetic flux, the stator iron is built up of thin laminations to reduce eddy current losses.

When carrying balanced three-phase currents, the armature will produce a magnetic field in the air gap rotating at synchronous speed. The field produced by the direct current in the rotor winding on the other hand, revolves with the rotor. For production of a steady torque, the fields of stator and rotor must rotate at the same speed. Therefore, the rotor must run at precisely the synchronous speed.

The number of field poles is determined by the mechanical speed of the rotor and electric frequency of stator currents. The synchronous speed is given by,

$$n = (120\ f\ )/\ p_f \qquad\qquad - (1.1)$$

where n is the speed in rev/min, f is the frequency in Hz, and p_f is the number of field poles.

Chapter 3

Mathematical Description
of Synchronous Machine

3.1 Assumptions for developing the equations for synchronous machine

In developing equations of a synchronous machine, the following assumptions are made:

(a)   The stator windings are sinusoidally distributes along the air-gap as far as the mutual effects with the rotor are concerned.

(b)   The stator slots cause no appreciable variation of the rotor inductances with rotor position.

(c)   Magnetic hysteresis is negligible.

(d)   Magnetic saturation effects are negligible.

Assumptions (a), (b), and (c) are reasonable. The principal justification comes from the comparison of calculated performance. Assumption (d) is made for convenience in analysis. With magnetic saturation neglected, we are required to deal with only linear coupled circuits, making superposition applicable. However, saturation effects are important.

Figure 3.1 shows the circuits involved in the analysis of a synchronous machine. The stator circuits involved in the analysis of a synchronous machine. The rotor circuits comprise field and amortisseur windings. The field winding is connected to a source of direct current. For purpose of analysis, the currents in the amortisseur (solid rotor and/or damper winding) may be assumed to flow in the two sets of closed circuits: one set whose flux is in line with that of the field along the d-axis and the other set whose flux is at right angles to the field axis or along the q-axis. The amortisseur circuits take different forms and distinct, electrically independent circuits may not exist. In Figure 3.1, only one amortisseur circuit is assumed in each axis.
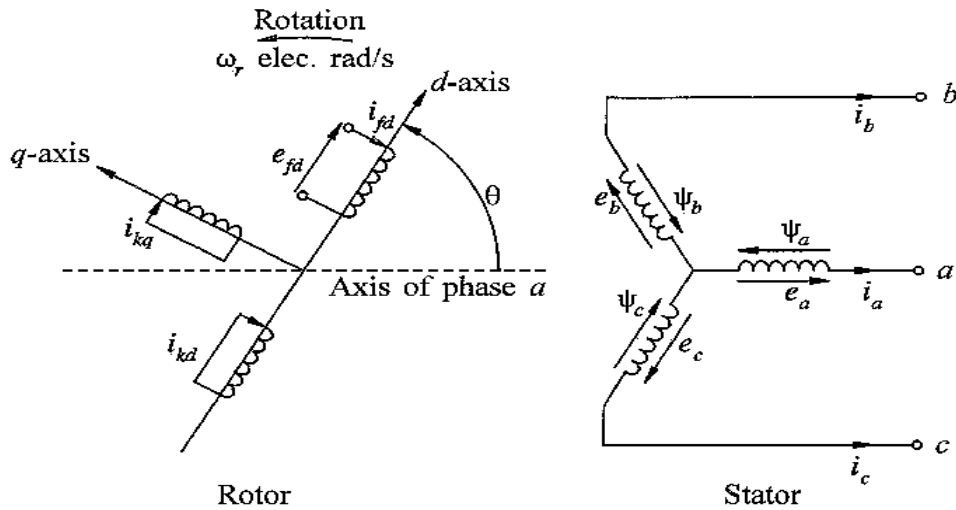
a, b,c : Stator phase windings
fd: Field winding
kd :   d-axis amortisseur circuit
kq :   q-axis amortisseur circuit
 k :   1,2,… n; n= no. of amortisseur circuits
 θ :   Angle by which d-axis leads the magnetic axis of phase a winding
wr: Rotor angular velocity, electrical rad/s

Figure 3.1 Stator and rotor circuits of a synchronous machine

In figure 3.1, θ is defined as the angle by which the d-axis leads the centerline of phase a winding in the direction of rotation. Since the rotor is rotating with respect to the stator, angle θ is continuously increasing and is related to the rotor angular velocity wr and time t as follows:

$$\theta = w_r\, t \qquad\qquad\qquad - (3.1)$$

The electrical performance equations of a synchronous machine can be developed by writing equations of the coupled circuits identified in Figure 3.1

3.2 Basic equations of a synchronous machine

The equations for the synchronous machine is developed using the generator convention for polarities so that the positive direction of a stator winding current is assumed to be out of the machine. The positive direction of field and amortisseur currents is assumed to be into the machine.

In addition to the large number of circuits involved, the fact that the mutual and self inductances of the stator circuits vary with rotor positions complicates the synchronous machine equations. The variations in inductances are caused by the variations in the permeances of the magnetic flux path due to non-uniform air-gap. This is pronounced in a salient pole machine in which permances in the two axes are significantly different. Even in a round rotor machine there are differences in the two axes due mostly to the large number of slots associated with the field winding.

The flux produced by a stator by a stator winding follows a path through the stator iron, across the air-gap, through the rotor iron, and back across the air-gap. The variations in permeance of this path as a function of the rotor position can be approximated as,

$$P = P0 + P2Cos2\alpha$$

- (3.2)

In the above equation, alpha is the angular distance from the d-axis along the periphery as shown in figure 3.2.
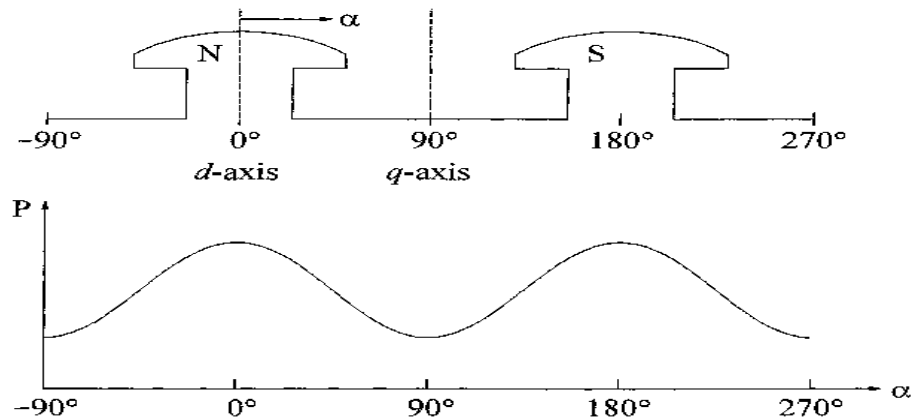
Figure 3.2 Variation of permeance with rotor position

A double frequency variation is used produced, since the permeances of the north and south poles are equal. Higher order even harmonics of permeance exist but are small enough to be neglected.

We will use the following notations in writing the equations for the stator and rotor circuits:

e_a, e_b, e_c	=	instantaneous stator phase to neutral voltages
i_a, i_b, i_c	=	instantaneous stator currents in phase a,b,c
i_{fd}, i_{kd}, i_{kq}	=	field and amortisseur currents
R_{fd}, R_{kd}, R_{kq}	=	rotor circuit resistances
l_{aa}, l_{bb}, l_{cc}	=	self inductance of stator windings
l_{ab}, l_{bc}, l_{ca}	=	mutual inductances between stator windings
$l_{afd}, l_{akd}, l_{akq}$	=	mutual inductances between stator and rotor windings
$l_{ffd}, l_{kkd}, l_{kkq}$	=	self inductance of rotor windings
R_a	=	armature resistance per phase
p	=	differential operator d/dt
e_{fd}	=	field voltage

3.3 Stator Circuit Equations:

The voltage equations of the three phases are-

$$e_a = (d\Psi a / dt) - i_a R_a = p\Psi a - i_a R_a \qquad \text{...(3.3)}$$
$$e_b = p\Psi b - i_b R_a \qquad \text{...(3.4)}$$
$$e_c = p\Psi c - i_c R_a \qquad \text{...(3.5)}$$

The flux linkage in the phase a winding at any instant is given by-

$$\Psi_a = -l_{aa} i_a - l_{ab} i_b - l_{ac} i_{fd} + l_{akd} i_{kd} + l_{akq} i_{kq} \qquad \text{...(3.6)}$$

Similar expressions apply to flux linkages of windings b and c. The units used are webers, henrys and amperes. The negative sign associated with the stator wonding currents is due to their assumed direction.

3.4 Stator Self-inductances:

The self-inductance laa is equal to the ratio of flux linking phase a winding to the current ia, with currents in all other circuits equal to zero. The inductance is directly proportional to the permeance, which as indicated earlier has a second harmonic variation. The inductance laa will be a maximum for $\theta = 0$ degree, a minimum for $\theta = 90$ degrees, a maximum again for $\theta = 180$ degrees and so on.

Neglecting space harmonics, the mmf of phase a has a sinusoidal distribution in space with its peak centred on the phase a axis. The peak amplitude of the mmf wave is equal to Naia, where Na is the effective turns per phase. As shown in figure 3.3, this can be resolved into two other sinusoidally distributed mmf's, one centred on the d-axis and other on the q-axis.

The peak values of the two component waves are-

$$\text{peak} \quad MMF_{ad} = N_a\, i_a\, \cos\theta \qquad\qquad \text{...(3.7)}$$
$$\text{peak} \quad MMF_{aq} = N_a\, i_a\, \cos(\theta+90) = -N_a\, i_a\, \sin\theta \qquad\qquad \text{...(3.8)}$$

The reason for resolving the mmf into the d-axis and q-axis components is that each acts on specific air-gap geometry of defined configurations. Air-gap per pole along the two axes are-

$$\Phi_{gad} = (N_a\, i_a\, \cos\theta)\, P_d \qquad\qquad \text{...(3.9)}$$
$$\Phi_{gaq} = (-N_a\, i_a\, \sin\theta)\, P_q \qquad\qquad \text{...(3.10)}$$
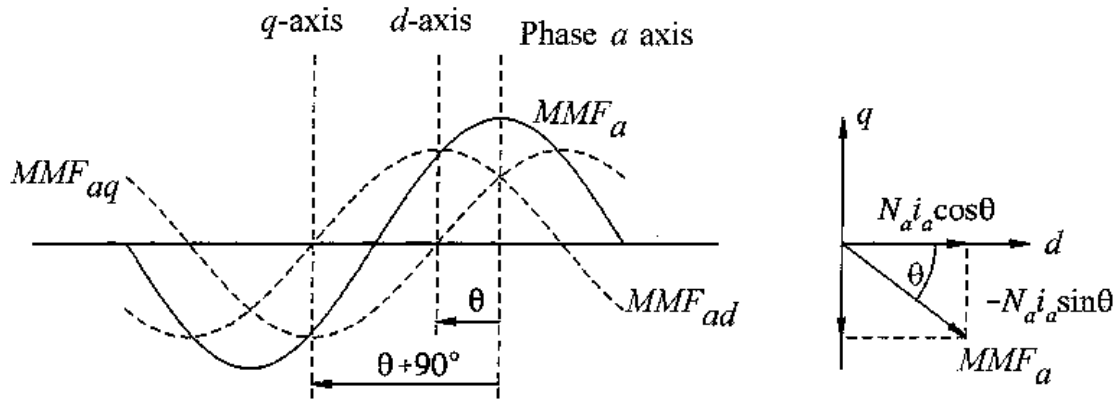
Figure 3.3 Phase *a* mmf wave and its components

The self inductance l_{ga} of phase a due to air-gap flux is-

$$\begin{aligned} l_{gaa} \;&=\; (N_a\, \phi_{goa})/i_a \\ &=\; N_a^2\, \{\, (P_d+P_q)/2 + (P_d-P_q)/2\, \cos2\theta\} \\ &=\; L_{g0} + L_{aa2}\cos2\theta \qquad\qquad \text{...(3.11)} \end{aligned}$$

The total self-inductance l_{aa} is given by adding to the above the leakage inductance L_{al} which represents the leakage flux not crossing the air-gap:

$$\begin{aligned} l_{aa} \;&=\; L_{al} + L_{gaa} \\ &=\; L_{al} + L_{g0} + L_{aa2}\, \cos2\theta \\ &=\; L_{aa0} + L_{aa2}\, \cos2\theta \qquad\qquad \text{...(3.12)} \end{aligned}$$

Since the windings of phases b and c are identical to that of phase a and are displaced from it by 120 degrees and 240 degrees respectively, we have

$$\begin{aligned} l_{bb} \;&=\; L_{aa0} + L_{aa2}\, \cos2(\theta-120) \\ l_{cc} \;&=\; L_{aa0} + L_{aa2}\, \cos2(\theta+120) \qquad\qquad \text{...(3.13)} \end{aligned}$$

3.5 Stator Mutual Inductance:

The mutual inductances between any two stator windings also exhibits a second harmonic variation because of the rotor shape. It is always negative, and has the greatest absolute value when the north and south poles are equidistant from the centres of the two windings concerned. For example, lab has maximium absolute value when θ = -30 degrees or θ = 150 degrees.

Thus the mutual inductances phase a and b, b and c, c and a are given as:

$$L_{ab} = L_{ba} = -L_{ab0} + L_{ab2} \cos(2\theta-120) \qquad\qquad ...(3.14)$$
$$= -L_{ab0} - L_{ab2} \cos(2\theta+120)$$

$$L_{bc} = L_{cb} = -L_{ab0} - L_{ab2} \cos(2\theta+120) \qquad\qquad ...(3.15)$$

$$L_{ca} = L_{ac} = -L_{ab0} - L_{ab2} \cos(2\theta+120) \qquad\qquad ...(3.16)$$

The variation of mutual inductance between phases a and b as a function of θ is illustrated in figure 3.4.
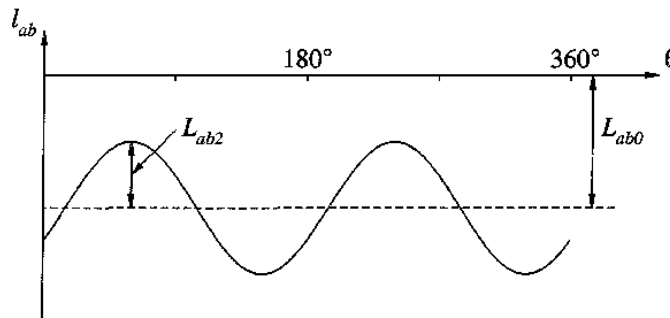
Figure 3.4 Variation of mutual inductance between stator windings

3.6 Mutual inductance between stator and rotor windings:

With the variations in air-gap due to stator slots neglected, the rotor circuits see a constant permeance. Therefore, the situation in this case is not one of variation of permeance; instead, the variation in the mutual inductance is due to the relative motion between the windings themselves.When a stator winding is lined up with a rotor winding, the flux linking the two windings is maximum and the mutual inductance is maximum. When the two windings are displaced by 90 degrees, no flux links the two circuits and the mutual inductance is zero.

With the sinusoidal distribution of mmf and flux waves,

$$\begin{aligned}
l_{afd} &= L_{afd}\cos\theta \\
l_{akd} &= L_{akd}\cos\theta \\
l_{akq} &= L_{akq}\cos(\theta+90) \\
&= -L_{akq}\sin\theta
\end{aligned} \right\} \quad\quad \ldots(3.17)$$

For considering the mutual inductance between phase b winding and the rotor circuits, θ is replaced by θ-120; for phase c winding θ is replaced by (θ+120).

Using the expressions for all the inductances that appear in stator voltage equations, we have:

$$\begin{aligned}
\Psi_a = \ &- i_a [L_{aa0} + L_{aa2}\cos 2\theta] + i_b [L_{ab0} + L_{aa2}\cos(2\theta+60) \\
&+ i_c [L_{ab0} + L_{aa2}\cos(2\theta-30)] + i_{fd} L_{afd} \cos\theta \\
&+ i_{kd} L_{akd}\cos\theta - i_{kq} L_{akq}\sin\theta
\end{aligned} \quad\quad \ldots(3.18)$$

Similarly,

$$\begin{aligned}
\Psi_b = \ &- i_a [L_{ab0} + L_{aa2}\cos(2\theta+60)] - i_b [L_{aa0} + L_{aa2}\cos 2(\theta-120) \\
&+ i_c [L_{ab0} + L_{aa2}\cos(2\theta-180)] + i_{fd} L_{afd} \cos(\theta-120) \\
&+ i_{kd} L_{akd}\cos(\theta-120) - i_{kq} L_{akq}\sin(\theta-120)
\end{aligned} \quad\quad \ldots(3.19)$$

and

$$\begin{aligned}
\Psi_c = \ &- i_a [L_{ab0} + L_{aa2}\cos(2\theta-60)] + i_b [L_{ab0} + L_{aa2}\cos 2(\theta-180) \\
&- i_c [L_{aa0} + L_{aa2}\cos 2(\theta+120)] + i_{fd} L_{afd} \cos(\theta+120) \\
&+ i_{kd} L_{akd}\cos(\theta+120) - i_{kq} L_{akq}\sin(\theta+120)
\end{aligned} \quad\quad \ldots(3.20)$$

3.7 Rotor circuit equations:

The rotor circuit voltage equations are:

$$e_{fd} = p\Psi_{fd} + R_{fd} i_{fd} \quad\quad \ldots(3.21)$$

$$0 = p\Psi_{kd} + R_{kd} i_{kd} \quad\quad \ldots(3.22)$$

$$0 = p\Psi_{kq} + R_{kq} i_{kq} \quad\quad \ldots(3.23)$$

The rotor circuit flux linkages may be expresses as follows:

$$\begin{aligned}
\Psi_{fd} &= L_{ffd} i_{fd} + L_{fkd} i_{kd} - L_{afd} [i_a\cos\theta + i_b\cos(\theta-120) + i_c\cos(\theta+120)] \\
\Psi_{kd} &= L_{fkd} i_{fd} + L_{kkd} i_{kd} - L_{akd} [i_a\cos\theta + i_b\cos(\theta-120) + i_c\cos(\theta+120)] \\
\Psi_{fq} &= L_{kkq} i_{kq} + L_{akq}[i_a\sin\theta + i_b\sin(\theta-120) + i_c\cos(\theta+120)]
\end{aligned} \right\} \quad \ldots(3.24)$$

The rotor circuits see constant permeance because of the cylindrical structure of the stator. Therefore, the self-inductances of rotor circuits and mutual inductances between each other do not vary with rotor positions. Only the rotor to stator mutual inductances vary periodically with θ.

Chapter 4

The dq0 Transformation

4.1 The dq0 Transformation:

The transformation from the abc phase variables to the dq0 variables can be written in the following matrix form:

$$
\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta-\frac{2\pi}{3}) & -\sin(\theta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}
$$

The inverse transformation is given by:

$$
\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta-\frac{2\pi}{3}) & -\sin(\theta-\frac{2\pi}{3}) & 1 \\ \cos(\theta+\frac{2\pi}{3}) & -\sin(\theta+\frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}
$$

4.2 Stator flux linkages in dq0 components:

Transforming the flux linkages and currents into dq0 components and with suitable reduction of terms involving trigonometric terms, we obtain the following expressions:

$$\Psi_d = -\left(L_{aa0} + L_{ab0} + \left(\frac{3}{2}\right)L_{aa2}\right)i_d + L_{afd} * i_{fd} + L_{akd} * i_{kd} \qquad ..(4.1)$$

$$\Psi_q = -\left(L_{aa0} + L_{ab0} + \left(\frac{3}{2}\right)L_{aa2}\right)i_q + L_{akq} * i_{kq} \qquad ..(4.2)$$

$$\Psi_0 = -(L_{aa0} + 2L_{ab0})i_0 \qquad ..(4.3)$$

Defining the following new inductances:

$$L_d = L_{aa0} + L_{ab0} + \left(\frac{3}{2}\right)L_{aa2} \qquad ..(4.4)$$

$$L_q = L_{aa0} + L_{ab0} - \left(\frac{3}{2}\right)L_{aa2} \qquad ..(4.5)$$

$$L_0 = L_{aa0} - 2L_{ab0} \qquad ..(4.6)$$

The flux linkage equation become

$$\Psi_d = -L_d\ i_d + L_{afd}\ i_{fd} + L_{akd}\ i_{kd} \qquad ..(4.7)$$
$$\Psi_q = -L_q\ i_q + L_{akq}\ i_{kq} \qquad ..(4.8)$$
$$\Psi_0 = -L_0\ i_0 \qquad ..(4.9)$$

The dq0 components of stator flux linkages are seen to be related to the components of stator and rotor currents through constant inductances.

4.3 Rotor flux linkages in dq0 components:

$$\Psi_{fd} = L_{ffd}\ i_{fd} + L_{fkd}\ i_{kd} - \frac{3}{2}L_{afd}\ i_d \qquad ..(4.10)$$

$$\Psi_{kd} = L_{fkd}\ i_{fd} + L_{kkd}\ i_{kd} - \frac{3}{2}L_{akd}\ i_d \qquad ..(4.11)$$

$$\Psi_{kq} = L_{kkq}\ i_{kq} - \frac{3}{2}L_{akq}\ i_q \qquad ..(4.12)$$

Again, all inductances are seen to be constant.

4.4 Stator voltage equations in dq0 components:

By applying dq0 transformation, following stator voltage equations are obtained:

$$e_d = p\Psi_d - \Psi_q\ p\theta - R_a\ i_d \qquad ..(4.13)$$

$$e_q = p\Psi_q - \Psi_d\ p\theta - R_a\ i_q \qquad ..(4.14)$$

$$e_0 = p\Psi_0 - R_a\ i_0 \qquad ..(4.15)$$

The angle θ is the angle between axis of phase a and d-axis. The term (p θ) in the above equations represents angular velocity of the rotor.

4.5 Advantages of dq0 transformation:

The dq0 transformation may be viewed as a means of referring the stator quantities to the rotor side.
The analysis of synchronous machine equations in terms of dq0 variables considerably simpler than in terms of phase quantities for the following reasons:

- The dynamic performance equations have constant inductances.
- For balanced conditions, zero sequence quantities disappear.
- For balanced steady-state operation, the stator quantities have constant values.
- The parameters associated with d- and q-axis may be directly measured from terminal tests.

4.6 Per unit representation:

In power system analysis, it is usually convenient to use a per unit system to normalize system variables.

$$\text{quantity in per unit} = \frac{\text{actual quantity}}{\text{base value of quantity}}$$

In the case of a synchronous machine, the per-unit system may be used to remove arbitrary constants and simplify mathematical equations so that they may be expressed in terms of equivalent circuits.

Per unit stator voltage equations:

$$
\begin{aligned}
e_d &= p\Psi_d - \Psi_q\, p\theta - R_a\, i_d \\
e_q &= p\Psi_q - \Psi_d\, p\theta - R_a\, i_q \\
e_0 &= p\Psi_0 - R_a\, i_0
\end{aligned}
$$

..(4.16)

Per unit rotor voltage equations:

$$
\begin{aligned}
e_{fd} &= p\Psi_{fd} + R_{fd}\, i_{fd} \\
p\Psi_{1d} + R_{1d}\, i_{1d} &= 0 \\
p\Psi_{1q} + R_{1q}\, i_{1q} &= 0 \\
p\Psi_{2q} + R_{2q}\, i_{2q} &= 0
\end{aligned}
$$

..(4.17)

For power system stability analysis, the machine equations are normally solved with all quantities expressed in per unit.

Chapter 5

Operational parameters of

Synchronous machine

5.1 Synchronous Machine Parameters:

The synchronous machine equations developed in Chapter 3 have the inductances and resistances of the stator and rotor circuits as parameters. These are referred to as fundamental or basic parameters and are identified by the elements of the d- and q-axis equivalent circuits. While the fundamental parameters completely specify the machine electrical characteristics, they cannot be directly determined from the measured responses of the machine. Therefore, the traditional approach to assigning machine data has been to express them in terms of derived parameters that are related to observed behaviour as viewed from the terminals under suitable test conditions.

5.2 Operational Parameters:

A convenient method of identifying the machine electrical characteristics is in terms of operational parameters relating the armature and field terminal quantities. Referring to Figure 4.1, the relationship between the incremental values of terminal quantities may be expressed in the operational form as follows:

$$\Delta\Psi_d(s) = G(s)\,\Delta e_{fd}(s) - L_d(s)\,\Delta i_d(s) \qquad \qquad \text{...(5.1)}$$

$$\Delta\Psi_q(s) = -L_q(s)\,\Delta i_q(s) \qquad \qquad \text{...(5.2)}$$
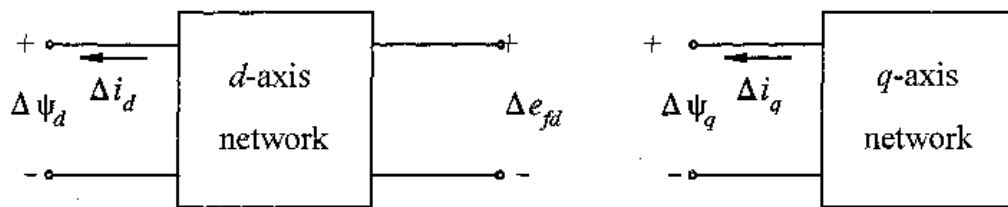
Figure 5.1 The d- and q-axis networks identifying terminals quantities

where,

G(s) is the stator to field transfer function

Ld(s) is the d-axis operational inductance

Lq(s) is the q-axis operational inductance

Equations 5.1 and 5.2 are true for any number of rotor circuits. With the equations in operational form, the rotor can be considered as a distributed parameter system. The operational parameters can be determined either from design calculations or more readily from frequency response measurements.

When a finite number of rotor circuits are assumed, the operational parameters can be expressed as a ratio of polynomial in *s*. The orders of the numerator and denominator polynomials of Ld(s) and Lq(s) are equal to the number of rotor circuits assumed in the respective axes, and G(s) has the same denominator as Ld(s), but a different numerator of order one less than the denominator..

We will develop here the expressions for the operational parameters of the model represented by the equivalent circuits shown in Figure 5.1. This model structure is generally considered adequate for stability studies and is widely used in large scale stability programs. The rotor characterstics are represented by the field winding and a damper winding in the d-axis and the two damper windings in the q-axis. The mutual inductances Lfd and Lad are assumed to be equal; this makes all mutual inductances in the d-axis equal.
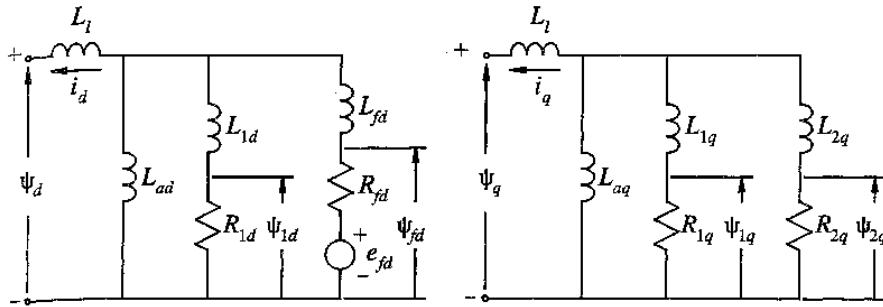
Figure 5.1 Structure of commonly used model

With equal mutual inductances, flux linkages for the d-axis in the operational form can be written as:

$$\psi_d(s) = -L_d i_d(s) + L_{ad} i_{fd}(s) + L_{ad} i_{1d}(s) \qquad \dots 5.3$$

$$\psi_{fd}(s) = -L_{ad} i_d(s) + L_{ffd} i_{fd}(s) + L_{ad} i_{1d}(s) \qquad \dots 5.4$$

$$\psi_{1d}(s) = -L_{ad} i_d(s) + L_{ad} i_{fd}(s) + L_{11d} i_{1d}(s) \qquad \dots 5.5$$

The operational forms for rotor voltages are:

$$e_{fd}(s) = s\psi_{fd}(s) - \psi_{fd}(0) + R_{fd} i_{fd}(s) \qquad \dots 5.6$$

$$0 = s\psi_{1d}(s) - \psi_{1d}(0) + R_{1d} i_{1d}(s) \qquad \dots 5.7$$

where $\psi_d(0)$, $\psi_{fd}(0)$ and $\psi_{1d}(0)$ denote initial values of the flux linkages. It is preferable to express the above equations in terms of incremental values about the initial operating condition so that the initial values drop out; this makes it more convenient to manipulate the operational equations. Substituting for the flux linkages in terms of the currents, the rotor voltage equations in incremental form become

$$\Delta e_{fd}(s) = s\Delta\psi_{fd}(s) + R_{fd}\Delta i_{fd}(s)$$

$$= -sL_{ad}\Delta i_d(s) + (R_{fd} + sL_{ffd})\Delta i_{fd}(s) + sL_{ad}\Delta i_{1d}(s) \qquad \dots 5.8$$

$$0 = s\Delta\psi_{1d}(s) + R_{1d}\Delta i_{fd}(s)$$

$$\qquad \dots 5.9$$

$$= -sL_{ad}\Delta i_d(s) + sL_{ad}\Delta i_{fd}(s) + (R_{1d} + sL_{11d})\Delta i_{1d}(s)$$

Our objective is to express the d-axis equations in the form of equations 5.1 and this can be achieved by eliminating the rotor currents in terms of the terminal quantities e_{fd} and i_d. Accordingly the solution of above two equations gives:

$$\Delta i_{fd}(s) = \frac{1}{D(s)}[(R_{1d} + sL_{11d})\Delta e_{fd}(s) + sL_{ad}(R_{1d} + sL_{1d})\Delta i_d(s)] \qquad \dots 5.10$$

$$\Delta i_{1d}(s) = \frac{1}{D(s)}[-sL_{ad}\Delta e_{fd}(s) + sL_{ad}(R_{fd} + sL_{fd})\Delta i_d(s)] \qquad \dots 5.11$$

Where

$$D(s) = s^2(L_{11d}L_{ffd} - L_{ad}^2) + s(L_{11d}R_{fd} + L_{ffd}R_{1d}) + R_{1d}R_{fd} \qquad \dots 5.12$$

Given that

$$L_d = L_{ad} + L_l$$

$$L_{ffd} = L_{ad} + L_{fd}$$

$$L_{11d} = L_{ad} + L_{1d}$$

substitution of equations 5.10 and 5.11 in the incremental form of equation 5.3 then gives the relationship between d-axis quantities in the desired form:

$$\Delta \psi_d(s) = G(s) \Delta e_{fd}(s) - L_d(s) \Delta i_d(s)$$

The expressions for the d-axis operational parameters are given by:

$$L_d(s) = L_d \frac{1+(T_4+T_5)s+T_4T_6s^2}{1+(T_1+T_2)s+T_1T_3s^2} \qquad \text{... 5.13}$$

$$G(s) = G_0 \frac{(1+sT_{kd})}{1+(T_1+T_2)s+T_1T_3s^2} \qquad \text{...5.14}$$

where,

$$G_0 = \frac{L_{ad}}{R_{fd}} \qquad\qquad T_{kd} = \frac{L_{1d}}{R_{1d}}$$

$$T_1 = \frac{L_{ad}+L_{fd}}{R_{fd}} \qquad\qquad T_2 = \frac{L_{ad}+L_{1d}}{R_{1d}} \qquad \text{... 5.15}$$

$$T_3 = \frac{1}{R_{1d}}\left(L_{1d}+\frac{L_{ad}L_{fd}}{L_{ad}+L_{fd}}\right) \qquad T_4 = \frac{1}{R_{fd}}\left(L_{fd}+\frac{L_{ad}L_l}{L_{ad}+L_l}\right)$$

$$T_5 = \frac{1}{R_{1d}}\left(L_{1d}+\frac{L_{ad}L_l}{L_{ad}+L_l}\right) \qquad T_6 = \frac{1}{R_{1d}}\left(L_{1d}+\frac{L_{ad}L_{fd}L_l}{L_{ad}L_l+L_{ad}L_{fd}+L_{fd}L_l}\right)$$

Equations 5.13 and 5.14 can be expressed in the factored form:

$$L_d(s) = L_d \frac{(1+sT_d')(1+sT_d'')}{(1+sT_{d0}')(1+sT_{d0}'')} \qquad \text{... 5.16}$$

$$G(s) = G_0 \frac{(1+sT_{kd})}{(1+sT_{d0}')(1+sT_{d0}'')} \qquad \text{... 5.17}$$

The expression for the q-axis operational inductance may be written by inspection and recognizing the similarities between d- and q- axis equivalent circuits. In the factored form, it is given by:

$$L_q(s) = L_q \frac{(1+sT_q')(1+sT_q'')}{(1+sT_{q0}')(1+sT_{q0}'')}$$

$$\dots 5.18$$

The time constants associated with the expressions for Ld(s), Lq(s) and G(s) in the factored form represent important machine parameters.

Chapter 6

Models of Synchronous machine

6.1 Different Models of synchronous machines:

Depending upon the number of rotor windings on d-axis and q-axis and degree of complexity following models are suggested:

1. Classical model (Model 0.0)
2. Field circuit only (Model 1.0)
3. Field circuit with one equivalent damper on q-axis (Model 1.1)
4. Field circuit with one equivalent damper on d-axis –
    (a) Model 2.1 (one damper on q-axis)
    (b) Model 2.2 (two damper on q-axis)
5. Field circuit with two equivalent damper circuits on d-axis –
    (a) Model 3.2 (with two damper on q-axis)
    (b) Model 3.3 (with three dampers on q-axis)

It is to be noted that in the classification of the machine models, the first number indicates the number of winding on the d-axis while the second number indicates the number of windings on the q axis.(Alternatively the number represent the number of state variables considered in the d axis and q axis).Thus, the classical model which neglects damper winding circuits and field flux decay, ignores all sate variable for the rotor coil and is termed (0.0)

6.2 Applications of different models:

Model (2.2) is widely used in the literature. Model (3.3) is claimed to be the most detailed model applicable to turbogenerator, while models (2.1) and (1.1) are widely used for hydro generators. **It is to be noted that while higher order models provide better result for such applications, they also require an exact determination of parameters**. With constraints on data availability and for study of large systems, it may be adequate to use model (1.1) if the data is correctly determined.

In the project, Model (0.0), Model(2.1) and Model(2.2) have been analysed mathematically and simulated to obtain machine's fundamental parameters.

Chapter 7

Analysis of Models for Synchronous machine

7.1 Model (2.1) :

The standard representation of a Synchronous machine is done by using Model(2.1) which includes field circuit and an equivalent damper winding on d-axis and a damper winding on q-axis.

Following assumptions are being made during analysis of the model :

- Main field flux decay is considered.
- An equivalent damper winding included in both q – axis and d-axis each.
- Speed is assumed to be constant.
- Saturation is neglected.

7.1.1 Equivalent circuits

Equivalent circuits representing the complete characteristics of the synchronous machines for direct axis and qudrature axis is shown in Fig-1 and Fig-2 respectively below-
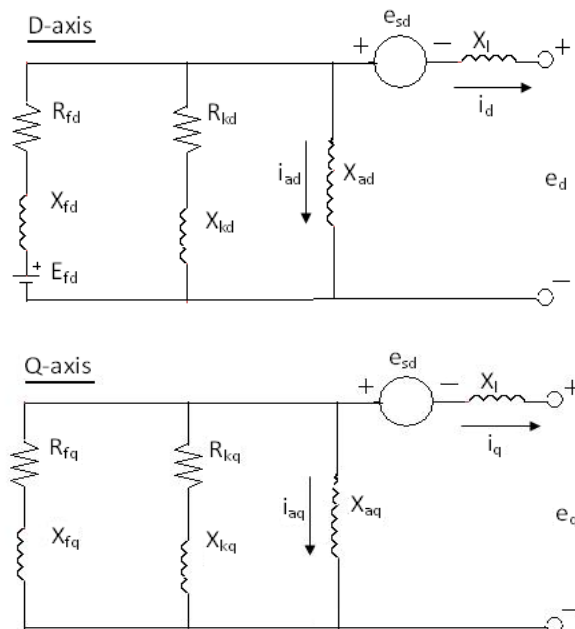
Fig-7.1 d-axis and q-axis equivalent circuits for model (2.1)

In the d-axis equivalent circuit, there is a field winding and a damper winding along with a field source. In the case of q-axis, there is no field winding and the amortisseurs represent the overall effect of the damper windings and eddy current paths.

7.1.2 Detailed analysis of the model:

Following notations are used in writing the equations for the stator and rotor circuits:

X_d = d-axis synchronous reactance

X_d' = d-axis transient reactance

X_d'' = d- axis subtransient reactance

X_q = q-axis synchronous reactance

X_q' = q-axis transient reactance

X_q'' = q- axis subtransient reactance

X_l = leakage reactance

T_{do}' = open circuit d-axis transient time constant

T_{do}'' = open circuit d-axis sub-transient time constant

T_{qo}' = open circuit q-axis transient time constant

T_{qo}'' = open circuit q-axis sub-transient time constant

T_d' = short circuit d-axis transient time constant

T_d'' = short circuit d-axis transient time constant

T_q' = short circuit q-axis transient time constant

T_q'' = short circuit q-axis transient time constant

R_{fd}, R_{fq}, R_{kq} = Rotor circuit resistances of field along d and q axis and

damper along q-axis respectively

Total flux produced by stator winding has two components such as mutual component and leakage component. Hence,
Along d axis:

$$X_{ad} = X_d - X_l \qquad \qquad …(7.1)$$

Along q axis:

$$X_{aq} = X_q - X_l \qquad \qquad …(7.2)$$

Now immediately following a fault, when a sudden disturbance occurs, flux can't change instantaneously in an inductive- resistive circuit. Hence for a small change :

$$\Delta\psi d = 0 \qquad \qquad …(7.3)$$

$$\Delta\psi 1d = 0 \qquad \qquad …(7.4)$$

Thus equivalent circuit is reduced to a open circuit consisting of three parallel branches and corresponding equation for d-axis is:

$$\frac{1}{X_{fd}} + \frac{1}{X_{kd}} + \frac{1}{X_{ad}} = \frac{1}{X_d{}^* - X_l}$$ ...(7.5)

Similarly for q axis equivalent equation can be written as –

$$\frac{1}{X_{fq}} + \frac{1}{X_{kq}} + \frac{1}{X_{aq}} = \frac{1}{X_q{}^* - X_l}$$ ...(7.6)

7.1.3 Derivation for obtaining open circuit time constants:

The relationship of open circuit time constants can be found by open circuiting the AB branch of the circuit (from fig. shown below). During open circuit condition, current through this branch is zero.

Thus, admittance $= \Delta id(s)/\Delta ed(s) = 0$
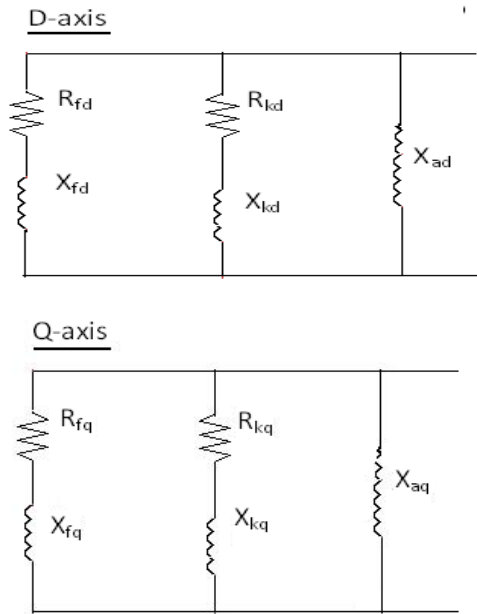
Figure 7.2 d-axis and q-axis equivalent circuits for model (2.1)
to obtain open circuit time constants

Thus the equations for transient and sub-transient case along d-axis and q-axis are:

$$\frac{1}{X_{fd} - 377T'_{do}R_{fd}} + \frac{1}{X_{kd} - 377T_{do}{}'R_{kd}} + \frac{1}{X_{ad}} = 0$$ ...(7.7)

$$\frac{1}{X_{fq} - 377T'_{qo}R_{fq}} + \frac{1}{X_{kq} - 377T_{q0}{}'R_{kq}} + \frac{1}{X_{aq}} = 0$$ ...(7.8)

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$$\frac{1}{X_{fd} - 377T_{do}R\_fd\ )+1/(X\_kd-377T\_d0\ R_{kd}} + \frac{1}{X_{ad}} = 0 \qquad \qquad …(7.9)$$

$$\frac{1}{X_{fq} - 377T_{qo}R\_fq\ )+1/(X\_kq-377T\_q0\ R_{kq}} + \frac{1}{X_{aq}} = 0 \qquad \qquad ..(7.10)$$

7.1.4 Derivation for Short circuit time constants :

Equivalent circuit diagram is short circuited to obtain the relations .Here only additional term X_l will be introduced which is obvious from the figure shown below:
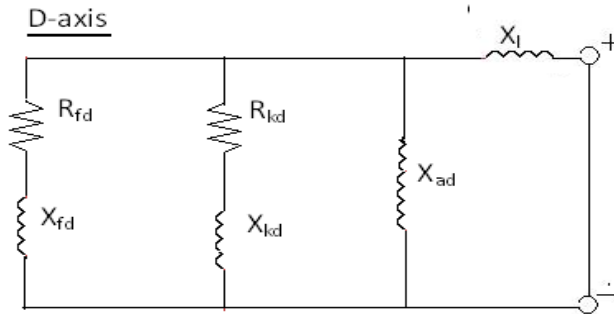
Figure 7.3 d-axis equivalent circuit for model (2.1)
to obtain short circuit time constants

The equations for transient and sub-transient conditions for short circuit situation along d-axis and q-axis are:

$$\frac{1}{X_{fd} - 377T_d'R_{fd}} + \frac{1}{X_{kd} - 377T_d'R_{kd}} + \frac{1}{X_{ad}} + \frac{1}{X_l} = 0 \qquad \qquad ..(7.11)$$

$$\frac{1}{X_{fq} - 377T_q'R_{fq}} + \frac{1}{X_{kq} - 377T_q'R_{kq}} + \frac{1}{X_{aq}} + \frac{1}{X_l} = 0 \qquad \qquad ..(7.12)$$

$$\frac{1}{X_{fd} - 377T_dR\_fd\ )+1/(X\_kd-377T\_d\ R_{kd}} + \frac{1}{X_{ad}} + \frac{1}{X_l} = 0 \qquad \qquad ..(7.13)$$

$$\frac{1}{X_{fq} - 377T_qR\_fq\ )+1/(X\_kq-377T\_q\ R_{kq}} + \frac{1}{X_{aq}} + \frac{1}{X_l} = 0 \qquad \qquad ..(7.14)$$

Now from operational analysis of inductance ,we know that-

$$X_d(s) = \frac{X_d(1 + sT_d')(1 + sT_d'')}{(1 + sT_{do}')(1 + sT_{do}'')} \qquad \qquad ..(7.15)$$

For sub-transient condition, when 's'tends to zero, sub-transient reactance along d-axis is obtained as:

$$[X_{(d)}" = \lim]_{T(s \to 0)} [X_{i}d\ (s)] = (X_{i}d\ (T_{i}d'T_{i}d\ "))/(\ T_{i}d0'\ T_{i}d0\ ") \qquad ..(7.16)$$

Similarly, Transient reactance along d-axis is obtained as

$$X_{d}' = \frac{X_{d}T_{d}'}{T_{d0}'} \qquad ..(7.17)$$

$$\text{Thus } X_{i}(d)\ " = (X_{i}d'T_{i}d\ ")/(T_{i}d0\ ") \qquad ..(7.18)$$

Similarly following relation can be obtained:

$$X_{i}(q)\ " = (X_{i}q'T_{i}q\ ")/(T_{i}q0\ ") \qquad ..(7.19)$$

To find the parameters involved in the equations Newton- raphson method has been applied where initial values are taken considering following equations-

$$X_{ad} = X_{d} - X_{l} \qquad ..(7.20)$$

$$X_{aq} = X_{q} - X_{l} \qquad ..(7.21)$$

$$\frac{1}{X_{fd}} = \frac{1}{X_{d}' - X_{l}} - \frac{1}{X_{ad}} \qquad ..(7.22)$$

$$\frac{1}{X_{fq}} = \frac{1}{X_{q}' - X_{l}} - \frac{1}{X_{aq}} \qquad ..(7.23)$$

$$1/X_{i}kd = 1/(X_{i}d\ " - X_{i}l\ ) - 1/(X_{i}d' - X_{i}l\ ) \qquad ..(7.24)$$

$$1/X_{i}kq = 1/(X_{i}q\ " - X_{i}l\ ) - 1/(X_{i}q' - X_{i}l\ ) \qquad ..(7.25)$$

$$R_{fd} = \frac{X_{fd} + X_{ad}}{377\ T_{d0}'} \qquad ..(7.26)$$

$$R_{fq} = \frac{X_{fq} + X_{aq}}{377\ T_{q0}'} \qquad ..(7.27)$$

$$R_{i}kd = (X_{i}kd\ X_{i}ad + X_{i}kd\ X_{i}fd + X_{i}ad\ X_{i}fd)/(377\ T_{i}d0\ ")(X_{i}ad + X_{i}fd\ ) \qquad ..(7.28)$$

$$R_{i}kq = (X_{i}kq\ X_{i}aq + X_{i}kq\ X_{i}fq + X_{i}aq\ X_{i}fq)/(377\ T_{i}q0\ ")(X_{i}aq + X_{i}fq\ ) \qquad ..(7.29)$$

$$T_{d}' = \frac{X_{d}'T_{d0}'}{X_{d}} \qquad ..(7.30)$$

$$T_q' = \frac{X_q'' T_{q0}'}{X_q}$$ ..(7.31)

$$T_{\downarrow}d'' = (X_{\downarrow}d'' T_{\downarrow}d0'')/X_{\downarrow}d'$$ ..(7.32)

$$T_{\downarrow}q'' = (X_{\downarrow}q'' T_{\downarrow}q0'')/X_{\downarrow}q'$$ ..(7.33)

These equations are being solved using NEWTON RAPHSON method and simulated in MATLAB using a set of manufacturer's data, taken from an IEEE Transaction on Power Apparatus and Systems, Vol. PAS-96, no.5. "First benchmark model for computer simulation of sub synchronous resonance."

7.1.5 Simulation Result:

The equations were simulated using manufacturer's data given in Table 6.1 and fundamental parameters were obtained shown in Table 6.2

Table 7.1 Manufacturer provided data

Xd (pu)	Xq (pu)	Xd' (pu)	Xq' (pu)	Xd'' (pu)	Xq'' (pu)	Tdo' (s)	Tqo' (s)	Tdo'' (s)	Tqo'' (s)	Xl (pu)
1.79	1.71	0.169	0.228	0.135	0.2	4.3	0.85	0.032	0.05	0.13

Table 7.2 d-axis and q-axis parameters for model(2.1)

Xad (pu)	Xaq (pu)	Xfd (pu)	Xfq (pu)	Xkd (pu)	X1q (pu)	Rfd (pu)	Rfq (pu)	Rkd (pu)	R1q (pu)	Td' (s)	Td'' (s)	Tq' (s)	Tq'' (s)
1.66	1.58	0.0399	0.1045	0.0057	0.2450	0.3953	1.98	1.398	6.86	0.4060	0.0256	0.1133	0.0439

7.2 Model(0.0):

This is the simplest model of the machine representation, also called as "Classical Model". The model has only field circuit on d-axis with no damper windings on either axis.

Following are the assumptions used during mathematical analysis of the model:

- Transformer voltages in the stator equations are neglected
- Speed is assumed constant
- Effect damper windings are neglected
- Saturation is not simulated
- Main flux linkages are assumed to be constant
- Transient saliency is neglected, that is approximating

7.2.1 Equivalent circuit:

The circuit diagram for model (0.0) is obtained from the flux model analysis and the circuit is shown below for both d-axis and q-axis axis:
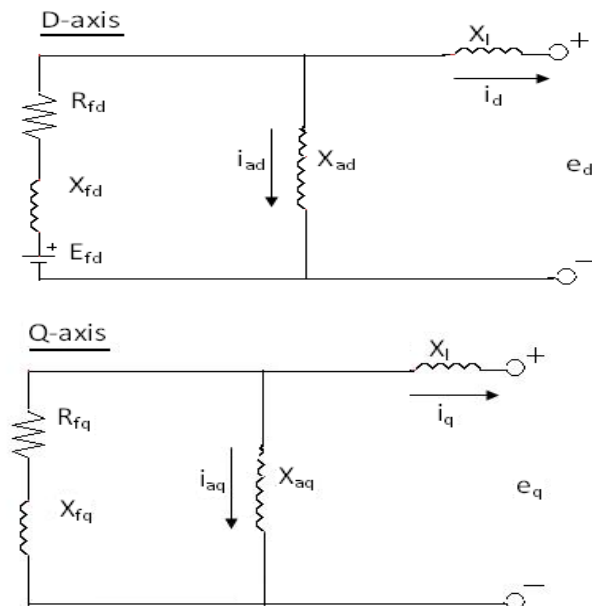
Fig-7.4 d-axis and q-axis equivalent circuits for model (0.0)

7.2.2: Circuit Equations:

Following equations can be derived from equivalent circuits using flux model analysis as done for model (2.1) :

$$X_{ad} = X_d - X_l \qquad \qquad ..(7.34)$$

$$X_{aq} = X_q - X_l \qquad \qquad ..(7.35)$$

$$\frac{1}{X_{fd}} = \frac{1}{X_d' - X_l} - \frac{1}{X_{ad}} \qquad \qquad ..(7.36)$$

$$\frac{1}{X_{fq}} = \frac{1}{X_q' - X_l} - \frac{1}{X_{aq}} \qquad \qquad ..(7.37)$$

$$R_{fd} = \frac{X_{fd} + X_{ad}}{377\ T_{d0}'} \qquad \qquad ..(7.38)$$

$$R_{fq} = \frac{X_{fq} + X_{aq}}{377\ T_{q0}'} \qquad \qquad ..(7.39)$$

$$T_d' = \frac{X_d'' T_{d0}'}{X_d} \qquad \qquad ..(7.40)$$

$$T_q' = \frac{X_q'' T_{q0}'}{X_q} \qquad \qquad ..(7.41)$$

$$T_1d'' = (X_1d'' T_1d0'')/X_1d' \qquad \qquad ..(7.42)$$

$$T_1q'' = (X_1q'' T_1q0'')/X_1q' \qquad \qquad ..(7.43)$$

7.2.3 Simulation Result:

Above equations were simulated using the same machine data provided by manufacturer for model(2.1) and following results were obtained as shown in Table 6.3:

Table 7.3 d-axis and q-axis parameters for model(0.0)

Xad (pu)	Xaq (pu)	Xfd (pu)	Xfq (pu)	Rfd (pu)	Rfq (pu)	Td' (s)	Td'' (s)	Tq' (s)	Tq'' (s)
1.66	1.58	0.0399	0.1045	0.3953	1.9817	0.4060	0.0256	0.1133	0.0439

7.3 Model (2.2):

This is a representation intended to maintain a balance by using two windings (one field, one equivalent damper)on d-axis and two equivalent dampers on q-axis.

Following assumptions have been used for analysis of the model:

- Main field flux decay is considered.
- Two equivalent damper winding included in q – axis.
- One equivalent damper winding included in d– axis.
- Speed is assumed constant.
- Saturation is neglected.

7.3.1 Equivalent circuit:

The circuit diagram for both d-axis and q- axis has been shown below :
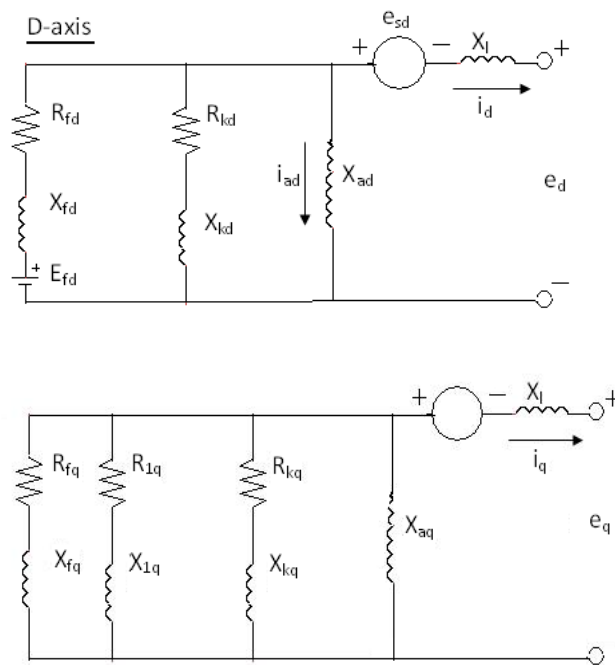
Fig-7.5 d-axis and q-axis equivalent circuits for model (2.2)

7.3.2 Circuit Equations:

As developed in previous models the relationship between various time constants and transient parameter can be found out from equivalent circuits. The circuit equations are shown below:

$$X_{ad} = X_d - X_l \qquad \qquad ..(7.44)$$

$$X_{aq} = X_q - X_l \qquad \qquad ..(7.45)$$

$$\frac{1}{X_{fd}} = \frac{1}{X_d{}' - X_l} - \frac{1}{X_{ad}} \qquad \qquad ..(7.46)$$

$$\frac{1}{X_{fq}} = \frac{1}{X_q{}' - X_l} - \frac{1}{X_{aq}} \qquad \qquad ..(7.47)$$

$$R_{fd} = \frac{X_{fd} + X_{ad}}{377 \; T_{d0}{}'} \qquad \qquad ..(7.48)$$

$$R_{fq} = \frac{X_{fq} + X_{aq}}{377 \; T_{q0}{}'} \qquad \qquad ..(7.49)$$

$$1/X_l kd = 1/(X_l d{}'' - X_l l) - 1/(X_l d' - X_l l) \qquad \qquad ..(7.50)$$

$$X_q{}' = X_l + \frac{X_{aq} \; X_{1q}}{X_{aq} + X_{1q}} \qquad \qquad ..(7.51)$$

$$X_q{}'' = X_l + \frac{X_{aq} \; X_{1q} \; X_{2q}}{X_{aq} \; X_{1q} + X_{aq} \; X_{2q} + X_{1q} \; X_{2q}} \qquad \qquad ..(7.52)$$

$$R_{kd} = \frac{X_{kd} \; X_{ad} + X_{kd} \; X_{fd} + X_{ad} \; X_{fd}}{(377 * T_{d0}{}'')(X_{ad} + X_{fd})} \qquad \qquad ..(7.53)$$

$$R_{1q} = \left(\frac{\left(X_{1q} + \left(\frac{X_{aq} \; X_{fq} \; X_{2q}}{X_{aq} \; X_{fq} + X_{aq} \; X_{2q} + X_{fq} \; X_{2q}} \right) \right)}{377 * T_{q0}{}''} \right) \qquad \qquad ..(7.54)$$

$$R_{2q} = \left(\frac{\left(X_{2q} + \left(\frac{X_{aq} \; X_{fq} \; X_{1q}}{X_{aq} \; X_{fq} + X_{aq} \; X_{1q} + X_{fq} \; X_{1q}} \right) \right)}{377 * T_{q0}{}''} \right) \qquad \qquad ..(7.55)$$

$$T_d{}' = \frac{X_d{}' T_{d0}{}'}{X_d} \qquad \qquad ..(7.56)$$

$$T_q' = \frac{X_q'' T_{q0}'}{X_q}$$ ..(7.57)

$$T_1 d'' = (X_1 d'' T_1 d0'')/X_1 d'$$ ..(7.58)

$$T_1 q'' = (X_1 q'' T_1 q0'')/X_1 q'$$ ..(7.59)

7.3.1 Simulation Result:

The above equations were simulated using NEWTON RAPHSON method in MATLAB using the same machine data provided by manufacturer as done for previous models .Following fundamental parameters were obtained as shown in Table 6.4:

Table 7.4 d-axis and q-axis parameters for model(2.2)

Xad (pu)	Xaq (pu)	Xfd (pu)	Xfq (pu)	Xkd (pu)	X1q (pu)	X2q (pu)	Rfd (pu)	Rfq (pu)	Rkd (pu)	R1q (pu)	R2q (pu)
1.66	1.58	0.0399	0.1045	0.0057	0.1045	0.2450	0.3953	1.9817	1.3980	3.4896	5.9114

Td' (s)	Td'' (s)	Tq' (s)	Tq'' (s)
0.4060	0.0256	0.1133	0.0439

Chapter 8

MATLAB Simulation for the Synchronous machine Models

8.1 MAIN FILE

```
% MAIN FILE

clear all;
close all;
clc
B=zeros(10,1);
J=zeros(10,10);
I=zeros(10,10);
resm=zeros(10,6);
resm1=zeros(10,6);
resd=zeros(10,6);
resd1=zeros(10,6);
disp('BTECH FINAL YEAR PROJECT')
disp('======================')
disp('Enter intial values :PARA METERS IN DATASHEET ')
% y1=input('Xd : ');
% y2=input('Xq : ');
% y3=input('Xd1 : ');
% y4=input('Xq1 : ');
% y5=input('Xd2 : ');
% y6=input('Xq2 : ');
% y7=input('Tdo1 : ');
% y8=input('Tqo1 : ');
% y9=input('Tdo2 : ');
% y10=input('Tqo2 : ');
% y11=input('Xl :');
y1=1.79;
y2=1.71;
y3=0.169;
y4=0.228;
y5=0.135;
y6=0.2;
y7=4.3;
y8=0.85;
y9=0.032;
y10=0.05;
y11=0.13;
disp('=====================================================================')
disp('FOR MODEL1 ....NO DAMPER ATALL... ')
disp('=====================================================================')
disp('=====================================================================')
disp('INITIALIZATION OF PARAMETERS TO B ESTIMATED..ENTER INITIAL VALUE... ')
disp('=====================================================================')
% x1=input('Xad : ');
% x2=input('Xaq : ');
% x3=input('Xfd : ');
% x4=input('Xfq : ');
% x5=input('Xkd : ');
% x6=input('Xkq : ');
```

```matlab
% x7=input('Rfd : ');
% x8=input('Rfq : ');
% x9=input('Rkd : ');
% x10=input('Rkq : ');
% x11=input('Td1 : ');
% x12=input('Td2 : ');
% x13=input('Tq1 : ');
% x14=input('Tq2 : ');

x1=1;
x2=1;
x3=0.01;
x4=0.1;
x5=0.001;
x6=0.1;
x7=0.001;
x8=0.001;
x9=0.001;
x10=0.01;
x11=0.01;
x12=0.01;
x13=0.1;
x14=0.01;

k=1;
DX =ones(14,1);
ecc=0.0001;
disp('===================WAIT ITERATION GOING ON===============')
for a=1:1:10
    k=k+1;
    for i=1:1:10
      d=1;j=1;
      B(i)=0- lfun1(x1,x2,x3,x4,x7,x8,x11,x12,x13,x14,y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,y11,i,j,d);
      j=2;
      for d=1:1:10
         J(i,d)=lfun1(x1,x2,x3,x4,x7,x8,x11,x12,x13,x14,y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,y11,i,j,d);
      end
    end
det(J);    I=inv(J);    DX=I*B;
disp(a)

%Updation of variables

x1= x1+DX(1);  x2= x2+DX(2);  x3= x3+DX(3);  x4= x4+DX(4);
x7= x7+DX(5);  x8= x8+DX(6);  x11= x11+DX(7);
x12= x12+DX(8); x13= x13+DX(9);x14= x14+DX(10);
resd(a,1)=a;        resd1(a,1)=a;       resd(a,2)=DX(1);    resd(a,3)=DX(2);        resd(a,4)=DX(3);
resd(a,5)=DX(4);
 resd(a,6)=DX(5);   resd1(a,2)=DX(6);       resd1(a,3)=DX(7);   resd1(a,4)=DX(8);       resd1(a,5)=DX(9);
resd1(a,6)=DX(10);

m1=x1;m2=x2;m3=x3;m4=x4;m7=x7; m8=x8; m11=x11;m12=x12;m13=x13;m14=x14;
```

```
resm(a,1)=a; resm(a,2)=m1;
resm(a,3)=m2;resm(a,4)=m3;
resm(a,5)=m4; resm(a,6)=m7*377;
resm1(a,1)=a; resm1(a,2)=m8*377;resm1(a,3)=m11;
resm1(a,4)=m12;resm1(a,5)=m13;resm1(a,6)=m14;

end
disp('ESTIMATED PARAMETERS AND RESIDUAL VALUES ARE')
disp('============================================')
disp('  ITERNO   Xad    Xaq    Xfd    Xfq    Rfd     ');
disp('  ======   ===    ===    ===    ===    ===     ');
disp(resm);
disp('  ITERNO   Rfq    Td1    Td2    Tq1    Tq2     ');
disp('  ======   ===    ===    ===    ===    ===     ');
disp(resm1);
disp('================================================================')

disp('               RESIDUE MATRIX');
disp('================================================================')
disp('  ITERNO   Xad    Xaq    Xfd    Xfq    Rfd     ');
disp('  ======   ===    ===    ===    ===    ===     ');
disp(resd);
disp('  ITERNO   Rfq    Td1    Td2    Tq1    Tq2     ');
disp('  ======   ===    ===    ===    ===    ===     ');
disp(resd1);
disp('================================================================')
disp('================================================================')
disp('FOR MODEL2 ....1 DAMPER IN D AXIS AND 1 IN Q AXIS... ')
disp('================================================================')
disp('================================================================')
disp('INITIALIZATION OF PARAMETERS TO B ESTIMATED..ENTER INITIAL VALUE... ')
disp('================================================================')
B=zeros(14,1);
J=zeros(14,14);
I=zeros(14,14);
resm=zeros(10,8);
resm1=zeros(10,8);
resd=zeros(10,8);
resd1=zeros(10,8);


k=1;
DX =ones(14,1);
ecc=0.0001;
disp('====================WAIT ITERATION GOING ON===============')
for a=1:1:10
    k=k+1;

    for i=1:1:14
       d=1;j=1;
       B(i)=0-
lfun2(x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,x13,x14,y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,y11,i,j,d);
       j=2;
```

```
        for d=1:1:14

J(i,d)=lfun2(x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,x13,x14,y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,y11,i,j,d);
        end
     end
        det(J);    I=inv(J);    DX=I*B;
     disp(a)
%Updation of variables
x1= x1+DX(1);    x2= x2+DX(2);    x3= x3+DX(3);
x4= x4+DX(4);    x5= x5+DX(5);    x6= x6+DX(6);
x7= x7+DX(7);    x8= x8+DX(8);    x9= x9+DX(9);
x10= x10+DX(10);  x11= x11+DX(11);
x12= x12+DX(12);  x13= x13+DX(13);  x14= x14+DX(14);

resd(a,1)=a;
resd1(a,1)=a;
resd(a,2)=DX(1);
resd(a,3)=DX(2);
resd(a,4)=DX(3);
resd(a,5)=DX(4);
resd(a,6)=DX(5);
resd(a,7)=DX(6);
resd(a,8)=DX(7);
resd1(a,2)=DX(8);
resd1(a,3)=DX(9);
resd1(a,4)=DX(10);
resd1(a,5)=DX(11);
resd1(a,6)=DX(12);
resd1(a,7)=DX(13);
resd1(a,8)=DX(14);

m1=x1;   m2=x2;   m3=x3;   m4=x4;   m5=x5;   m6=x6;   m7=x7;   m8=x8;   m9=x9;
m10=x10;   m11=x11;  m12=x12;   m13=x13;  m14=x14;

resm(a,1)=a;
resm(a,2)=m1;
resm(a,3)=m2;
resm(a,4)=m3;
resm(a,5)=m4;
resm(a,6)=m5;
resm(a,7)=m6;
resm(a,8)=m7*377;
resm1(a,1)=a;
resm1(a,2)=m8*377;
resm1(a,3)=m9*377;
resm1(a,4)=m10*377;
resm1(a,5)=m11;
resm1(a,6)=m12;
resm1(a,7)=m13;
resm1(a,8)=m14;


end
```

```
disp('ESTIMATED PARAMETERS AND RESIDUAL VALUES ARE')
disp('============================================')
disp('   ITERNO   Xad    Xaq    Xfd    Xfq    Xkd    Xkq    Rfd      ');
disp('   ======   ===    ===    ===    ===    ===    ===    ===      ');
disp(resm);
disp('   ITERNO   Rfq    Rkd    Rkq    Td1    Td2    Tq1    Tq2      ');
disp('   ======   ===    ===    ===    ===    ===    ===    ===      ');
disp(resm1);
disp('=================================================================================
======')

disp('                     RESIDUE MATRIX');
disp('=================================================================================
======')
disp('   ITERNO   Xad    Xaq    DXfd   Xfq    Xkd    Xkq    Rfd      ');
disp('   ======   ===    ===    ===    ===    ===    ===    ===      ');
disp(resd);
disp('   ITERNO   Rfq    Rkd    Rkq    Td1    Td2    Tq1    Tq2      ');
disp('   ======   ===    ===    ===    ===    ===    ===    ===      ');
disp(resd1);
disp('========================================================================')
disp('FOR MODEL3 ....1 DAMPER IN D AXIS AND 2 IN Q AXIS... ')
disp('========================================================================')
disp('========================================================================')
disp('INITIALIZATION OF PARAMETERS TO B ESTIMATED..ENTER INITIAL VALUE... ')
disp('========================================================================')

B=zeros(16,1);
J=zeros(16,14);
I=zeros(16,14);
resm=zeros(7,9);
resm1=zeros(7,9);
resd=zeros(7,9);
resd1=zeros(7,9);
y1=1.79;
y2=1.71;
y3=0.169;
y4=0.228;
y5=0.135;
y6=0.2;
y7=4.3;
y8=0.85;
y9=0.032;
y10=0.05;
y11=0.13; x1=1;
x2=1;
x3=0.01;
x4=0.1;
x5=0.001;
x6=0.2;
x7=0.001;
x8=0.001;
x9=0.001;
```

```matlab
x10=0.02;
x11=0.01;
x12=0.01;
x13=0.1;
x14=0.01;
x15=0.2;
x16=0.02;

%  x1=input('Xad : ');
%  x2=input('Xaq : ');
%  x3=input('Xfd : ');
% x4=input('Xfq : ');
% x5=input('Xkd : ');
% x6=input('X1q : ');
% x15=input('X2q : ');
% x7=input('Rfd : ');
% x8=input('Rfq : ');
% x9=input('Rkd : ');
%  x10=input('R1q : ');
%  x16=input('R2q : ');
%  x11=input('Td1 : ');
% x12=input('Td2 : ');
%  x13=input('Tq1 : ');
%  x14=input('Tq2 : ');

k=1;
DX =ones(16,1);
ecc=0.0001;
disp('===================WAIT ITERATION GOING ON===============')
for a=1:1:7
     k=k+1;

     for i=1:1:16
        d=1;j=1;
        B(i)=0-
lfun4(x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,x13,x14,x15,x16,y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,y11,i,j,d);
        j=2;
        for d=1:1:16

J(i,d)=lfun4(x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,x13,x14,x15,x16,y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,y11,i,j,
d);
        end
     end
det(J);
I=inv(J);
DX=I*B;
disp(a)

%Updation of variables

x1= x1+DX(1);    x2= x2+DX(2);    x3= x3+DX(3);
x4= x4+DX(4);    x5= x5+DX(5);    x6= x6+DX(6);
x7= x7+DX(7);    x8= x8+DX(8);    x9= x9+DX(9);
```

```
x10= x10+DX(10);  x11= x11+DX(11);  x12= x12+DX(12);
x13= x13+DX(13);  x14= x14+DX(14);  x15= x15+DX(15);    x16= x16+DX(16);
resd(a,1)=a;
resd1(a,1)=a;
resd(a,2)=DX(1);
resd(a,3)=DX(2);
resd(a,4)=DX(3);
resd(a,5)=DX(4);
resd(a,6)=DX(5);
resd(a,7)=DX(6);
resd(a,8)=DX(15);
resd(a,9)=DX(7);
resd1(a,2)=DX(8);
resd1(a,3)=DX(9);
resd1(a,4)=DX(10);
resd1(a,5)=DX(16);
resd1(a,6)=DX(11);
resd1(a,7)=DX(12);
resd1(a,8)=DX(13);
resd1(a,9)=DX(14);

m1=x1;m2=x2; m3=x3;m4=x4;m5=x5;m6=x6;m7=x7;m8=x8;m9=x9;
m10=x10;m11=x11;m12=x12; m13=x13;m14=x14;m15=x15;m16=x16;

resm(a,1)=a;
resm(a,2)=m1;
resm(a,3)=m2;
resm(a,4)=m3;
resm(a,5)=m4;
resm(a,6)=m5;
resm(a,7)=m6;
resm(a,8)=m15;
resm(a,9)=m7*377;
resm1(a,1)=a;
resm1(a,2)=m8*377;
resm1(a,3)=m9*377;
resm1(a,4)=m10*377;
resm1(a,5)=m16*377;
resm1(a,6)=m11;
resm1(a,7)=m12;
resm1(a,8)=m13;
resm1(a,9)=m14;

end
disp('ESTIMATED PARAMETERS AND RESIDUAL VALUES ARE')
disp('================================================')
disp('   ITERNO    Xad    Xaq    Xfd    Xfq    Xkd    X1q    X2q    Rfd      ');
disp('   ======    ===    ===    ===    ===    ===    ===    ===    ==== ');
disp(resm);
disp('   ITERNO    Rfq    Rkd    R1q    R2q    Td1    Td2    Tq1    Tq2       ');
disp('   ======    ===    ===    ===    ===    ===    ===    ===    === ');
disp(resm1);
```

```
disp('=============================================================================
======')

disp('                    RESIDUE MATRIX');
disp('=============================================================================
======')
disp('  ITERNO    Xad    Xaq    Xfd    Xfq    Xkd    X1q    X2q    Rfd        ');
disp('  ======   ===    ===    ===    ===    ===    ===    ===    ====  ');
disp(resd);
disp('  ITERNO    Rfq    Rkd    R1q    R2q    Td1    Td2    Tq1    Tq2        ');
disp('  ======   ===    ===    ===    ===    ===    ===    ===    ===  ');
disp(resd1);
disp('=============================================================================
======')
disp('                  ********THANKING YOU******** ')
disp('=============================================================================
======')
```

FUNCTION CODE FOR MODEL(0.0) :

```
Function f1=lfun1(x1,x2,x3,x4,x7,x8,x11,x12,x13,x14,y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,y11,i,j,d);
syms z1;
syms z2;
syms z3;
syms z4;

syms z7;
syms z8;

syms z11;
syms z12;
syms z13;
syms z14;

if i==1
g=y1-y11-z1;
end

if i==2
g=y2-y11-z2;
end

if i==3
g=(1/(y3-y11))-(1/z1)-(1/z3);
end

if i==4
g=(1/(y4-y11))-(1/z2)-(1/z4);
end

if i==5
g=((z3+z1)/(377*y7)) -z7;
end

if i==6
g=((z4+z2)/(377*y8))-z8;
end

if i==7
g=(y3*y7)/y1 - z11;
end

if i==8
g=(y4*y8)/y2 - z13;
end

if i==9
g=(y5*y9)/y3 - z12;
end

if i==10
```

```
g=(y6*y10)/y4 - z14;
end

if(j==1)
f2=subs(g,{z1,z2,z3,z4,z7,z8,z11,z12,z13,z14},{x1,x2,x3,x4,x7,x8,x11,x12,x13,x14});
f1=double(f2);
end

if(j==2)
if d==1
der=diff(g,z1);
end

if d==2
der=diff(g,z2);
end

if d==3
der=diff(g,z3);
end

if d==4
der=diff(g,z4);
end

if d==5
der=diff(g,z7);
end
if d==6
der=diff(g,z8);
end
if d==7
der=diff(g,z11);
end
if d==8
der=diff(g,z12);
end
if d==9
der=diff(g,z13);
end
if d==10
der=diff(g,z14);
end

f2=subs(der,{z1,z2,z3,z4,z7,z8,z11,z12,z13,z14},{x1,x2,x3,x4,x7,x8,x11,x12,x13,x14});
f1=double(f2);
end
end
```

FUNCTION CODE FOR MODEL(2.1) :

```
function f1=lfun2(x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,x13,x14,y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,y11,i,j,d);
syms z1;
syms z2;
syms z3;
syms z4;
syms z5;
syms z6;
syms z7;
syms z8;
syms z9;
syms z10;
syms z11;
syms z12;
syms z13;
syms z14;
if i==1
g=y1-y11-z1;
end
if i==2
g=y2-y11-z2;
end
if i==3
g=(1/(y3-y11))-(1/z1)-(1/z3);
end
if i==4
g=(1/(y4-y11))-(1/z2)-(1/z4);
end
if i==5
g=(1/(y5-y11))-(1/(y3-y11))-(1/z5);
end
if i==6
g=(1/(y6-y11))-(1/(y4-y11))-(1/z6);
end
if i==7
g=((z3+z1)/(377*y7)) -z7;
end
if i==8
g=((z4+z2)/(377*y8))-z8;
end
if i==9
g=((z5*z1 + z5*z3 + z1*z3)/((377*y9)*(z1+z3))) - z9;
end
if i==10
g=((z6*z2 + z6*z4 + z2*z4)/((377*y10)*(z2+z4))) - z10;
end
if i==11
g=(y3*y7)/y1 - z11;
end
if i==12
g=(y4*y8)/y2 - z13;
end
```

```
if i==13
g=(y5*y9)/y3 - z12;
end
if i==14
g=(y6*y10)/y4 - z14;
end
if(j==1)
f2=subs(g,{z1,z2,z3,z4,z5,z6,z7,z8,z9,z10,z11,z12,z13,z14},{x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,x13,x14}
);
f1=double(f2);
end
if(j==2)
if d==1
der=diff(g,z1);
end
if d==2
der=diff(g,z2);
end
if d==3
der=diff(g,z3);
end
if d==4
der=diff(g,z4);
end
if d==5
der=diff(g,z5);
end
if d==6
der=diff(g,z6);
end
if d==7
der=diff(g,z7);
end
if d==8
der=diff(g,z8);
end
if d==9
der=diff(g,z9);
end
if d==10
der=diff(g,z10);
end
if d==11
der=diff(g,z11);
end
if d==12
der=diff(g,z12);
end
if d==13
der=diff(g,z13);
end
if d==14
der=diff(g,z14);
```

```
end
f2=subs(der,{z1,z2,z3,z4,z5,z6,z7,z8,z9,z10,z11,z12,z13,z14},{x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,x13,x1
4});
f1=double(f2);
end
end
```

FUNCTION CODE FOR MODEL(2.2):

```
function
f1=lfun4(x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,x13,x14,x15,x16,y1,y2,y3,y4,y5,y6,y7,y8,y9,y10,y11,i,j,d);
syms z1;
syms z2;
syms z3;
syms z4;
syms z5;
syms z6;
syms z7;
syms z8;
syms z9;
syms z10;
syms z11;
syms z12;
syms z13;
syms z14;
syms z15;
syms z16;
if i==1
g=y1-y11-z1;
end
if i==2
g=y2-y11-z2;
end
if i==3
g=(1/(y3-y11))-(1/z1)-(1/z3);
end
if i==4
g=(1/(y4-y11))-(1/z2)-(1/z4);
end
if i==5
g=(1/(y5-y11))-(1/(y3-y11))-(1/z5);
end
if i==6
   g=y11+(1/((1/z2)+(1/z6)))-y4;
% g=(1/(y6-y11))-(1/(y4-y11))-(1/z6)-(1/z15);
end
if i==7
g=((z3+z1)/(377*y7)) -z7;
end
if i==8
g=((z4+z2)/(377*y8))-z8;
end
if i==9
```

```matlab
g=((z5*z1 + z5*z3 + z1*z3)/((377*y9)*(z1+z3))) - z9;
end
if i==10
    g=(1/(377*y10))*(z6+(z15*z2*z4/(z15*z2+z15*z4+z2*z4)))-z10;
end
if i==11
g=(y3*y7)/y1 - z11;
end
if i==12
g=(y4*y8)/y2 - z13;
end
if i==13
g=(y5*y9)/y3 - z12;
end
if i==14
g=(y6*y10)/y4 - z14;
end
if i==15
 g=y11+(1/((1/z2)+(1/z6)+(1/z15)))-y6;
% g=y11+(1/((1/x2)+(1/x6)+(1/x15)+(1/x4)))-y5;
end
if i==16
g=((z15+(z6*z2*z4/(z6*z2+z6*z4+z2*z4)))/(377*y10))-z16;
end
if(j==1)
f2=subs(g,{z1,z2,z3,z4,z5,z6,z7,z8,z9,z10,z11,z12,z13,z14,z15,z16},{x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,
x13,x14,x15,x16});
f1=double(f2);
end
if(j==2)
if d==1
der=diff(g,z1);
end
if d==2
der=diff(g,z2);
end
if d==3
der=diff(g,z3);
end
if d==4
der=diff(g,z4);
end
if d==5
der=diff(g,z5);
end
if d==6
der=diff(g,z6);
end
if d==7
der=diff(g,z7);
end
if d==8
der=diff(g,z8);
```

```
end
if d==9
der=diff(g,z9);
end
if d==10
der=diff(g,z10);
end
if d==11
der=diff(g,z11);
end
if d==12
der=diff(g,z12);
end
if d==13
der=diff(g,z13);
end
if d==14
der=diff(g,z14);
end
if d==15
der=diff(g,z15);
end
if d==16
der=diff(g,z16);
end
f2=subs(der,{z1,z2,z3,z4,z5,z6,z7,z8,z9,z10,z11,z12,z13,z14,z15,z16},{x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x1
2,x13,x14,x15,x16});
f1=double(f2);
end
end
```

Chapter 9

Conclusion

10.1 A Comparative Study of Fundamental Parameters for different Models of Synchronous Machine:

`Sl. No.	Parameters	Model(0.0)	Model(2.1)	Model(2.2)
1.	Xad	1.66	1.66	1.66
2.	Xaq	1.58	1.58	1.58
3.	Xfd	0.0399	0.0399	0.0399
4.	Xfq	0.1045	0.1045	0.1045
5.	Xkd	-	0.0057	0.0057
6.	X1q	-	0.2450	0.1045
7.	X2q	-	-	0.2450
8.	Rfd	0.3953	0.3953	0.3953
9.	Rfq	1.9817	1.9817	1.9817
10.	Rkd	-	1.3980	1.3980
11.	R1q	-	6.8600	3.4896
12.	R2q	-	-	5.9114
13.	Td1	0.4060	0.4060	0.4060
14.	Td2	0.0256	0.0256	0.0256
15.	Tq1	0.1133	0.1133	0.1133
16.	Tq2	0.0439	0.0439	0.0439

Table 10.1 Comparative chart for fundamental parameters of same synchronous machine represented by three different models

10.2 Discussion:

Stability analysis is one of the most important tasks in power system operations and planning. Synchronous generators play a very important role in this way. A valid model for synchronous generators is essential for a reliable analysis of stability and dynamic performance. Almost three quarters of a century after the first publications in modeling synchronous generators, this subject is still a challenging and attractive research topic.

Two axis equivalent circuits are commonly used to represent the behavior of synchronous machines. The direct determination of circuit parameters from design data is very difficult due to intricate geometry and nonlinear constituent parts of machines. So several tests have been developed which indirectly obtain the parameter values of equivalent circuits.

10.3 Comparison among different models:

Synchronous machine models of various degrees of complexity have been developed from the fundamental parameters.The comparison of machine models is useful in the evaluation of the transient performance of multimachine power systems. Synchronous-machine models of various degrees of complexity which are developed from the fundamental machine equations show different responses. They can be used to simulate the transient behavior of a simple multimachine power system under both non-pole-slipping and pole-slipping conditions. The comparisons made between predicted and actual responses can show the degree of accuracy which may be expected for the various models employed.

Model (2.2) is widely used in the literature. Model (3.3) is claimed to be the most detailed model applicable to turbogenerator, while models (2.1) and (1.1) are widely used for hydro generators. It is to be noted that while higher order models provide better result for such applications, they also require an exact determination of parameters.With constraints on data availability and for study of large systems, it may be adequate to use model (1.1) if the data is correctly determined.

Models in which sub transient phenomena are simulated, but where some transformer voltages in the stator equations, together with sub transient saliency, are neglected,

provide a model which is adequate and economical in computing demands for system disturbances including those in which the machine may momentarily fall from synchronism. Model (2.2) can fulfill these requirements in all but specialized studies of an exacting nature, with certain simplification like Model (2.2) becomes more economical in computational requirements.

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