A COMPARATIVE STUDY OF NEW AND CONVENTIONAL METHODS OF MEASUREMENT OF SYNCHRONOUS MACHINE QUANTITIES

BY

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This is to certify that this work has been done by me and it has not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

An accurate determination of the synchronous machine parameters under sub-transient, transient and synchronous conditions is essential for the pre-determination of the behaviour of synchronous machines under different conditions. A number of conventional methods are used to determine these parameters. Recently two new methods, namely the indicial response method and the low frequency response method have been developed. This work evaluates the applicability of the new methods for measurement of machine parameters.

The new tests are made with the machine in the standstill condition. The indicial response method consists of applying a dc voltage to a winding of the synchronous machine and recording the transient waveform of current. In low frequency response method, a variable very low-frequency (1 – 5Hz) is applied to a winding, the rms values of voltage, current and phase angle between them are measured at different frequencies. With these experimental values, the parameters are calculated using equations.

The theoretical basis of the new methods of measurement together with a summary of the conventional methods of measurement have been presented.

The parameters of a three-phase laboratory alternator have been measured both by the new methods and by conventional methods. Results of the new methods, of measurement have been found to be in close agreement with those of conventional methods.

The advantages of the new methods are that each test is made with the machine in the standstill condition and that the power requirement for each test is small. With large machines, the new methods will prove to be very convenient compared to the running tests by conventional methods.

The analysis of results of this investigation leads to the conclusion that, in course of time, the new methods will be accepted as standard methods with other conventional methods for measurement of synchronous machine quantities.

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<u>NOMENCLATURE</u>

E	D.C voltage
e	a.c. voltage
e_a, e_b, e_c, e_f	Voltage of stator phases a,b,c and field respectively
f	frequency
i_a, i_b, i_c	Currents of stator phases a,b,c,
i_f, i_d, i_q	currents of field, d-axis damper and q-axis damper
i_d, i_q	Stator currents in d-axis and q-axis
I_{ao}, I_{as}	Transient current in a phase stator coil with field open and closed respectively.
I_{a1O}, I_{a2O}	Decaying components of I_{ao}
$I_{a1s}, I_{a2s}, I_{a3s}$	Decaying components of I_{as}
$K_{aD}, K_{aQ}, K_{af}, K_{fd}$	Coupling coefficient between a-phase armature - d-axis damper, a-phase armature - q-axis damper, a-phase armature-field and field-d-axis damper respectively.
L_{aa}, L_{aao}, L_{a2O}	Self inductance of a-phase armature, equation (2.3)
L_{ab}, L_{abo}	Mutual inductance between a and b phases of armature, eqn. (2.4).
L_{af}, L_{aD}, L_{aQ}	Mutual inductance of armature with field, d-axis damper and q-axis damper respectively.
L_{aad}, L_{aaq}	Self inductance of d-axis and q-axis respectively
L_{ado}, L_{aqo}	Equivalent inductance of a-phase armature winding in d-axis and q-axis with field open circuited.
L_{ads}	Equivalent inductance of a-phase armature winding in d-axis with field closed.
L_{fdo}	Equivalent inductance of field.

R_{ado}, R_{aqo}	Equivalent resistance of a-phase armature winding in d-axis and q-axis with field open.
R_{ads}	Equivalent resistance of a-phase armature winding in d-axis with field closed.
R_{fdo}	Equivalent resistance of field.
r, r_D, r_Q, r_f	Resistance of armature, d-axis damper, q-axis damper and field respectively.
T_D, T_Q, T_{ad}, T_f	Time constant of d-axis damper, q-axis damper, armature in d-axis and field respectively.
T_{a1o}, T_{a2o}	Time constants of I_{a1o}, I_{a2o} respectively
$T_{a1s}, T_{a2s}, T_{a3s}$	Time constant of $I_{a1s}, I_{a2s}, I_{a3s}$ respectively.
x_d, x_q	Synchronous reactances in d and q-axes.
x'_d, x'_q	transient reactance in d and q-axes.
x''_d, x''_q	sub-transient reactance in d and q-axes
$w = 2\pi f$	angular velocity
ψ_a, ψ_b, ψ_c	Flux linkages of stator phases a,b,c
ψ_d, ψ_q	Stator flux linkages of d and q axes
ψ_D, ψ_Q	Flux linkages of d-axis and q-axes damper
ψ_f	Flux linkage of field

CHAPTER 1

INTRODUCTION

1.1 Introduction

Electricity is used in almost every sphere of our lives in the present day world. This important source of energy is generated mainly by electromechanical means using synchronous machines. Although at present there are some direct methods of converting other form of energy into electrical energy, but these methods are nither efficient nor economical. Moreover bulk amount of electrical energy can not be generated by these methods. Synchronous machines remains still the only source of bulk supply of electrical energy.

In order to maintain a reliable and adequate supply of electrical energy, the behaviour of synchronous machine must be acertained under different conditions of its operation such as changes in excitation, changes in load, sudden fault in the system, transient and steady state stability problems. The behaviour can be acertained using the constants of synchronous machines. These constants should therefore, be determined accurately for pre-determination of machine behaviours.

1.2 Historical Development of Two-reaction Theory

Before the development of the two-reaction theory of synchronous machine, relatively few machine constants were used. A single value of reactance (usually called armature leakage reactance) was used to calculate the initial short-circuit current and the standstill decrement curve was used to determine the decay. But it was noted lateron that for salient pole synchronous machine, the flux distribution is not exactly sinusoidal and for field with distributed iron and copper, somewhat higher results are obtained than actual test results. In order to overcome this difficulty professor Andre Blondel published in 1904[7] his two-reaction theory in which the machine was divided into two axes. The method was examined in detail[14] by Doherty and Nackel, who published a series of important papers[8,9,10,11,12]. A valuable contribution to the subject was made by Park in a set of three papers[15,16,17]. These papers not only developed the two-axis equations of synchronous machine, but they indicated how the equations can be applied to many important problems. Parks transformation provides the most important fundamental concept in the development of generalized two-reaction theory. This generalized two-reaction theory is now applied to determine the constants of synchronous machines.

1.3 Purpose of Investigation

A numbers of conventional methods such as those described in IEEE test procedure[1,2], 1965 are generally used to determine experimentally the parameters of synchronous machines. A number of these tests have to be performed if all the machine constants are to be determined. Moreover most of these tests are made with the machine in the running condition and consequently, involves elaborate experimental setups as well as considerable efforts with large generators. In 1968 Mr. H. Kaminosono and Mr. K. Uyeda[18] published a paper on a new method of measurement of synchronous machine quantities using the indicial response method and the low frequency response methods, which have also been considered by other investigators elsewhere.

This work evaluates the applicability of the new methods for measurement of synchronous machine quantities. A mathematical description of the synchronous machine and a concise summary of the important conventional methods of measurement of machine constants has been presented. The theoretical basis of the new methods has been developed. The constants of a laboratory alternator has been determined experimentally using the conventional methods as well as the new methods, inorder to present a comparison of the two methods and to suggest modification and improvement of the new methods.,

CHAPTER 2

THE SYNCHRONOUS MACHINES

2.1 Methematical Discription of Synchronous Machine

The schematic layout of the winding of a 2 pole, 3-phase synchronous machine is shown in Fig. 2-1. The magnetic flux paths have different permeances in the direct (polor) and quadrature (interpolar) axes of the machine. The direct and quadrature axes revolves with the rotor, while the magnetic axes of three stator phases abc remains fixed in space. The main field winding lies along the polar axis and the damper windings are represented by two short-circuited coils, one in each axis. The machine is idealized by making following assumptions:

1. Saturation and hysteresis effects are negligable.
2. A current in any stator winding sets only a fundamental mmf wave, which is sinusoidally distributed in space around the air gap.

The machine is replaced by six coils. These results six self inductances and different mutual inductances between the six coils.

2.2 The Voltage Relation

The voltage equations of all the six windings in terms of flux linkages, resistances and currents are,

$$e_a = p\,\psi_a - ri_a$$

$$e_b = p\,\psi_b - ri_b$$

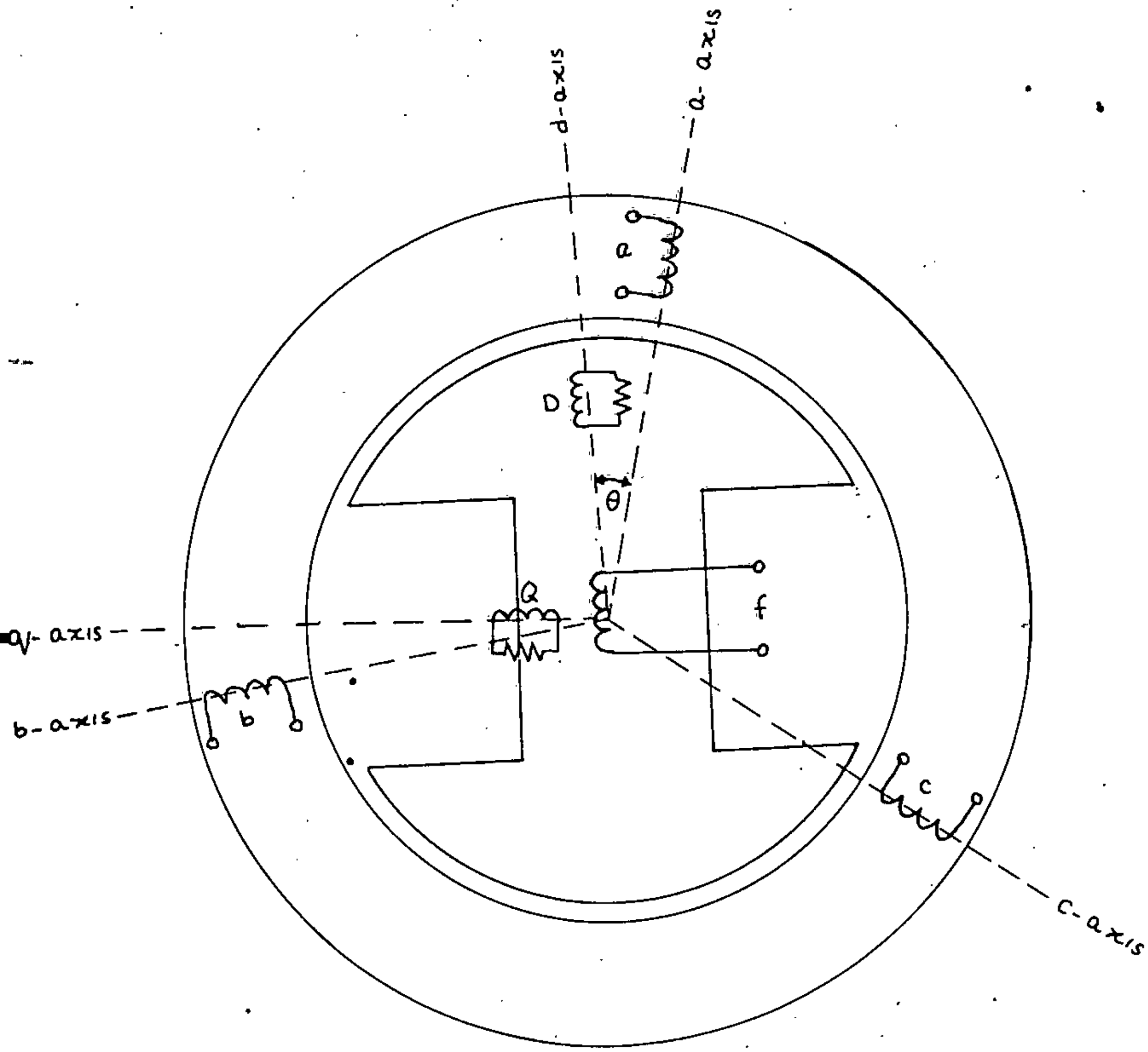


Fig. 2.1 Schematic layout of the windings of a Synchronous Machine.

$$e_c = p\psi_c - ri_c$$
$$e_f = p\psi_f + r_f i_f$$
$$0 = p\psi_D + r_D i_D \qquad (2.1)$$
$$0 = p\psi_Q + r_Q i_Q$$

Since the flux linkage is = Li. The above flux linkages of armature windings ( ), field winding ( ) and damper windings ( ) are

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_f \\ \psi_D \\ \psi_Q \end{bmatrix} = \begin{bmatrix} -L_{aa} & -L_{ab} & -L_{ac} & L_{af} & L_{aD} & L_{aQ} \\ -L_{ba} & -L_{bb} & -L_{bc} & L_{bf} & L_{bD} & L_{bQ} \\ -L_{ca} & -L_{cb} & -L_{cc} & L_{cf} & L_{cD} & L_{cQ} \\ -L_{fa} & -L_{fb} & -L_{fc} & L_{ff} & L_{fD} & L_{fQ} \\ -L_{Da} & -L_{Db} & -L_{Dc} & L_{Df} & L_{DD} & L_{DQ} \\ -L_{Qa} & -L_{Qb} & -L_{Qc} & L_{Qf} & L_{QD} & L_{QQ} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \\ i_D \\ i_Q \end{bmatrix} \qquad (2.2)$$

2.3.1 Stator Self Inductances

The armature winding self inductance varies according to different angular position of the rotor with respect to the stator. The inductance varies from a minimum when the interpolar axis is in line with the phase axis to a maximum when the polar axis is in line with the phase. This varying inductance consists of a fixed value and a variable value, which depends on the angular position of the rotor. Therefore, the self inductances are given by

$$L_{aa} = L_{aao} + L_{aa2} \text{ Cos } 2\theta$$

$$L_{bb} = L_{aao} + L_{aa2} \text{ Cos } 2(\theta - 120) \qquad (2.3)$$

$$L_{cc} = L_{aao} + L_{aa2} \text{ Cos } 2(\theta + 120)$$

2.3.2 Stator Mutual Inductances

The mutual inductances between armature windings also depends on rotor position. The mutual inductances of phase abc are

$$L_{ab} = L_{ba} = -\left[L_{abo} + L_{aa2} \text{ Cos } 2\ (\theta + 30)\right]$$

$$L_{bc} = L_{cb} = -\left[L_{abo} + L_{aa2} \text{ Cos } 2\ (\theta - 90)\right] \qquad (2.4)$$

$$L_{ca} = L_{ac} = -\left[L_{abo} + L_{aa2} \text{ Cos } 2(\theta + 150^{\circ})\right]$$

2.3.3 Rotor Self-Inductances

The rotor self inductances L_{ff}, L_{DD} and L_{QQ} are constant and are independent of rotor position with respect to the stator, neglecting the effect of rotor slot and saturation.

2.3.4 Rotor Mutual Inductances

All mutual inductance between any two circuits both in any axis (direct-or quadrature) is constant. Therefore $L_{fD} = L_{Df}$ = constant There is no mutual inductance between any direct and quadrature axis. That is,

$$L_{FQ} = L_{Qf} = L_{DQ} = L_{QD} = 0 \qquad (2.5)$$

2.3.5 Mutual Inductances Between ~~and~~ Stator and Rotor Circuits

All stator-to-mutual inductances vary sinusoidally with rotor angle and they become maximum when the two coils in question are in line

$$
\begin{aligned}
L_{af} &= L_{fa} = l_{af}\ \mathrm{Cos}\ \theta \\
L_{bf} &= L_{fb} = l_{af}\ \mathrm{Cos}(\theta-120) \\
L_{cf} &= L_{fc} = l_{af}\ \mathrm{Cos}\ \theta \\
L_{bD} &= L_{Db} = l_{aD}\ \mathrm{Cos}\ (\theta - 120) \\
L_{cD} &= L_{Dc} = L_{aD}\ \mathrm{Cos}\ (\theta + 120) \\
L_{aQ} &= L_{Qb} = -\ l_{aQ}\ \mathrm{Sin}\ \theta \\
L_{bQ} &= L_{Qb} = -\ l_{aQ}\ \mathrm{Sin}\ (\theta - 120) \\
L_{cQ} &= L_{Qc} = -\ l_{aQ}\ \mathrm{Sin}\ (\theta + 120)
\end{aligned}
\qquad (2.6)
$$

2.4 Park's Transformation

The phase variables abc can be transformed into dqo variables by Park's transformation. The transformation of abc variables into dqo variables are defined by

$$
\begin{bmatrix} \partial_d \\ \partial_q \\ \partial_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \mathrm{Cos}\ \theta & \mathrm{Cos}(\theta-120) & \mathrm{Cos}(\theta+120) \\ -\ \mathrm{Sin}\ \theta & -\mathrm{Sin}(\theta-120) & -\mathrm{Sin}(\theta+120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} \partial_a \\ \partial_b \\ \partial_c \end{bmatrix} \qquad (2.7)
$$

where ∂ stands for voltage, current and fluxlinkage.

The inverse transformation of dqo variables into abc variables is given by

$$
\begin{bmatrix} \partial_a \\ \partial_b \\ \partial_c \end{bmatrix} = \begin{bmatrix} \mathrm{Cos}\ \theta & -\ \mathrm{Sin}\ \theta & 1 \\ \mathrm{Cos}(\theta - 120) & -\ \mathrm{Sin}(\theta-120) & 1 \\ \mathrm{Cos}(\theta+120) & -\ \mathrm{Sin}(\theta+120) & 1 \end{bmatrix} \begin{bmatrix} \partial_d \\ \partial_q \\ \partial_o \end{bmatrix} \qquad (2.8)
$$

2.5 Synchronous Reactances

The values of inductance coefficients from equation (2.3) to (2.6) are substituted in the flux linkage equation (2.2) and the phase variables of the resulting equations are transformed into dqo variables by using Park's transformation to give.

$$
\begin{aligned}
\psi_d &= -(L_{aao} + L_{abo} + \tfrac{3}{2} L_{aa2}) i_d + L_{af} i_f + L_{aD} i_D \\
\psi_q &= -(L_{aao} + L_{abo} - \tfrac{3}{2} L_{aa2}) i_q + L_{aQ} i_Q \qquad (2.9) \\
\psi_o &= -(L_{aao} - 2 L_{abo}) i_o
\end{aligned}
$$

In equation (2.9) ψ_d and ψ_q may be regarded as corresponding to flux linkage in coils moving with the rotor and centred over the direct and quadrature axes respectively. The equivalent direct axis and qudrature axis moving armature circuits have the per unit reactances

$$
\begin{aligned}
X_d &= \text{direct axis reactance} = L_{aao} + L_{abo} + \tfrac{3}{2} L_{aa2} \\
X_q &= \text{quadrature axis reactance} = L_{aao} + L_{abo} - \tfrac{3}{2} L_{aa2} \qquad (2.10)
\end{aligned}
$$

In the light of the relation of permeability, the steady-state component of mutual inductance between armature windings L_{abo} of equation (2.4) may be taken to be approximately half the steady-state component of self undôctance of arm-ture winding L_{aao} i.e $L_{abo} = \frac{1}{2} L_{aa0}$

Also the inductances of armature winding in direct and quadrature axes are obtained by putting $\theta = 0$ and $\theta = 90$ respectively in equation (2.3),

$$L_{aad} = L_{aa0} + L_{aa2}$$
$$L_{aaq} = L_{aa0} - L_{aa2} \qquad (2.11)$$

The per-unit reactances are numerically equal to per unit inductances for negligible variation in frequency. Therefore the per unit dq axes reactances are

$$X_d = L_{aa0} + L_{ab0} + \frac{3}{2} L_{aa2}$$
$$= L_{aa0} + \frac{L_{aa2}}{2} + \frac{3}{2} L_{aa2}$$
$$= \frac{3}{2} (L_{aa0} + L_{aa2})$$
$$X_d = \frac{3}{2} L_{aad} \qquad (2.12)$$

$$X_q = (L_{aa0} + L_{ab0} - \frac{3}{2} L_{aa2})$$
$$= (L_{aa0} + \frac{L_{aa0}}{2} - \frac{3}{2} L_{aa2}) = \frac{3}{2} (L_{aa0} - L_{aa2})$$
$$X_q = \frac{3}{2} L_{aaq} \qquad (2.13)$$

2.6 Operational Reactances

From equations (2.2) and (2.7) we have

$$\psi_f = - \frac{3}{2} L_{af} i_d + L_{ff} i_f + L_{fD} i_D$$
$$\psi_D = - \frac{3}{2} L_{aD} i_d + L_{fD} i_f + L_{DD} i_D \qquad (2.14)$$
$$\psi_Q = - \frac{3}{2} L_{aQ} i_q + L_{QQ} i_Q$$

Using the expression ψ_f , ψ_D , and ψ_Q of equation (2.14) in the voltage equation (2.1), the last three voltage equation for e_f, e_D and e_Q can be written in the per unit form as

$$e_f = \frac{p}{w_o}\left[-\frac{3}{2}L_{af}\,i_d + L_{ff}\,i_f + L_{fD}\,i_D\right] + r_f\,i_f$$

$$e_D = 0 = \frac{p}{w_o}\left[-\frac{3}{2}L_{aD}\,i_d + L_{fD}\,i_f + L_{DD}\,i_D\right] + r_D\,i_D \qquad (2.15)$$

$$e_Q = 0 = \frac{p}{w_o}\left[-\frac{3}{2}L_{aQ}\,i_q + L_{QQ}\,i_Q\right] + r_Q\,i_Q$$

where $\frac{p}{w_o} = \frac{1}{w_o}\frac{d}{dt}$ = per unit differential operator.

From equation (2.9) and (2.10) we have

$$\psi_d = -x_d\,i_d + L_{af}\,i_f + L_{aD}\,i_D$$

$$\psi_q = -x_q\,i_q + L_{aQ}\,i_Q \qquad (2.16)$$

If flux linkage relations and the voltage equations are linear, the rotor circuit veriables i_f, i_D and i_Q can be elemenated from equations (2.15) and (2.16), so that ψ_d and ψ_q can be written in operational form as:

$$\psi_d = \frac{p(L_{DD}\,L_{af} - L_{fD}\,L_{aD}) + L_{af}\,r_D}{p^2(L_{DD}\,L_{ff} - l_{fD}^2) + p(L_{DD}\,r_f + L_{ff}\,r_D) + r_D\,r_f}\,e_f \qquad (2.17)$$

$$-\left[x_d - \frac{\{p^2(L_{DD}L_{af}^2 - 2L_{fD}\,L_{aD}\,L_{af} + L_{ff}\,L_{aD}^2) + p(L_{af}^2 r_D + L_{aD}^2 r_f)\}}{p^2(L_{DD}L_{ff} - L_{fD}) + p(L_{DD}\,r_f + L_{ff}\,r_D) + r_D\,r_f}\right] i_d$$

$$\psi_q = -\left[x_q - \frac{p\,L_{aQ}^2}{p\,L_{QQ} + r_Q}\right] i_q \qquad (2.18)$$

In compact form equation (2.17) and (2.18)

$$\psi_d = G(p)e_f - x_d(p)\,i_d$$

$$\psi_q = -x_q(p)\,i_q \qquad (2.19)$$

where $G(p)$ is a function and $x_d(p)$ and $x_q(p)$ are operational impedances defined by equation (2.17) and (2.18).

The upper limit of currents can be obtained by neglecting resistances. This is equivalent to put $p = \alpha$ in equations (2.17) and (2.18).

$$x_d(p) = x_d'' = x_d(p=\alpha) = x_d - \frac{L_{DD} L_{af}^2 - 2L_{fD}L_{aD}L_{af} + L_{ff}L_{aD}^2}{L_{DD} L_{ff} - L_{fD}^2} \qquad (2.20)$$

$$x_q(p) = x_q'' = x_q(p = \alpha) = x_q - \frac{L_{aQ}^2}{L_{QQ}} \qquad (2.21)$$

2.7 Coupling Coefficients

The coupling coefficient K_{xy} between any two winding x and y is defined as

$$K_{xy}^2 = \frac{L_{xy}^2}{L_{xx} L_{yy}} \qquad (2.22)$$

where L_{xx} = self inductance of coil x

L_{yy} = self inductance of coil y

L_{xy} = mutual inductance between coil x and y

Using the above defination of coupling coefficient, the coupling coefficients between the different windings of synchronous machine are

Armature Vs field winding, $K_{af}^2 = \dfrac{L_{af}^2}{L_d L_{ff}}$ (2.23)

where $L_d = \frac{3}{2} L_{aad}$

Arm ture Vs direct axis damper winding

$$K_{aD}^2 = \frac{L_{aD}^2}{L_d L_{DD}} \tag{2.24}$$

Armature Vs quadrature axis damper winding

$$K_{aQ}^2 = \frac{L_{aQ}^2}{L_q L_{QQ}} \tag{2.25}$$

where $L_q = \frac{3}{2} L_{aaq}$

field Vs damper winding

$$K_{fD}^2 = \frac{L_{fD}^2}{L_{ff} L_{DD}} \tag{2.26}$$

2.8 Subtransient and Transient Reactances

Using the above coupling coefficients fromx equation (2.23) to (2.26), equation (2.20) and (2.21) becomes.

x''_d = subtransient direct axis reactance

$$= x_d \left(1 - \frac{K_{af}^2 + K_{aD}^2 - 2K_{fD} K_{aD} K_{af}}{1 - K_{fD}^2}\right) \tag{2.27}$$

x''_q = substransient quadrature axis reactance

$$= x_q (1 - k_{aQ}^2) \tag{2.28}$$

The transient reactances are defined by assuming that there is no rotor circuit (damper windings) except the field winding. Therefore the terms for damper winding in equations (2.27) and (2.28) are neglected to give the transient reactances.

x_d' = transient direct axis reactance

$$= x_d(1 - K_{af}^2) \quad (2.29)$$

x_q' = transient quadrature axis reactance

$$= x_q'' \quad (2.30)$$

2.9 Time Constants of the Windings of Synchronous Machine

The time constant of any winding x, is defined as $T_x = \frac{L_{xx}}{r_x}$, where T_x is the time constant of the winding, L_{xx} is the self inductance of the winding and r_x is the resistance of the winding.

The time constants of synchronous machine windings, by definition are

Direct-axis damper winding time constant, $T_D = \frac{L_{DD}}{r_D}$

Quadrature axis damper winding time constant $T_Q = \frac{L_{QQ}}{r_Q}$

Field winding time constant, $T_f = \frac{L_{ff}}{r_f}$

Direct axis armature winding time constant $T_{ad} = \frac{L_{aad}}{r}$

Quadrature axis armature winding time constant $T_{aq} = \frac{L_{aaq}}{r}$

2.10 New Methods of Measurement of Synchronous machine Paramters

The synchronous machine quantities can be measured by two new methods, namely indicial response method and low frequency response method . Both of the new methods do not require that the machine is in running condition. Instead the test is made with the machine in the standstill condition. Therefore, these tests are very convenient for measurement of parameters of large machines. The tests are applicable to both salient and non-salient synchronous machines. In the indicial response method the transient waveform of current due to sudden application of a d.c. voltage to a stator coil is recorded on a photographic film and the waveform is analysed to obtain the important synchronous machine parameters. In low frequency response method a variable low frequency (1 - 5Hz) is applied to a phase winding, with the machine in the standstill condition. The rms values of the voltage and current together with the phase difference between them are required for calculation of machine parameters. The rms values are obtained by using a voltmeter and an ammeter and the phase difference can be noted from the oscilloscope screen. For greater accuracy the waveforms of the voltage and current can be recorded on a photographic film to find the phase difference.

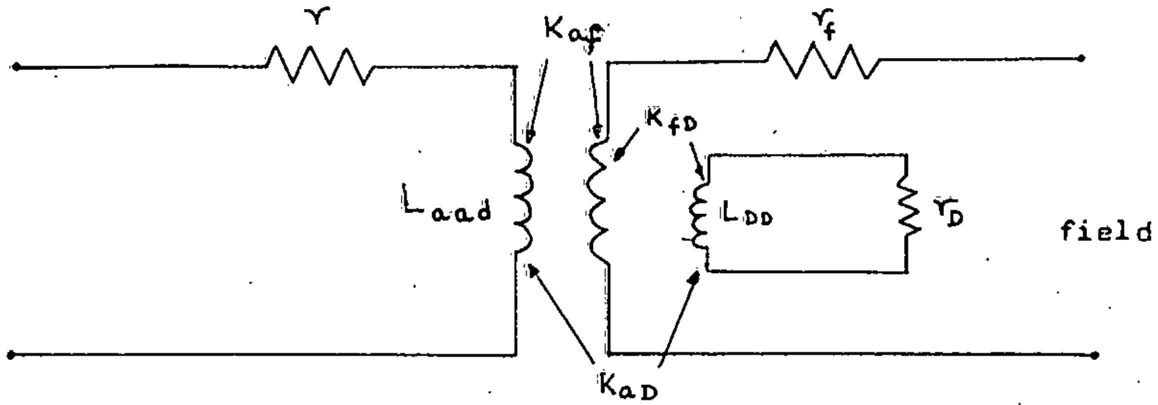
2.10.1 Indicial Response Method

If a d.c. voltage is suddenly applied to an armature winding with other two armature windings open circuited, the transient phenomena occuring can be expressed by the following voltage - current differential equations (fig. 2.2).

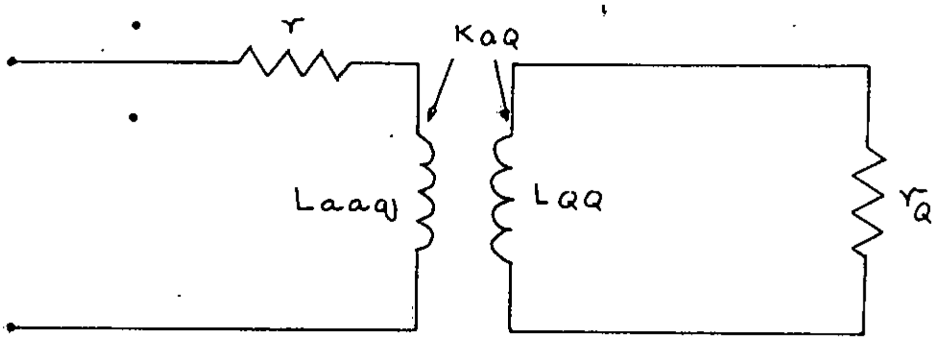
When the field winding is open circuited and the rotor is in polar axis

$$\begin{bmatrix} E \\ 0 \end{bmatrix} = \begin{bmatrix} p\,L_{aad} + r & -p\,K_{aD} \\ -p\,K_{aD} & p + \frac{1}{T_D} \end{bmatrix} \begin{bmatrix} I_a \\ I_D \end{bmatrix} \qquad (2.21)$$

when the field winding is short circuited and the rotor is in polar axis.



d-axis



q-axis

Fig. 2.2 Circuit and Quantities of Each Axis.

$$\begin{bmatrix} E \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} p\,L_{aad} + r & -p\,K_{aD} & -K_{af} \\ -pK_{aD} & p + \frac{1}{T_D} & -pK_{fD} \\ -pK_{af} & -p\,K_{fD} & p + \frac{1}{T_f} \end{bmatrix} \begin{bmatrix} I_a \\ I_D \\ I_f \end{bmatrix} \qquad (2.32)$$

The transient armature current, with field winding open circuited is obtained by solving the equation (2.31) using the laplace transformation (Appendix E). The current is given by

$$I_{ao} = I_{aao} - I_{alo}\, e^{-(t/T_{al8})} - I_{a2o}\, e^{-(t/T_{a2o})} \qquad (2.33)$$

where '0' signifies that the field circuit is open.

The parameters of equation (2.31) can be related to the time constants T_{a10}, T_{a20} and the currents I_{a10}, I_{a20} by

Resistance of armature winding,

$$\gamma = \frac{E}{I_{aao}} \qquad (2.34)$$

self inductance of armature winding in direct axis

$$L_{aad} = r\,\frac{T_{a10}\left(1 + \frac{I_{a20}}{I_{a10}} \times \frac{T_{a20}}{T_{a10}}\right)}{I + \frac{I_{a20}}{I_{a10}}} \qquad (2.35)$$

Time constant of d-axis damper winding,

$$T_D = \frac{T_{a10}\left(\frac{I_{a20}}{I_{a10}} + \frac{T_{a20}}{T_{a10}}\right)}{I + \frac{I_{a20}}{I_{a10}}} \qquad (2.36)$$

Time constant of armature winding, in d-axis,

$$T_{ad} = \frac{L_{aad}}{r} \qquad (2.37)$$

Coupling coefficient between d-axis damper and armatue winding

$$K_{aD}^{2} = \frac{\frac{I_{a20}}{I_{a10}}\left(1 - \frac{T_{a20}}{T_{a10}}\right)^{2}}{\left(\frac{I_{a20}}{I_{a10}} + \frac{T_{a20}}{T_{a10}}\right)\left(1 + \frac{I_{a20}}{I_{a10}} \times \frac{T_{a20}}{T_{a10}}\right)} \qquad (2.38)$$

The above values of L_{aad}, T_D, K_{aD}^2, T_{ad} are required for calculation of machine parameters.

Similarly the transient current through the armature winding with field winding closed and rotor in polar axis is given by three decaying components of currents I_{a1s}, I_{a2s}, I_{a3s} and time constants, T_{a1s}, T_{a2s}, T_{a3s}, where's' signifies that the field circuit is short circuited.

The solution of the equation (2.32) is given by

$$I_{as} = I_{aac} - I_{a1s}\, e^{-(t/T_{a1s})} - I_{a2s}\, e^{-(t/T_{a2s})} - I_{a3s}\, e^{-(t/T_{a3s})} \qquad (2.39)$$

where, time constant of field winding is

$$\frac{1}{T_f} = \frac{1}{T_{a1s}} + \frac{1}{T_{a2s}} + \frac{1}{T_{a3s}} - \frac{1}{T_{ad}} - \frac{1}{T_D} \qquad (2.40)$$

Coupling coefficient between damper and field winding is

$$K_{fD}^{2} = \frac{I_{a1s}}{E}\left(\frac{1}{T_{a1s}} - \frac{1}{T_{a2s}}\right)\left(\frac{1}{T_{a3s}} - \frac{1}{T_{a1s}}\right) + \left(\frac{T_{a1s}}{T_D} - 1\right)\left(\frac{T_{a1s}}{T_f} - 1\right) \qquad (2.41)$$

and coupling coefficient between armature and field winding is

$$K_{af}^{2} = \frac{1}{T_{ad}T_D}\Big[T_f\, T_D(\ - K_{fD}^{2}) + T_D\, T_{ad}\,(1 - K_{aD}^{2}) - T_{a1s}\, T_{a2s} - T_{a2s}\, T_{a3s} - T_{a3s}\, T_{a1s}\Big] \qquad (2.42)$$

With the magnitudes and time constants of decaying components of transient current, thus obtained the reactances x_d, x_d' and x_d'' are calculated using equation (2.12), (2.29) and (2.27) respectively.

The quantities with respect to the quadrature axis are obtained in similar way with rotor in the interpolar (quadrature) axis . The numerical calculations of all machine quantities by step response method using the appropriate equations are given in section 4.1.

2.10.2 Low Frequency Response Method

A variable low frequency (1 - 5Hz) is applied to an armature winding with the other two armature windings open circuited and with the rotor in direct axis. The test must be carried out at least at the different frequencies.

In this case the current-voltage equations are similar to those of the step response method i.e. equation (2.31) and (2.32) except that the differential operator p is replaced by jw

when the field winding is open,

$$\begin{bmatrix} e \\ o \end{bmatrix} = \begin{bmatrix} jw\,L_{aad} + r & -jw\,K_{aD} \\ -jw\,K_{aD} & jw + \frac{1}{T_D} \end{bmatrix} \begin{bmatrix} i_a \\ i_D \end{bmatrix} \qquad (2.43)$$

when the field winding is short circuited

$$\begin{bmatrix} e \\ o \\ o \end{bmatrix} = \begin{bmatrix} jw\,L_{aad} + r & -jw\,K_{aD} & -jw\,K_{af} \\ -jw\,K_{aD} & jw + \frac{1}{T_D} & -jw\,K_{fD} \\ -jw\,K_{af} & -jw\,k_{fD} & jw + \frac{1}{T_f} \end{bmatrix} \begin{bmatrix} i_a \\ i_D \\ i_f \end{bmatrix} \qquad (2.44)$$

The d-axis equivalent resistance and inductance as seen from the stator is determined by measuring the voltage (e) and current (i_a) of the armature winding and the phase angle (ϕ) between them at two different frequencies with the rotor in the d-axis.

$$\text{Equivalent resist nce, } R_{ado} = \frac{e}{i_a} \cos \phi \tag{2.45}$$

$$\text{Equivalent inductance } L_{ado} = \frac{1}{w} \sin \phi \tag{2.46}$$

The expression for equivalent resistance and inductance of the armature winding with the field winding open, that is, $(R_{ado} + jw L_{ado})$ can be extracted from equation (2.43). They are

$$R_{ado} = r + \frac{L_{aad} \frac{K_{aD}^2}{T_D}}{1 + \left(\frac{1}{w T_D}\right)^2} \tag{2.47}$$

$$L_{ado} = L_{aad} \quad 1 - \frac{K_{aD}^2}{1 + \left(\frac{1}{wT_D}\right)^2} \tag{2.48}$$

The experimental values of R_{ado} and L_{ado} at two different frequencies can substituted in equation (2.47) and (2.48) to give two equations for R_{ado} and also two equations for L_{ado}. These equations can be solved to give.

The self inductance of arm ture winding,

$$L_{aad} = L_{ado1} + \frac{w_1^2}{w_1^2 - w_2^2} \left(L_{ado} + \frac{w_2^2 L_{ado}^3}{R_{ado}^2}\right) \tag{2.49}$$

Resistance of armature winding

$$r = R_{ado1} - \frac{w_1^2}{w_1^2 - w_2^2}\left(R_{ado} + w_2^2 \frac{L_{ado}^2}{R_{ado}}\right) \tag{2.50}$$

Coupling coefficients between d-axis damper and armature winding

$$K_{aD}^2 = \frac{(R_{ado}^2 + w_1^2 L_{ado}^2)(R_{ado}^2 + w_2^2 L_{ado}^2)}{R_{ado}^2 L_{ado} L_{ado1}(w_1^2 - w_2^2) + w_1^2 L_{ado}(R_{ado}^2 + w_2^2 L_{ado}^2)} \qquad (2.51)$$

Time constant of d-axis damper winding

$$T_D = \frac{L_{ado}}{R_{ado}} \qquad (2.52)$$

where L_{ado1}, L_{ado2} equivalent d-axis inductance at w_1 and w_2 respectively.

R_{ado1}, R_{ado2} equivalent d-xis resistance at w_1 and w_2 respectively.

$$L_{ado} = L_{ado2} - L_{ado1}$$

$$R_{edo} = R_{ado1} - R_{ado2}$$

$$w_1 = 2\pi f_1$$

$$w_2 = 2\pi f_2$$

f_1 and f_2 are two different frequencies. The symbol 'O' in all the above equations signifies that the field winding is open circuited.

The q-axis quantities L_{aeq}, T_Q, K_{aQ}^2 are determined by similar procedure as those described for d-axis quantities except that the rotor is now placed in the q-axis and the field winding is left open circuited as before. Equations (2.43) is applicable if the subscript 'd' is replaced by 'q' and 'D' is replaced by 'Q'. The relevent expression for L_{aaq}, K_{aQ}^2 and T_Q are obtained from equations (2.49), (2.51) and (2.52) respectively by replacing the subscript 'd' by 'q' and 'D' by 'Q'.

The time constant of field winding T_f and the coupling coefficient between field and d-axis damper K_{fD} are obtained by applying low frequency voltage to th field ~~www~~ winding with the armature windings open circuited. The expressions for K_{fD}^2 and T_f are similar to equation (2.51) and (2.52) except that subscript 'a' is replaced by f.

The coupling coefficient between arm ture nd field winding K_{af} can be extracted from equation (2.44). Here a low voltage at a single frequency is applied to a phase winding, after the field winding has been short-circuited with the rotor in the d-axis. Equation (2.44) gives the equivalent short circuited resistance and inductance of the armature as

$$R_{ads} = r + \frac{L_{aad}\ \dfrac{K_{af}^2}{T_D}\left(1 + \dfrac{T_f}{T_D}\right)}{\left[1 + \left(\dfrac{1}{wT_D}\right)^2 + \left(\dfrac{T_f}{T_D}\right)^2 + 2K_{fD}^2\ \dfrac{T_f}{T_D}\right]} \tag{2.53}$$

$$L_{ads} = L_{aad}\left[1 - \frac{K_{fD}^2\ \left(\dfrac{T_f}{T_D}\right)^2 + \left(\dfrac{K_{aD}}{K_{af}}\right)^2 + 2K_{fD}\left(\dfrac{K_{aD}}{K_{af}}\right)\left(\dfrac{T_f}{T_D}\right)}{1 + \left(\dfrac{1}{wT_D}\right)^2 + \left(\dfrac{T_f}{T_D}\right)^2 + 2K_{fD}^2\ \dfrac{T_f}{T_D}}\right] \tag{2.54}$$

with $w = w_1$, equation (2.53) can be rearranged to give

$$K_{af}^2 = \frac{(R_{ads1} - r)\ T_D}{\left(1 + \dfrac{T_f}{T_D}\right)}\left[1 + \left(\frac{1}{w_1 T_D}\right)^2 + \left(\frac{T_f}{T_D}\right)^2 + 2K_{fD}^2\ \frac{T_f}{T_D}\right] \tag{2.55}$$

where R_{ads1} = Equivalent armature resistance at frequency w_1.

CHAPTER 3

EXPERIMENTAL METHODS

A number of important conventional methods has been described here. The experimental techniques of the indicial response method and the low frequency response method have been described separately.

3.1 Some Conventional Methods of Determination of Synchronous Machine Quantities

3.1.1 Slip Test

This is an important a conventional method to determine the direct and quadreture axis synchronous reactances of synchronous machine. In this method the field of the synchronous machine is left open circuited and a 3-phase reduced voltage (one fourth rated voltage) is applied to the armature terminals and the rotor of the machine is driven with a primemover at a slightly different speed from synchronous speed. It is to be noted that the direction of rotation of primemover is same as the direction of rotation of flux of the synchronous machine. This is acertained by noting the direction of rotation of the rotor after applying a three-phase voltage to the stator when the machine is in the standstill condition.

When the speed of the machine is slightly below the synchronous speed, the voltage as well as the current fluctuates. The voltage and current waveforms are then recorded (Fig. 3.1).

Then $$x_d = \frac{\text{voltage maximum}}{\text{current minimum}}$$

$$x_q = \frac{\text{voltage minimum}}{\text{current maximum}}$$

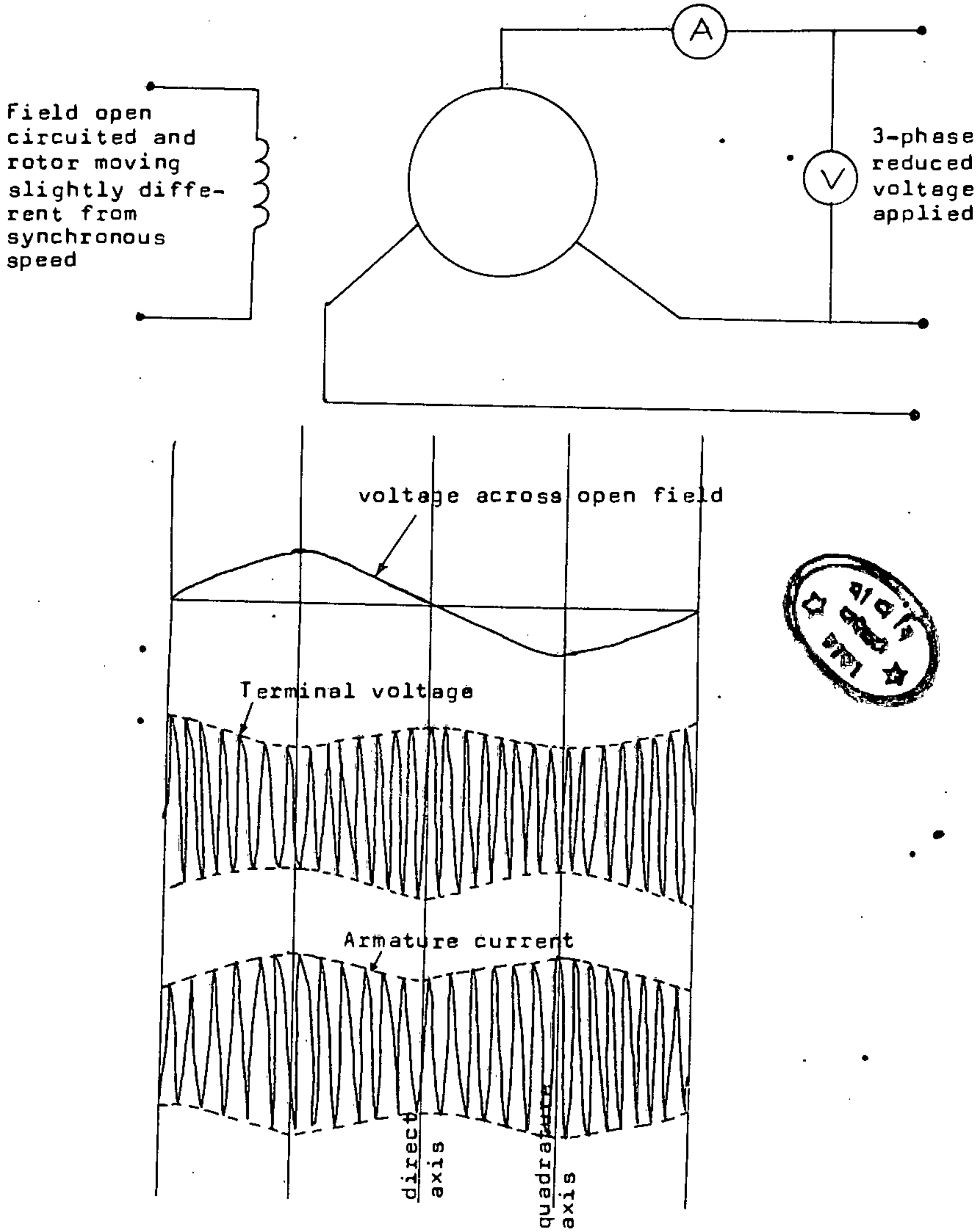


Fig. 3.1 Slip Test of Obtaining x_d and x_q.

3.1.2 Blocked Rotor Test

Blocked rotor test is used to determine subtransient reactences. In this method a single phase reduced voltage is applied to one of the armature windings and the rotor circuit is short circuted (fig. 3.2). Then the rotor is rotated slowly with hand and the voltage and current readings are taken using a voltmeter and an ammeter. When the rotor is in such an angular position that maximum current flows, the ratio of applied voltage to the maximum current equals x''_d . When the rotor is in such position that minimum armature current is obtained, then the ratio of applied voltage to minimum current equals x''_q.

3.1.3 Dalton and Cameron Method

This method is an improvement of the blocked rotor test. Here the rotor windings are also short circuited and a single phase voltage is applied to the two of the terminals. The voltage current ratios are calculated. The single phase voltage is applied in turn to each of the other two possible pairs of stator terminals, the respective third terminal being open and the voltage and current readings are taken in each case.

The results of these three measurements gives three values of stator voltage-current ratio i.e. subtransient reactances between stator terminals corresponding to three different position of rotor. These ratio may be designated A, B and C.

The constant offset and displacement component (Fig. 3.3) is $K = \frac{(A + B + C)}{3}$.

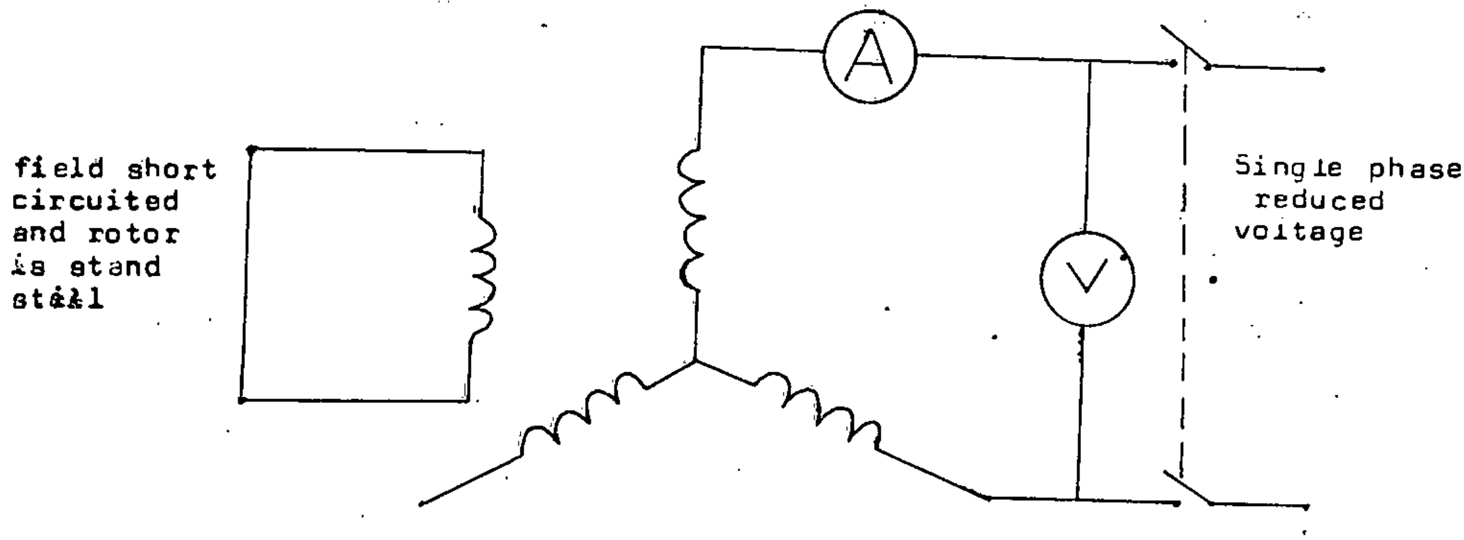


Fig. 3.2 Blocked rotor Test to Determine x''_d and x''_q.

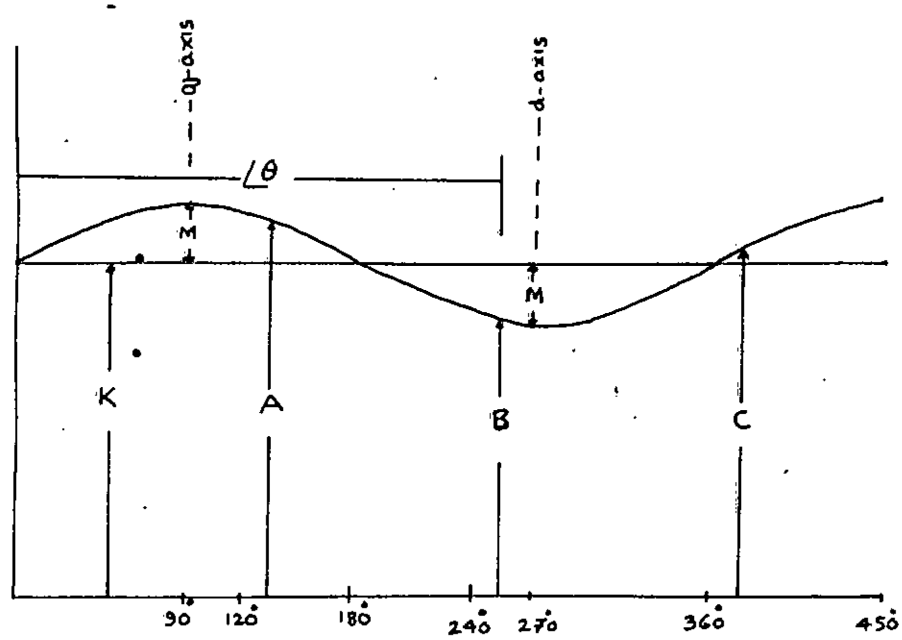


Fig. 3.3 In Dalton and Cameron Method, the displaced sine wave of subtransient reactance between stator terminals , M = Amplitude of wave, K = displacement or offset of the wave. ABC = any set of three values, spaced 120° apart.

The amplitude of the sine curve component measured from its offset zero line is

$$M = \sqrt{(B-K)^2 + \frac{(C-A)^2}{3}}$$

The reactances from terminal to neutral in ohms are given by

$$x''_d = \frac{K-M}{2} \quad , \quad x''_q = \frac{K+M}{2}$$

3.1.4 Phase-to-Phase Short-Circuit Test

This test is used to determine negative sequence reactance x_2, of the synchronous machine. The machine is Y-connected and is driven at rated speed with a substained single phase short circuit between two of the armature terminals (Fig. 3.4). The short circuit current and the voltage between the short circuited terminals and the terminal of the open phase are measured. A single phase wattmeter with its current coil actuated from current in the short circuited phase and the above mentioned voltage across its potential coil reads power. If V, I and W are respectively the readings of voltmeter, ammeter and wattmeter. Then negative sequence impedence is

$$Z_2 = r_2 + jx_2 = \frac{V}{\sqrt{3}I}(\sin\theta + j\cos\theta)$$

where $\theta = \cos^{-1} \frac{W}{VI}$

The negative sequence re ctance is, $x_2 = \frac{V}{\sqrt{3}I} \cos\theta$

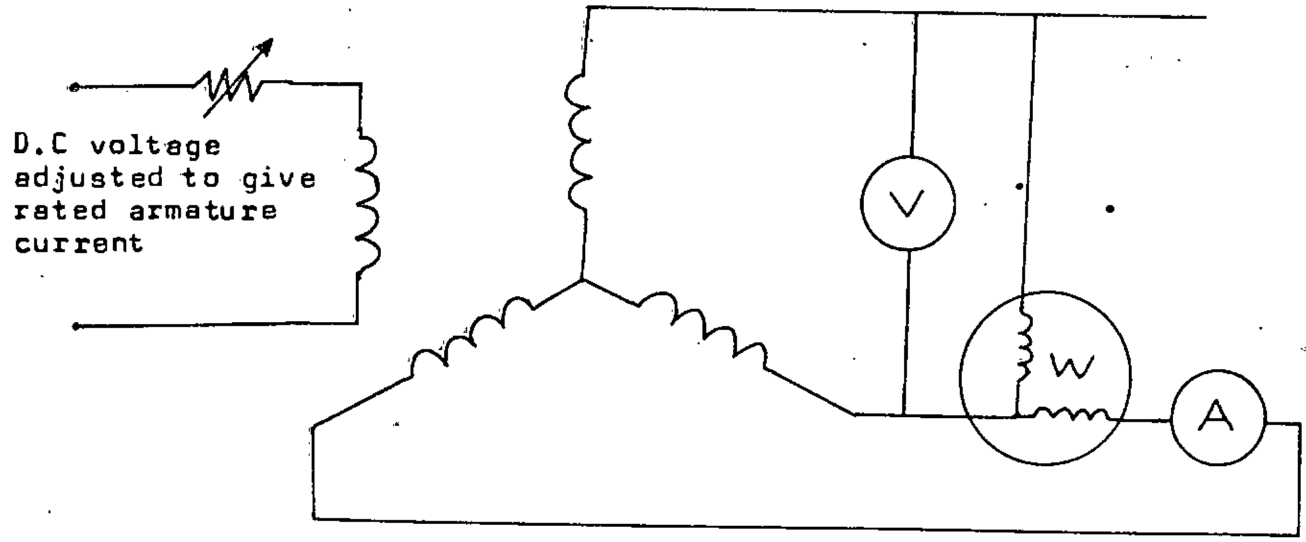


Fig. 3.4 Phase to Phase Short Circuit Test to Obtain Negative Sequence Reactance, X_2.

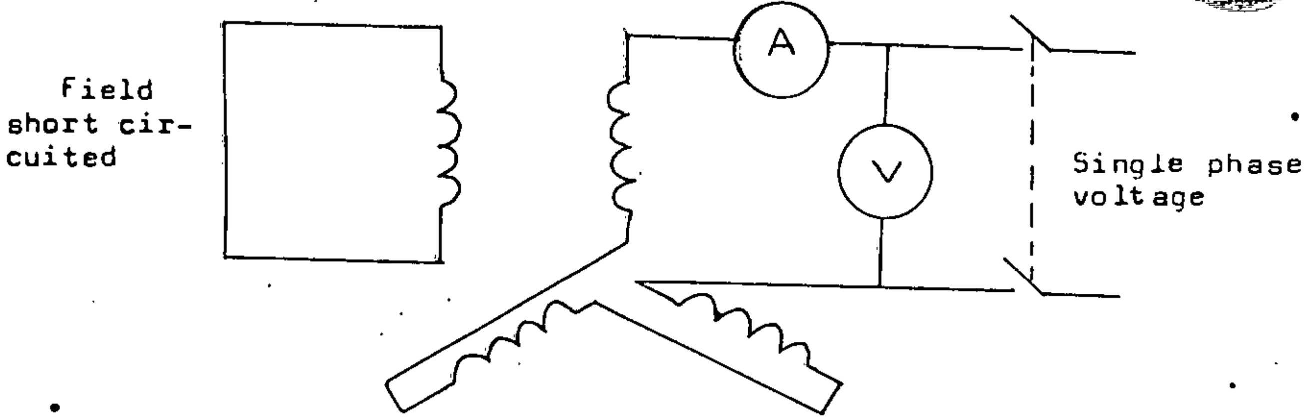


Fig. 3.5 3-Phase in Series Test to Determine Zero sequence reactance x_o.

3.1.5 3-Phase in Series Test

The zero sequence reactance of the machine is determined by this test. The synchronous machine under test is either driven at rated speed or kept at stand-still with the field winding short circuited. All the three phases are connected in series and a single phase voltage is applied across the open terminals (Fig. 3.5). Readings are taken of current and voltage when the rated value of current flows through machine. The zero sequence reactance of the synchronous machine is given by

$$x_o = \frac{V}{3I}$$, where V = applied voltage
I = armature current

3.1.6 Three Phase Sudden Short Circuit

This test is used to determine direct axis transient and subtransient reactences. Here the current waves of a three-phase short circuit suddenly applied to the synchronous machine operating at no load and rated speed is noted (fig. 3.6). The direct axis transient reactance (x_d') is equal to the ratio of the noload voltage to the corresponding value of the armature current given by the extrapolation of the envelopes of the a.c. components of armature current wave at the instant of the sudden application of the short circuit, neglecting the higher decrement current during the first few cycles Fig. 3.7, 3.8. illustrates this method of determining the x_d'.

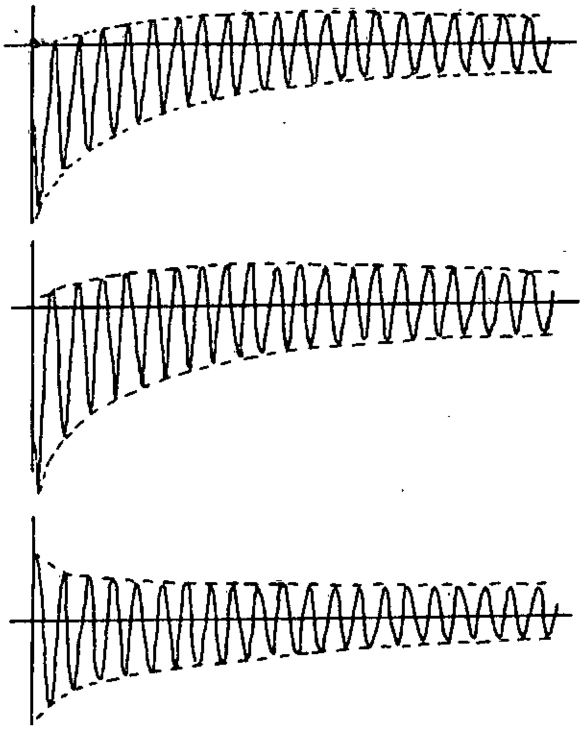


Fig. 3.6 Typical wave for 3-phase short circuit.

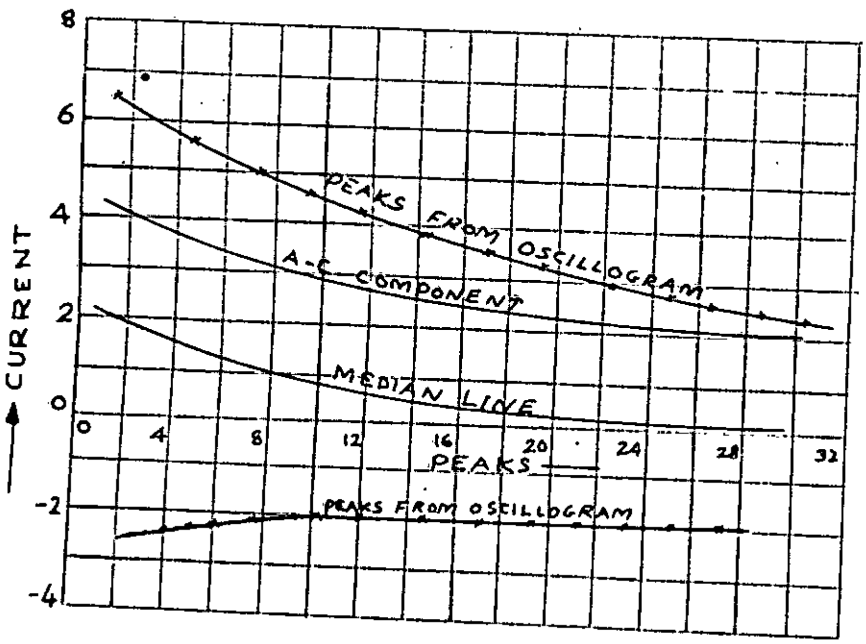


Fig. 3.7 Peak values of instantaneous short circuit currents and deviation of A.C component.

The ordinate for curve B at t = 0 is equal to the sum of the ordinates at t = 0 from straight lines. The ordinate for the a.c. component at t = 0 is then determined by adding the sustained short circuit current to the ordinate of the curve B at t = 0. The curve for the transient component plus the sustained value of the current is determined by adding the sustain short ~~current~~circuit current to the extended straight line of curve B.

$$x'_d = \frac{e}{I'}$$

where e = open circuit voltage of the machine immediately before the short circuit.

I' = current for the transient component plus the sustained value at t = 0 (Fig. 3.8).

x''_d can be determined from the sudden three phase short circuit of the alternator and having the oscillograms of current waves.

$$x''_d = \frac{e}{I''}$$

where e = open circuit voltage just before the short circuit

I'' = current from the a.c. component curve at t = 0.

An alternative way of finding x''_d from 3-phase short-current oscillogram of 3-phase current is to draw ~~a~~ median line for each of three waves and these are then plotted on semilog paper. The curve is extrapolated back to zero time and three initial values a, b, c are obtained. These three components are laid on three

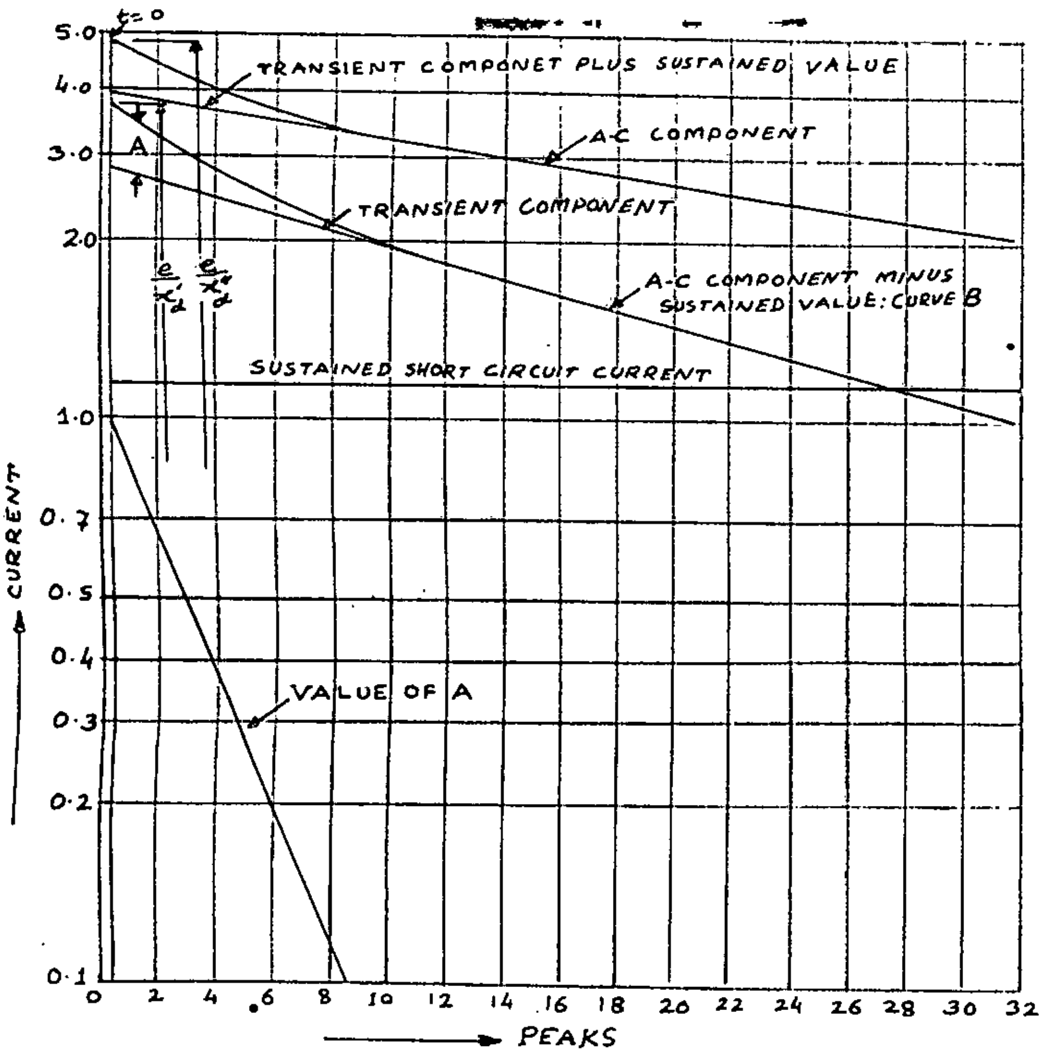


Fig. 3.8 Analysis of A.C. component of short circuit current.

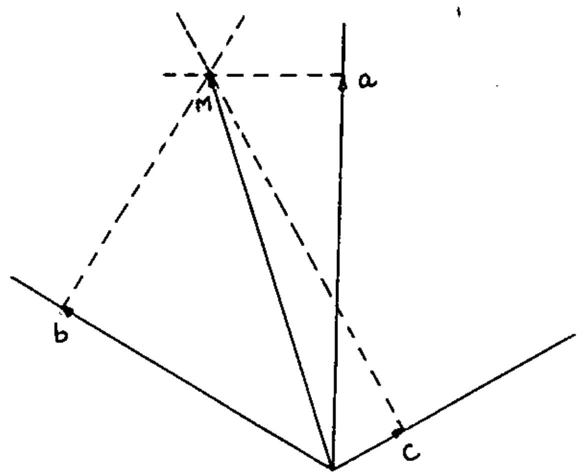


Fig. 3.9 Determination of Maximum possible asymmetrical component.

radial lines 60 degrees apart radiating from a point O, the largest of the three values being laid off on the middle line (Fig.3.9). Perpendiculars are drawn through the end points of each of the three lines and the point where they meet determine point M. In case the perpendiculars donot meet in a point but forms a small triangle. M is located in the approximate centre of the triangle. Then OM, dist nce represents the maximum possible asymmetrical component, to the same scale as the three radial lines. Then,

$$x''_d = \frac{a}{OM}$$

3.2 Indicial Response Method

A stable low voltage d.c. source is required for this test. The source must be able to supply the rated current of the machine.

The experiment is carried out in three steps. First the d.c voltage is applied to an armature with the field winding open circuited and the rotor is placed in direct axis i.e. the polar axis is in line with magnetic axis of a phase winding. Second step consists of similar arrangement as the first with the rotor in the quadrature axis. In the last setup the rotor is placed in the d-axis and the field winding is short-circuited.

3.2.1 First Set-up

In this setup the two armature windings and the field winding are open circuited and a d.c voltage is suddenly applied to the remaining third armature winding. The rotor of machine is placed in the direct axis. The d-axis of the machine should be located first. For this a single-phase voltage is applied to one phase of the armature winding and the field winding is short-circuited. The rotor is turned slowly and the fluctuation of the armature current is noted using an ammeter. The minimum current position of the armature is the q-axis and the maximum current position the d-axis.

A voltmeter, an ammeter and a storage oscilloscope is connected to one phase winding as shown in Fig. 3.10. The d.c. voltage is applied suddenly and the rise in armature current is recorded on a film using the oscilloscope camera.

The response shape is shown in Fig. 3.11. The voltmeter and ammeter readings are noted to get the values of the applied voltage and the steady state current.

A curve is plotted on semilog paper with ordinate as the difference between the steady state current and the gradually rising current and the abcissa as the time. The shape of the curve is shown in Fig. 3.12. From this curve the values of two currents and two time-constants are taken as shown in Fig. 3-12.

From the above data of voltage, currents and time constants, the resistance (r), time constants of armature winding (T_{ad}), coupling coefficient between armature and damper winding (K_{an}^2), time constant of damper winding (T_{1d}) and direct axis synchronous reactance (x_d) are obtained by using the equations (2.34-2.38,2.16).

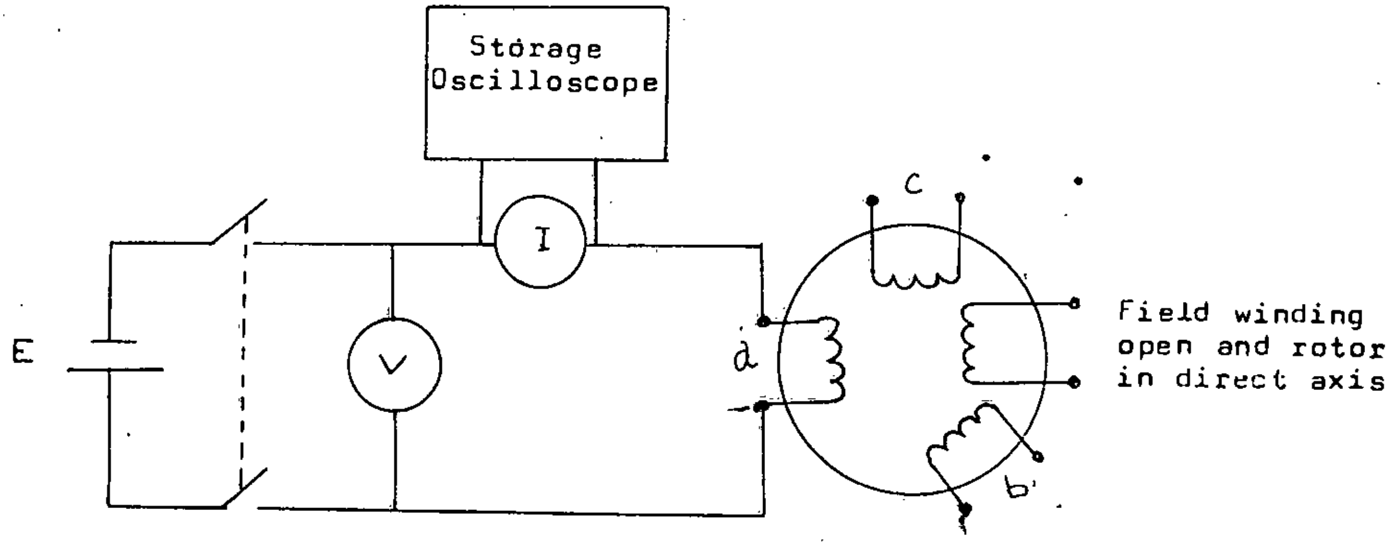


Fig. 3.10 Circuit Arrangement for 1st setup.

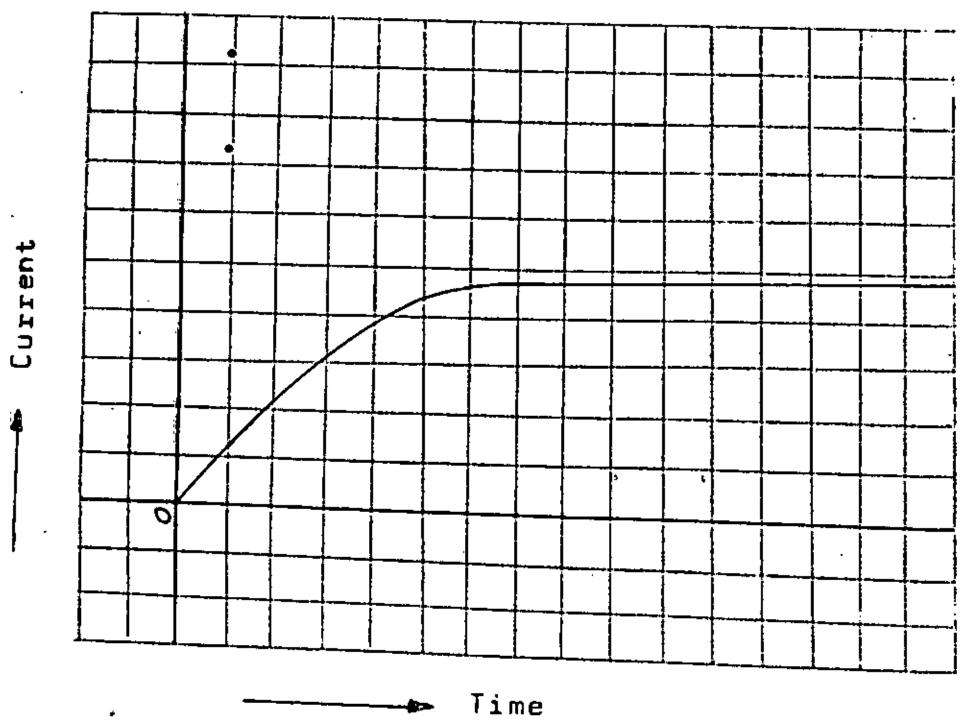


Fig. 3.11 Oscillogram for 1st setup in indicial response method at $\theta = 0$ and field open circuited.

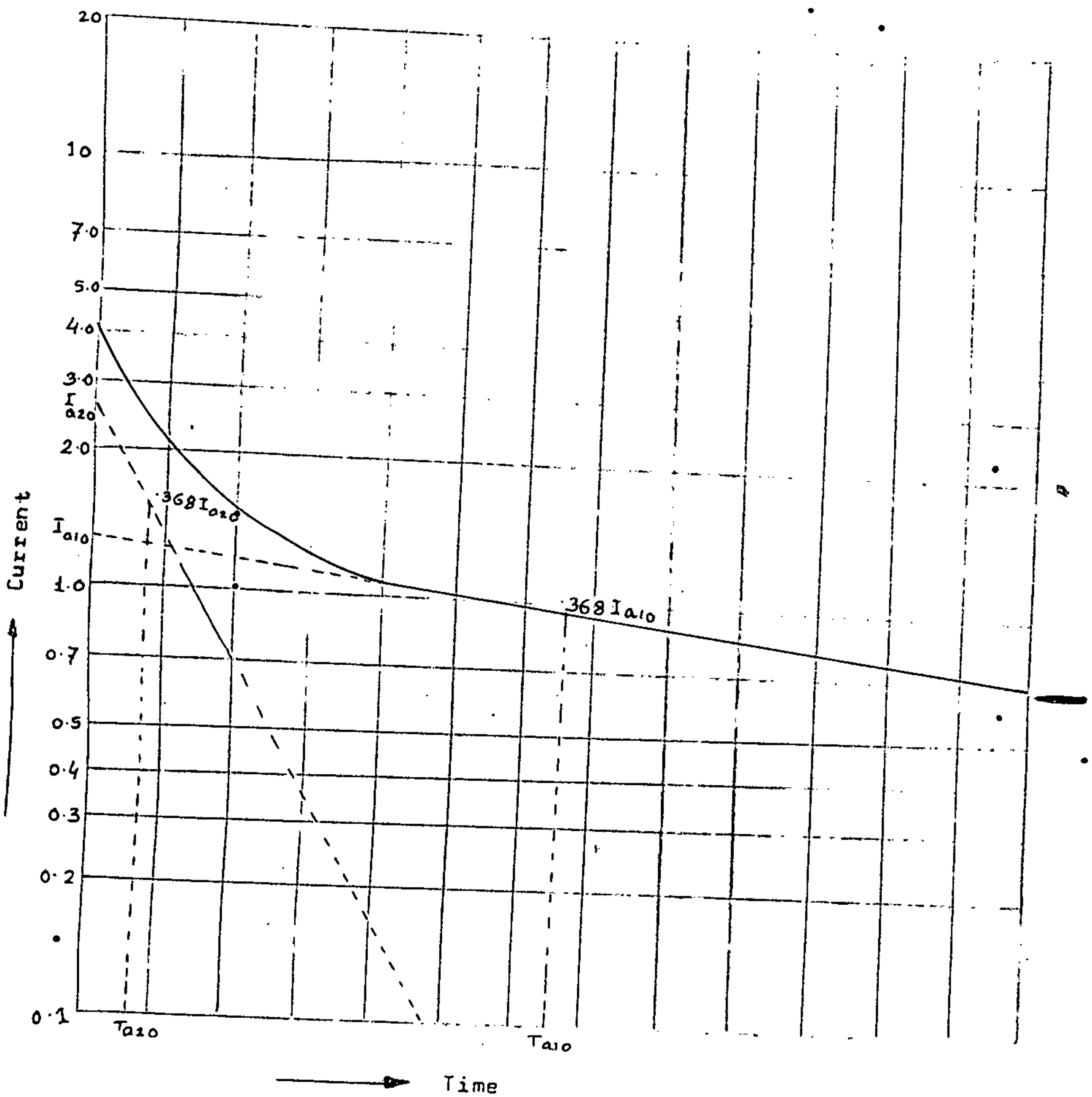


Fig. 3.12 Analysis of Transient current of indicial response method in 1st setup.

3.2.2 Second Setup:

In this setup the rotor is placed in quadrature axis with the field winding open circuited. The exx circuit arrengement is shown in Fig. 3.13. As in the first setup, the response curve of current is recorded (Fig. 3.14). The semilog plot is done as before and two corresponding values of currents and time constants are obtained as shown in Fig. 3.15.

From the values of current and time constant. Coupling coefficient of damper-armature winding in q-axis (K_{aQ}), time constant of q-axis damperxx (T_Q) and quadrature axis synchronous reactances (X_q), and transient, subtransient reactence (X'_q, X''_q) are obtained using equation (2.13)(2.30)(2.28).

3.2.3 Third Setup:

In this setup the rotor is placed in direct axis with field winding short circuited. The circuit arrangement is shown in Fig.3.16. As in first setup the response curve of current is recorded (Fig.3.17) The samilog plot is done as before and three corresponding values of current and time constants are obtained (Fig. 3.18).

From the values of currents and time constants, coupling coefficient of field and damper winding (K_{fD}), coupling coefficient of armature and field winding (K_{af}) and transient and subtransient reactances of directaxis (X'_d, X''_d) are obtained using equations (2.41), (2.42),(2.29) and (2.27) respectively.

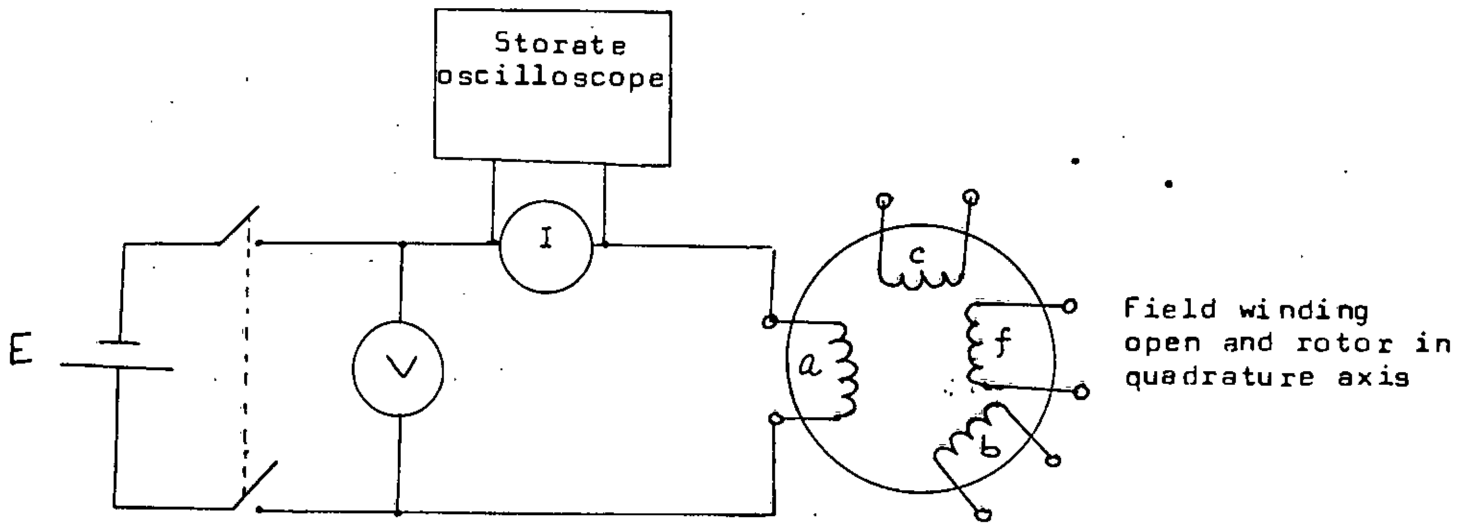


Fig. 3.13 Circuit Arrangement for 2nd setup.

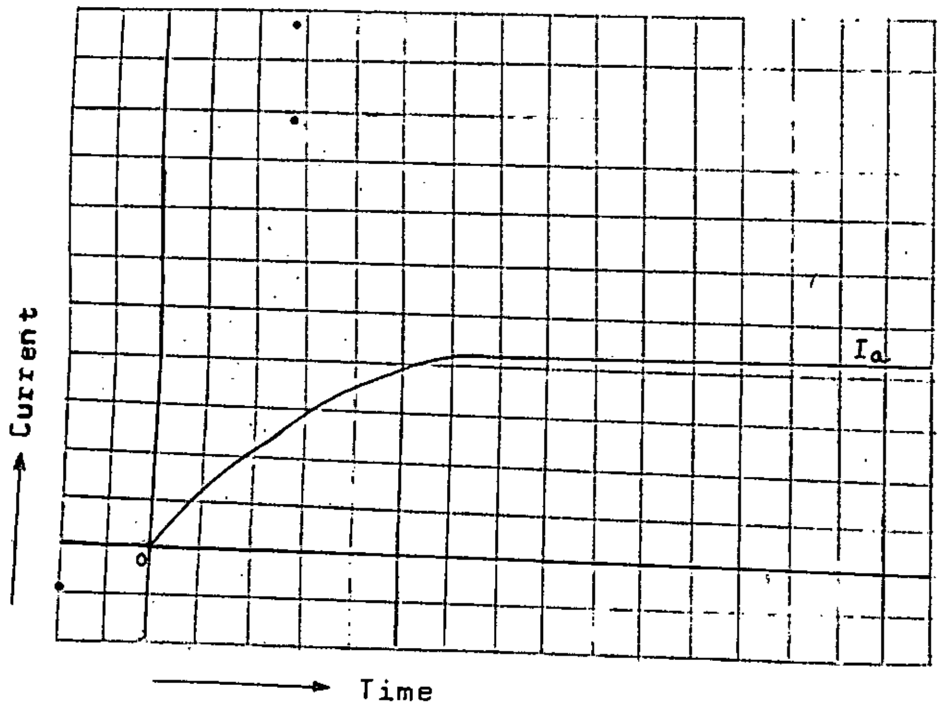


Fig. 3.14 Osillogram for 2nd setup in indicial response method at $\theta = 90^o$ and field open circuited.

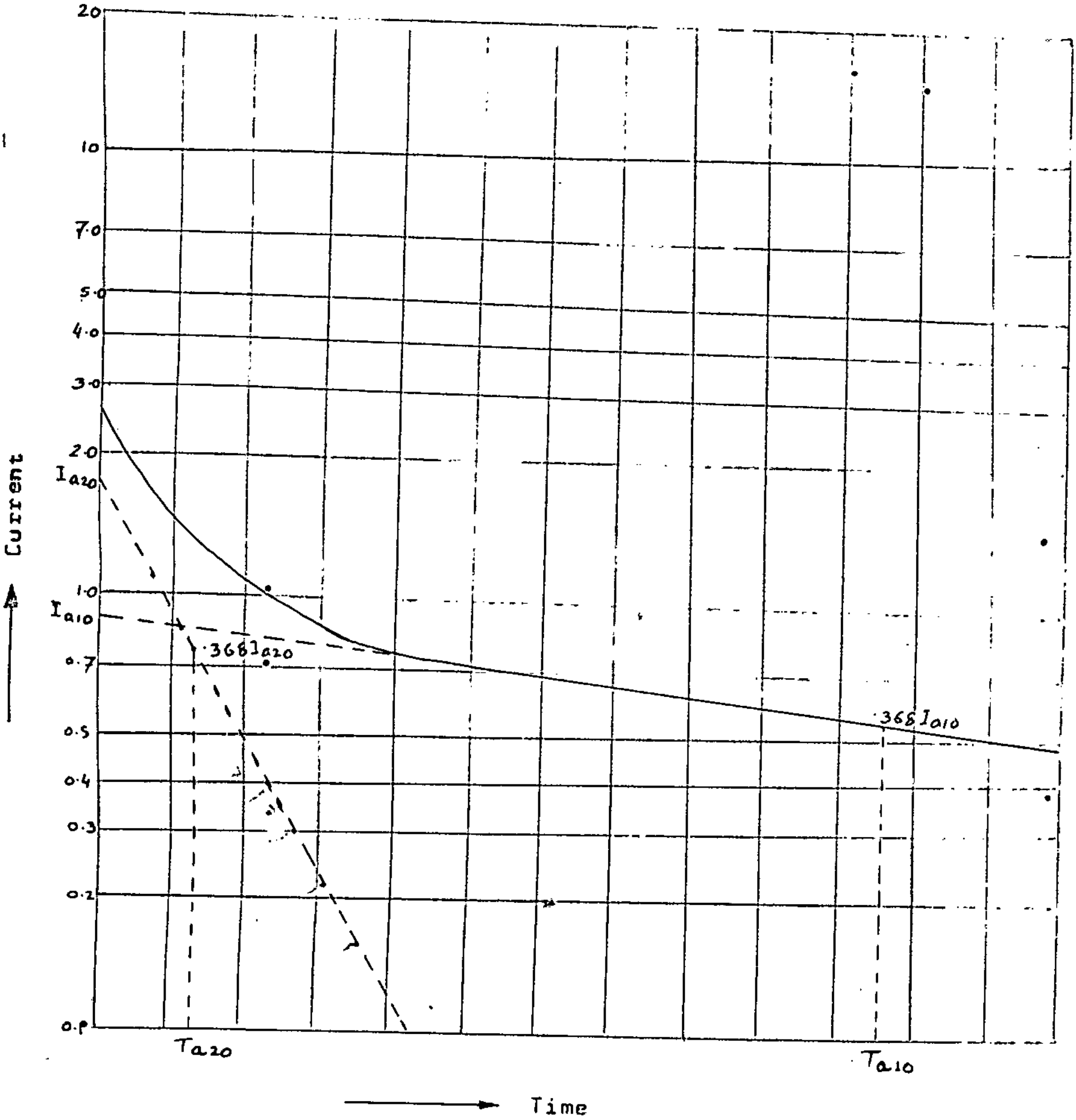


Fig. 3.15 Analysis of Transient current of indicial response method in 2nd setup.

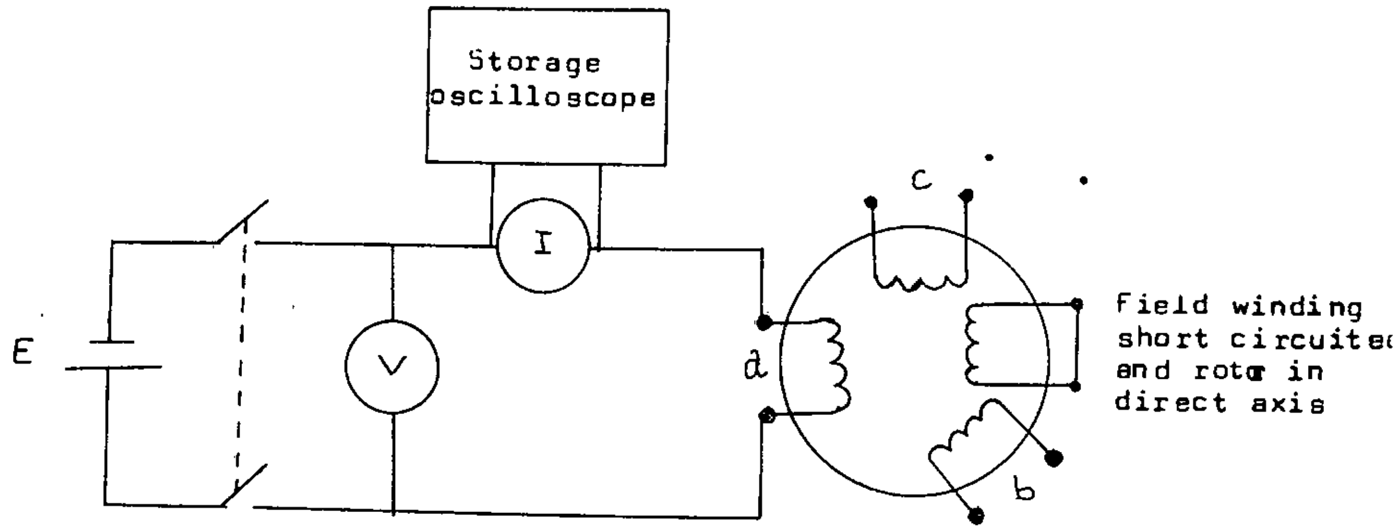


Fig. 3.16 Circuit arrangement of 3rd setup.

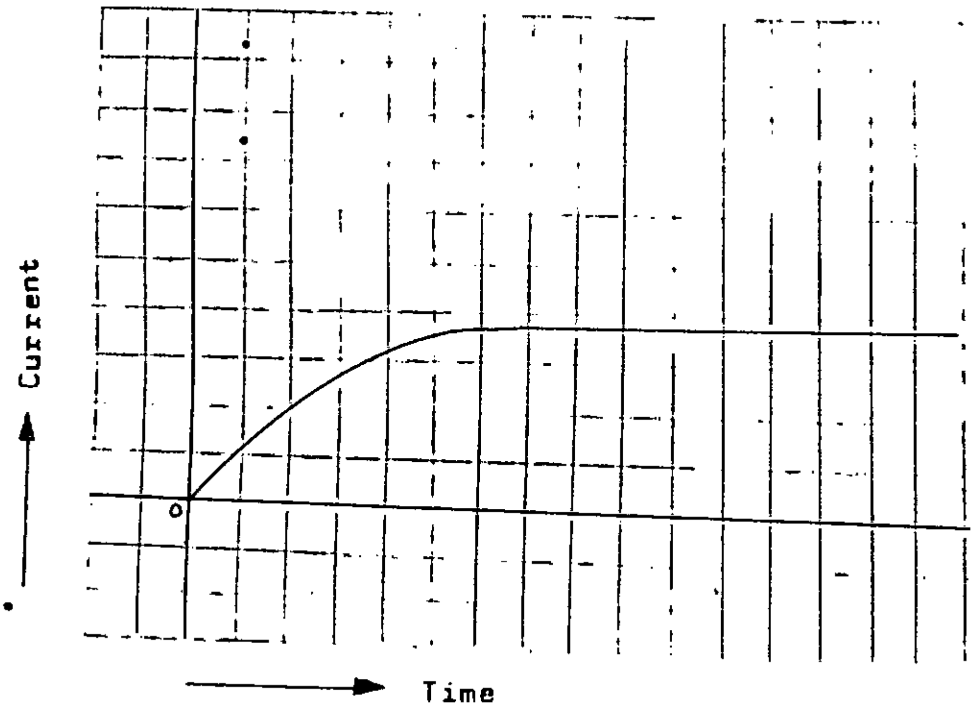


Fig. 3.17 Oscillogram for 3rd setup in indicial response method at $\theta = 0$ and field short circuited.

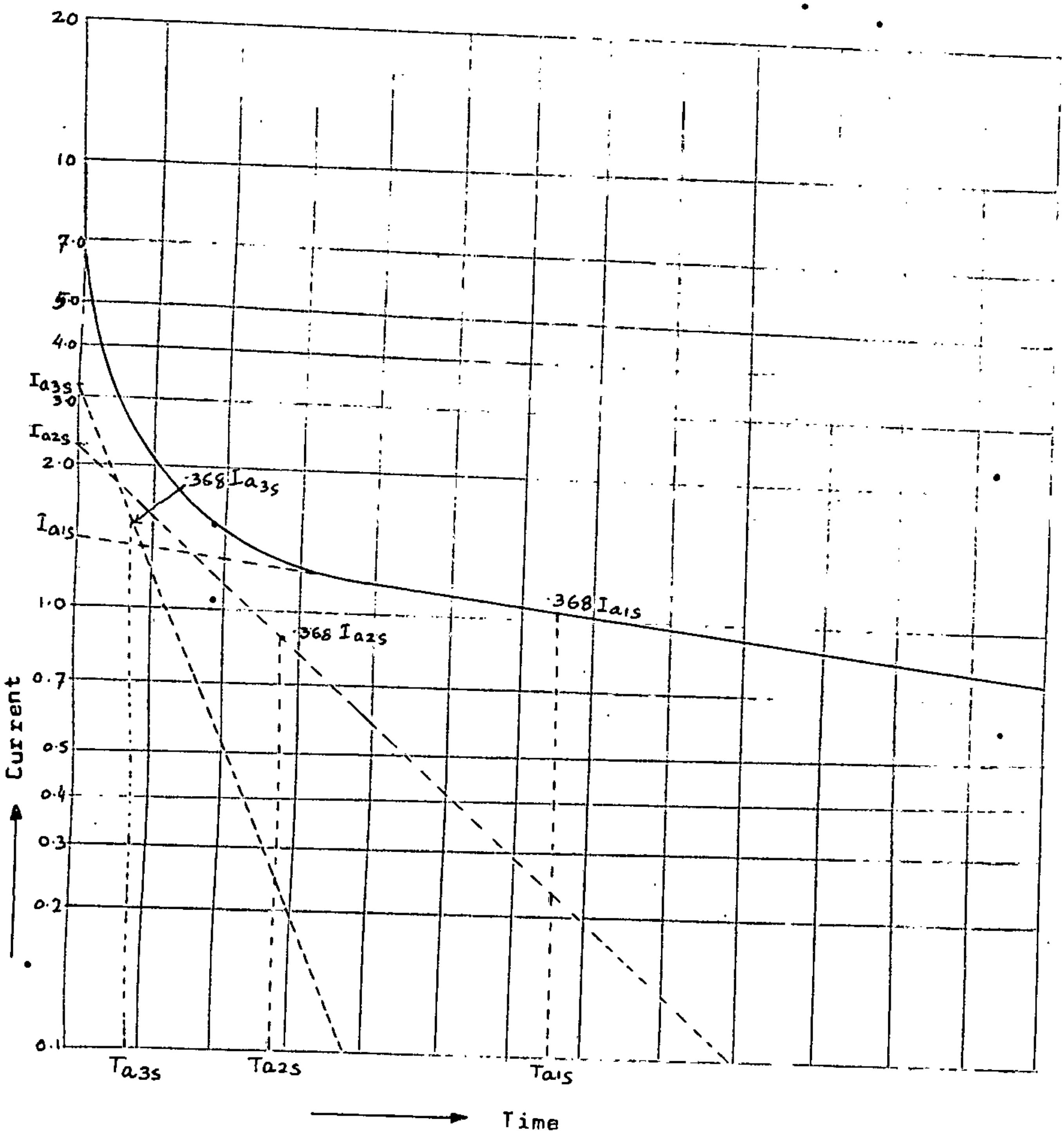


Fig. 3.18 Analysis of transient current of indicial response method in 3rd setup.

3.3 Low Frequency Response Method

A variable low frequency (1 to 5 Hz) supply is required for this test. The source must be able to supply sufficient current for testing the machine without appreciable variation in supply voltage.

The experiment is carried out in four setups. In first setup the variable low frequency is applied to an armature winding with field winding open circuited and the rotor is placed in direct axis. The second setup consists of similar arrangement as in the first, with the rotor in the quadrature axis. In the third setup the variable low frequency is applied to the field winding with armature winding open circuited. In the last setup the rotor is placed in the direct axis and the field winding is shortcircuited.

3.3.1 First Setup

In this setup the two armature windings and the field winding are open circuited and a low frequency voltage is applied to the remaining third armature winding. The rotor of the machine is placed in the direct axis. A voltmeter, an ammeter and an oscilloscope is connected to an armature winding as shown in Fig. 3.19. The waveforms of arm ture voltage and current are recorded on a photographic film using the oscilloscope Camera.

The frequency is varied and the corresponding readings of voltage and current are taken and the phase angle between voltage and current are obtained from their waveforms, recorded on photographic film.

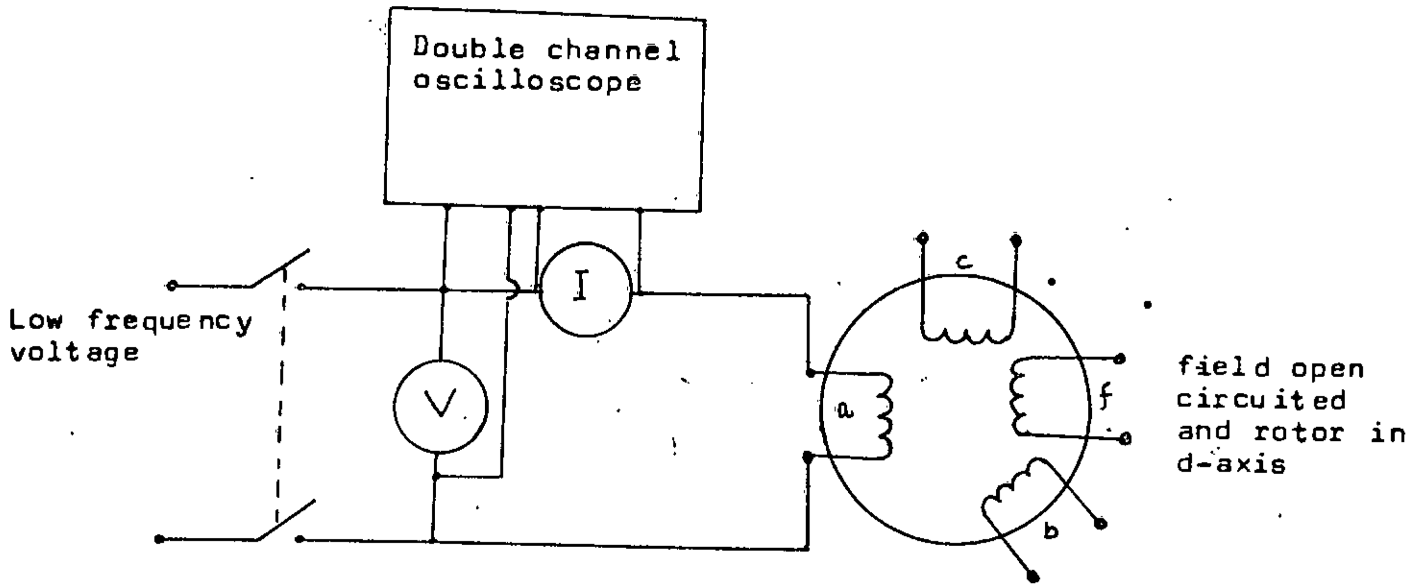


Fig. 3.19 Circuit arrangement for 1st setup in low frequency response method.

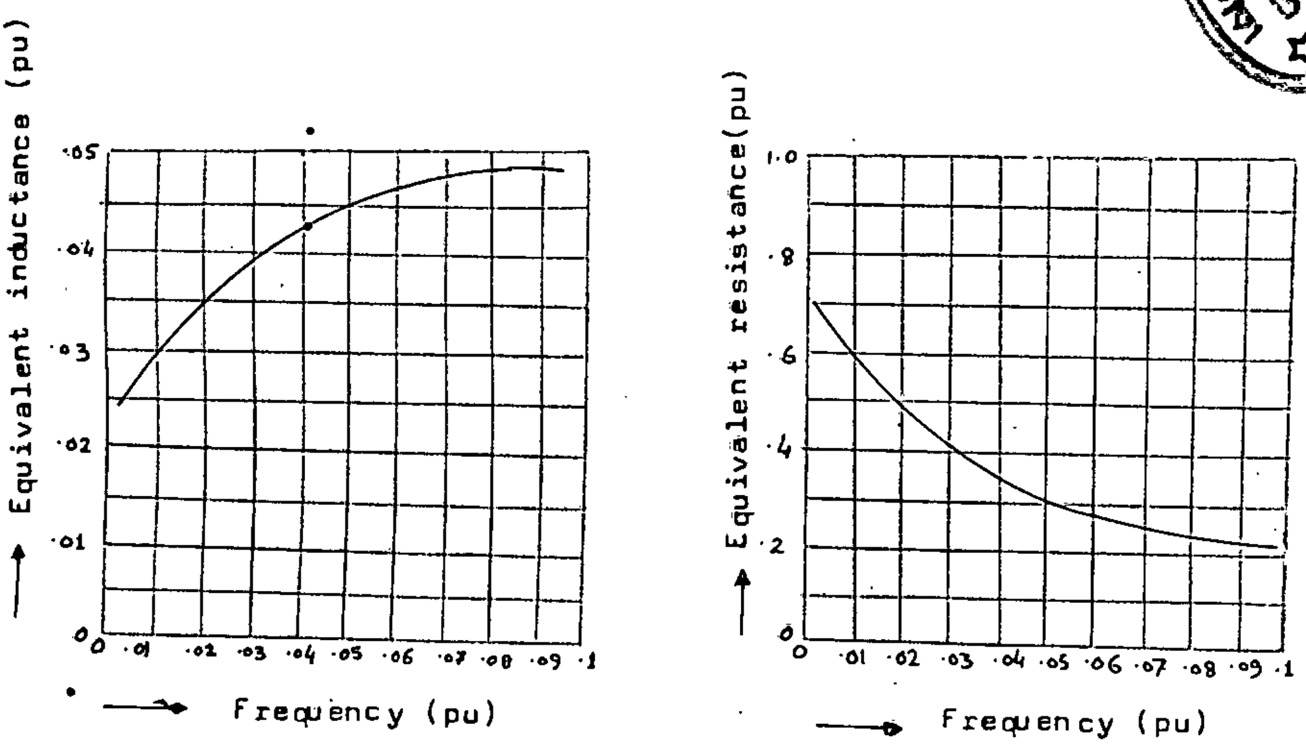


Fig. 3.20 Frequency characteristics of equivalent inductance and resistance for 1st setup.

With the experimental values of e, i_a and $\emptyset$, equivalent resistances and inductances are calculated using equations (2.46). The curves of the equivalent resistance and inductance against frequency are then plotted (Fig. 3.20). With the values of resistances and inductances at two different frequencies taken from the curves, the self inductance of armature winding (L_{aad}), resistance of armature winding (r), coupling coefficient between d-axis damper and armature winding (K_{aD}) and time constant of d-axis damper (T_D) are calculated using equations (2.49) to (2.52). Finally the direct axis synchronous reactance (x_d) is calculated using equation (2.12).

3.3.2 Second Setup

Here the rotor is placed in the quadrature axis with the field winding open circuited. The circuit arrangement is shown in Fig.3.21. As in the first setup the low frequency is applied to one of the armature winding, while other armature windings open circuited. The frequency is varied and readings of voltages and current are taken and their waveforms are recorded to find the phase angle between them. The equivalent resistances and inductances are calculated from equations (2.45) and (2.46). The resistance vs. frequency and inductance vs. frequency curves are then plotted.

With the values of L_1, L_2, R_1, R_2, at w_1 and w_2 taken from curves and using equations (2.49) to (2.52) as stated in section 2.10.2, the quadrature axis self inductance of armature winding (L_{aaq}), the coupling coefficient between q-axis damper and armature winding (K_{aQ}) and time constant of q-axis damper winding are obtained. Then the quadrature axis synchronous reactance (x_q), transient

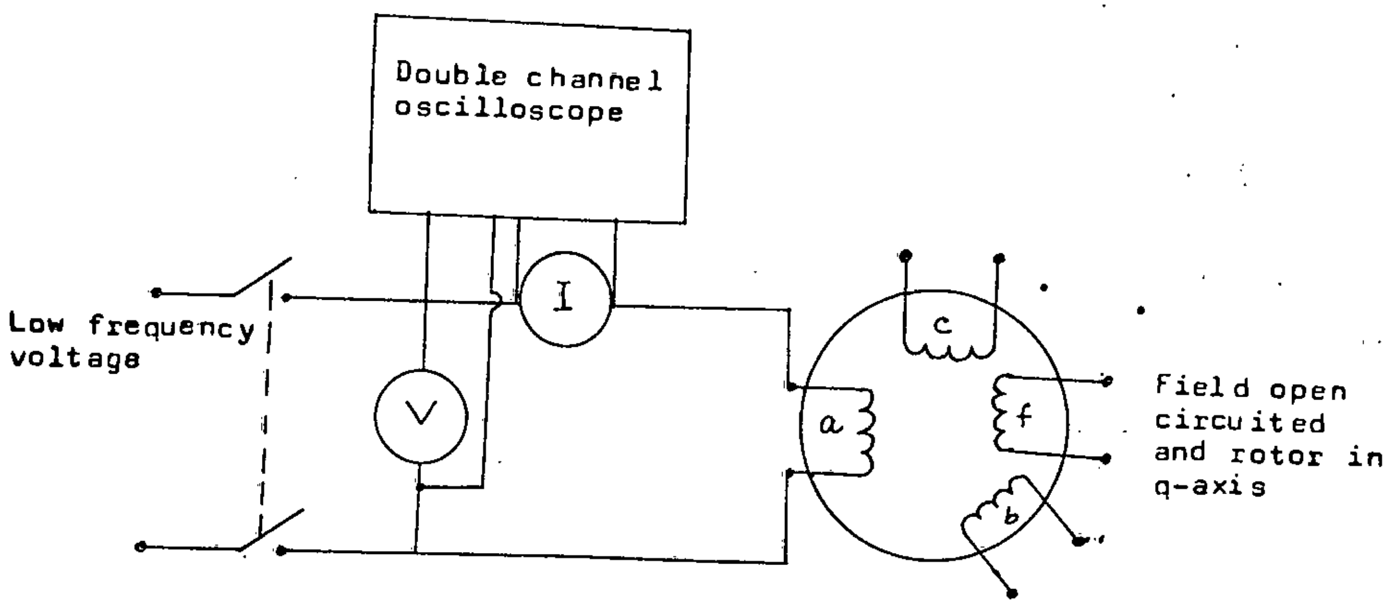


Fig. 3.21 Circuit arrangement for 2nd setup, in low frequency response method.

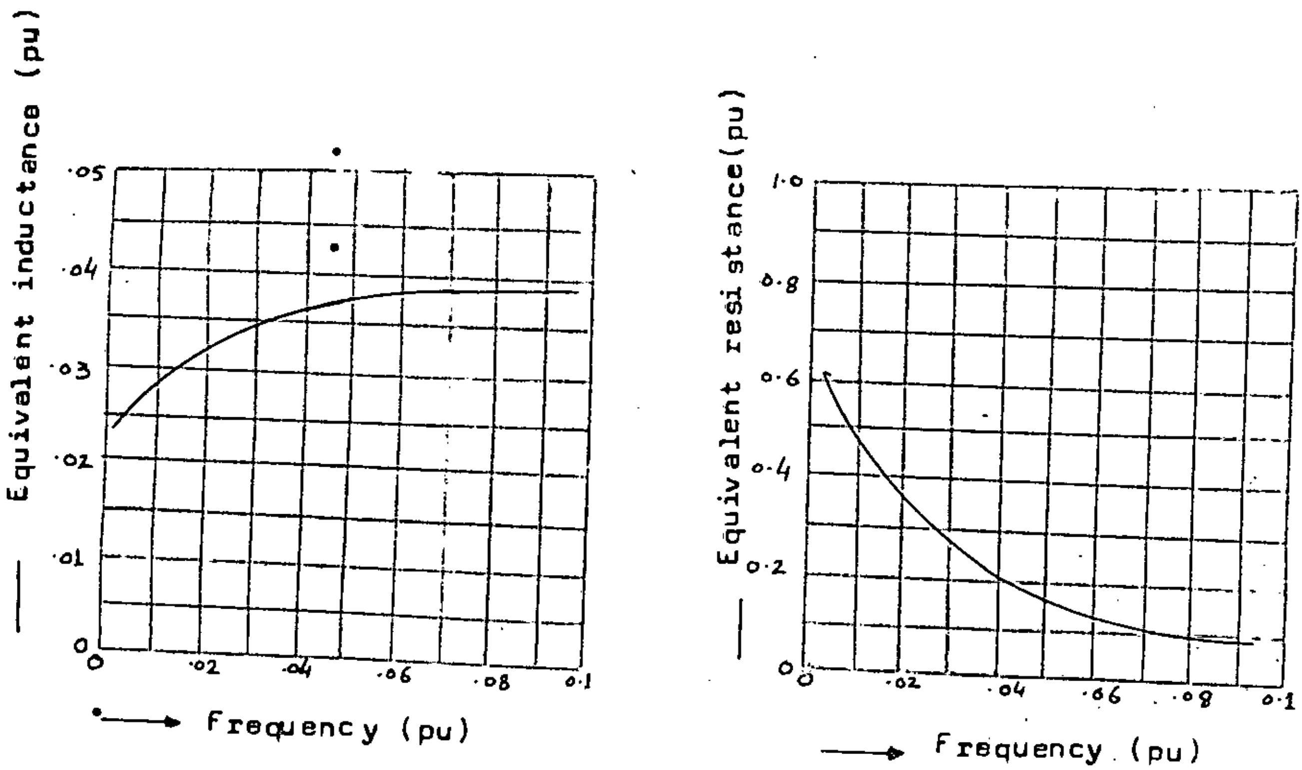


Fig. 3.22 Frequency characteristics of equivalent inductance and resistance for 2nd setup.

reactance (x_q') and substransient reactance (x_q'') are calculated using equations (2.13), (2.28) and (2.30).

3.3.3 Third Setup

In this setup, the field winding is excited with a low frequency voltage. The rotor of the machine may be in any position and all the armature wwindings are open circuited. The circuit arrangement is shown in Fig. 3.23. The frequency is varied and the resistance-frequency and inductance frequency curves are plotted (Fig.3.24).

From the plot the coupling coefficients between field and d-axis damper (K_{fD}), time constant of the field winding (T_f) are obtained by choosing two frequencies and using equations (2.51) and (2.52) with the subscript 'a' replaced by 'f'.

3.3.4 Fourth Setup

In this last setup the field winding is short circuited, the rotor is placed in the direct axis and the low frequency is applied to an armature winding. The other two armature windings are open circuited. The circuits arrangement is shown in Fig. 3.25. As before the frequency is varied, R - w and L - w curves are plotted (Fig.3.27).

With a value of equivalent resistance at a frequency, taken from a plot, the coupling coefficient between armature and field winding (K_{af}) is calculated using equation (2.55).

Finally the transient and subtransient reactances of direct axis (x_d', x_d'') are calculated using equations (2.29) and (2.27) respectively.

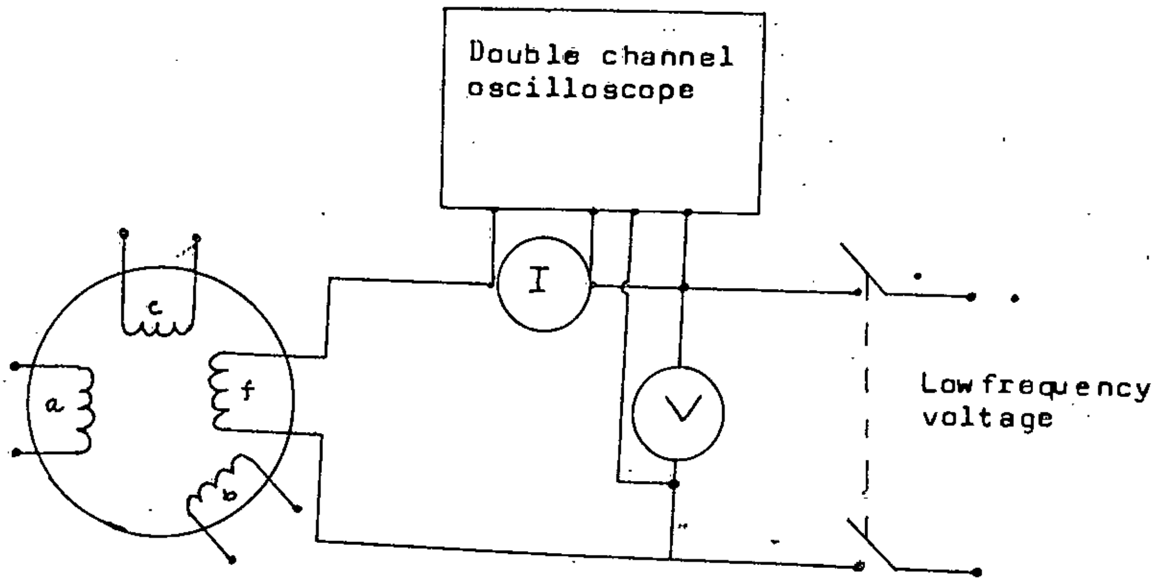


Fig. 3.23 Circuit arrangement for 3rd setup, in low frequency response method.

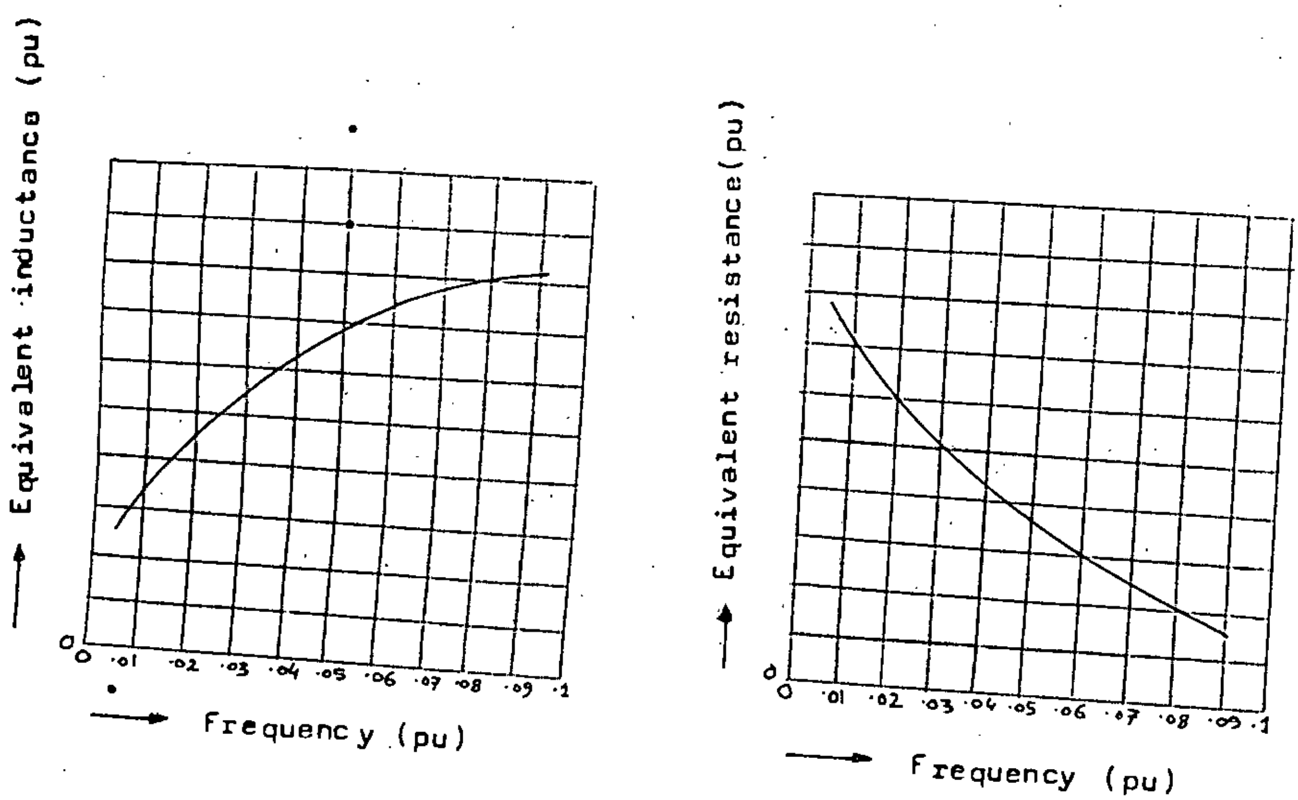


Fig. 3.24 Frequency characteristics of equivalent inductance and resistance for 3rd setup.

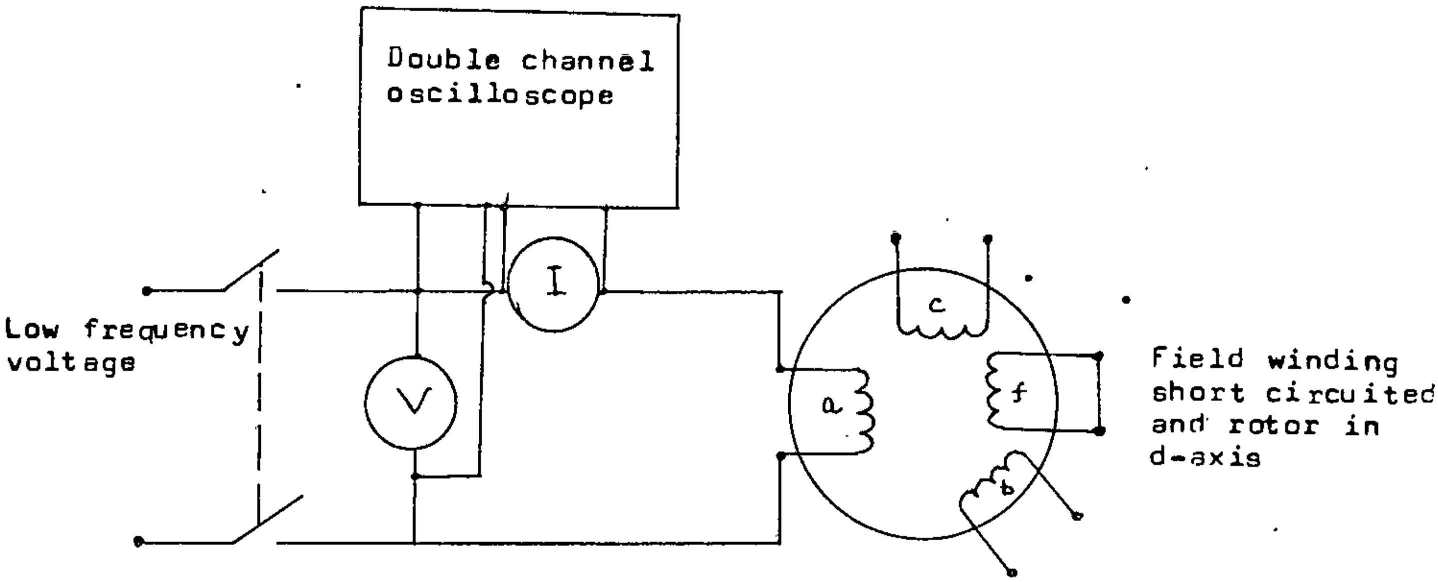
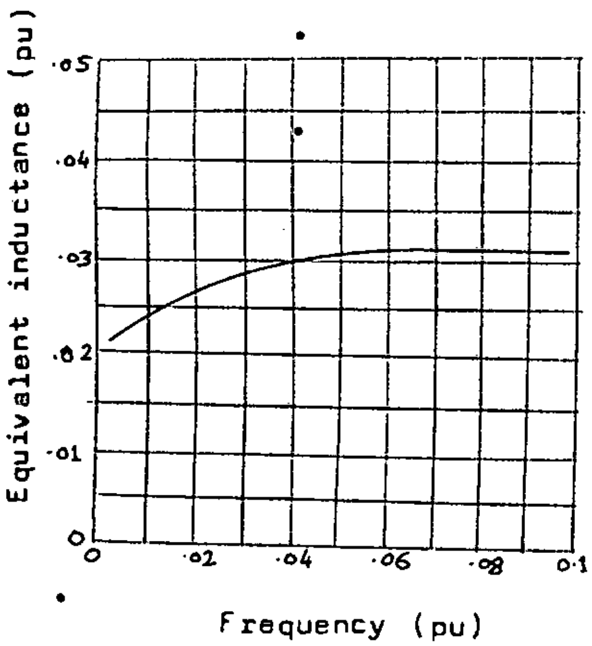


Fig. 3.25 Circuit arrangement for 4th setup in low frequency response method.



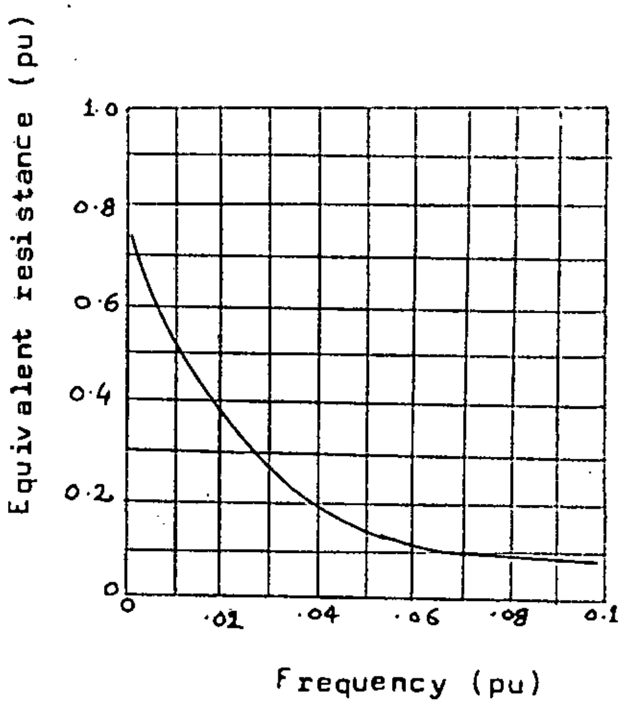


Fig. 3.26 Frequency characteristics of equivalent inductance and resistance for 4th setup.

CHAPTER 4

EXPERIMENTAL RESULTS

The experimental results of the indicial response and low frequency response methods are given here. The tests were carried out on a laboratory alternator. A universal machine was used to generate the low frequency voltage for carrying out the low frequency test. The detailed numerical calculations of all the important synchronous machine quantities by the new methods are given. The results of the important conventional methods of measurement on the same machine are also given here. A comparison of the results of the new method, of measurement with that of the conventional methods of measurement has been presented.

4.1 Indicial Response Method

Following the procedure detailed in section 3.2. The tests on the synchronous machine to determine machine quantities by indicial response method, was performed in three steps.

4.1.1. The Test Machine

A salient-pole synchronous machine, having damper windings was used for the test. The specification of the machine are given below:

Armature Circuit

Voltage=110/220 volts (A.C)

Current=15.8/7.9 Amps

KVA = 3.0

Speed = 1000 rpm

Frequency = 50 Hz

Numbers of poles = 6

Field Circuit

Voltage = 125 volts (D.C)

Current=2.6 Amps.

The voltage and current ratings of the machine are 220 volts and 7.9 Amps. for Y-connection of the armature winding. The per unit values of the machine quantities are calculated using the following base values:

Base KVA = 3

Base voltage = 220 volts

Base current = 7.9 Amps.

Base impedance = 16.07 ohms

Base inductance = 0.0515 henry

Base current ratio = 0.2195

4.1.2 First Setup

In this set up, the field winding was open circuited the rotor was placed in the direct-axis and a d.c. voltage was applied suddenly to an armature winding, with the other two armature winding open circuited. The circuit arrangement is shown in Fig. 3.10 (Chapter 3). The following experimental results were obtained:

Applied d.c. voltage = 1.893 volts

Steady state d.c. current = 3.65 Amps.

Time scale in the response (on oscilloscope) = 50 milli sec./cm

The transient rise in current from zero to steady state value was, as shown in Fig. 4.1.

The difference between the steady state current and the gradually rising current at different points on the time-axis of Fig. 4.1 is tabulated in Table 4.1. The current-time curve of Fig. 4.2 was plotted using data of Table 4.1, with the difference-current values plotted on logarithm scale.

From the curves of Fig. 4.2, the following components of currents and time constants were obtained:

$I_{ao0} = 3.65$ A

$I_{a10} = 2.8$ A

$I_{a20} = 0.85$ A

$T_{a10} = 73.2$ milli second

$T_{a20} = 28.25$ milli second

The armature resistance (r) is calculated, using equation (2.34) -

$$r = \frac{E}{I_{ao0}} = \frac{1.893}{3.65} = 0.5185 \text{ ohms}$$

$$= \frac{0.5185}{16.07} \text{ per unit} = 0.03228 \text{ per unit}$$

The direct axis armature inductance (L_{aad}) is obtained from equation (2.35) -

$$L_{aad} = r \frac{T_{a10}\left(1 + \frac{I_{a20}}{I_{a10}} \times \frac{T_{a20}}{T_{a10}}\right)}{1 + \frac{I_{a20}}{I_{a10}}}$$

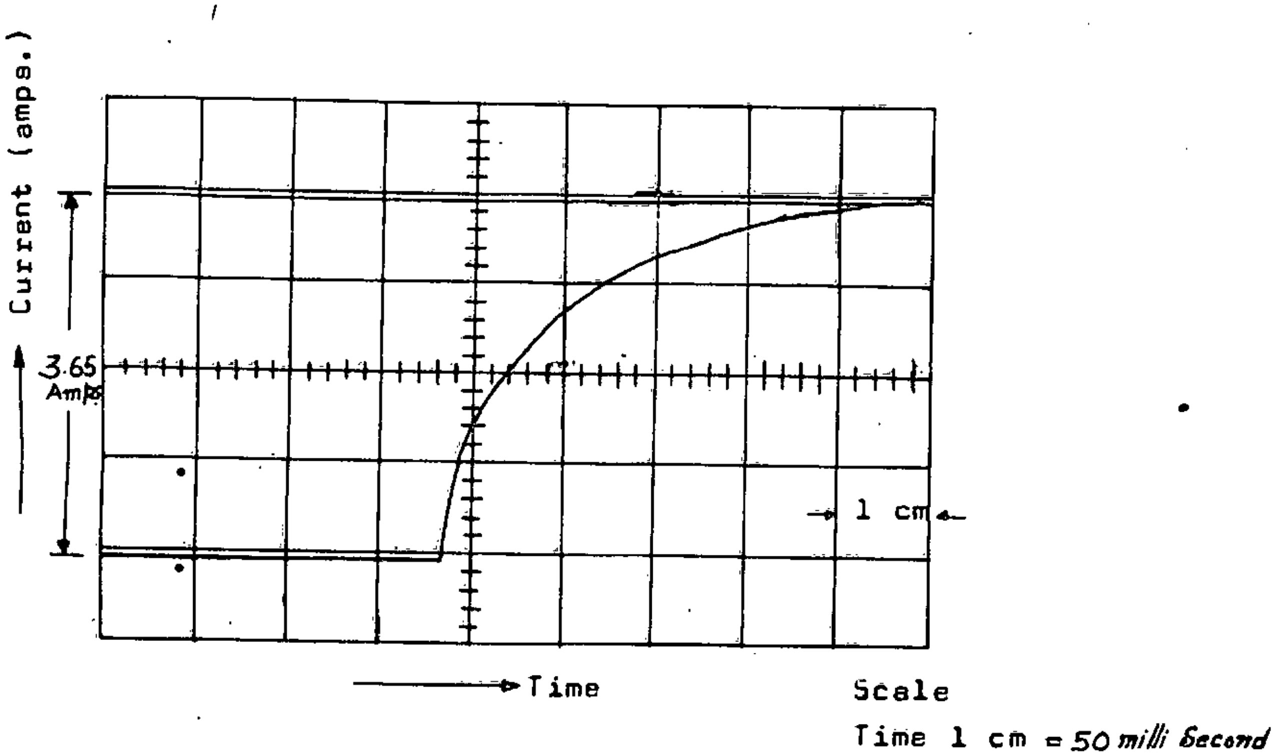


Fig. 4.1 Oscillogram of the Transient Rise in Current from zero to steady state value when the field is open circuited and rotor in d-axis.

Table 4.1 Difference between steady state and gradually rising current at different time (from Fig. 4.1)

Time (milli second)	Current (amps)
2.085	3.39
4.215	3.19
5.20	3.029
6.86	2.815
8.5	2.64
10.4	2.54
16.44	2.28
20.0	2.1
26.07	1.95
35.0	1.743
42.5	1.568
50.5	1.38
62.8	1.2045
73.3	1.027
89.5	0.837
105.0	0.6615
126.65	0.5248
146.8	0.3875
166.5	0.2925
186.9	0.190
206.8	0.135

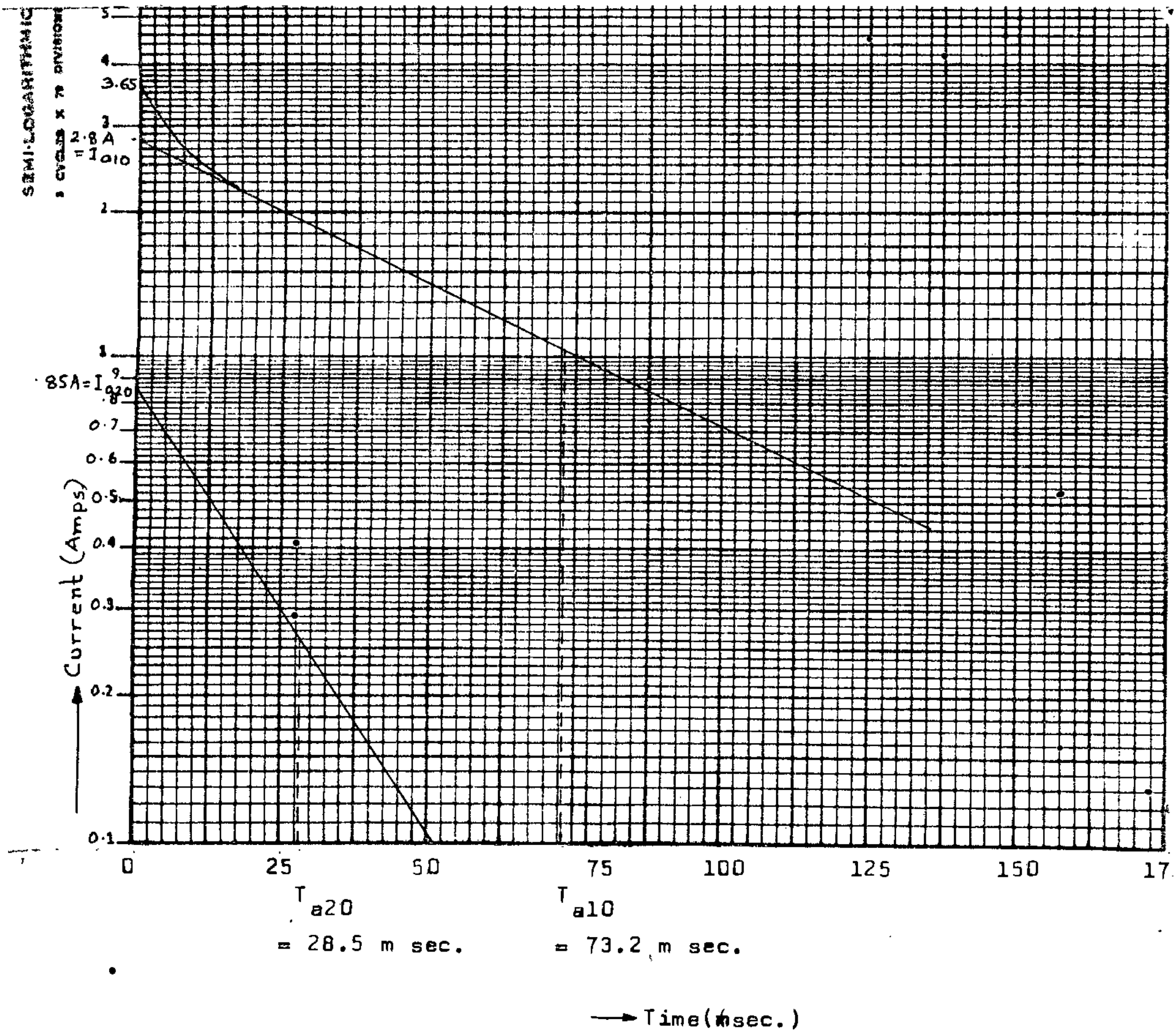


Fig. 4.2 Analysis of Transient Current in Indicial Response Method in 1st Setup.

$$= \frac{0.5185 \times 73.2\times10^{-3} \left(1 + \frac{.85}{2.8} \times \frac{28.25\times10^{-3}}{73.2\times10^{-3}} \right)}{1 + \frac{.85}{2.8}} \text{ Henry}$$

$$= \frac{0.5185\times73.2\times10^{-3}\times1.117}{1.3034} \text{ Henry}$$

$$= \frac{.5185\times73.2\times10^{-3}\times1.117}{1.3034\times.05115} \text{ per unit } = 0.631 \text{ per unit}$$

The direct-axis synchronous reactance is given by equation (2.12) -

$$x_d = \frac{3}{2} L_{aad} = \frac{3}{2} \times .631 = 0.9465 \text{ per unit}$$

The coupling coefficient between d-axis armature and d-axis damper winding (K_{aD}) is calculated using equation (22) of Appendix-E

$$K_{aD}^2 = L_{aad} - \frac{r \cdot T_{a20}}{2}$$

$$= 0.631 - \frac{.03228\times28.5\times10^{-3}}{2 \times .02} = 0.6296$$

$$K_{aD} = 0.795$$

Equation (2.37) gives, the d-axis time constant of the armature winding -

$$T_{ad} = \frac{L_{aad}}{r} = \frac{0.631\times0.05115}{0.5185} = 0.0622 \text{ second}$$

The time constant of d-axis damper winding is obtained from equation (2.36) -

$$T_D = \frac{T_{a10}\left(\frac{I_{a20}}{I_{a10}} + \frac{T_{a20}}{T_{a10}} \right)}{1 + \frac{I_{a20}}{I_{a10}}}$$

$$= \frac{73.2\times10^{-3}\left(\frac{.85}{2.8} + \frac{28.25\times10^{-3}}{73.2\times10^{-3}}\right)}{1 + \frac{.85}{2.8}} = .03865 \text{ second}$$

4.1.3 <u>Second Setup</u>

In this setup, the field winding was open circuited, the rotor was placed in the quadrature axis and a d.c. voltage was suddenly applied to an armature winding with the other armature winding open circuited (Fig. 3.13). The following experimental results were obtained:-

Applied d.c. voltage = 1.91 volts

Steady state d.c. current = 3.6 Amps

Time scale on oscilloscope = 50 milli second/cm.

The transient rise of the armature current to steady state value was recorded (Fig. 4.3).

From the response curve of Fig. 4.3, the values of differences between steady state and gradually rising currents at various points on the time-axis were tabulated in Table 4.2. The data of Table 4.2, were plotted on the semilogarithm paper as shown in Fig. 4.4.

From the curve of Fig. 4.4, the following components of currents and time constants were obtained:-

I_{aa0} = 3.6 Amps

I_{a10} = 2.635 Amps

I_{a20} = 0.955 Amps

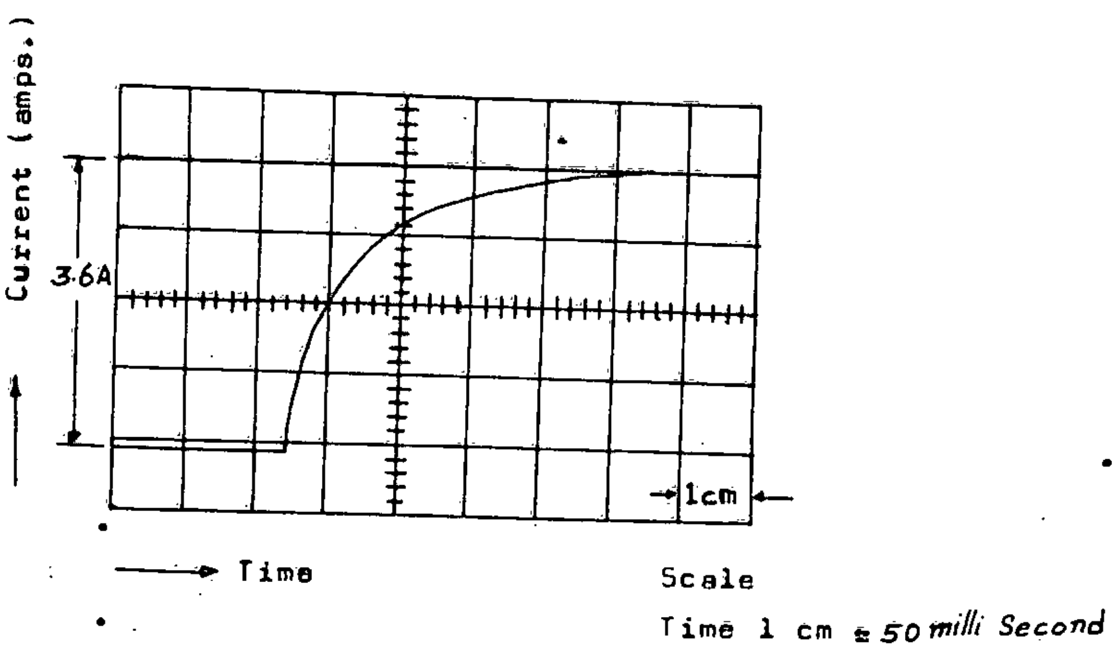


Fig. 4.3 Oscillogram of the transient rise in current from zero to steady state value when the field open circuited and rotor in q-axis.

Table 4.2 Difference between steady state and gradually rising current at different time (from Fig. 4.3)

Time (milli second)	Current (ampe.)
1.59	3.375
6.375	2.85
7.825	2.95
9.25	2.79
10.325	2.7
12.26	2.43
13.8	2.267
17.27	2.06
20.08	1.89
26.5	1.723
31.2	1.56
39.2	1.38
46.02	1.19
56.0	1.03
67.7	0.857
86.2	0.68
99.5	0.505
132.0	0.3196

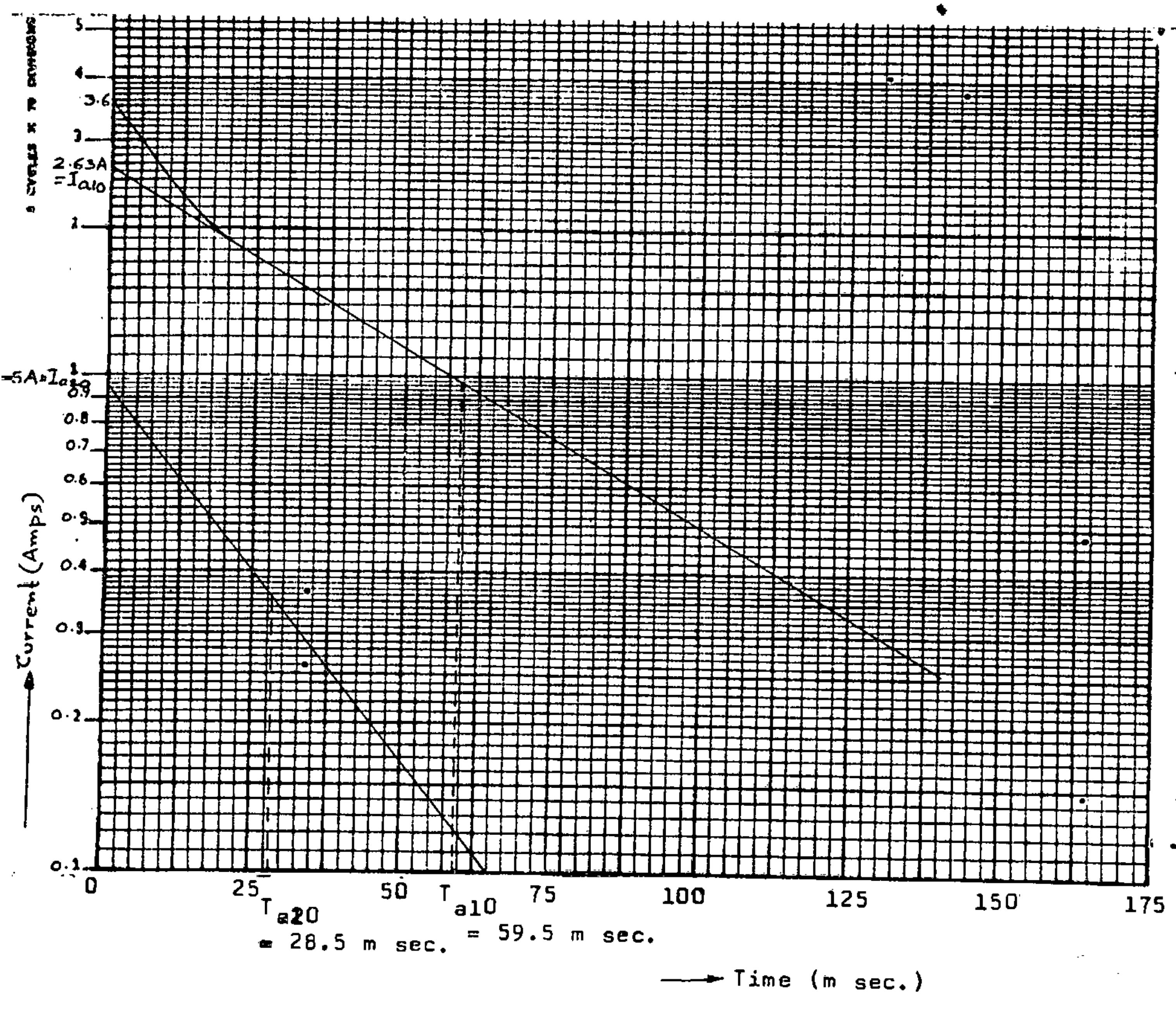


Fig. 4.4 Analysis of Transient Current in Indicial Response Method in 2nd Setup.

T_{a10} = 59.5 milli second

T_{a20} = 28.5 milli second

The quadrature axis inductance is

$$L_{aaq} = \frac{r\, T_{a10} \left(1 + \frac{I_{a20}}{I_{a10}} \times \frac{T_{a20}}{T_{a10}}\right)}{I + \frac{I_{a20}}{I_{a10}}}$$

where $r = \frac{E}{I_{aao}} = \frac{1.91}{3.6} = 0.53$ ohm

$$L_{aaq} = \frac{0.53 \times 59.5 \times 10^{-3} \left(1 + \frac{0.955}{2.635} \times \frac{28.5}{59.5}\right)}{1 + \frac{0.955}{2.635}} \text{ Henry}$$

$$= \frac{0.53 \times 59.5 \times 10^{-3} \times 1.736}{1.3623} \text{ Henry}$$

$$= \frac{0.53 \times 59.5 \times 10^{-3} \times 1.736}{1.3623 \times 0.05115} \text{ per unit} = 0.532 \text{ per unit}$$

Equation (2.13) gives the quadrature axis synchronous reactance

$$x_q = \frac{3}{2}\ L_{aaq} = \frac{3}{2} \times 0.532 = 0.798 \text{ per unit}$$

The coupling coefficient between q-axis damper and armature windings (Appendix-E) is

$$K_{aQ}^{\ 2} = L_{aaq} - \frac{r\, T_{a20}}{2}$$

$$= 0.532 - \frac{0.53 \times 0.0285}{2 \times 0.02} = 0.5093$$

$$K_{aQ} = 0.7145$$

The sub-transient quadrature-axis reactance is calculated from equation (2.28) –

$$x_q'' = x_q\,(1 - K_{aQ}^{\,2}) = 0.798(1 - 0.5093) = 0.3915 \text{ per unit}$$

The transient reactance of q-axis is obtained from equation (2.30) -

$$x_q' = x_q'' = 0.3915 \text{ per unit}$$

The time constant of q-axis damper winding is

$$T_Q = \frac{T_{a10}\left(\dfrac{I_{a20}}{I_{a10}} + \dfrac{T_{a20}}{T_{a10}}\right)}{1 + \dfrac{I_{a20}}{I_{a10}}}$$

$$= \frac{0.0595\left(\dfrac{0.955}{2.635} \times \dfrac{28.5\times10^{-3}}{29.5\times10^{-3}}\right)}{1 + \dfrac{0.955}{2.635}}$$

$$= 0.0363 \text{ second}$$

4.1.4 Third Setup

In this setup the field winding was short circuited, rotor was placed in the direct-axis, and a d.c. voltage was suddenly applied to an armature winding with other armature windings open circuited.

Experimental Data:

Applied d.c. voltage = 1.90 volts

Steady state d.c. current = 3.58 Amps

Time scale on oscilloscope = 50 milli second/cm

The transient rise in the current was recorded (Fig.4.5). The response curve of Fig. 4.5 was analysed to prepare Table 4.3 and to plot the curve of Fig. 4.6. The following results are obtained from Fig. 4.6 -

$I_{aos} = 3.58$ Amps

$I_{a1s} = 0.76$ Amps

$I_{a2s} = 1.72$ Amps

$I_{a3s} = 1.1$ Amps

$T_{a1s} = 65.0$ milli seconds

$T_{a2s} = 33.5$ milli seconds

$T_{a3s} = 8.2$ milli seconds

The time constant of field winding T_f is calculated using equation (2.40) -

$$\frac{1}{T_f} = \frac{1}{T_{a1s}} + \frac{1}{T_{a2s}} + \frac{1}{T_{a3s}} - \frac{1}{T_D} - \frac{1}{T_{ad}}$$

$$= \frac{1}{65\times10^{-3}} + \frac{1}{33.5\times10^{-3}} + \frac{1}{8.2\times10^{-3}} - \frac{1}{0.03865} - \frac{1}{0.0622}$$

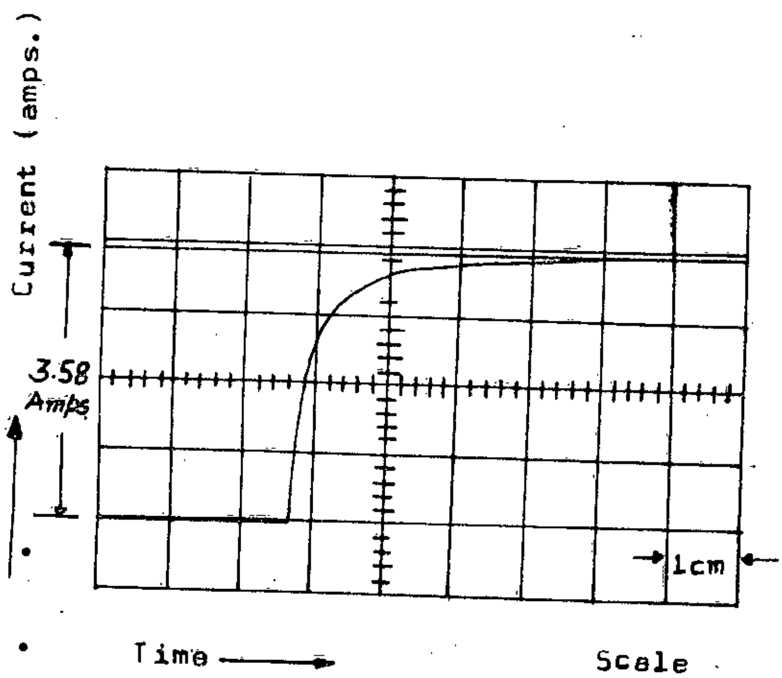
$$= 123.99$$

$\therefore \quad T_f = 0.00008$ second

Equation (2.41) gives the coupling coefficient between d-axis damper and field winding -

$$K_{fD}^2 = \frac{I_{a1s}}{E} \left(\frac{1}{T_{a1s}} - \frac{1}{T_{a2s}}\right)\left(\frac{1}{T_{a3s}} - \frac{1}{T_{a1s}}\right)$$

$$+ \left(\frac{T_{a1s}}{T_D} - 1\right)\left(\frac{T_{a1s}}{T_f} - 1\right)$$



Scale
Time, 1 cm = 50 milli Second

Fig. 4.5 Oscillogram of the transient rise in current from zero to steady state value when the field is short circuited and rotor in d-axis.

Table 4.3 Difference between steady state and gradually rising current at different time (from fig. 4.5)

Time (milli second)	Current (amps)
0	3.85
3.32	2.63
8.5	1.737
18.5	1.14
28.5	0.794
38.5	0.595
48.5	0.476
58.5	0.367
68.5	0.278
78.5	0.228
88.5	0.1986
98.5	0.1736
108.5	0.149
118.5	0.124
128.5	0.0992
163.5	0.0795
173.5	0.0695
183.5	0.0496

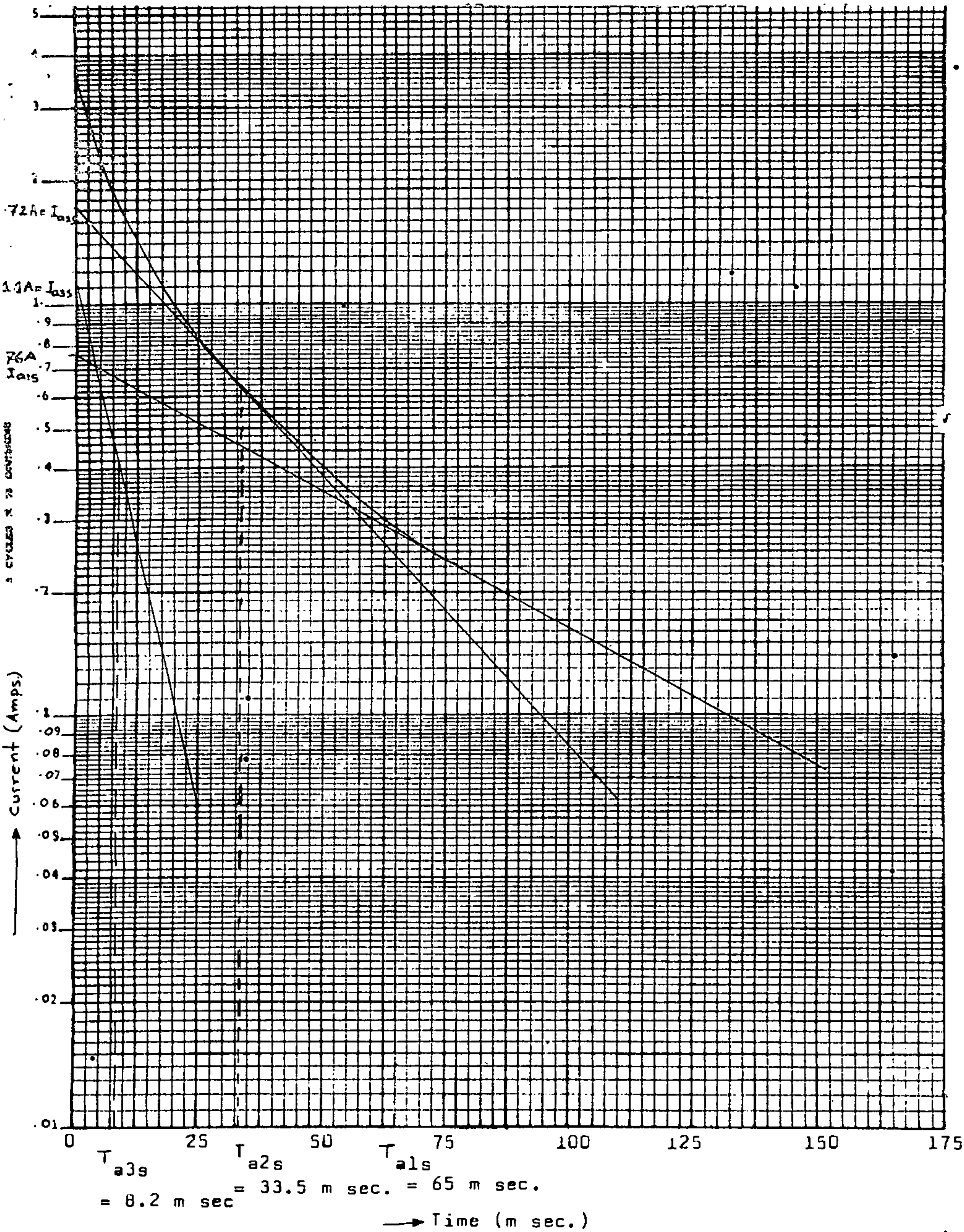


Fig. 4.6 Analysis of Transient Current in Indicial Response Method in 3rd setup.

$$= 16.07\times4\times10^{-4}\times\frac{0.76}{1.9}\left(\frac{1}{65\times10^{-3}} - \frac{1}{33.5\times10^{-3}}\right)\left(\frac{1}{8.2\times10^{-3}} - \frac{1}{65\times10^{-3}}\right)$$

$$+\left(\frac{65\times10^{-3}}{0.00808} - 1\right)\left(\frac{65\times10^{-3}}{0.03865} - 1\right).$$

$= 0.80$

$K_{fD} = 0.895$

The coupling coefficient between armature and field winding (K_{af}) is calculated using equation (2.42) -

$$K_{af}^2 = \frac{1}{T_{ad}T_D}\left(T_fT_D(1 - K_{fD}^2) + T_DT_{ad}(1 - K_{aD}^2) - T_{a1s}T_{a2s}\right.$$

$$\left. - T_{a2s} - T_{a3s} - T_{a3s}\,T_{a1s}\right)$$

$$= \frac{1}{.0622\times.03865}(.00808\times.03865(1-.8)+.03865\times.0622\times1(1-.629594)$$

$$- .065\times.0335-.065\times.0082$$

$= .85$

$K_{af} = .925$

The d-axis transient reactance is obtained from euqation (2.29)-

$$x'_d = x_d(1 - K_{af}^2)$$

$$= .9465(1 - .85) = .142 \text{ per unit}$$

and the d-axis subtransient reactance, from equation (2.27) -

$$x''_d = x_d\left(1 - \frac{K_{af}^2 + K_{aD}^2 - 2K_{fD}\,K_{aD}\,K_{af}}{1 - K_{fD}^2}\right)$$

$$= .9465\left(1 - \frac{.85+.629594-2\times0.895\times.795\times.924}{1 - 0.8}\right) = 0.163 \text{ per unit}$$

4.2 Low Frequency Method

A variable low frequency was generated first. The BKB Universal Machine was used for generating the variable low frequency by running it as a motor-generator set. The motor x side was connected as a d.c. shunt motor and the generator side as 2 pole, 3-phase alternator (circuit arrangement, Fig. 4.7).

The frequ ncy of an alternator can be varied by varying the speed of prime mover ($N = \frac{120f}{P}$). The speed of the prime mover, in this case d.c. shunt motor was varied by varying the voltage across the armature terminal with the help of a suitable rehostat. Thus a variable supply voltage was generated at low frequency.

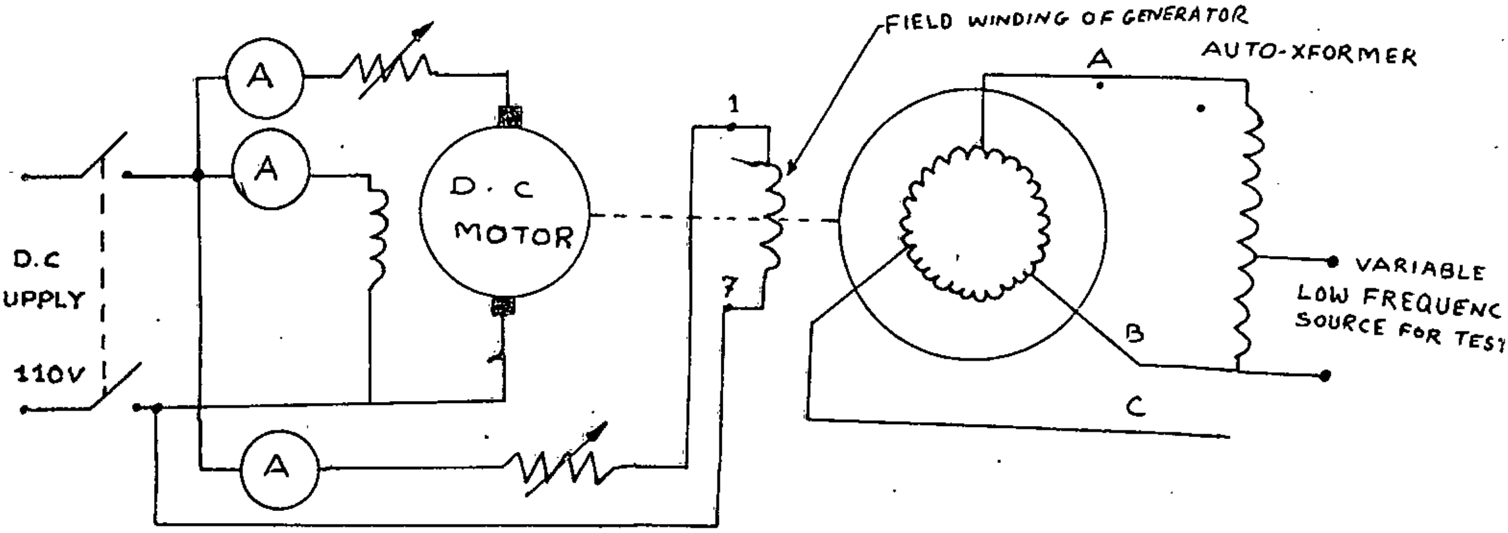
Following the detailed procedure described in section 3.3, the low frequency test was done in four stages.

4.2.1 First Set-up

The rotor was placed in direct axis with the field winding open circuited and a low frequency voltage was applied to an armature winding with other armature windings open circuited.

The test data are shown in Table 4.4. The waveforms of the voltage and currents were recorded as shown in Fig. 4.8 to Fig. 4.12(The current waveform was shifted by 180^0 to facilitate the measurement of phase angle between voltage and current. This was done with the help of oscilloscope adjusment).

From each waveforms (Fig. 4.8 to Fig. 4.12), the phase angle between current and voltage was determined and the frequency was



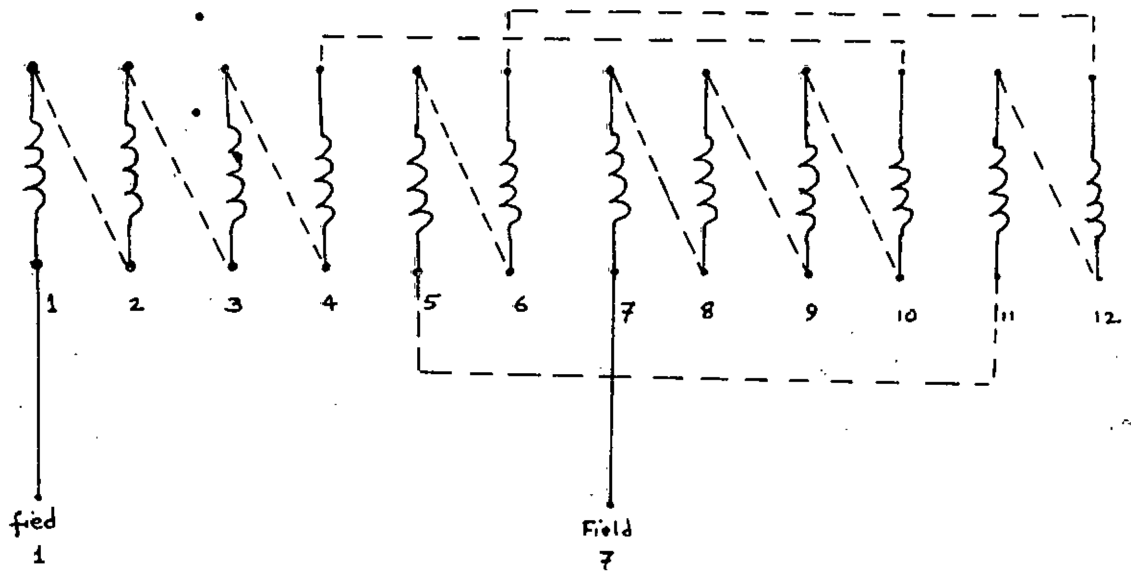


Fig. 4.7 Circuit arrangement on B.K.B universal machine for generation of variable low frequency voltage.

Table 4.4 Experimental Data of first Setup

Observation No.	Voltage applied (volts)	Current (amps.)	Time scale onoscilloscope
1	1.45	1.805	0.1 sec/cm
2	1.50	2.00	"
3	1.35	1.80	"
4	1.25	1.60	0.2 sec/cm
5	1.15	1.30	"

Table 4.5 Calculated Frequency and Phase Angle in First Setup

Observation No.	Voltage applied (volts)	Current (amps.)	Frequency f (cycle/sec.)	Ø phase angle (degree)
1	1.45	1.805	4.32	40.5
2	1.50	2.00	3.10	35.0
3	1.35	1.80	2.92	27.0
4	1.25	1.60	1.80	24.0
5	1.15	1.30	1.35	16.0

Table 4.6 Calculated Equivalent Resistance and Inductances in first setup

Observation No.	Voltage (volts)	Current (amps)	frequency f (cycle/sec)	Frequency (pu)	Eq. Resistance R (pu)	Eq. inductance (pu)
1	1.45	1.805	4.32	.0863	.038	.3398
2	1.50	2.00	3.1	.062	.0382	.346
3	1.35	1.80	2.92	.05845	.0415	.36
4	1.25	1.60	1.8	.036	.0445	.55
5	1.15	1.30	1.35	.027	.053	.562

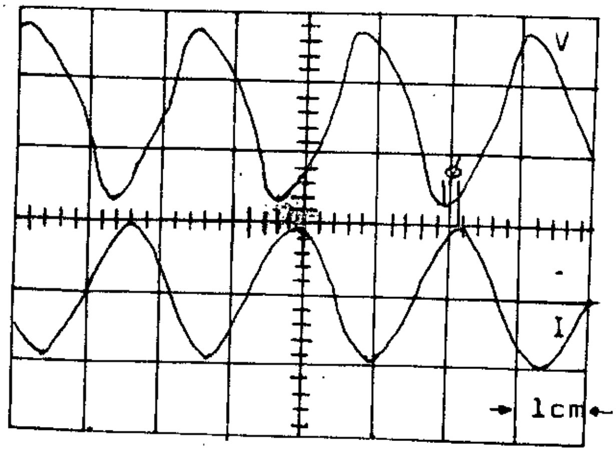


Fig. 4.8 Wave forms of voltage and current at low frequency (observation No. 1, 1st setup) Time scale = .1 sec/c

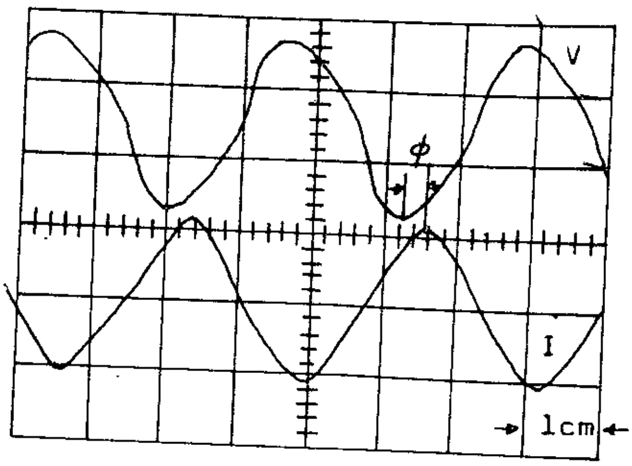


Fig. 4.9 Wave forms of voltage and current in low frequency (observation No.2, 1st setup) Time scale =.1 sec/cm.

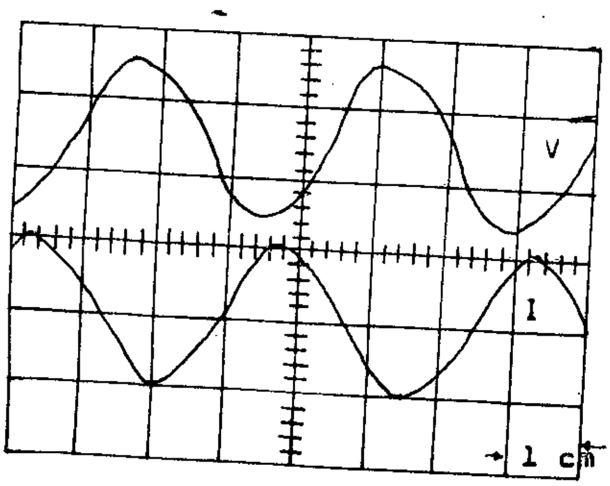
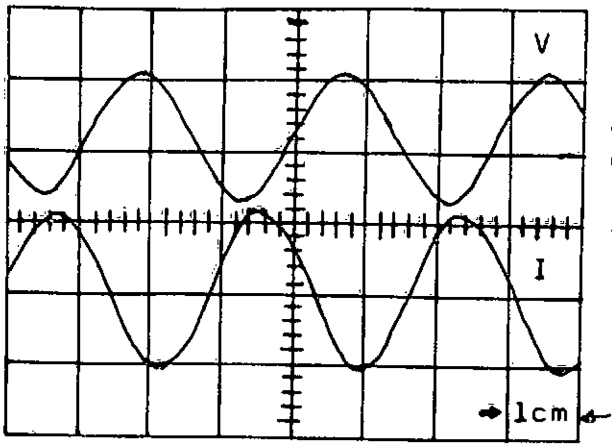
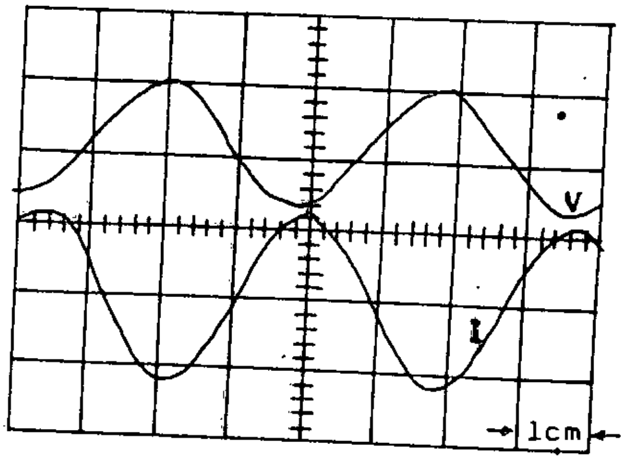


Fig. 4.10 Waveforms of voltage and current at low freqency (observation No. 3, 1st up) Time scale = .1 sec/cm.



4.11 Waveform of voltage and current at low frequency (Observation No. 4, 1st setup)
Time scale = 0.2 sec/cm.

Fig. 4.12 Waveforms of voltage and current at low freouency (observation No. 5, 1st setup) time scale = 0.2 sec./cm)



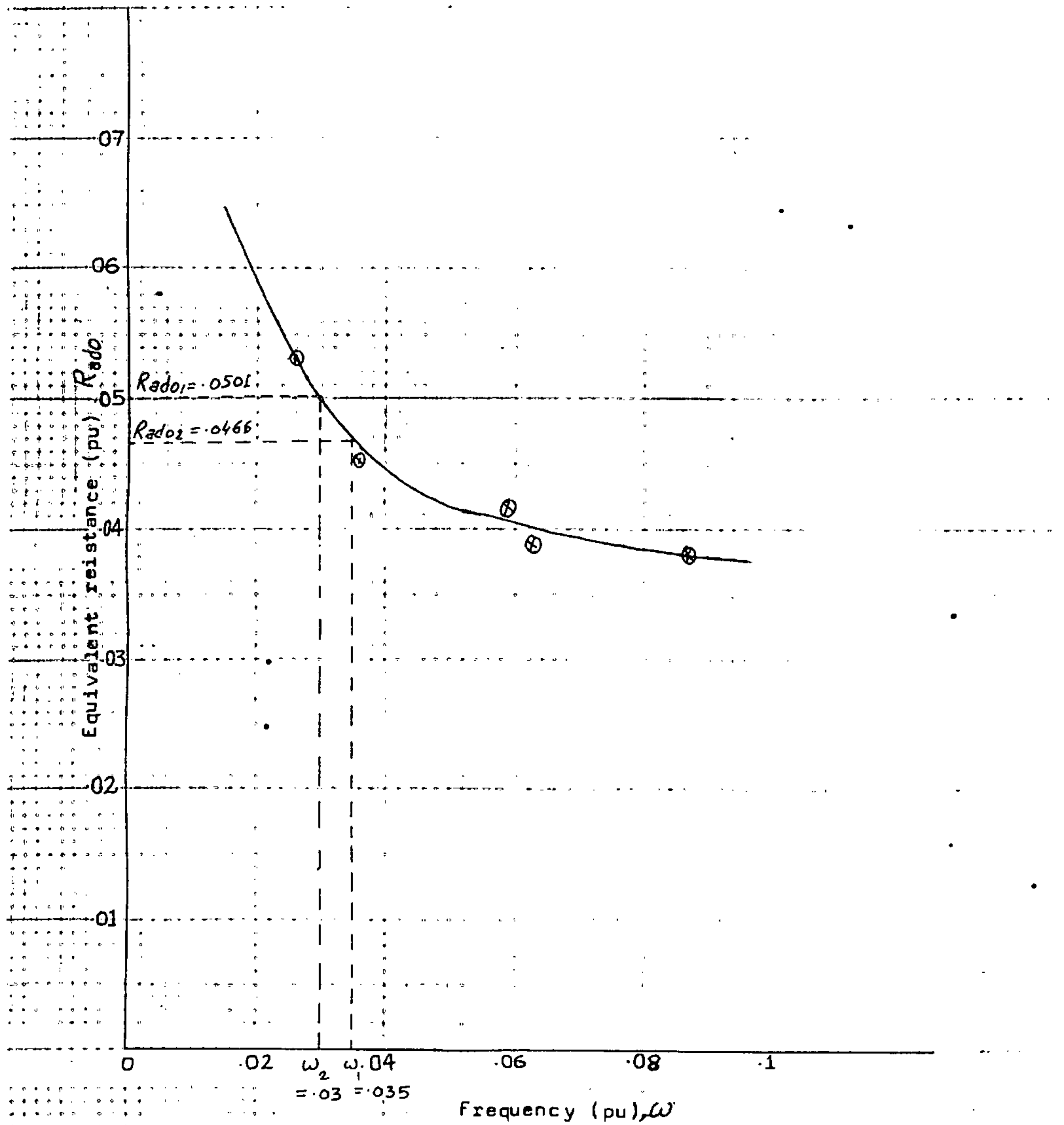


Fig. 4.13 Frequency characteristics of equivalent resistance in 1st setup, with field open circuited and rotor in the d-axis.

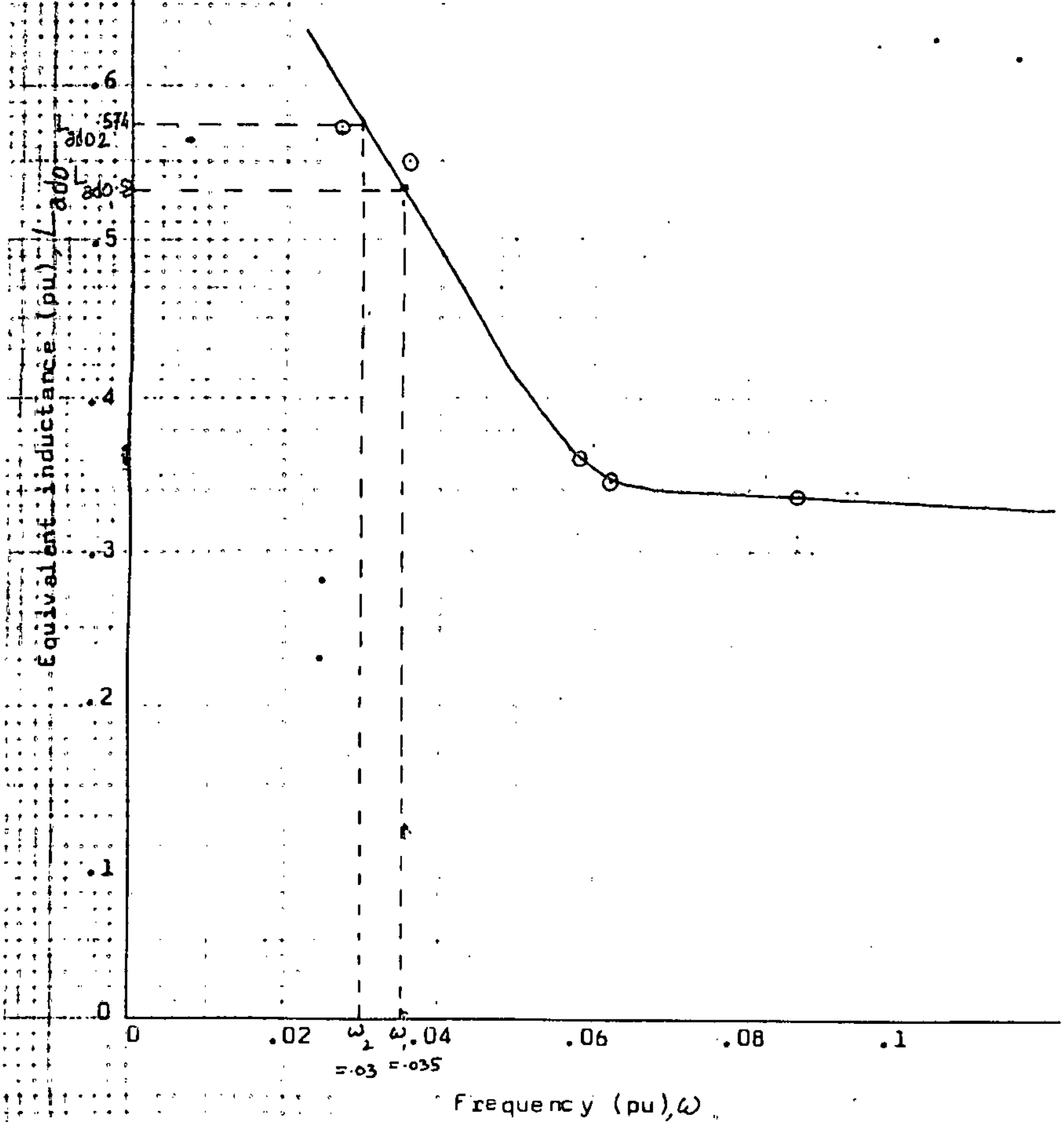


Fig. 4.14 Frequency characteristics of equivalent inductance in 1st setup, with field open circuited and rotor in the d-axis.

obtained from the time scale (Table 4.4) The results are shown in Table 4.5.

The equivalent resistances (R_{ado}) and inductances (L_{ado}) are calculated using equations (2.45) and (2.46). The per unit values are given in Table 4.6. Using the results of Table 4.7, the resistance vs. frequency curve and inductance vs. frequency curve were plotted as shown in Figs. 4.13 and 4.14.

4.2.2 Second Setup

With the field-winding open circuited and the rotor placed in quadrature-axis, a variable low frequency voltage was applied to one of the armature windings with other windings open circuited.

The voltage, current and time scale on the oscilloscope were noted (Table 4.7). The waveforms of voltage and currents were photographed. (Figs. 4.15 to 4.19). The phase angles between current and voltage were obtained from the waveforms of Fig. 4.15 to 4.19 (Table 4.8).

The equivalent resistances (R_{aqo}) and inductance (L_{aqo}) in per unit are obtained as in first setup and the results are tabulated in Table 4.9.

The resistance vs. frequency and inductance vs. frequency curves are plotted as shown in Fig. 4.20 and 4.21.

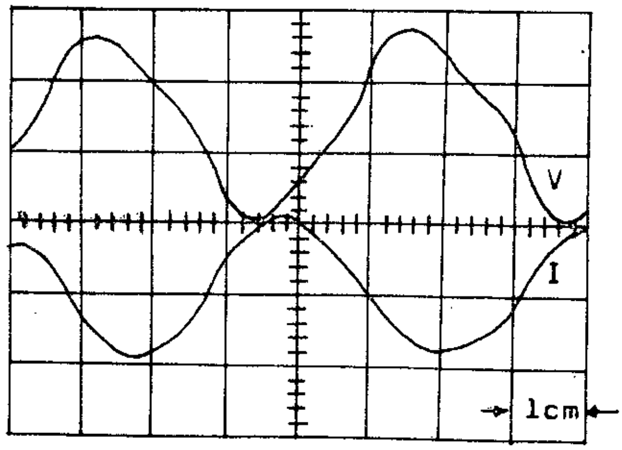


Fig. 4.15 Waveforms of voltage and current at low frequency (Observation No.1, 2nd setup) Time scale = 50 m sec/cm.

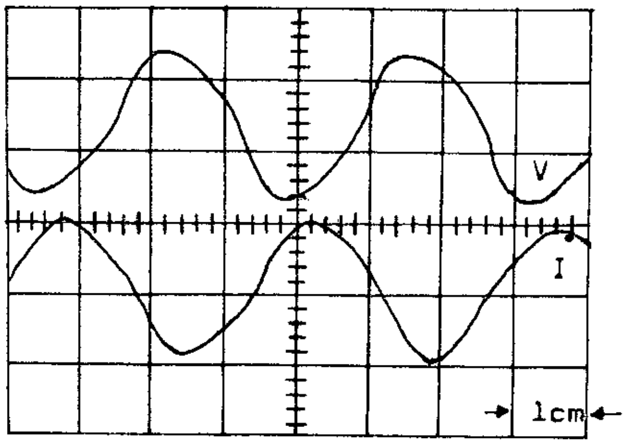


Fig. 4.16 Waveform of voltage and current at low frequency (Observation No.2, 2nd setup) Time scale = 0.1 Sec/cm.

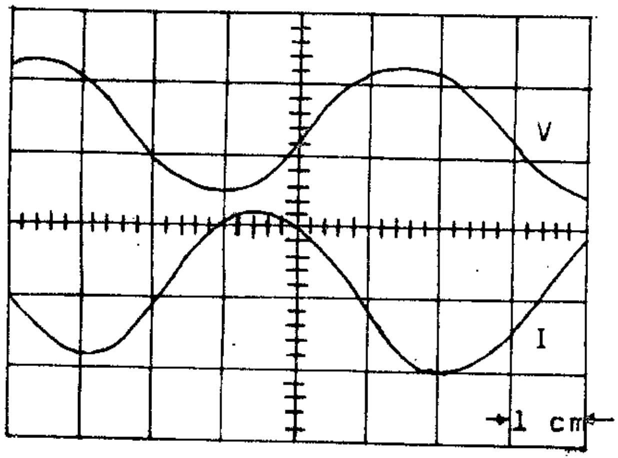


Fig. 4.17 Waveforms of voltage and current at low frequency (Observati No. 3, 2nd setup) Time scale =.1 se

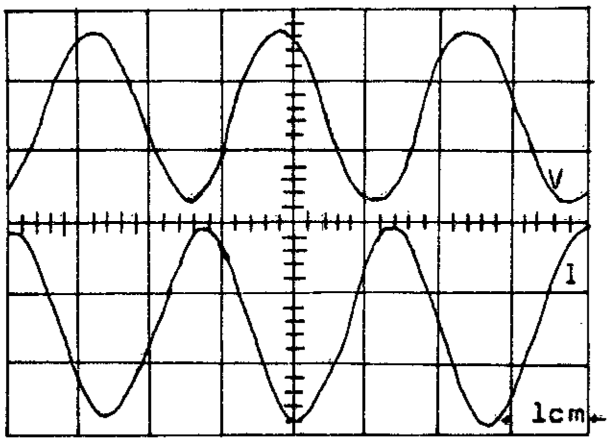


Fig. 4.18 Waveforms of voltage and current at low frequency (Observation no:4, 2nd setup), Time scale = 0.2 sec/cm.

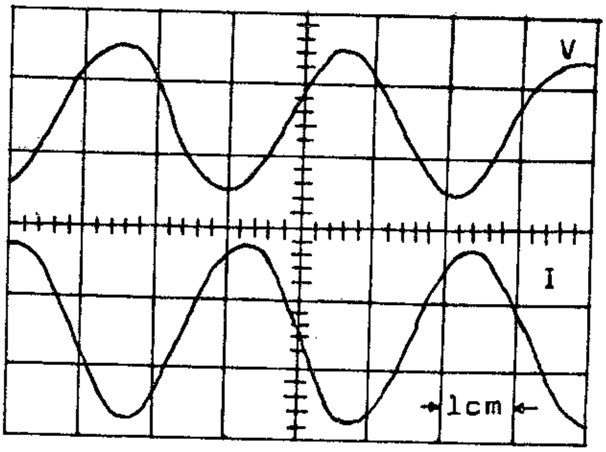


Fig. 4.19 Waveforms of voltage and current at low frequency (Observation No.5, 2nd setup) Time scale = 0.2 sec/cm.

Table 4.7 Experimental Data of 2nd Setup

Observation No.	Voltage applied (volts)	Current (amps.)	Time scale on oscilloscope
1	1.55	1.95	50 m sec/cm
2	1.25	1.70	0.1 sec/cm
3	1.30	1.60	"
4	1.60	2.15	0.2 m sec/cm
5	1.35	1.65	"

Table 4.8 Calculated Frequency and Phase Angle in 2nd Setup

Observation No.	Voltage applied (volts)	Current (amps.)	Frequency f (cycle/sec.)	Ø phase angle (degree)
1	1.55	1.95	4.57	30
2	1.25	1.70	2.9	25.7
3	1.30	1.60	1.93	24.5
4	1.60	2.15	1.92	22
5	1.35	1.65	1.60	18

Table 4.9 Calculated Equivalent Resistances and Inductances in 2nd setup

Observation No.	Voltage (volts)	Current (amps)	Frequency f (cycle/sec)	Frequency (pu)	Eq. Resistance R (pu)	Eq. inductance (PU)
1	1.55	1.95	4.57	0.09135	.04285	.2708
2	1.25	1.7	2.9	0.0580	.0413	.3440
3	1.30	1.6	1.93	0.03879	.046	.5415
4	1.60	2.15	1.92	0.0382	.0428	.4520
5	1.35	1.65	1.60	0.0322	.0492	.4935

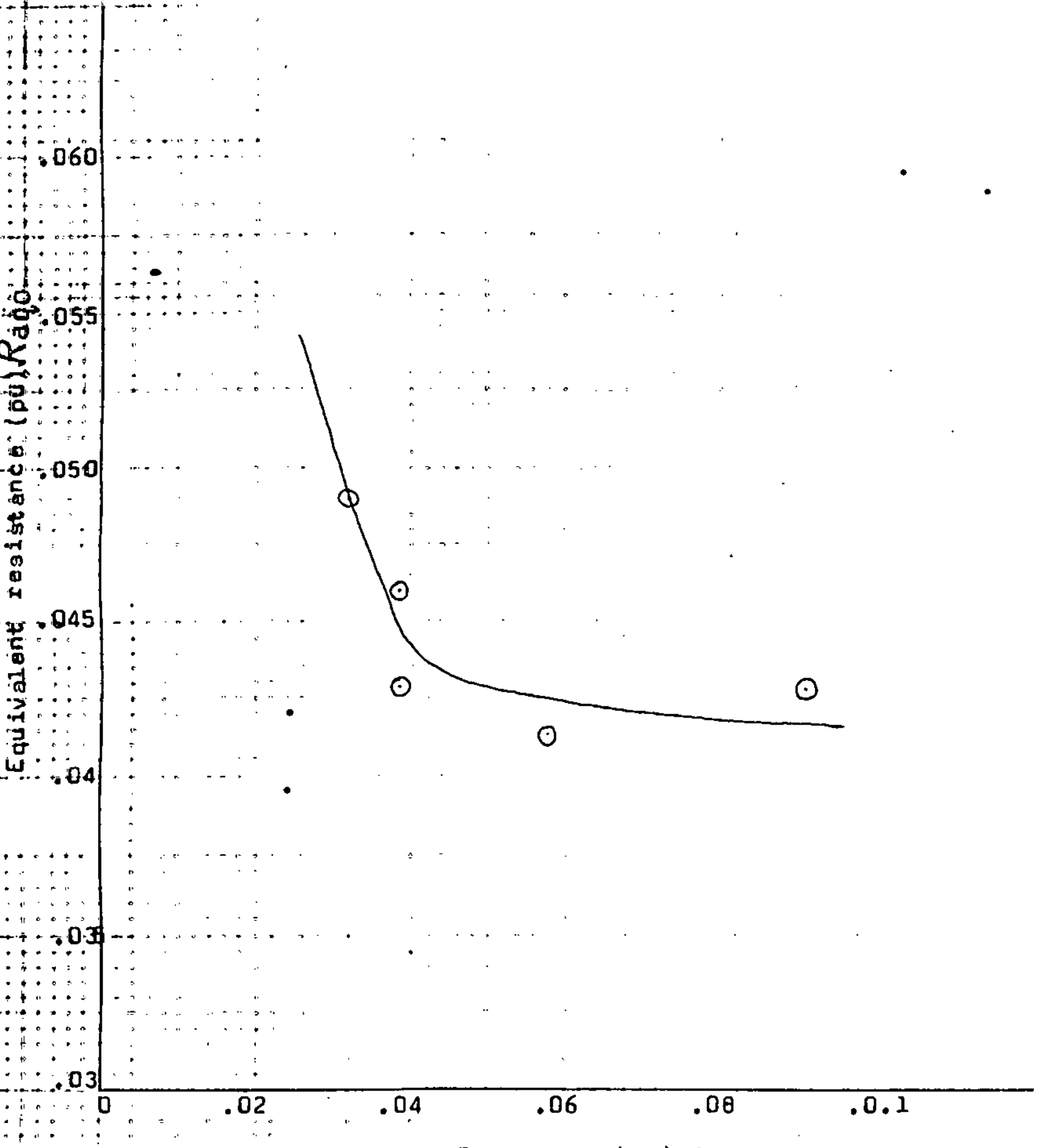


Fig. 4.20 Frequency characteristics of equivalent resistance in 2nd. setup, with field open circuited and rotor in the q-axis.

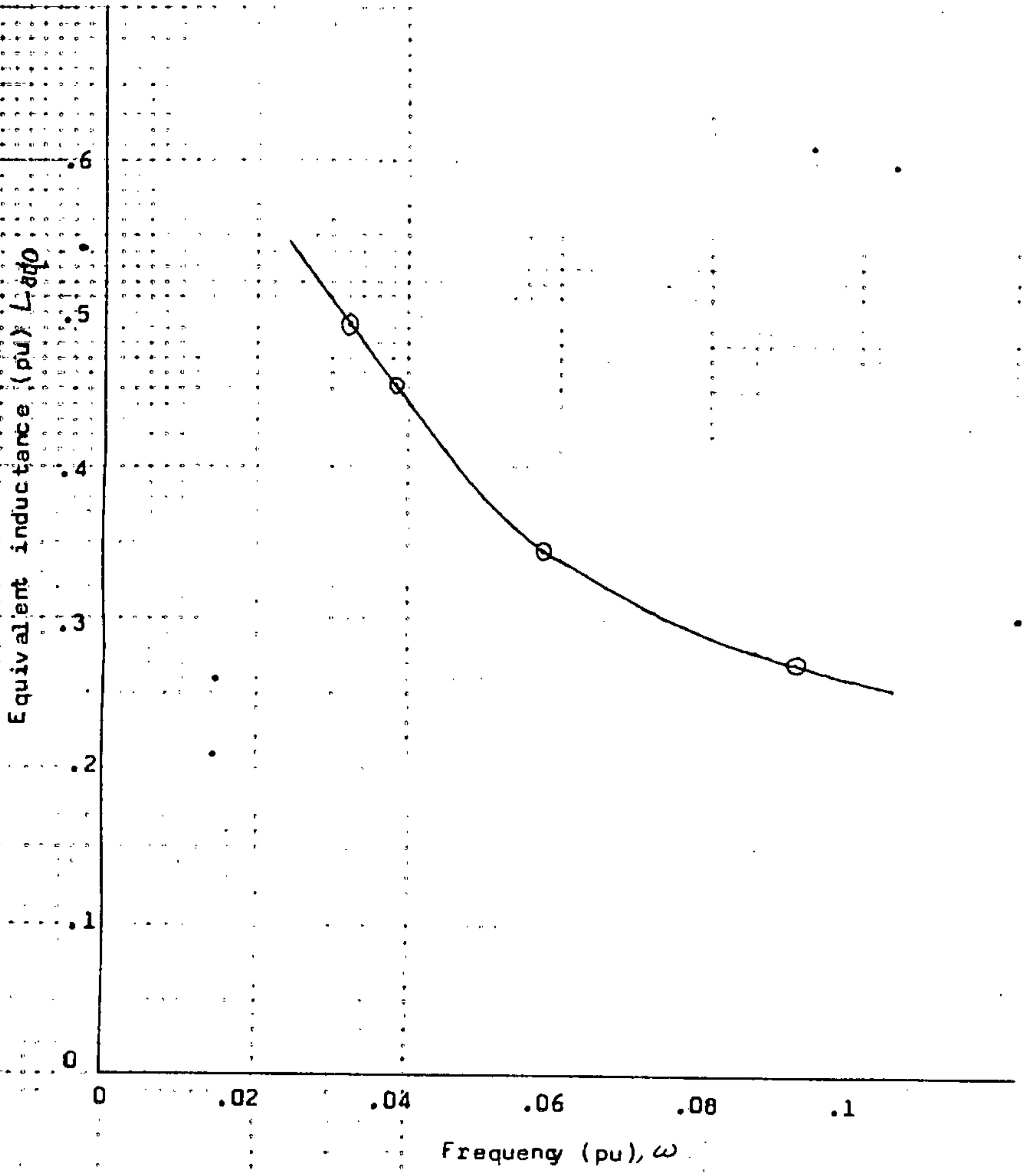


Fig. 4.21 Frequency characteristics of equivalent inductance in 2nd setup, with field open circuited androtor in the q-axis.

4.2.3 Third Setup

The field winding was excited with a variable low frequency voltage and all the armature windings were left open. The values of current, voltage and time scale on oscilloscope were recorded (Table 4.10). The waveforms of voltages and currents were photographed (Figs. 4.22 to 4.26). The phase angle between current and voltage was obtained from waveforms (Figs. 4.22 to 4.26) and the frequency was calculated using the time scale of the oscilloscope. The results are given Table 4.11. The equivalent resistance (R_{fdo}) and equivalent inductance (L_{fdo}) were calculated using equations (2.45)and (2.46). The results are given ~~tab~~ in Table 4.12. The calculated values were used to plot the R_{fdo} Vs w and L_{fdo} Vs w. curves as shown in Figs. 4.27 and 4.28.

4.2.4 Fourth Setup

The field winding was shortcircuited, the rotor was placed in the direct-axis and a variable low frequency voltage was applied to one of the armature windings with the other armature windings open circuited.

The rms values of the voltage and currents were measured using meters. The voltage and current waveforms were photographed as shown in Fig. 4.29 to Fig. 4.33 and the time scale settings on the oscilloscope were recorded (Table 4.13).

The phase angle between voltage and current and the frequency of the applied voltage were obtained from the above results. These

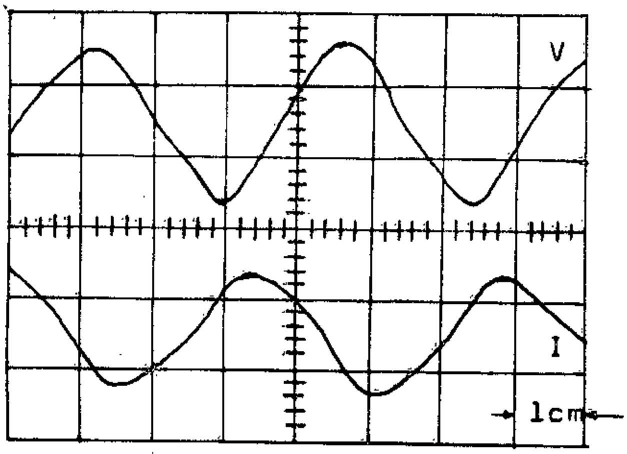


Fig. 4.22 Waveforms of voltage and current at low frequency (Observation No.1, 3rd setup) Time scale = 50 m sec/cm.

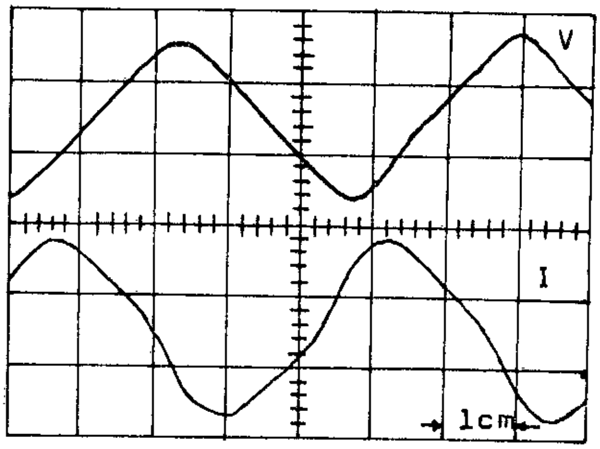


Fig. 4.23 Waveform of voltage current at low frequency (Observation No.2, 3rd setup) Time scale = 50 m sec/cm.

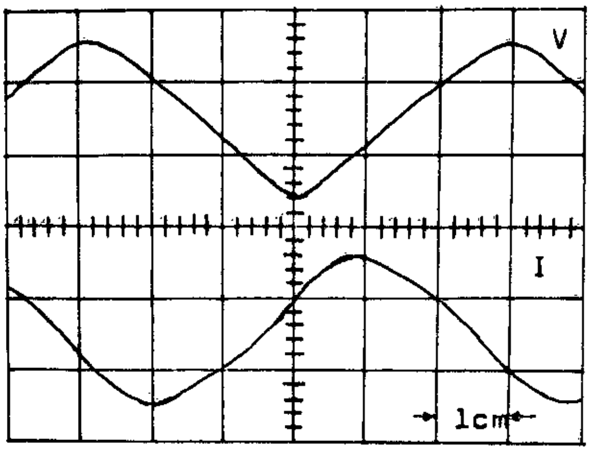


Fig. 4.24 Waveform of voltage and current at low frequency (Observation No.3, 3rd setup) Time scale = 50 m sec/cm.

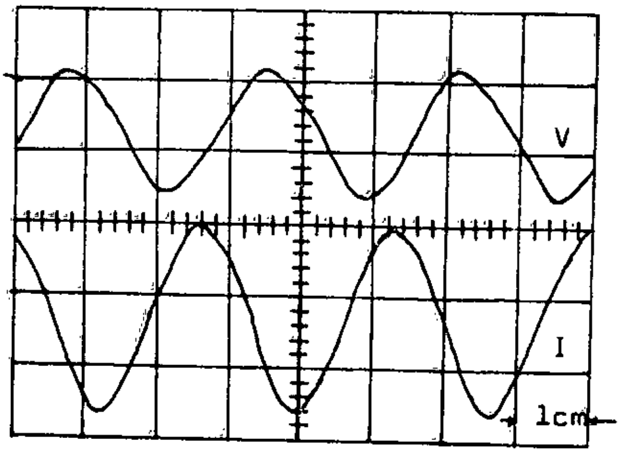


Fig. 4.25 Waveforms of voltage and current at low frequency (Observation No.4, 3rd setup) Time scale = 0.2 sec/cm.

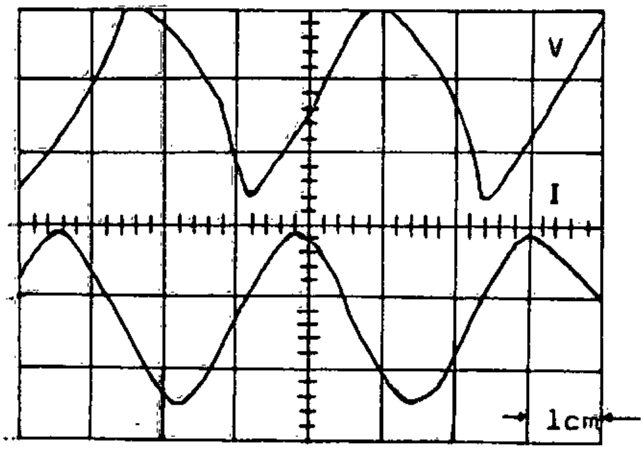


Fig. 4.26 Waveforms of voltage and current at low frequency (Observation No.5, 3rd setup) Time scale = 0.2 Sec/cm.

Table 4.10 Experimental Data of 3rd Setup

Observation No.	Voltage applied (volts)	Current (amps.)	Time scale on oscilloscope
1	27.0	0.16	50 m sec/cm
2	22.0	0.16	"
3	16.5	0.15	"
4	9.0	0.13	0.2 sec/cm
5	7.0	0.12	"

Table 4.11 Calculated Frequency and Phase Angle in ~~2nd~~ 3rd Setup

Observation No.	Voltage applied (volts)	Current (amps.)	Frequency f (cycle/sec.)	Ø phase angle (degree)
1	27.0	0.16	5.57	56
2	22.0	0.16	4.3	65
3	16.5	0.15	3.45	65
4	9.0	0.13	1.85	68
5	7.0	0.12	1.52	66

Table 4.12 Calculated Equivalent Resistance and Inductances in 3rd Setup

Observation No.	Voltage (volts)	Current (amps.)	Frequency f (cycle/sec)	Frequency (pu)	Eq. Resistance (pu)	Eq. inductance (pu)
1	27.0	0.16	5.57	0.11125	0.422	5.61
2	22.0	0.16	4.30	0.0860	0.2605	6.47
3	16.5	0.15	3.45	0.0690	0.208	6.47
4	9.0	0.13	1.85	0.0370	0.1166	7.70
5	7.0	0.12	1.52	0.0304	0.1065	7.77

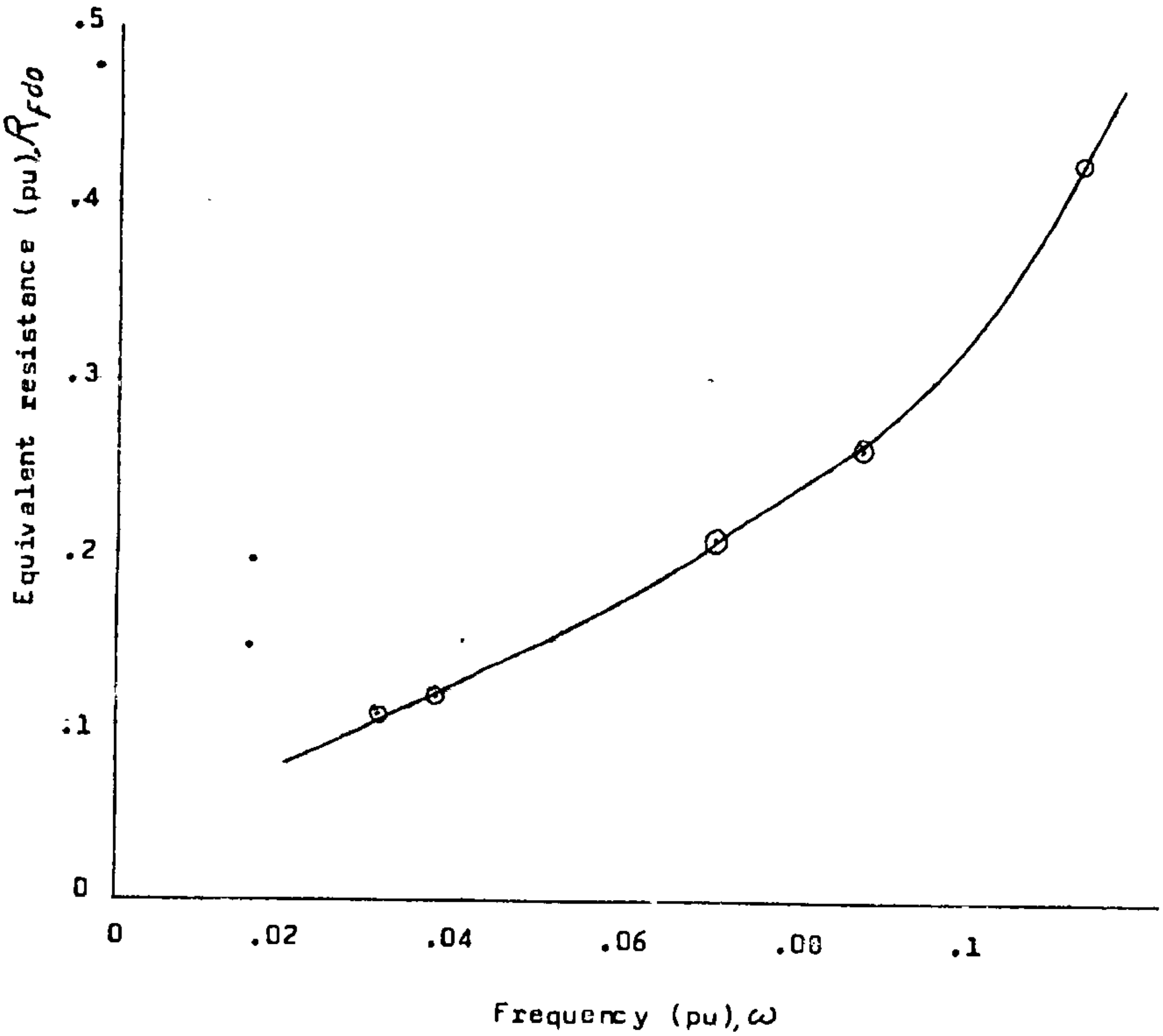


Fig. 4.27 Frequency characteristics of equivalent resistance in 3rd setup, with field winding excited by low frequency voltage.

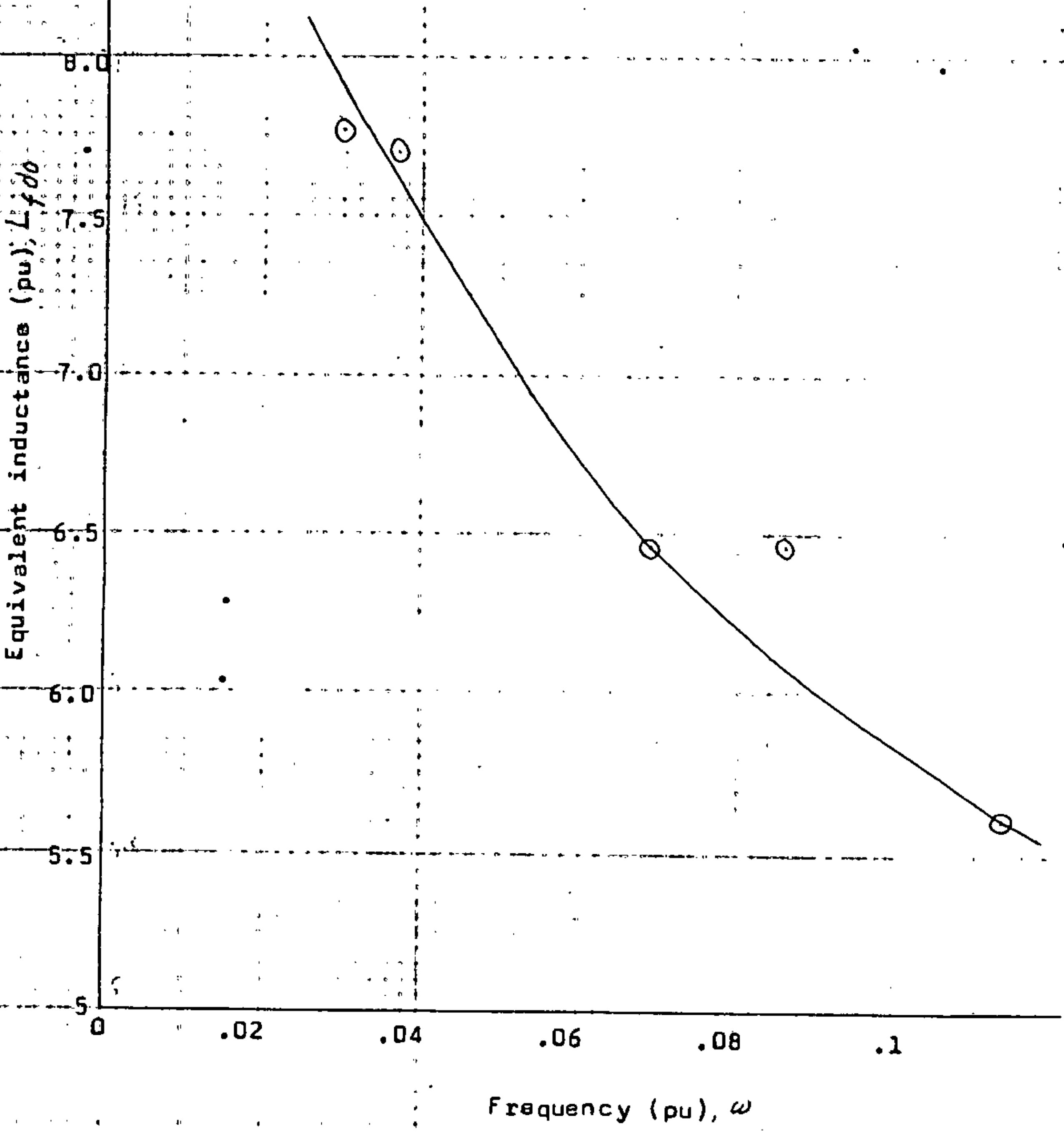


Fig. 4.28 Frequency characteristics of equivalent inductance in 3rd setup, with field winding excited by low frequency voltage.

Table 4.13 Experimental Data of 4th Setup

Observation No.	Voltage applied (volts)	Current (amps.)	Time scale on oscilloscope
1	1.35	1.80	50 m sec/cm
2	1.15	1.50	0.1 sec/cm
3	1.70	2.45	"
4	1.30	1.85	"
5	1.20	1.43	0.2 sec/cm

Table 4.14 Calculated frequency and phase angle in 4th Setup

Observation No.	Voltage applied (volts)	current (amps.)	frequency f (cycle/sec.)	Ø phase angle (degree)
1	1.35	1.80	5.0	37
2	1.15	1.50	4.40	35
3	1.70	2.45	2.91	21.2
4	1.30	1.85	2.285	18.07
5	1.20	1.43	1.37	16.5

Table 4.15 Calculated Equivalent Resistance and Industances in 4th Setup

Observation No.	Voltage (volts)	Current (amps.)	Frequency f (cycle/sec)	Frequency (pu)	Eq. Resistance (pu)	Eq. inductance (pu)
1	1.35	1.80	5.0	0.1	0.03727	0.273
2	1.15	1.50	4.4	0.088	0.03917	0.3115
3	1.70	2.45	2.91	0.0582	0.0403	0.2175
4	1.30	1.85	2.285	0.0458	0.0414	0.320
5	1.20	1.43	1.37	0.0274	0.053	0.550

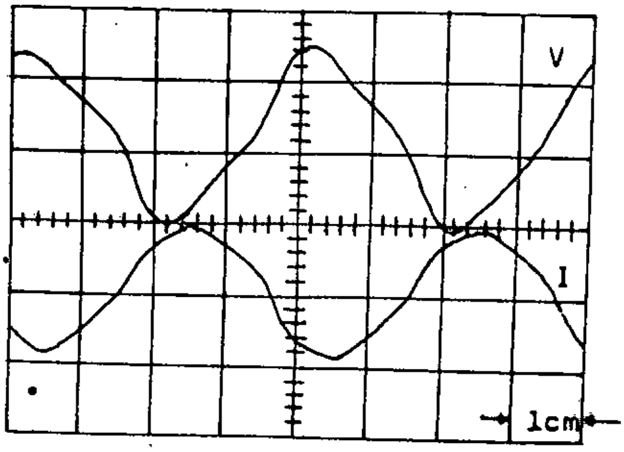


Fig. 4.29 Waveforms of voltage and current at low frequency (Observation No. 1, 4th setup) Time scale= 50 msec/

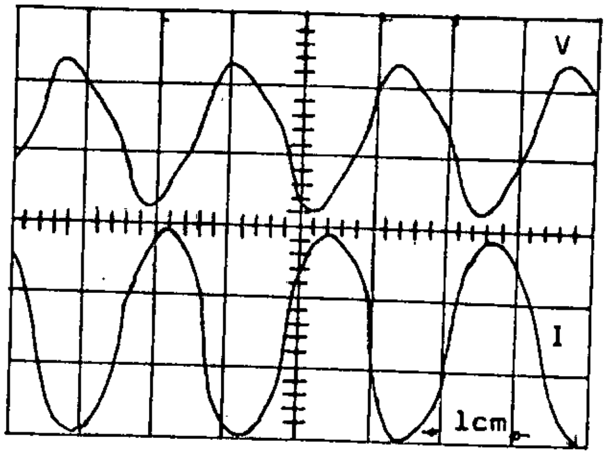


Fig. 4.30 Waveforms of voltage and current at low frequency (Observation No. 3, 4th setup) Time scale = 0.1 sec/cm.

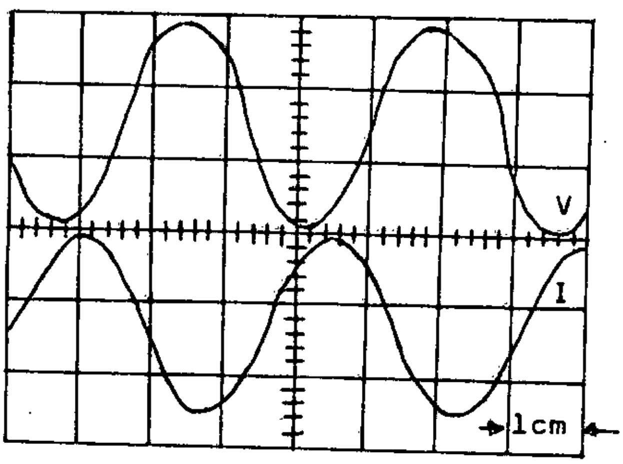


Fig. 4.31 Waveforms of voltage and current at low frequency (Observation No. 3, 4th setup) Time scale = 0.1 sec/cm.

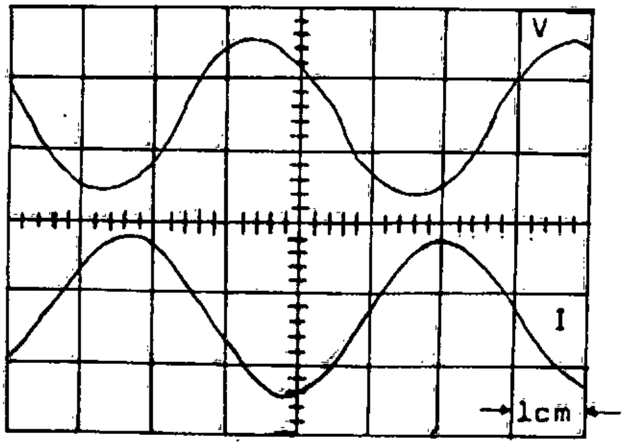


Fig. 4.32 Waveforms of voltage and current at low frequency (Observation No.4, 4th setup) Time scale = .1 sec/cm.

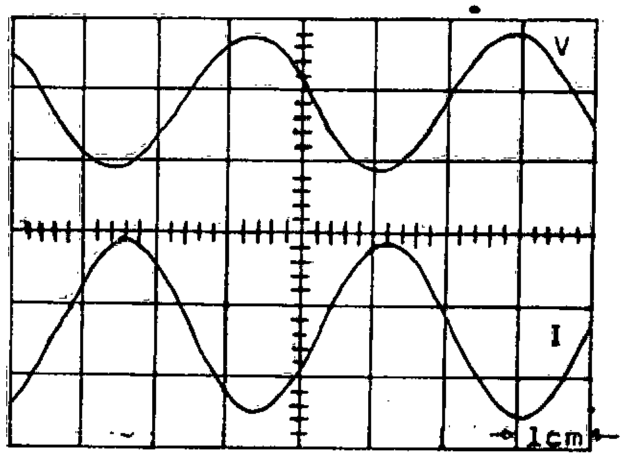


Fig. 4.33 Waveforms of voltage and current at low frequency (Observation No.5, 4th setup) Time scale = .2 sec/cm.

values are given in Table 4.14. Using equations (2.45) and (2.46) the equivalent resistance (R_{ads}) and equivalent inductance (L_{ads}) are calculated (Table 4.15). Then the R_{ads} Vs w and L_{ads} Vs w curves were plotted as shown in Fig. 4.34 and Fig. 4.35.

4.2.5 Calculation of r, x_d and x_q

The following values of R_{ado} and L_{ado} at two different frequencies w_1 and w_2 were taken from the curves of Fig. 4.13 and Fig. 4.14.

w_1 = 0.035 per unit R_{ado1} = 0.0466 pu L_{ado1} = 0.53 pu

w_2 = 0.030 per unit R_{ado2} = 0.0501p u L_{ado2} = 0.574 pu

Therefore $R_{ado} = R_{ado2} - R_{ado1} = 0.0501 - 0.0466 = 0.0035$ per unit

and $L_{ado} = L_{ado2} - L_{ado1} = 0.574 - 0.53 = 0.044$ per unit

The resistance of the armature winding, using equation (2.50) is

$$r = R_{ado2} - \frac{w_1^2}{w_1^2 - w_2^2} \left(R_{ado} + w_2^2 \frac{L_{ado}^2}{R_{ado}} \right)$$

$$= 0.0501 - \frac{(0.035)^2}{(0.035)^2 - (0.03)^2} \left[(0.0035 + \frac{(0.03)^2 \times (0.044)^2}{0.0035}) \right]$$

$= 0.03486$ per unit.

The self inductance of armature winding in d-axis is calculated using equation (2.49) -

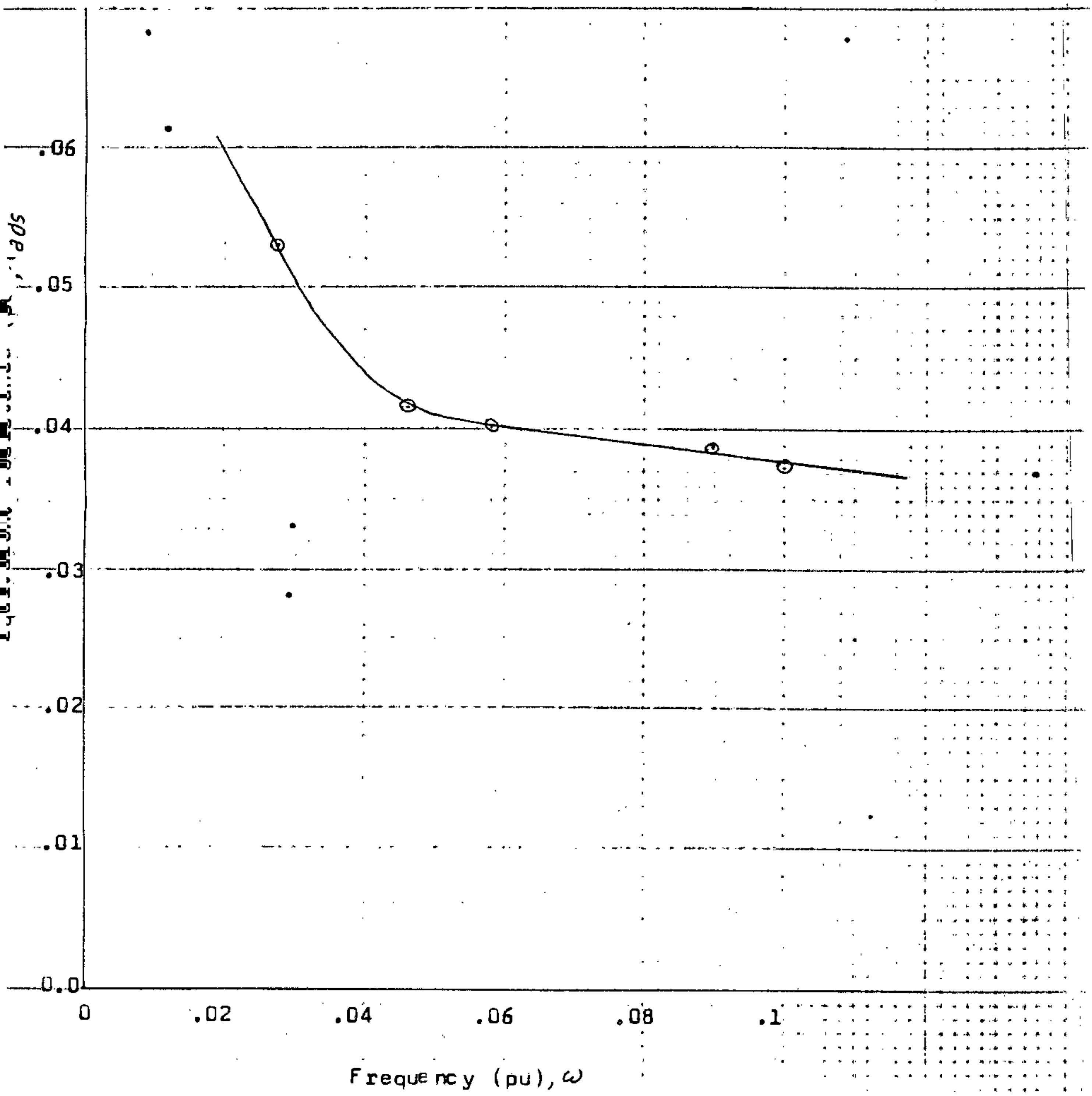


Fig. 4.34 Frequency characteristics of equivalent resistance in 4th setup, with field short circuited and rotor in the d-axis.

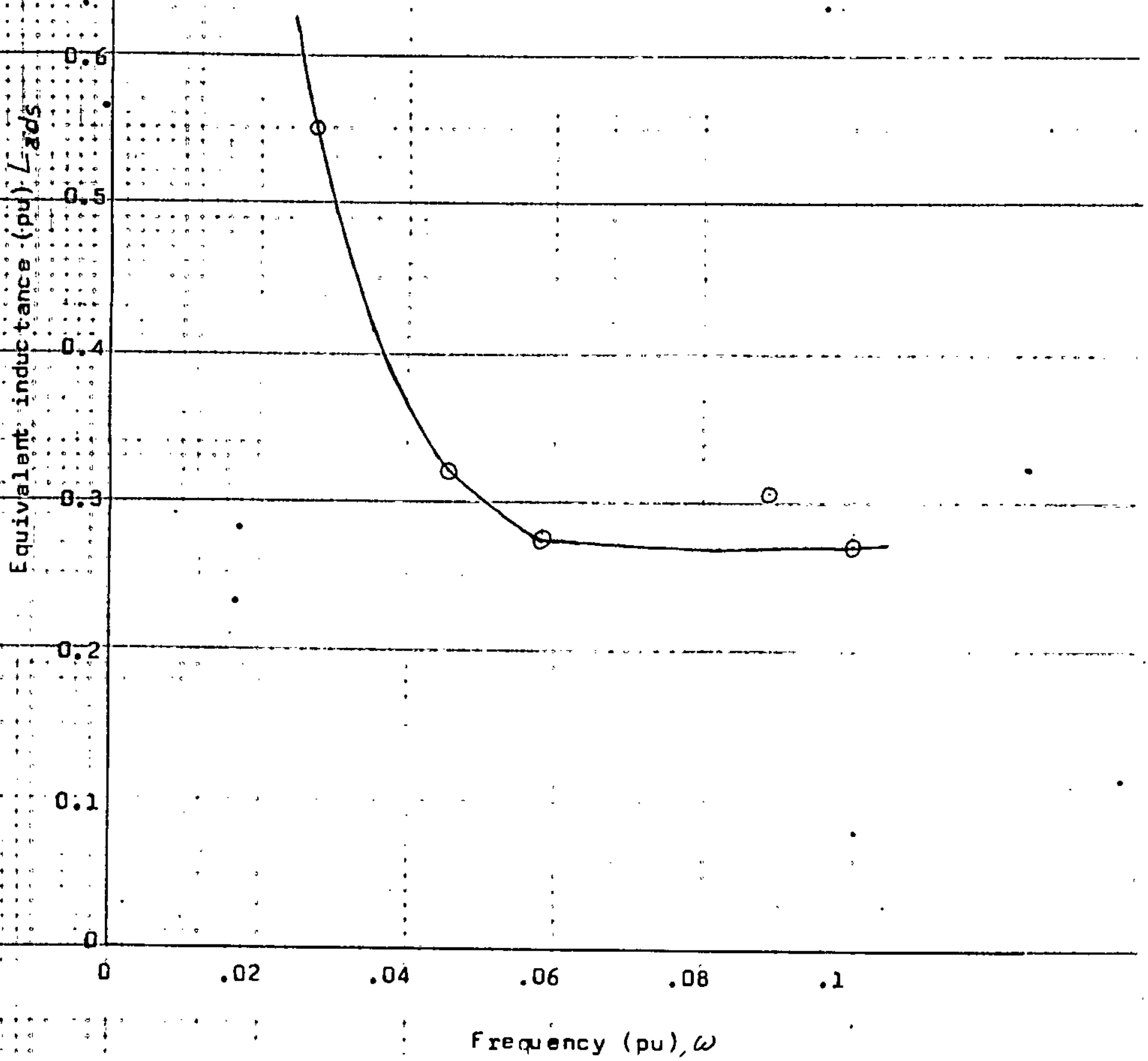


fig. 4.35 Frequency characteristics of equivalent inductance in 4th setup, with field short circuited and rotor in the d-axis.

$$L_{aad} = L_{ado1} + \frac{w_1^2}{w_1^2 - w_2^2} \left(L_{ado} + w_2^2 \frac{L_{ado}^3}{R_{ado}^2} \right)$$

$$= 0.53 + \frac{(0.035)^2}{(0.035)^2 - (0.03)^2} \left(0.044 + \frac{(0.03)^2 (0.044)^3}{(0.0035)^2} \right)$$

$$= 0.7304 \text{ per unit}$$

from equation (2.12)

$$x_d = \frac{3}{2} \; L_{add} = \frac{3}{2} \times 0.7304 = 1.0956 \text{ per unit}$$

From curves of Fig. 4.20 and Fig. 4.21,

$w_1 = 0.035$ per unit $\quad R_{aqo1} = 0.0475$ pu $\quad L_{aqo1} = 0.4745$ pu

$w_2 = 0.030$ per unit $\quad R_{aqo2} = 0.05125$ pu $\quad L_{aqo2} = 0.5095$ pu

Therefore $R_{aqo} = R_{aqo2} - R_{aqo1} = 0.00450$ per unit

and $\qquad L_{aqo} = L_{aqo2} - L_{aqo1} = 0.0350$ per unit

The self inductance in the q-axis is

$$L_{aaq} = L_{aqo1} + \frac{w_1^2}{w_1^2 - w_2^2} \left(L_{aqo} + \frac{w_2^2 \, L_{aqo}^3}{R_{aqo}^2} \right)$$

$$= 0.4745 + \frac{(0.035)^2}{(0.035)^2 - (0.03)^2} \left[0.035 + \frac{(0.03)^2 (0.035)^3}{(0.0045)^2} \right]$$

$$= 0.6155 \text{ per unit}$$

from equation (2.13)

$$x_q = \frac{3}{2} \, L_{aaq} = \frac{3}{2} \times 0.6155 = 0.9235 \text{ per unit}$$

4.2.6 Calculation of x_d', x_d'', x_q' and x_q''

Calculation of K_{aD}

From curves of Fig. 4.13 and Fi . 4.14.

$w_1 \doteq 0.05$ per unit $R_{ado1} = 0.0415$ per unit $L_{ado1} = 0.41$ per unit

$w_2 = 0.04$ per unit $R_{ado2} = 0.0445$ per unit $L_{ado2} = 0.49$ per unit

Therefore $R_{ado} = R_{ado2} - R_{ado1} = 0.003$ per unit

and $L_{ado} = L_{ado2} - L_{ado1} = 0.08$ per unit

The coupling coefficient between armature and d-axis dampter is given by equation (2.51) -

$$K_{aD}^2 = \frac{(R_{ado}^2 + w_1^2 L_{ado}^2)(R_{ado}^2 + w_2^2 L_{ado}^2)}{R_{ado}^2 L_{ado} L_{ado1}(w_1^2 - w_2^2) + w_1^2 L_{ado}^2 (R_{ado}^2 + w_2^2 L_{ado}^2)}$$

$$= \frac{\left[(.003)^2 + (.05)^2(.08)^2\right]\left[(.003)^2 + (.04)^2(.08)^2\right]}{(.003)^2(.08)(.41)\left[(.05)^2 - (.04)^2\right] + (.05)^2(.08)^2\left[(.003)^2 + (.04)^2 (.08)^2\right]}$$

$$= 0.837$$

$$K_{aD} = 0.915$$

Time constant of d-axis damper from equation (2.52)

$$T_D = \frac{L_{ado}}{R_{ado}} = \frac{0.08 \times .05115}{0.003 \times 16.07} = 0.085 \text{ second}$$

Calculation of K_{aQ}^2

From the curves of figs. 4.20 and 4.21.

w_1 = 0.05 per unit R_{aqo1} = 0.043 per unit L_{aqo1} = 0.3835 per unit

w_2 = 0.04 per unit R_{aqo2} = 0.4455 per unit L_{aqo2} = 0.4415 per unit

with these values

$$R_{aqo} = R_{aqo2} - R_{aqo1} = 0.00155 \text{ per unit}$$

and $L_{aqo} = L_{aqo2} - L_{aqo1} = 0.058$ per unit

The coupling coefficient between armature and d-axis damper is given by

$$K_{aQ}^2 = \frac{(R_{aqo}^2 + w_1^2 L_{aqo}^2)(R_{aqo}^2 + w_2^2 L_{aqo}^2)}{R_{aqo}^2 L_{aqo} L_{aqo1}(w_1^2 - w_2^2) + w_1^2 L_{aqo}(R_{aqo}^2 + w_2^2 L_{aqo}^2)}$$

$$= \frac{[(.0015)^2 + (.05)^2 \times (.058)^2][(.0015)^2 + (.04)^2 (.058)^2]}{(.00155)^2 \times (.058)(.3835)[(.05)^2 - (.04)^2] + (.05)^2 (.058)^2 [(.00155)^2 + (.04)^2 (.058)^2]}$$

$= 0.743$

Thus $K_{aQ} = 0.875$

Time constant of q-axis damper

$$T_Q = \frac{L_{aqo}}{R_{aqo}} = \frac{.058 \times .05115}{.00155 \times 16.07} = 0.119 \text{ second}$$

x'_q and x''_q, from equations (2.28) and (2.30) -

$$x'_q = x''_q = x_q(1 - K_{aQ}^2) = 0.9232\ (1-0.743) = 0.237 \text{ per unit}$$

Calculation of K_{fD}^2

w_1 = .05pu R_{fdo1} = .1490 per unit L_{fdo1} = 7.09 per unit

w_2 = .04 pu R_{fdo2} = .1250 per unit L_{fdo2} = 7.50 per unit

Therefore, $R_{fdo} = R_{fdo2} - R_{fdo1}$ = .0248 per unit

and $L_{fdo} = L_{fdo2} - L_{fdo1}$ = 0.41 per unit

The coupling coefficient between field and d-axis damper is given by

$$K_{fD}^2 = \frac{(R_{fdo}^2 + w_1^2 L_{fdo}^2)(R_{fdo}^2 + w_2^2 L_{fdo}^2)}{R_{fdo}^2 . L_{fdo} L_{fdo1}(w_1^2 - w_2^2) + w_1^2 L_{fdo}^2(R_{fdo}^2 + w_2^2 L_{fdo}^2)}$$

$$= \frac{[(0.0248)^2+(.05)^2(.41)^2][(.0248)^2+(.04)^2(.41)^2]}{(.0248)^2(.41)(7.09)[(.05)^2-(.04)^2]+(.05)^2 x(.41)^2 [(.0248)^2 + (.04)^2 (.41)^2]}$$

$$= .551$$

Thus K_{fD} = .7465

The time constant of field winding is

$$T_f = \frac{L_{fdo}}{R_{fdo}} = \frac{0.41x.05115}{.345x16.07} = .0525 \text{ second}$$

Calculation of K_{af}

The coupling coefficient between armature and field winding (K_{af}) is calculated by taking an equivalent re istance at a frequency from the curve of Fig. 4.34 and using equation (2.55).

From Fig. 4.34.

at w_1 = .05 per unit $\quad R_{adsl}$ = .04099 per unit

From equation (2.55)

$$K_{af}^2 = \frac{(R_{adsl} - r)\, T_D}{(1 + \frac{T_f}{T_D})} \left[1 + (\frac{1}{w_1 T_D})^2 + (\frac{T_f}{T_D})^2 + 2K_{fD}^2 \; \frac{T_f}{T_D}) \right]$$

$$= \frac{(.04099 - .03486) \times 16.07 \times .085}{(1 + \frac{.0525}{.085}) \times (.8835) \times .05115} \left[1 + \frac{1}{\frac{.05}{.02} \times 2\pi(.085)^2} \right.$$

$$\left. + (\frac{.0525}{.085})^2 + 2 \times .551 \times \frac{.052}{.085} \right]$$

$$= .3634$$

K_{af} = .604

x'_d is obtained from equation (2.29)

$x'_d = x_d(1 - K_{af}^2) = 1.0956(1 - .3634) = .43$ per unit

x''_d from equation (2.27) is

$$x''_d = x_d \left(1 - \frac{K_{af}^2 + K_{aD}^2 - 2K_{fD}\, K_{aD}\, K_{af}}{1 - K_{fD}^2}\right)$$

$$= 1.0956 \left(1 - \frac{.3634 + .837 - 2 \times .7465 \times .915 \times .604}{1 - .551}\right)$$

$$= .1785 \text{ per unit}$$

The results of low frequency as well as indicial response method are given in Table 4.16.

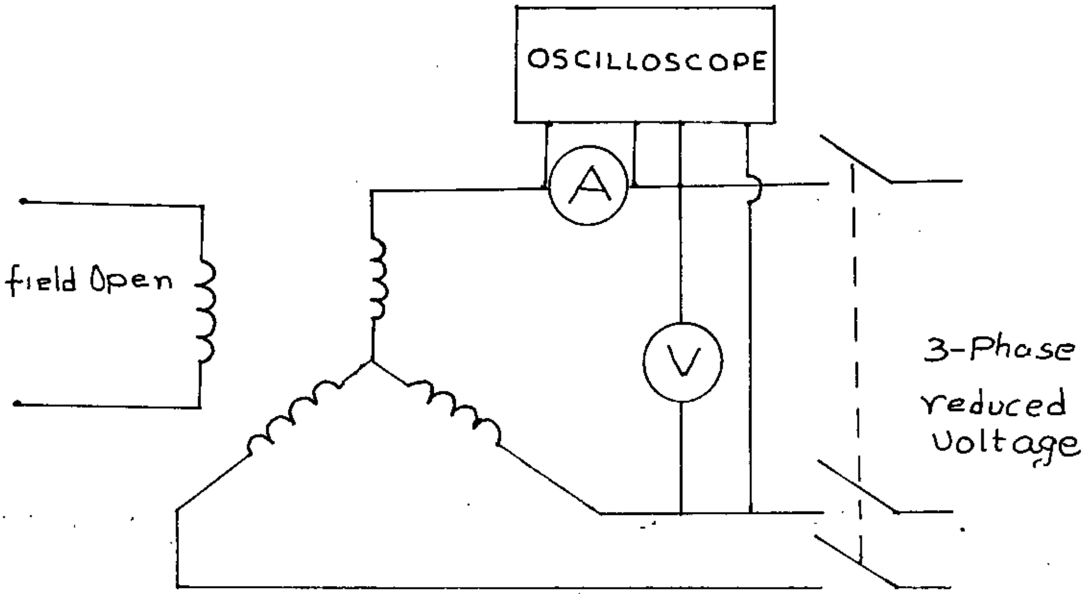
Table 4.16 Results of Indicial Response Method and Low Frequency Response Method

Parameter	Indicial Response Method	Low Frequency Response Method
X_d (per unit)	0.945	1.0956
x'_d (per unit	0.142	0.43
x''_d (per unit)	0.163	0.1785
x_q (per unit)	0.798	0.92325
x'_q (per unit)	0.3915	0.237
x''_q (per unit)	0.3915	0.237
Armature resistance, r (per unit)	0.03228	0.03484
Inductance of armature in d-axis Lead (per unit)	0.631	0.70304
Inductance of armature in q-axis L_{aeq} (per unit)	0.532	0.6155
Time constant of d-axis damper winding T_D (second)	0.03865	0.085
Time constant of q-axis damper winding T_Q (second)	0.0363	0.119
Time constant of field winding T_f (second)	0.00808	0.0525
Coupling coefficient between d-axis damper and armature K_{aD}	0.795	0.915
Coupling coefficient between q-axis damper and armature K_{aQ}	0.7145	0.875
Coupling coefficient between field and damper K_{fD}	0.895	0.7465
Coupling coefficient between armature and field K_{af}	0.924	0.604

4.3 Results of Conventional Methods:

4.3.1 Slip Test

CIRCUIT ARRANGEMENT:



Results:

Graduation of oscilloscope : 3 amp = 1.8 cm

8.8 volt= 1.5 cm

1st observation: Maximum current = 2.5 cm = 4.165A

Minimum current = 1.8 cm = 3.0 cm

Maximum voltage = 7.95 = 46.65V

Minimum voltage = 7.8 = 45.75V

$$\therefore \quad x_d = \frac{46.65}{3.0} = 15.55 \text{ ohms} = \frac{15.55}{16.07} = .9685 \text{ pu}$$

$$x_q = \frac{45.75}{4.165} = 1.099 \text{ ohms} = 0.685 \text{ per unit}$$

2nd observation: Maximum current = 2.7 cm = 4.4 amps

Minimum current = 1.9 cm = 3.16 amp

Maximum voltage = 8.7 cm = 51.7 volts

Minimum voltage = 8.4 cm = 49.4 volts

$$\therefore \quad x_d = \frac{51.7}{3.16} = 16.67 \text{ ohms} = 1.038 \text{ per unit}$$

$$x_q = \frac{49.4}{4.4} = 1.123 \text{ ohms} = 0.7 \text{ per unit}$$

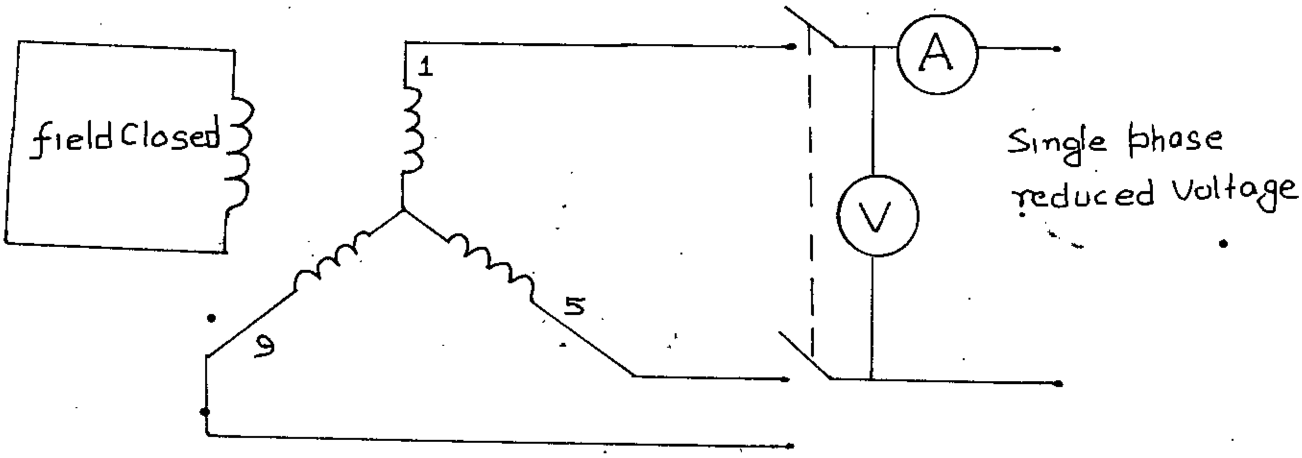
Therefore taking average values of above two observations

x_d = 1.0533 per unit

x_q = 0.6923 per unit

4.3.2 Dalton and Cameron Method

CIRCUIT ARRANGEMENT:



Results:

1st setup	Voltage applied between terminals	voltage (volts	current (amp)
	1 and 5	4.65	1.21
	1 and 9	6.15	1.01
	5 and 9	5.15	1.24

Therefore $A = \frac{4.65}{1.21} = 4.67$, $B = \frac{6.15}{1.01} = 6.08$, $C = \frac{5.15}{1.24} = 4.16$

$$K = \frac{A+B+C}{3} = \frac{4.67+6.08+4.16}{3} = 4.97$$

$$M = \sqrt{(B-K)^2 + \frac{(C-A)^2}{3}}$$

$$= \sqrt{(6.08-4.97)^2 + \frac{(4.16-4.67)^2}{3}} = 1.146$$

Therefore $x''_d = \frac{K-M}{2} = \frac{4.97-1.146}{2} = 1.917$ ohms = .1193 per unit

and $x''_q = \frac{K+M}{2} = \frac{4.97+1.146}{2} = 3.058$ ohms = .1903 per unit

2nd set

Voltage applied between terminals	voltage (volts)	current (amps.)
1 and 5	4.65	1.02
1 and 9	5.85	1.01
9 and 5	4.95	1.05

Therefore $A = \frac{4.65}{1.02} = 4.56$, $B = \frac{5.85}{1.01} = 5.8$, $C = \frac{4.95}{1.05} = 4.715$

$$K = \frac{A+B+C}{3} = \frac{4.56+5.8+4.715}{3} = 5.025$$

$$M = \sqrt{(B-K)^2 + \frac{(C-A)^2}{3}}$$

$$= \sqrt{(5.8-5.025)^2 + \frac{(4.715-4.56)^2}{3}} = .778$$

Therefore $x''_d = \frac{K-M}{2} = \frac{5.025-.778}{2} = 2.1235$ ohms = 0.132 per unit

$x''_q = \frac{K+M}{2} = \frac{5.025+.778}{2} = 2.9015$ ohms = 0.181 per unit

Average of above two observation is

$$X''_d = \frac{.1193+.132}{2} = 0.12565 \text{ per unit}$$

$$x''_q = \frac{.1903+.181}{2} = 0.18565 \text{ per unit}$$

The results of above conventional method is compared in table 4.17 with the results of new methods.

Table 4.17 Reactances obtained by New and Conventional Methods

Method	x_d	x_q	x''_d	x''_q
Low frequency response method	1.0956	0.92325	0.1785	0.237
Indicial response method	0.945	0.798	0.163	0.3915
Slip test	1.0533	0.6923	-	-
Dalton and Cameron Method	-	-	0.12565	0.18565

4.4 Discussion of Results

4.4.1 Indicial Response Method

While recording the fast transient current response particular attention should be given to the sharpness of the waveform. It is found that the accuracy of the results dependsmainly on how accurately the various components of currents are separated from the transient response and how accurately the semilog plots has been made (Figs. 4.2, 4.4 and 4.6).

Results obtained by indicial response method are given in Table 4.16 with those of the low frequency response method. It is found that the value of x_d' of 0.142 is unacceptably low because it is lower than x_d'' of 0.163. The value of K_{af} obtained by this method differs with that of the low frequency response method and $x_d' = xd(1- K_{af}^2)$. The error can be partly attributed to the inaccuracy in the separation of components and partly to the inherent limitation of this method compared to the low frequency response method. It may be mentioned here that the value of x_d' has not be included in the paper by Kaminosono and Uyed[18].

4.4.2 Low Frequency Response Method

The accuracy of the low frequency response method depend particularly on the accurate determination of the phase angle between voltage and current. The rms values of current and voltage should also be measured accurat ly using a voltmeter and an ammeter. The phase angle between current and voltage at low frequency can not be accurately measured using a voltmeter, an ammeter and a wattmeter.

The waveforms of voltage and current are used to determine the phase angle between current and voltage. The waveforms of current and voltage were recorded carefully with a double channel oscilloscope.

The low frequency voltage which is used in the test must be sinusoidal, because the mathematical formulae used in the calculation are derived for sinusoidal forcing function. The harmonics in the low frequency voltage shall be reduced as far as possible.

The equivalent inductance in the low frequency response should decrease with the increase of the frequency, as it is evident from the equation (2.48). From the experimental results it is found that equivalent inductance decreases with increase of frequency. This is due to the effect of the damper winding. It is also found that the rate of decrease is small with the open field winding than with closed field winding. The closed field winding also accentuates that the action of d-axis damper and at.1 per unit frequency and above, the equivalent inductance takes a constant value corresponding to sub-transient reactance. It is also noted that equivalent inductances at a very low frequency becomes equal to the self-inductance of the armature winding.

The parameters of the synchronous mechine determined by the low-frequency response method depends somewhere on the selection of the two frequencies, which are used in calculation. It is found that accurate results are obtained if the frequencies are chosen at frequencies below 0.1 per unit.

After all the parameters of synchronous machine obtained by low-frequency response method are in the normal range of the value of the parameters (Appendix-A). It is observed that the low frequency response method gives more accurate results than the indicial response method as shown in Table 4.16. The results are in close agreement with those of the conventional method, Table 4.17.

CHAPTER- 5

CONCLUSION

5.1 Conclusion

An accurate determination of the synchronous machine parameters are important for pre-determination of the synchronous machine behaviour during a fault or changes in its excitation or load. Two new methods namely the indicial response method and low frequency response method has been evaluated here. The mathematical model of the synchronous machine is analysed to give the important machine quantities in terms of inductance and coupling coefficients. The theoretical basis of the two new methods has been presented. The important conventional methods which are normally used as test procedure to determine the parameters of synchronous machine are also summarised. The experimental technique of the indicial response method and the low frequency response method are given. The generation of low frequency voltage on a laboratory universal Machine is shown. The tests were carried out on a laboratory alternator.

The investigation shows that the results obtained from the new methods are in the normal range of the values of the parameters. The result shows a close aggrement with those of the conventional methods. The low frequency response method gives more precise results than the indicial response method.

The influence of saturation is neglected in each method. Since the saturated values of reactances are not needed for normal calculation. The methods are important in determining the quantities of synchronous machine.

The results of low frequency response method is very much impressive, but major difficulty arises in the generation of the low frequency. Since the test are done with machine in the standstill condition, the power requirement is very small. For a 3 KVA 220 volt three phase machine, a 50 watt supply is sufficient. If the generation of such variable low frequency voltage with suitable power output is overcome, the new methods will prove to be more convenient than the conventional methods.

The major advantage of the new methods are that the machine is kept in standstill condition. The tests are applicable to any size of both salient and nonsalient synchronous machine. The test is convenient because a single experimental arrangement is required to determine all the important parameters of the synchronous machine.

5.2 Suggestion for Further Work

A suitable low frequency sinusoidal source and an accurate low frequency phase meter should be procured or developed to facilitate experimentation with the new methods.

The effect of saturation on machine parameters is of major importance. The new methods may be extended to include the effect of saturation on the parameters and also to evaluate the open circuit and short-circuit time constants of the machine.

APPENDIX-A

TYPICAL REACTANCES OF 3 PHASE SYNCHRONOUS MACHINES

Reactances are perunit value. Values below the lines give the range of value while those above give average v lues.

	X_d	X_q	X'_d	X''_d	X''_q	X_2	X_o
2-pole Turbo-generator	1.10 .95-1.45	1.07 .92-1.42	0.15 .12-21)	0.09 .07-.14	0.09 .07-.14	0.09 .07-.14	.C8 .01-0.08
4 - ple turbo generator	1.10 .95-1.45	1.08 .97-1.42	0.23 .20-.28	0.14 .12-.17	0.14 .12-.17	.14 .12-.17	.08 .015-.14
Salient pole generator and motor with damper	1.15 .60-1.45	0.75 .40-1.00	0.30 .20-.50	0.20 .13-32	0.30 .23-42	0.20 .13-.32	0.18 .03-.23
Salient pole generator and motor without damper	1.15 .60-1.45	.75 .40-.95	0.30 .20-.45	0.30 .20-.45	0.70 .45-.95	0.50 .30-70	0.19 .03-.24
Con enser	1.8 1.5-2.2	1.15 .95-1.40	0.40 .30-.60	0.25 .18-.35	0.30 .23-.43	0.24 .17-.37	0.12 .025-.15

APPENDIX-B DEFINATIONS OF REACTANCES OF SYNCHRONOUS MACHINE

1. Direct Axis Synchronous Reactance: x_d

It is the ratio of the fundamental component of reactive armature voltage, due to fundamental direct-axis component of armature current, to this component of current under blanced steady state conditions and rated frequency.

2. Direct-Axis Transient Reactance: x'_d

It is the ratio of the funamentel component of reactive armature voltage, due to fundamental direct-axis alternating current component of armature current, to this component of current under suddenly applied load conditions and at rated frequency, the value of current to be determined by the extrapolation of the envelope of the alternating current component of the current wave to the instant of sudden application of load, neglecting the high decrement currents during the first few cycles.

3. Direct Axis Sub-transient Reactance: x''_d

It is the ratio of the fundamental component of reactive armature voltage, due to initial value of the fundamental direct axis component of the alternating current component of the armature current, to this component of current under suddenly applied load conditions and rated frequency.

4. Quadrature Axis Synchronous Reactance: x_q

It is the ratio of the fundamental component of reactive armature voltage due to the fundamental quadrature-axis component of armature current, to this component of current under steady state condition and at rated frequency.

5. Quadrature Axis Transient Reactance : x'_q

It is the ratio of the fundamental component of reactive armature voltage, due to the fundamental quadrature axis component of alternating current component of armature current, to this component of current under suddenly applied load conditions at rated frequency, the value of current to be determined by the extrapolation of the envelope of the alternating current component of the current wave to the instant of the sudden application of load, neglecting the high-decrement current during the first few cycles.

6. Quadrature Axis Sub-Transient Reactances: x''_q

The quadrature axis subtransient reactance is the ratio of the fundamental component of reactive armature voltage, due to the initial value of the fundamental quadrature axis component of the alternating current component of the armature current, to this component of current under suddenly applied balanced load conditions and at rated frequency, the value of current to be determined by the extrapolation of the envelope of the alternating current component of the current wave to the instant of the sudden application of load, neglecting the high decrement currents during the first few cycles.

7. Negative - Sequence Reactance: x_2

It is the ratio of the fundamental reactive component of negative sequence armature voltage, resulting from the presence of fundamental negative sequence armature current of rated frequency, to this current, the machine being operated at rated speed.

8. Zero Sequence Reactance: x_0

The zero sequence reactance is the ratio of the fundamental component of reactive armature voltage, due to the fundamental zero sequence component of armature current to this component at rated frequency.

APPENDIX-C SATURATION EFFECT ON SYNCHRONOUS MACHINES QUANTATIES[24]

A synchronous machine consists of an electromagnetic circuit. An electromagnetic circuit attends a state of saturation at which the flux generation is not varing linearly with applied emf. A synchronous machine attends saturation if its excitation is increased or if its armature current is increased. Due to this saturation, no more the linear relation remains between voltage and current and synchronous machine parameters changes with saturation. The constant attends different values at different degree of saturation due to armature/excitation current. Due to saturation, the reactances are decreased. Saturation effects the different parameters to different extent. For some parameter inclusion of saturation is x essential and for some parameters they may be neglected.

For x_d, the effect of saturation under load can be taken into account with good accuracy with the use of saturation factor, determined from the open circuit characteristics of the machine. x_d is assumed to be consists of two part, one is constant and is independent of saturation, while second part is effected by saturation. The constant part can be found by potier triangle, which is based on the assumption that over excited zero power factor characteristic is identical with the open characteristics, shifted vertically downward by a constant voltage drop and horizontally to the right by a constant mmf. The x_d may be continuously adjusted for saturation as a machine's operating condition changes.

X_q is affected lesser than x_d by saturation. Because of the interpolar space, saturation in the iron portion of the q-axis magnetic circuit plays only a negligible part in determining the permeance of course q-axis saturation can be included through the use of two saturation factor, one dependant on total flux and one on direct axis flux.

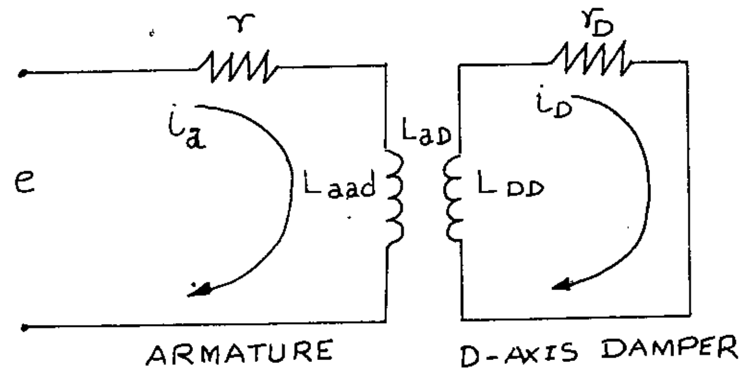
The d-axis transient and sub-transient reactances x_d' and x_d'' are predominantly determined by armature leakage and field or damper winding leakage. They are therefore, influenced by saturation to lesser extent then x_d. Nevertheless they are influenced, for heavy armature currents during a disturbance tends to increase the saturation in the leakage flux path as well as in the main flux . paths. Usually two values of each reactance are available. One called the rated voltage, or saturated, value is determined from the short circuit tests in which the field current is adjusted to give rated prefault terminal voltage. The other called, the rated-current, or unsaturated, value is found from the short circuit test with the field current reduces so that the initial symmetrical transient or subtransient current is equal to rated current.

The q-axis transient and subtransient reactances x_q' and x_q'' also vary with saturation. Since x_q', x_q'' are equal for salient pole machine, they are treated alike in that case. For solid rotor turbo alternator x_q' and x_d' may be treated in the same manner since they are approximately equal. The subtransient reactance x''_q is handled in the same manner as x_d''.

APPENDIX-D

DERIVATION OF EQUIVALENT RESISTANCE AND INDUCTANCE IN LOW FREQUENCY RESPONSE METHOD

Let the field is open circuited and rotor is in d-axis



Then

$$e = (r + jw\, L_{aad})\, i_a - jw\, L_{aD}\, i_D$$

$$0 = (r_D + jw\, L_{DD})\, i_D - jw\, L_{aD}\, i_q$$

Therefore

$$i_D = \frac{jw\, L_{aD}}{r_D + jw\, L_{DD}}$$

$$e = (r + jw\, L_{aad})\, i_a - jw\, L_{aD}\, \frac{jw\, L_{aD}\, i_a}{r_D + jw\, L_{DD}}$$

$$\frac{e}{i_a} = r + jw\, L_{aad} + \frac{L_{aD}^2\, w^2}{r_D + jw\, L_{DD}}$$

$$= r + jw\, L_{aad} + \frac{L_{aD}^2\, L_{aad}\, L_{DD}}{L_{aad}\, L_{DD}} \; \frac{w^2}{r_D + jw\, L_{DD}}$$

$$= r + jw\, L_{aad} + \frac{K_{aD}^2\, L_{aad}\, L_{DD}\, w^2}{r_D + jw\, L_{DD}}$$

$$\frac{e}{i_a} = r + jw\,L_{aad} + \frac{K_{aD}^2\,L_{aad}\,w^2}{\frac{r_D}{L_{DD}} + jw}$$

$$= r + jw\,L_{aad} + \frac{K_{aD}^2\,L_{aad}\,w^2}{\frac{1}{T_D} + jw}$$

$$= r + jw\,L_{aad} + \frac{w^2\,K_{aD}^2\,L_{aad}(jw - \frac{1}{T_D})}{(\frac{1}{T_D} + jw)(jw - \frac{1}{T_D})}$$

$$= r + jw\,L_{aad} + \frac{K_{aD}^2\,L_{aad}\,(jw - \frac{1}{T_D})}{(1 + (\frac{1}{wT_D})^2}$$

$$= r + \frac{k_{aD}^2\,\frac{L_{aad}}{T_D}}{1 + (\frac{1}{w\,T_D})^2} + jw((L_{aad} - \frac{K_{aD}^2\,L_{aad}}{1 + (\frac{1}{w\,T_D})^2}$$

Again $\frac{e}{i_a} = R_{ado} + jw\,L_{aado}$

Therefore equivalent resistance

$$R_{ado} = r + \frac{L_{aad}\,\frac{K_{aD}^2}{T_D}}{1 + (\frac{1}{w\,T_D})^2}$$

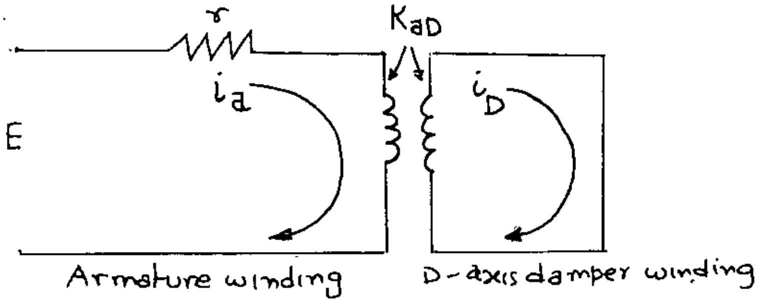
and equivalent inductance

$$L_{aado} = L_{aad}\,((1 - \frac{K_{aD}^2}{1 + (\frac{1}{w\,T_D})^2}))$$

APPENDIX-E

Indicial Response Method

When the rotor is in d-axis and field is open, we can write



$$E = \frac{d}{dt} L_{aad}\, i_a + r\, i_a - \frac{d}{dt} K_{aD}\, i_D \qquad (1)$$

$$0 = - \frac{d}{dt} K_{aD}\, i_a + \frac{d}{dt}\, i_d + \frac{I_d}{T_B} \qquad (2)$$

Taking leplace transformation of above equations

$$\frac{E}{S} = L_{aad}\, S I_a + r\, I_a - K_{aD}\, S\, I_D \qquad (3)$$

$$0 = - K_{aD}\, S\, I_a + \frac{I_D}{T_D} + S\, I_D \qquad (4)$$

From (4) $$I_D = \frac{K_{aD}\, S\, I_a}{\left(\frac{1}{T_D} + S\right)} \qquad (5)$$

$$\therefore \quad \frac{E}{S} = L_{aad}\, S\, I_a + r\, I_a - K_{aD} S \, \frac{K_{aD}\, S\, I_a}{\frac{1}{T_D} + S}$$

Therefore $$I_a = \frac{E/S}{\left(L_{aad}\, S + r \quad \frac{K_{aD}^2\, S^2}{\frac{1}{T_D} + S} \right)}$$

$$I_a = \frac{E\,(1 + S\, T_D)}{S((\,S^2(L_{aad}\, T_D - K_{aD}^2\, T_D + S\,(L_{aad} + T_D\, r) + r\,))} \qquad (6)$$

Let $$I_a = \frac{K_o}{S} + \frac{K_1}{S - S_1} + \frac{K_2}{S - S_2} \qquad (7)$$

Where S_1 and S_2 are two roots of equation

$$S^2(L_{aad}\,T_D - K_{aD}^{2}\,T_D) + S(L_{aad} + T_D r) + r = 0$$

$$S_1 = \frac{-(L_{aad} + T_D r) + \sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}\,T_D - K_{aD}^{2}T_D)}}{2(L_{aad}\,T_D - K_{aD}^{2}\,T_D)} \qquad (8)$$

$$S_2 = \frac{-(L_{aad} + T_D r) - \sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}\,T_D - K_{aD}^{2}\,T_D)}}{2(L_{aad}\,T_D - K_{aD}^{2}\,T_D)} \qquad (9)$$

$$K_o = \frac{E(1 + ST_D)}{S^2(L_{aad}\,T_D - K_{aD}^{2}\,T_D) + S(L_{aad} + T_D r) + r}\Bigg|_{S=0}$$

$$K_o = \frac{E}{r} \qquad (10)$$

$$K_1 = \frac{E(1 + S\,T_D)}{S(S - S_2)}\Bigg|_{S = S_1}$$

$$= \frac{2E(L_{aad}T_d - K_{aD}^2 T_D) + E\,T_D\left(-(L_{aad}+T_D r) + \sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}T_D - K_{aD}^2 T_D)}\right)}{\left[-(L_{aad}+T_D r) + \sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}T_D - K_{aD}^2 T_D)}\right]\sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}T_D - k_{aD}^2 \times T_D)}}$$

$$K_1 = \frac{E(L_{aad}T_D - K_{aD}^2 T_D)\left[\left[2(L_{aad}T_D - K_{aD}^2\,T_D) + T_D\left[-(L_{aad}+T_D r) + \sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}T_D - K_{aD}^2 T_D)}\right]\right]\right]}{\left[(L_{aad}+T_D r) + \sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}T_D - K_{aD}^2 T_D)}\right]\sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}T_D - K_{aD}^2 T_D)}} \qquad (11)$$

$$K_2 = \frac{E(L_{aad}\,T_D - K_{aD}^2\,T_D)\left[2(L_{aad}\,T_D - K_{aD}^2\,T_D) + T_D\left\{-(L_{aad}+T_D r) \sqrt{(L_{aad}+T_D r)^2 - 4r\,(L_{aad}\,T_D - K_{aD}^2\,T_D)}\right\}\right]}{\left[-L_{aad} + T_D r) - \sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}\,T_D - K_{aD}^2\,T_D)}\right] \cdot \left[-\sqrt{(L_{aad} + T_D r)^2 - 4r(L_{aad}\,T_D - K_{aD}^2\,T_D)}\right]} \quad (12)$$

Taking the inverse laplace transformation of equation (7)

$$i_a = K_o + K_1\,e^{st_1} + K_2\,e^{st_2} \quad (13)$$

Putting the values of K_o, K_1 and K_2 from equations (10),(11) and (12) in equation (13)

$$i_a = \frac{E}{r}$$

$$+ \frac{E(L_{aad}T_D - K_{aD}^2 T_D)\left[2(L_{aad}\,T_D - K_{aD}^2 T_D) + T_D\left\{-(L_{aad}+T_D r) + \sqrt{(L_{aad} + T_D r)^2 - 4r\,(L_{aad}\,T_D - K_{aD}^2 T_D)}\right\}\right]}{\left[(-L_{aad} + T_D r) + \sqrt{(L_{aad} + T_D r) - 4r\,(L_{aad}T_D - K_{aD}^2\,T_D)}\right]\left[\sqrt{(L_{aad} + T_D r)^2 - 4r\,(L_{aad}\,T_D - K_{aD}^2\,T_D)}\right]}$$

$$\times\, e^{t\,\frac{-(L_{aad} + T_D r) + \sqrt{(L_{aad} + T_D r)^2 - 4r\,(L_{aad}\,T_D - K_{aD}^2\,T_D)}}{2(L_{aad}\,T_D - K_{aD}^2\,T_D)}} \quad (14)$$

$$+ \frac{E(L_{aad}\,T_D - K_{aD}^2\,T_D)\left[2(L_{aad}\,T_D - K_{aD}^2 T_D) + T_D\left\{-(L_{aad}+T_D) - \sqrt{(L_{aad} + T_D r)^2 - 4r\,(L_{aad}T_D - K_{aD}^2 T_D)}\right\}\right]}{\left[(L_{aad}+T_D r) + \sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}T_D - K_{aD}^2 T_D)}\right]\left[\sqrt{(L_{aad}+T_D r)^2 - 4r\,(L_{aad}T_D - K_{aD}^2 T_D)}\right]}$$

$$\times\, e^{t\,\frac{-(L_{aad}+T_D r) - \sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}T_D - K_{aD}^2 T_D}}{2(L_{aad}\,T_D - K_{aD}^2\,T_D)}}$$

But the actual cur ent is in the form

$$i_a = I_{aa0} - I_{a20}\, e^{-t/T_{a20}} - I_{a10}\, e^{-t/T_{a10}} \qquad (15)$$

Therefore,

$$T_{a20} = \frac{2(L_{aad}\, T_D - K_{aD}^{\,2} T_D)}{-(L_{aad} + T_D r) + \sqrt{(L_{aad} + T_D r)^2 - 4r(L_{aad} T_D - K_{aD}^{\,2} T_D)}} \qquad (16)$$

$$T_{a10} = \frac{2(L_{aad} T_D - K_{aD}^{\,2}\, T_D)}{-(L_{aad} + T_D r) - \sqrt{(L_{aad} + T_D r)^2 - 4r(L_{aad} T_D - K_{aD}^{\,2} T_D)}} \qquad (17)$$

$$I_{a20} = \frac{-E(L_{aad} T_D - K_{aD}^{\,2} T_D)\left[2(L_{aad} T_D - K_{aD}^{\,2} T_D) + T_D \left\{-(L_{aad} + T_D r) + \sqrt{(L_{aad} + T_D r)^2 - 4r(L_{aad} T_D - K_{aD}^{\,2} T_D)}\right\}\right]}{\left[-(L_{aad} + T_D r) + \sqrt{(L_{aad} + T_D r)^2 - 4r(L_{aad}\, T_D - K_{aD}^2\, T_D)}\right]\left[\sqrt{(L_{aad} + T_D r)^2 - 4r(L_{aad} T_D - T_D\, K_{aD}^2)}\right]} \qquad (18)$$

$$I_{a10} = -\frac{E(L_{aad} T_D - K_{aD}^{\,2} T_D)\left[2(L_{aad} T_D - K_{aD}^{\,2} T_D) + T_D \left\{-(L_{aad} + T_D r) - \sqrt{(L_{aad} + T_D r)^2 - 4r(L_{aad} T_D - K_{aD}^{\,2} T_D)}\right\}\right]}{\left[(L_{aad} T_D r) + \sqrt{(L_{aad} + T_D r)^2 - 4r(L_{aad} T_D - K\text{-}D^2 T_D)}\right]\left[\sqrt{(L_{aad} + T_D r) - 4r(L_{aad}\, T_D - K_{aD}^{\,2}\, T_D)}\right]} \qquad (19)$$

Since the value of r is very small, so the terms involving r in the expressions $\sqrt{(L_{aad} + T_D r)^2 - 4r(L_{aad}\, T_D - K_{aD}^{\,2}\, T_D)}$ may be neglected. Also the term $(L_{aad} T_D - K_{aD}^2\, T_D)$ is very small

Therefore,

$$\sqrt{(L_{aad}+T_D r)^2 - 4r(L_{aad}T_D - K_{aD}{}^2 T_D)} - L_{aad} \qquad (20)$$

Using equation (20) the equation (16) is $T_{a20} = \dfrac{-2(L_{aad}T_D - K_{aD}{}^2 T_D)}{-(L_{aad}+T_D r)+L_{aad}}$ (21)

$$T_{a20} = \frac{2(L_{aad} - K_a D^2)}{r} \qquad (22)$$

Using equation (20) equation (17), (18) and (19) are

$$T_{a10} = \frac{2(L_{aad}\ T_D - K_{aD}{}^2 T_D)}{T_D r - 2L_{aad}} \qquad (23)$$

$$I_{a20} = \frac{E(L_{aad}T_D - K_{aD}{}^2\ T_D)\quad 2(L_{aad}T_D - K_{aD}{}^2 T_D) - T_D{}^2 r}{(-T_D r\ L_{aad})} \qquad (24)$$

$$I_{a10} = -\frac{E(L_{aad}T_D - K_{aD}{}^2 T_D)\quad 2(L_{aad}T_D(-K_{aD}{}^2 TD)+T_D\ -(2L_{aad}+T_D r)}{(-T_D r\ L_{aad})} \qquad (25)$$

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