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AUTOMATIC RESYNCHRONISATION OF SYNCHRONOUS MACHINES

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ABSTRACT

The theme of the project was the development of a scheme to re-establish synchronism automatically in the contingency of a synchronous machine falling out-of-step while in operation. To establish the necessary criteria on which the proposed scheme for resynchronisation could be based, machine behaviour during asynchronous operation and the process of resynchronisation has been studied in detail.

Rotors in common use are of two different types; laminated and solid. The two types produce different damping effects and both have been studied. All the studies have been performed on a general-purpose analogue computer. To study the two types of rotor, mathematical models have been developed. Each of these models is suitable for cylindrical or salient-pole construction. Results obtained on the analogue computer have been verified by comparison with results obtained on both actual large alternators and laboratory micro-machines.

Auxiliary equipment can play a significant part during asynchronous operation and in the process of resynchronisation. The effects of various auxiliary equipment, different machine parameters and system conditions on out-of-synchronous operation and resynchronisation, have been studied. Investigations have been made into the process of pulling-into-step from the state of steady asynchronous operation using an entirely different approach and the process is explained in simple physical terms.

Based on the results obtained from various studies, a transistor relay, for the automatic resynchronisation of synchronous machines, using static relaying techniques is proposed. This relay has been constructed and its effectiveness has been demonstrated on a micro-machine.

The proposed scheme for automatic resynchronisation is particularly adaptable to the controls of the future and is suited to 'on line' computer control.

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INDEX

LIST OF SYMBOLS

Most commonly used symbols and notations are defined below. Any symbol not given below will be explained where used in the text.

Unless otherwise stated, all quantities are expressed in per-unit. In general, varying quantities are denoted by small letters and constant quantities by capital letters.

Main symbols

f - Frequency in cycles per second

i - Instantaneous value of current

I - Constant or phasor value of current

e - Instantaneous value of voltage

E - Constant or phasor value of voltage

r - Resistance

x - Reactance

X - Total reactance

ℓ - Leakage inductance

L - Total self inductance

t - Time in seconds

T - Torque *or* Time-constant

p - Number of pole pairs *or* Operator d/dt

P - Power

s - Instantaneous machine slip

Z - Impedance

j - Operator $\sqrt{-1}$

H - Machine Inertia constant in KW sec/KVA *or* Magnetising force in AT/metre

J - Current density in amperes/metre^2 or Moment of Inertia in lb. ft.^{2}

B - Flux density in Weber/metre^2

N - Effective number of stator turns in series per phase

ℓ - Length of flux path through the rotor iron in metres

w - Axial length of the rotor in metres

S - Reluctance in AT/Weber

$x_d(p)$ - Operational impedance relating i_d to ψ_d

$x_q(p)$ - Operational impedance relating i_q to ψ_q

$G(p)$ - Operational quantity relating e_f to ψ_d

$(T_{as})_m$ - Asynchronous mean torque

$\left.\begin{matrix} Y_a, Y_b \\ Y_c, Y_d \end{matrix}\right\}$ - Operational admittances as derived from $x_d(p)$ and $x_q(p)$

$\left.\begin{matrix} \alpha_{d1}, \alpha_{d2} \\ A_{d1}, A_{d2} \\ B_{d1}, B_{d2} \end{matrix}\right\}$ - Coefficients as defined in Section 4.4.2

ω_o - Angular velocity of infinite bus in radians per second (Synchronous speed)

ω - Slip in radians per second

Ω - Instantaneous speed

ν - Angular velocity of rotor in radians per second

θ - Angular position of rotor in space

δ - Load-angle of synchronous machine with respect to bus

λ - Phase angle or Value of θ at zero time

ρ - Resistivity in Ohm - metre

ψ - Flux linkages

ϕ - Flux per pole in Webers

Subscripts

a - Acceleration *or* phase A *or* Armature
d - Direct axis
q - Quadrature axis
f - Field winding
k - Damper winding
e - Electrical *or* External
m - Magnetising *or* Mean *or* Mechanical *or* Maximum
g - Governor
s - Synchronous
as - Asynchronous
md - Direct axis mutual
mq - Quadrature axis mutual
t - Turbine
o - Initial *or* Surface value

Superscripts

' - Transient
'' - Sub-transient

CHAPTER 1

INTRODUCTION

1.1 Historical review

> " ... the least known or available in literature are the phenomena of pulling into step ... (of a) synchronous motor in that range of speed where it is not an induction motor anymore and where it is not yet a synchronous motor." 1

It is more than half a century since the above words, equally applicable to synchronous machines in general, were said by Steinmetz. At present, a lot more is known of the process of synchronisation, which in the earlier years was studied primarily from the point of view of pulling-in of synchronous motors when starting up. The problem of dealing with a synchronous motor that accidentally lost synchronism while on load was, however, given only cursory attention.

By virtue of the availability of a prime mover, power-systems engineers introduced the method of fine synchronisation to connect their synchronous machine (generator) to the system. To deal with the eventuality of accidental loss of synchronism, the easy way out was adopted. This has resulted in the present usual accepted practice in power-system operation, that in the event of an alternator losing synchronism either due to loss of excitation or following system disturbances of any kind, it is immediately disconnected from the system. With the continued increase in the size of the individual generating units, the process of shutting down and bringing the set back onto the bus-bars ab initio entails a considerably long period which is very undesirable both from the point of view of un-interrupted maintenance of supply and economic operation of the system. In many such cases it would be very desirable if the machine is able to operate asynchronously for a short period until synchronism can be restored.

Although some attention was paid to the asynchronous operation and resynchronisation of synchronous machines in the early thirties[2,3,4,5], it is only in the last decade that serious attention has started to be devoted to this problem. References 6 to 22 give a selected bibliography for this period.

Full scale tests reported in various references have shown that, under certain conditions and for a limited period, it is permissible to leave the machine connected to the system until some action can be taken to bring it back into synchronism. From these tests, it has been observed that after a time the machine settles down to a condition of steady asynchronous operation and is capable of supplying a reasonably large percentage of its rated output at quite low slip. For a given power output, currents are, however, high compared with the values during normal synchronous operation and currents in the supply leads pulsate.

This problem received international recognition when it was explicitly referred to the C.I.G.R.E. Study Committee No. 17. A report on the work of this committee is given in Ref. 23. The present attitude to this problem is well summed up in the following concluding remarks[24] to the discussion on asynchronous working and resynchronisation at C.I.G.R.E. Convention No. 18, 1960:

> " This type of operation runs certain risks, but it would seem that these risks have been over estimated and that asynchronous operation can be permitted in certain cases and in fact can render certain services."

1.2 Formulation and study of the problem

Instances have been observed in practice[2,3] when the machine lost synchronism temporarily and pulled back into synchronism without any prolonged asynchronous operation. In other cases when it does not pull back into synchronism, but settles down to a steady asynchronous operation, it can be resynchronised either manually or automatically. Ref. 5 has given certain conditions for resynchronisation based on full scale experiments conducted in Russia. Further theoretical investigations have been conducted by various authors (References 8, 14, 15, 25 to 29) but none of these investigators has carried out a sufficiently comprehensive study of the effect of various parameters of the system on asynchronous operation and process of resynchronisation. In addition, all of them have adopted certain sweeping assumptions in the working out of their results without establishing the validity of the same.

Study of asynchronous operation and resynchronisation requires the solution of a number of non-linear differential equations. To simplify the solution, most of the authors referred above have adopted the following assumptions in their investigations:

i) Voltage behind the transient reactance is constant; and

ii) Variation in speed during the transient process is small in comparison with the steady state speed. ~~This results in neglecting~~ The effects of all such terms as $p\psi_d$, $p\psi_q$, etc. are neglected.

The effect of these assumptions may be referred to as neglecting the stator transients.[30]

In addition to the above two assumptions, the third, most commonly adopted, simplifying factor is to neglect stator resistance of the synchronous machine.

1.3 Present work

The problem under study in this thesis originated with the development of the synchronous machine. It has been studied and discussed in one form or another since that time. It is, therefore, rather a difficult exercise to differentiate between that which is new and that is old. However, this is believed to be the first time that such a systematic study of the problem has been made in its entirety, particularly with so elaborate a representation of the synchronous machine.

The study has been divided into a series of logical steps culminating in the devising of a suitable scheme for automatically resynchronising the machine in the event of an accidental loss of synchronism. The various steps are outlined below.

1.3.1 Assumptions

Assumptions mentioned in Section 1.2 above are the standard assumptions made in most transient stability studies. They make the problem easily amenable to a solution by the well-known step-by-step method[31,32,33] on an A.C. Network Analyser[34,35] or a digital computer[36,37]. In this field they have rendered a very useful service in the past. Doubts have, however, already been expressed as to the justification of these assumptions and a better representation of the synchronous machine is becoming more and more desirable.

Although these assumptions may have some justification in transient stability studies, they cannot be justified in the study of asynchronous operation and resynchronisation. In the present work, the synchronous machine has been simulated by adopting the minimum number of assumptions possible. In fact, most of the work is based on assumptions no more than those inherent in the two-reaction theory of synchronous machines as enunciated by Park in his classical papers[38,39].

1.3.2 Scope of studies

Theoretically, a synchronous machine will operate reversibly either as a generator or a motor depending upon the direction of flow of power and current. Thus there is no difference in its behaviour during asynchronous operation and the process of resynchronisation. It is, therefore, desirable that any system of equations should be equally valid for either of the generating and motoring modes of operation. Treatment of a synchronous machine, described henceforth, is on the most general basis without any distinction, whatsoever, between motor and generator. Equations are equally applicable to both machines, so far as proper sign convention is used to interpret the results in a physical sense.

Because of the different positions occupied by the two machines in a system, it is essential that there should be enough scope to include the effect of other associated equipment. The system of equations described and the method of simulation adopted for the representation of a synchronous machine is very adaptable, such that, the effect of any major or auxiliary equipment associated with the machine to be studied can very easily be included. Thus it is easy to study the effect of turbine or load characteristics, voltage regulators, speed governors, transmission lines or other system conditions. Effect of changing any of the electrical or mechanical parameters of the machine can also easily be studied.

Success or otherwise of any series of studies can be gauged by their usefulness when applying them to actual system operating conditions. Full scale tests are therefore conducted from time to time to verify the validity of various theories. These tests can only be representative and not exhaustive. For more exhaustive studies, resort must be made to various other methods such as analytical investigations, physical models or mathematical models. Each of these methods has its usefulness and limitations in certain respects. The method to be adopted depends upon the requirements of each individual case.

In the present investigations, the system has been studied by a mathematical model on an electronic analogue computer. To test the efficacy of the simulation some full scale tests conducted by the C.E.G.B.[20,40] on its system in the past, have been simulated and the results obtained from the computer compared with the test results. Even though a reasonable agreement was obtained between these two, it was not considered sufficient to justify the adoption of results obtained from exhaustive studies on the mathematical model only. Micro-machines[41,42] have proved very useful as physical models for the study of power system problems[40,43,44]. It was decided to carry out the simulation by mathematical model on the computer and simultaneously perform tests on the micro-machine as a physical model.

Investigations have been carried out using both these model forms and also by an analytical method suggested elsewhere[44]. Encouraging agreement has been found between the results of the mathematical model and those of the physical model and full scale tests. In contrast, wide differences between the laboratory results and those based on assumptions of earlier investigators, not only shows the need to reduce these assumptions to the minimum, but also clearly establishes the validity of the proposed simulation.

1.3.3 Rotor construction

Any system of equations representing the salient-pole rotor construction can be easily modified to study cylindrical rotor machines by suitably choosing the direct and quadrature axis parameters. The main difference lies in different damping effects caused by eddy currents in the laminated and solid rotors.

This thesis is divided into two parts to deal with the laminated and solid rotors separately. Two different sets of equations and simulations have been developed and the complete phenomena studied under each heading.

1.3.4 Asynchronous operation

Study of resynchronisation implies that the machine is already in the asynchronous mode of operation. Before attempting to pull the machine back into synchronism, it is essential that its behaviour during asynchronous operation be known. An investigation has, therefore, been made into the asynchronous operation with both types of rotors. The effect of various electrical and mechanical parameters, alternative field connections, system conditions, and auxiliary equipment, on the behaviour of the machine has also been studied.

The theoretical study is based on the well known Park's[38,39] theory as put forward in a more comprehensive form by Adkins[45].

1.3.5 Resynchronisation

Most of the earlier studies of resynchronisation are based on the hypothesis that 'the instantaneous slip of the machine during a slip cycle should pass through zero' is a necessary condition to be realised prior to successful resynchronisation. During the present investigations, it has been shown that this is a myth, and that successful resynchronisation can be achieved without this pre-condition being fulfilled, provided, certain other conditions have been established. Necessary conditions for resynchronisation have been detailed in Chapters 7 and 8.

1.3.6 Automatic resynchronisation relay

Based on the results of the various studies detailed above, a scheme is proposed for the automatic re-establishment of synchronism. A relay based on static relaying principles has been built according to this scheme and tested on the micro-machine. This relay is designed to sense loss of synchronism, and initiate necessary corrective action to re-establish synchronism automatically in the shortest possible time without any human intervention. The relay can be assembled from standard logic units and is very easily adaptable to suit the operating characteristics of any particular machine in the context of its location in a system.

The proposed scheme for automatic resynchronisation is particularly suitable for use with 'on line' computer controls which are envisaged for the future.

CHAPTER 2

EQUIPMENT SPECIFICATIONS

2.1 Introduction

The usefulness of a mathematical model lies in the degree to which its results can be relied upon in practical cases. To establish the validity of the models developed in the present work, it was considered desirable to simulate some actual full scale tests and to compare the results obtained. Data of three full scale tests conducted by the C.E.G.B. on two large machines in 1960[20,40] and on one machine in 1962[46] was available. These three series of tests have been simulated and the results discussed later.

For a proper investigation into any phenomena, it is essential to carry out a large number of studies. For these studies to be realistic, two different sets of micro-machines have been used, so that results obtained on the analogue computer can be correlated.

2.2 Test machines

The C.E.G.B. carried out series of asynchronous tests on a 60 MW turbo alternator at Marchwood power station in March, 1960[20] and on a 30 MW turbo alternator at Goldington power station in May, 1960[40]. Imperial College actively participated in these tests. Some data about the physical parameters of these machines and some test results are available in references 20, 40 and 47.

Some further data not available in these references has been collected from Ref. 48 and from the records available in the power-systems laboratories of the Imperial College. All the relevant machine data required for the present studies is given in Appendix 'A'.

In addition to the above, tests conducted on a 120 MW reheat type turbogenerator in June, 1962 have been simulated. Details of this set are given in Appendix 'A'.

2.3 Micro-machines

2.3.1 Electrical characteristics

Micro-machines[41,42] have become quite a handy and useful tool in the hands of power-system analysts in Britain[42], U.S.S.R.[43], and France[49] for investigations into theories associated with synchronous machines. Different types of problems[40,44] studied have shown them to be very reliable for this type of work. For a fuller study of the present problem, two sets of micro-machines - one with a laminated salient-pole rotor and the other with a solid cylindrical rotor - have been used.

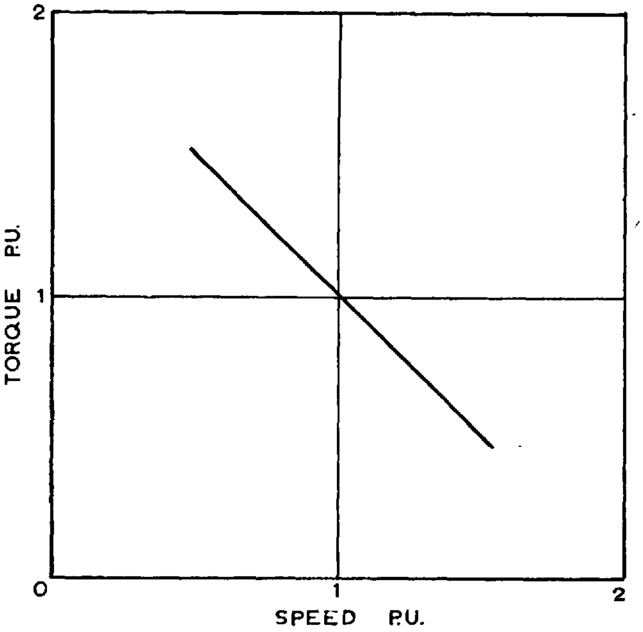
To be able to compare and check the results obtained from the mathematical model set up on the analogue computer, various constants of each micro-machine set were first evaluated by well known tests[50]. These constants and other parameters were then used to calculate the coefficients for the equations to be solved on the computer. All the necessary data about the two sets of micro-machines used is given in Appendix 'A'. A perusal of the data will show that, except in one or two respects, to be mentioned later, micro-machines are quite comparable with typical large machines and can be said to be reliable models for the purpose of investigating practical problems associated with synchronous machines.

2.3.2 Mechanical characteristics

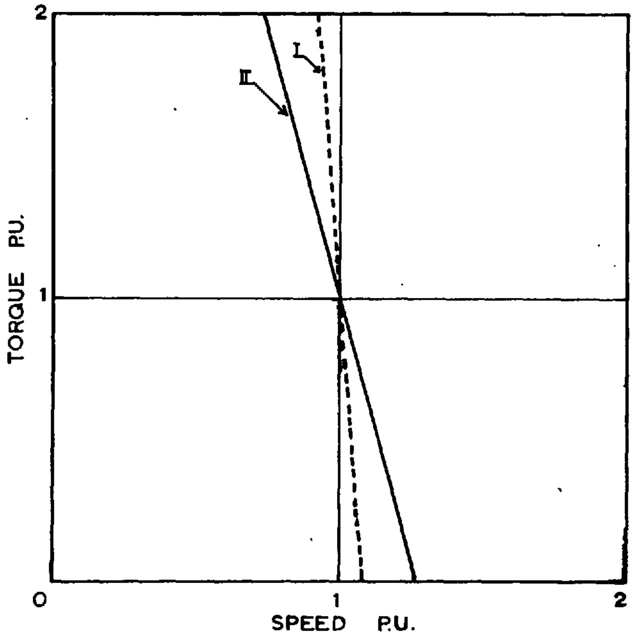
Simulation of the mechanical characteristics of synchronous machines consists essentially of simulating the machine inertia, the inherent torque-speed characteristics of the turbine driving a generator or the load imposed on a motor. In addition, time constants of the turbine speed-governor are required in the case of the generator.

The inertia constant of the micro-machine was obtained by means of a deceleration test[51]. It could be adjusted to any desired value by means of additional flywheels. Actual values of the inertia constants used in the present work are given in Appendix 'A'.

The torque-speed characteristics of a turbine can be approximately represented as shown in Fig. 2.1(a)[33], having a slope of -1. The prime mover of the micro-machine is a d.c. shunt motor having a slope of the order of -20 or more as shown in Fig. 2.1(b). By adding resistance in series with the armature of the d.c. machine, it is possible to reduce the slope of the torque-speed characteristics. Because of the limitations of the current rating of the motor and of the supply voltage, it was not possible to achieve an ideal turbine characteristic. By adding resist-



(a) Approximate turbine characteristic



(b)Approximate micro-machine drive characteristic

I. Micro-machine drive characteristic

II. Modified micro-machine drive characteristic

Fig. 2.1

ance in the armature and increasing the supply voltage, a slope of about -8 was obtained.

2.3.3 Auxiliary equipment

By suitable auxiliary equipment, it is possible to simulate and study the effect of different field time-constants and field connections, external reactance, bus-bar voltage, moment of inertia, turbine speed governor and voltage regulator characteristics.

The control panel associated with the micro-machines contains auto-transformers and reactors with a number of taps, by which different values of bus-bar voltages and various magnitudes of external reactances can conveniently be arranged. Operation with different field connections can very simply be studied by making suitable connections.

The field resistance of a micro-machine, on a per-unit basis, is much higher than in a large machine. This results in a comparatively low field transient time-constant. An electronic device called "The time-constant regulator"[52] has been developed to reduce the effective field resistance and thereby alter the transient time-constant to the required value. This equipment operates essentially by introducing controlled values of negative resistance in the field circuit by means of feed-back circuits. By introducing different values of feed-back resistance, it is possible to simulate different field time-constants. Use of this equipment has been made to study the effect of varying time-constants on the behaviour of the machine.

Apparatus is being developed to control the d.c. driving motor in such a way as to simulate a turbine drive. As this control apparatus was not yet ready when the studies were performed, the effect of the speed governor could not be demonstrated on the micro-machine, even though a few studies with speed governor action were performed on the computer.

With the micro-machine tests it was possible to record the variations in electrical power, VArs, current and machine terminal voltage by recording equipment. For a few tests, the instantaneous electrical power was measured by a small analogue computer using operational amplifiers and electronic multipliers with suitable voltage and current transformers. The output of this miniputer was recorded by an UV recorder. By using the same equipment, instantaneous VArs could also be measured and recorded.

2.4 Analogue computer

Most of the investigations into synchronous machine problems by mathematical models have tended to employ special purpose electronic computers and simulators (References 53 to 61). With these models it has been possible to simulate synchronous machines and associated equipment to a fairly good degree of accuracy and to achieve a very good correlation between full scale tests and predicted results. By their nature, their applications have, however, tended to be rather restricted to the type of problem for which they were specifically designed.

The mathematical models developed and described in the present work are such that no special analogue equipment is required. All the studies described were carried out on an ordinary electronic differential analyser - the P.A.C.E. TR48 computer in the mathematical machines laboratory of Imperial College. TR48[62] is a general purpose analogue computer comprising standard computing elements that would be available in any good computer. The following facilities are available on this computer.

i) D.C. operational amplifiers used for summation and integration - maximum of 48 amplifiers including 16 integrators.
ii) Potentiometers - maximum of 60. Four out of every five have one end earthed.
iii) Diode function generators.
iv) Quarter-square multipliers.
v) Servo-multipliers.
vi) Relay comparators and manually operated function switches.
vii) Operation modes - Pot set, Reset, Hold, Operate and Repetitive.
viii) Two voltmeters - one digital and one dial type.

The problem is set on a removable patch-board using plugging leads.

The present analogue computer has only 42 operational amplifiers and 50 potentiometers.

An X-Y plotter was used in conjunction with the computer to record any one variable with time or with any other variable.

CHAPTER 3

GENERAL MACHINE EQUATIONS

3.1 General

The mathematical basis for the investigation of the problem of resynchronisation is a set of operational equations which express the relationships between the various voltages, currents and flux linkages in the machine. These equations known as the 'general equations' of the synchronous machine are the basic equations of the two axis general theory of electrical machines[45] and are based on the assumption that the machine is ideal as defined by Park[63].

3.2 Per-unit system

To be able to correlate results obtained from machines of widely different physical dimensions, the method of reducing all the quantities to a per-unit basis is used. It is, however, desirable that the per-unit system adopted should be consistent. There are a number of different per-unit systems in use at present. All the equations and other quantities given in this thesis are expressed in per-unit terms as defined by Rankin[64,65].

The base-current ratio termed by Rankin as the 'x_{ad}' base[65] has been adopted as the standard base. According to this definition, base field current is that field current which will induce in each stator phase a voltage equal to $x_{ad} \cdot i_{ao}$. The main advantage of using this base is that it makes x_{mfd} numerically equal to x_{ad} (equal to x_{md}).

3.3 Sign convention

The sign convention adopted is that of Adkins[45]. The reference axes are fixed and the direction of rotation of the rotor, relative to the axes, is anticlockwise as shown in Fig. 3.1[45]. The primary axis windings are located on the rotating member and those of the field and dampers on the stationary member. The coil voltages are assumed positive when impressed on the coils from an external source and currents are measured in the same direction as the driving positive voltage.

With this convention, the instantaneous power flows into the circuit from outside if both voltage and current are positive. A positive current is assumed to produce a positive flux in a direction along the axis away from the centre. Positive electrical torque is obtained when mechanical power is passing into the machine from outside at a positive speed. Positive torque thus indicates generator action.

The sign convention adopted corresponds directly to motor operation and introduces negative signs for generator operation.

3.4 Assumptions

It has already been mentioned that the 'General

Theory of Electrical Machines'[45] is based on the assumption that the machine is ideal as defined by Park[63]. In addition, the following generally accepted assumptions[45] have been made in working out the theory.

i) Symmetrical conditions exist on the system, i.e. zero sequence quantities are nil.

ii) Per-unit mutual inductances for all the coils on a particular axis are equal.

iii) Damping circuits can be represented by a single coil on each axis. For the present, the impedance of the damping circuit will be assumed to be a function of slip. It may thus be written as

$$Z_k(j\omega) = r_k(j\omega) + j\omega\ell_k(j\omega) \quad . \; . \; .(3.1)$$

with appropriate subscripts for the two axes.

3.5 Voltage equations

3.5.1 Fundamental equations

On the basis of the above assumptions, the voltage impressed on each coil of the idealised synchronous machine, represented by Fig. 3.1(a), can be written in terms of the corresponding currents and flux linkages. This leads to a set of equations on a three phase basis. When the phase quantities are transformed into the axis quantities, using the usual transformations[45], the following equations are obtained, neglecting zero sequence quantities:

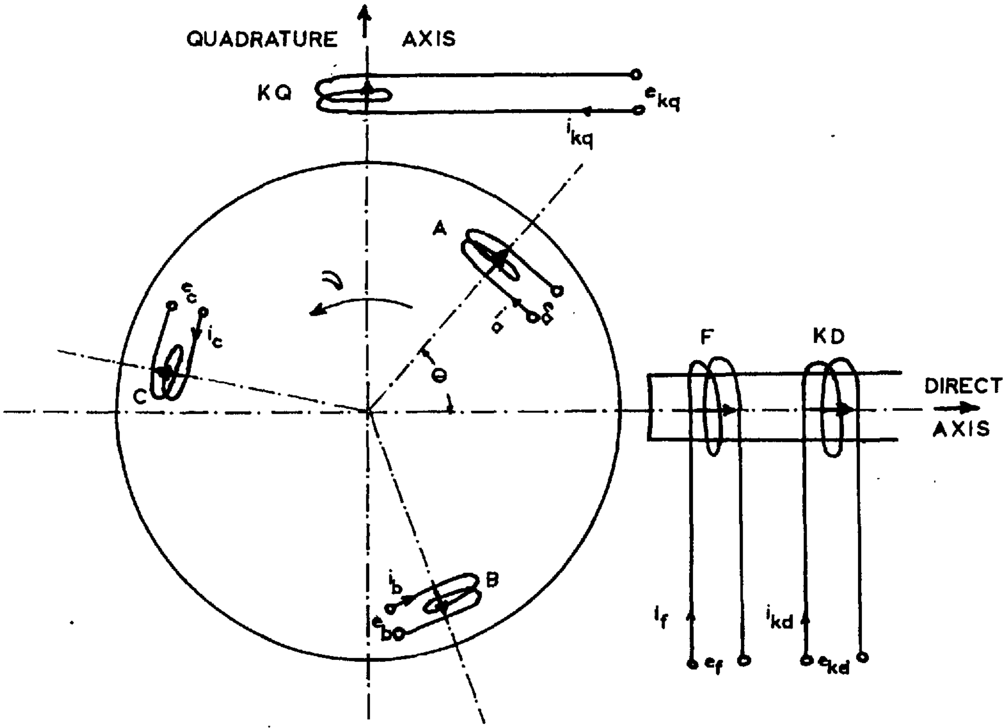


Fig.3.1a Diagram of an idealised Synchronous machine

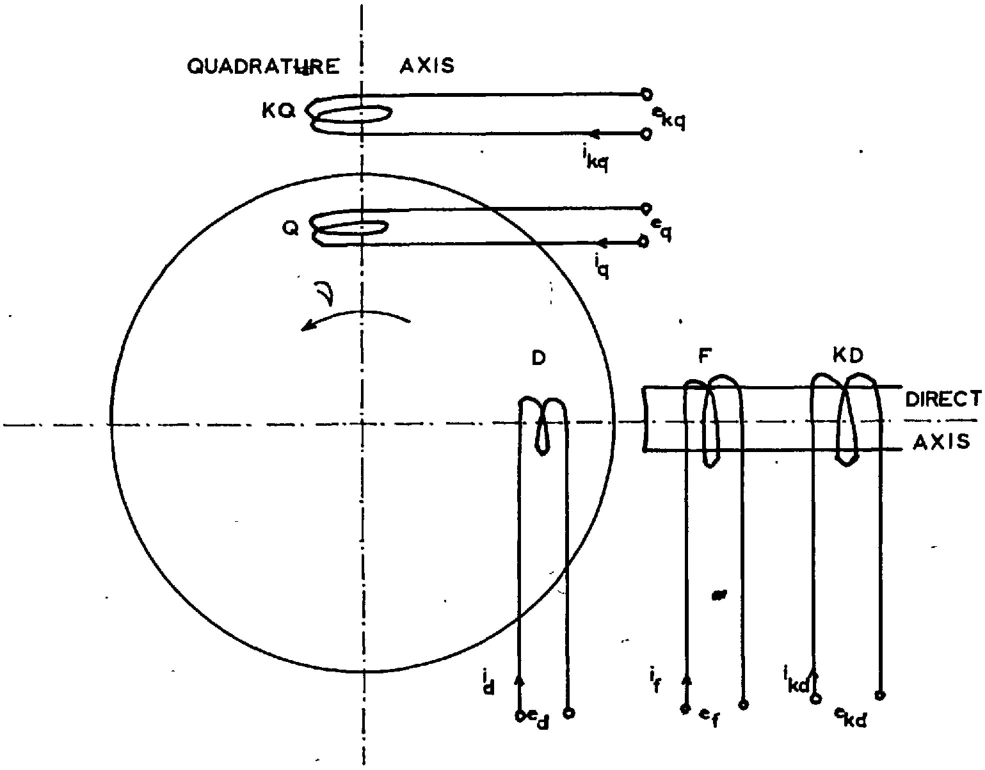


Fig.3.1b Diagram of a Synchronous machine with two damper coils

$$e_d = p\psi_d + \nu\psi_q + r_a \cdot i_d \qquad \ldots(3.2)$$

$$e_q = -\nu\psi_d + p\psi_q + r_a \cdot i_q \qquad \ldots(3.3)$$

The voltages e_d and e_q in Eqns. (3.2) and (3.3) can be physically interpreted as the voltages impressed on fictitious coils on the direct and quadrature axes respectively. With this interpretation, the three 'phase coils' of Fig. 3.1(a) are replaced by the direct and quadrature axis coils as shown in Fig. 3.1(b), which is thus the two axis equivalent diagram of the synchronous machine.

3.5.2 Simplified equations for a machine connected to a fixed supply voltage

Considering a synchronously rotating axis, its position at any time 't' can be written as

$$\theta_r = \omega_o t \qquad \ldots(3.4)$$

During asynchronous operation, the position θ of the machine rotor, assuming the value of θ at zero time is λ, is given by

$$\theta = \omega_o t - \delta + \lambda \qquad \ldots(3.5)$$

which on differentiation gives

$$\nu = \frac{d\theta}{dt} = \omega_o - p\delta \qquad \ldots(3.6)$$

With a sinusoidal applied voltage at frequency $\omega_o/2\pi$, the voltage of phase A can be expressed as

$$e_a = E_m \cdot \mathrm{Sin}(\omega_o t + \lambda') \qquad \ldots(3.7)$$

where, E_m is the maximum value of the fixed supply voltage, and the phase is given by an angle λ'.

For an a.c. problem, the instant of zero time can be chosen arbitrarily. In the present instance, working is considerably simplified if zero time is chosen so that $\lambda = \lambda'$. Substituting $\omega_o t = (\theta + \delta - \lambda)$ from Eqn. (3.5) in Eqn. (3.7) and expanding, gives

$$e_a = E_m \cdot \mathrm{Sin}\delta \cdot \mathrm{Cos}\theta + E_m \cdot \mathrm{Cos}\delta \cdot \mathrm{Sin}\theta \qquad \ldots(3.8)$$

Also the transformation relating e_a to e_d and e_q gives[45]

$$e_a = e_d \cdot \mathrm{Cos}\theta + e_q \cdot \mathrm{Sin}\theta \qquad \ldots(3.9)$$

The two values of e_a must be identical for all values of t. Hence, equating the coefficients of Cosθ and Sinθ in Eqns. (3.8) and (3.9), gives

$$e_d = E_m \cdot \mathrm{Sin}\delta \qquad \ldots(3.10)$$

$$e_q = E_m \cdot \mathrm{Cos}\delta \qquad \ldots(3.11)$$

Substituting Eqns. (3.6), (3.10) and (3.11) in Eqns. (3.2) and (3.3) gives

$$e_d = E_m \cdot \mathrm{Sin}\delta = p\psi_d + \omega_o\psi_q - \psi_q p\delta + r_a \cdot i_d \qquad \ldots(3.12)$$

$$e_q = E_m \cdot \mathrm{Cos}\delta = -\omega_o\psi_d + \psi_d \cdot p\delta + p\psi_q + r_a \cdot i_q \qquad \ldots(3.13)$$

3.6 General equations of the synchronous machine

With the assumptions given in Section 3.4, the equations for a system of stationary mutually coupled coils as shown in Fig. 3.1(b) can be written down in terms of their individual currents, flux linkages and mutual and self inductances. These equations are:

i) Direct axis equations;

$$\psi_d = L_{md} \cdot i_f + L_{md} \cdot i_{kd} + (L_{md} + \ell_a) i_d \qquad \ldots (3.14)$$

$$e_f = [r_f + (L_{md} + \ell_f) p] i_f + L_{md} \cdot p i_{kd} + L_{md} \cdot p i_d \qquad \ldots (3.15)$$

$$e_{kd} = L_{md} \cdot p i_f + \{ r_{kd}(j\omega) + [L_{md} + \ell_{kd}(j\omega)] p \} i_{kd}$$
$$+ L_{md} \cdot p i_d \qquad \ldots (3.16)$$

ii) Quadrature axis equations;

$$\psi_q = L_{mq} \cdot i_{kq} + (L_{mq} + \ell_a) i_q \qquad \ldots (3.17)$$

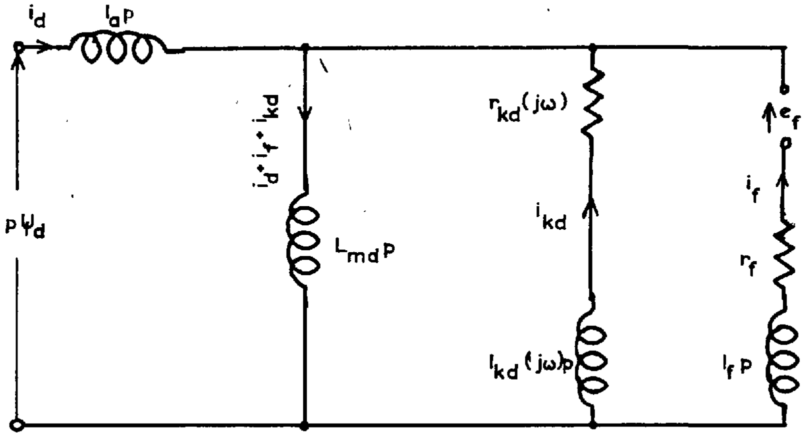
$$e_{kq} = \{ r_{kq}(j\omega) + [L_{mq} + \ell_{kq}(j\omega)] p \} i_{kq} + L_{mq} \cdot p i_q \qquad \ldots (3.18)$$

The two damper windings KD and KQ [Fig. 3.1(b)] would in general be short-circuited, and hence

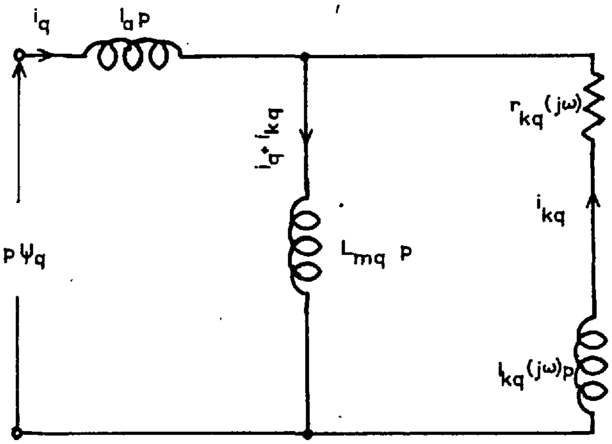
$$e_{kd} = e_{kq} = 0$$

3.7 The equivalent circuits

Eqns. (3.14) to (3.18) can be represented by two equivalent circuits[45], one for the direct and one for the quadrature axis as shown in Fig. 3.2. The equivalent circuits are of value in that they show a clearer picture



(a) Direct axis



(b) Quadrature axis

Fig.3.2 Equivalent circuits

of the mathematical representation given by Eqns. (3.14) to (3.18) and also for solving a.c. problems for which the numerical results can be obtained. The way they have been used in the present work will be shown in Chapter 5.

3.8 The operational impedances

Eliminating i_f and i_{kd} from the direct-axis Eqns. (3.14) to (3.16), the following equation is obtained:

$$\psi_d = \left[\frac{1 + (T_4 + T_5)p + T_4 \cdot T_6 p^2}{1 + (T_1 + T_2)p + T_1 \cdot T_3 p^2} \right] L_d \cdot i_d$$

$$+ \left[\frac{1 + T_{kd} p}{1 + (T_1 + T_2)p + T_1 \cdot T_3 p^2} \right] \frac{L_{md}}{r_f} \cdot e_f \qquad \ldots (3.19)$$

which can be put in the form

$$\psi_d = \frac{x_d(p)}{\omega_o} \cdot i_d + \frac{G(p)}{\omega_o} \cdot e_f \qquad \ldots (3.20)$$

In a similar way it can be shown that by eliminating i_{kq} from the quadrature axis Eqns. (3.17) and (3.18),

$$\psi_q = \frac{1 + T_q'' p}{1 + T_{qo}'' p} L_q \cdot i_q \qquad \ldots (3.21)$$

$$= \frac{x_q(p)}{\omega_o} \cdot i_q \qquad \ldots (3.22)$$

where the functions $x_d(p)$ and $x_q(p)$ are termed operational impedances and the time constants T_1 to T_6, T_{kd}, T''_{qo} and T''_q are as defined in Ref. 45.

It may be mentioned here that Eqns. (3.19) and (3.21) as obtained from the literature are particularly applicable to laminated rotor machines. Eqns. (3.20) and (3.22) are a more general form of the same and can be applied to both laminated and solid rotor machines. Reasons for this difference will be given in Chapters 4 and 5.

3.9 Torque equation

3.9.1 Expression for electrical torque

The electrical torque is obtained from the power passing into the direct and quadrature axis armature coils due to the rotational voltage terms in the Eqns. (3.2) and (3.3)[45]. The electrical power is

$$P_e = \frac{1}{2}\Big[(\text{Rotational component of } e_d) \times i_d + (\text{Rotational component of } e_q) \times i_q\Big]$$

which on substitution from Eqns. (3.2) and (3.3) gives

$$P_e = \frac{\nu}{2}(\psi_q \cdot i_d - \psi_d \cdot i_q) \qquad \ldots (3.23)$$

Hence per-unit torque is given by[45]

$$T_e = -P_e \frac{\omega_o}{\nu} = \frac{\omega_o}{2}(\psi_d \cdot i_q - \psi_q \cdot i_d) \qquad \ldots (3.24)$$

3.9.2 Torque equation under asynchronous operating conditions

Under sufficiently prolonged abnormal conditions on the system or the machine, such as sustained short-circuit, loss of load or loss of field with a generator on load and tied in with a system, the speed of a synchronous generator will increase above synchronous. Under these conditions, it will normally continue operating as an induction generator supplying energy to the system - the magnitude of slip and load supplied being dependent upon the initial loading, generator constants, impedance of the system connected to the generator and the turbine speed-governor characteristics. Under steady asynchronous operating conditions, the average generator power is in equilibrium with the turbine power, which decreases when the slip increases as shown in Fig. 2.1(a). The steady state should consequently correspond to the point of intersection of the generator characteristic - which indicates how the average power depends on the slip - with the turbine governor characteristic as shown in Fig. 3.3(a)[66]. In this figure, the slip s_m and the corresponding asynchronous torque $(T_{as})_m$ are the quantities which describe the state of steady asynchronous operation.

In actual practice, the machine will not follow the straight path A-B shown in Fig. 3.3(a) to come to a stable state, because of the dead zone (if any) of the speed governor and the delay in the servo-motor. Depending upon the time constant of the governor, it will settle down after a few oscillations around the point of stable asynchronous operation (A) as shown by the helical path in Fig. 3.3(b).

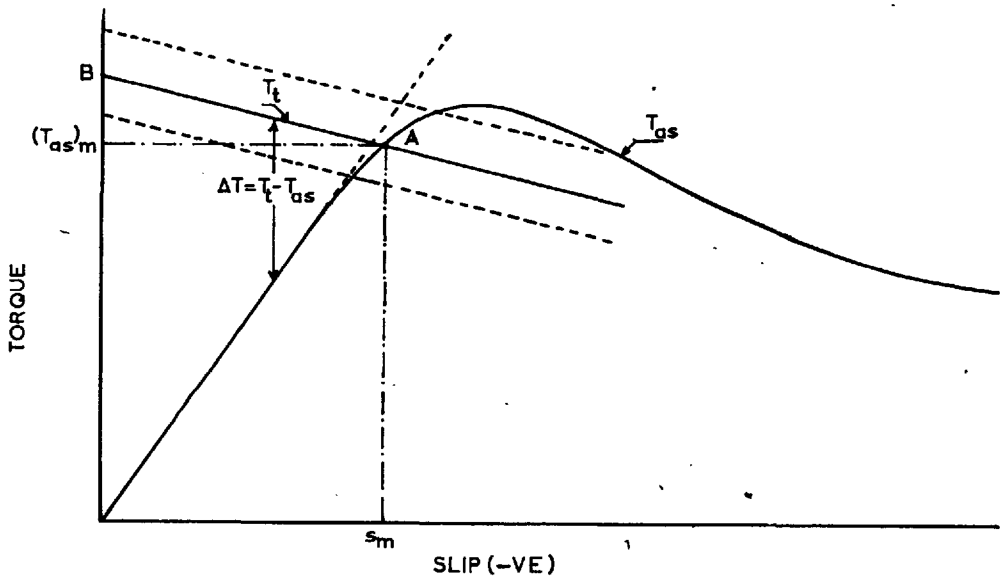


Fig.3.3a Asynchronous generator torque (T_{as}) and turbine torque (T_t) as functions of slip

(Figure not to scale)

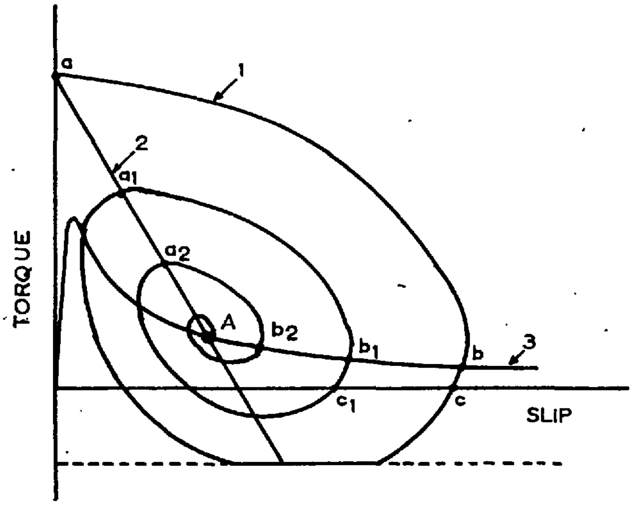


Fig.3.3b Change of turbine torque with slip

1. Change of turbine torque with slip (actual)
2. Turbine torque _slip characteristics (theoretical)
3. Asynchronous torque _ slip characteristic

Under these conditions, the summation of the instantaneous torques acting upon the mechanical system must be zero. Consequently, the relative motion of the generator rotor is determined by the equation

$$\Sigma T = \text{Accelerating torque} = \text{Input torque(mechanical)} - \text{Output torque(electrical)} \quad .(3.25)$$

Now,

$$\text{Accelerating torque}^{67} = J\,\frac{d^2\delta}{dt^2} = \frac{2H}{\omega_o}\cdot\frac{d^2\delta}{dt^2} \quad \ldots(3.26)$$

$$\text{Input torque(mechanical)}^{25}\; T_t = T_o + ap\delta + N \quad \ldots(3.27)$$

where T_o = initial torque per-unit,
a = slope of prime mover torque speed curve[33] $= -T_o$,
$N = \frac{b\cdot p\delta}{1 + T_g p}$, turbine governor characteristics . . .(3.28)
(simulating the governor characteristics by a single time constant — T_g, and governor amplification factor — b).

Output torque(electrical) as given by Eqn. (3.24)

$$= \frac{\omega_o}{2}\,(\psi_d \cdot i_q - \psi_q \cdot i_d)$$

Eqn. (3.25) may be re-written as

$$\frac{2H}{\omega_o}\cdot p^2\delta = -\frac{\omega_o}{2}\,(\psi_d \cdot i_q - \psi_q \cdot i_d) + T_t \quad \ldots(3.29)$$

Eqn. (3.29) is equally applicable in the case of synchronous motors, when T_t is suitably represented to take account of the characteristics of the driven load.

CHAPTER 4

SIMULATION OF LAMINATED ROTOR MACHINE

4.1 Introduction

Operating characteristics of synchronous machines are generally defined by certain well-known constants. In the strictest terms, these constants are not constant as they vary with slip, which in turn depends on the operating conditions in the system. This dependence of the machine parameters on the system operating conditions makes an exact solution of the equations impossible. Also, due to the rotor not being symmetrical on its two axes, currents in the supply leads pulsate. This results in pulsations in the watts and VArs components of the asynchronous volt-amps accompanied by constant oscillations of speed (slip) about a fixed average value.

The solution of the machine equations by analytical methods[44] is possible only by adopting simplifying assumptions. The validity of solutions thus obtained is doubtful. With the help of an analogue computer, it is possible to solve these equations without adopting any further assumptions.

Using the parameters of a set of micro-machines, the equations have been solved both by an analytical method and as a mathematical model on an analogue computer. The results obtained by these two methods have been compared with those obtained on the micro-machine itself. It is shown that the results obtained by the mathematical model produce a much better correlation than those obtained by the analytical method.

The analytical method and the analogue computer simulation are described below.

4.2 Representation of the damping circuit

Because of the laminated construction of the rotor, eddy currents in the rotor body are eliminated to a very large extent. Instead a squirrel-cage damper winding is provided to produce the necessary damping effect. In practice, this winding consists of a number of circuits carrying different currents and would require a large number of coils for its exact representation. However, for most practical purposes, representation of the damper winding by only two coils KD and KQ, as shown in Fig. 3.1, is well accepted as sufficiently accurate[45]. In this case, impedance Z_k of the damper circuit given by Eqn. (3.1) is generally taken to be

$$Z_k = r_{k/s} + j\omega_o \ell_k = r_{k/s} + jx_k \qquad \ldots(4.1)$$

The values of constants r_{kd}, r_{kq}, x_{kd} and x_{kq} cannot be obtained directly by any test. They have to be obtained either from design calculations or indirectly by suitable manipulation of the expressions for the constants T_1 to T_6, T''_{qo} and T''_q [Eqns. (3.19) and (3.21)] as given in Ref. 45.

Out of the time-constants T_1 to T_6, T''_{qo} and T''_q, constants T_1, T_3, T_4, T_6, T''_{qo} and T''_q were obtained directly by tests[50] and all other parameters were calculated there-from. The value of stator leakage reactance x_a has, however, still to be calculated either from design data or it may be approximated by the Potier reactance x_p. For the set of micro-machines used in the laminated rotor study, the value of x_a as calculated by Widger[68] from design data was adopted.

4.3 Analytical method

A number of equations describing asynchronous operation, given in Chapter 3, are functions of slip (speed). Owing to pulsations in speed, an exact analysis of asynchronous operation would require the solution of non-linear differential equations. One of the methods of solving these would be by the well-known step-by-step process[31,32,33] usually adopted in transient stability studies of power systems.

To be of any value for the asynchronous operating conditions, normal step-by-step methods would have to be refined to take into account, in each interval, the changes of the turbine output, the synchronous power and the asynchronous power. Not only will this make the calculations extremely lengthy and laborious, the results obtained will still be of doubtful value, as they will depend directly upon the accuracy with which the turbine output and asynchronous power with varying speed can be predicted. To simplify this cumbersome process, an approximate method has been suggested by Mehta and Adkins[44]. By this method, the pulsations in torque are calculated on the following assumptions:

i) Speed is constant; for which condition the equations become linear.

ii) Slip is very small, i.e. slow transient changes; thus terms which depend on the rate of change of ψ_d, ψ_q or δ can be neglected.

iii) Armature resistance is neglected.

These torque pulsations are then used to determine the pulsations of speed.

Details of this method are given in Appendix B.

4.4 Mathematical model

4.4.1 General

It would be observed from Section 4.3 above, that some of the assumptions made to arrive at an analytical solution of the asynchronous operation are very drastic and difficult to justify for the particular conditions under study. To obtain more reliable and accurate results, it is imperative that the number of assumptions be kept to a minimum and the direct effect of maximum possible system parameters be included in the solution.

In 1935, Shoults et. al.[69], carried out certain studies on the pull-in characteristics of synchronous motors using a mechanical differential analyser. In the present work, their approach has been suitably modified to study the asynchronous operation of synchronous machines in general. Various studies described henceforth were carried out on the TR48 analogue computer described in Section 2.4.

The main advantages of using the analogue computer are detailed below.

i) The number of assumptions made is reduced to a minimum. In fact no more assumptions than those inherent in the basic theory enumerated in Section 3.4 are made to arrive at the solution of the resulting non-linear differential equations.

ii) With the use of mathematical models, it is possible to achieve, without any special difficulties, a wide variation of the parameters of the machine. Characteristics and parameters of the auxiliary equipment such as turbine speed-governors and voltage regulators, and the size of the system, as is compatible with the size of the analogue computer available, can be studied in detail.

iii) The equations developed for simulation on the analogue computer permit the application of suggested methods[33] of allowing for saturation.

iv) As will be seen in Section 7.2, analytical study of the process of resynchronisation by the method of Section 4.3 will involve still further assumptions and will lead to very approximate results. By the use of an analogue computer, it is possible to study both the asynchronous operation and the process of resynchronisation by a single programme without making any further assumptions. Also, this programme can very easily be adapted to study all modes of operation.

v) Investigation by mathematical models makes it possible to define and analyse those problems which are either not defined at all in other methods or require special devices for defining them.

4.4.2 Formulation of the mathematical model

The problem of asynchronous operation and resynchronisation can be studied in full by the simultaneous solution of Eqns. (3.12), (3.13), (3.19), (3.21) and (3.29) on an analogue computer. However, to be capable of easy representation, these equations will be stated in a modified form. Here Eqns. (3.19) and (3.21) are to be interpreted on the basis of Eqn. (4.1).

(a) Eqns. (3.12) and (3.13)

By re-arranging Eqns. (3.12) and (3.13), the following more suitable form is obtained:

$$p\psi_d = E_m \cdot \text{Sin}\delta - r_a \cdot i_d - \omega_o\psi_q + \psi_q \cdot p\delta \quad \ldots(4.2)$$

$$p\psi_q = E_m \cdot \text{Cos}\delta - r_a \cdot i_q + \omega_o\psi_d - \psi_d \cdot p\delta \quad \ldots(4.3)$$

(b) Eqn. (3.19)

Let $\psi_d = L_d \cdot i_d + \psi_{d1} + \psi_{d2}$ . . .(4.4)

where $$\psi_{d1} = \frac{L_d(A_{d1} \cdot pi_d + \alpha_{d1} \cdot B_{d1} \cdot e_f)}{p + \alpha_{d1}} \quad \ldots(4.5)$$

and $$\psi_{d2} = \frac{L_d(A_{d2} \cdot pi_d + \alpha_{d2} \cdot B_{d2} \cdot e_f)}{p + \alpha_{d2}} \quad \ldots(4.6)$$

From Eqn. (4.5), ψ_{d1} can be expanded and is

$$\psi_{d1} = L_d \cdot A_{d1} \cdot i_d + \frac{L_d \cdot B_{d1} \cdot \alpha_{d1} \cdot e_f}{p} - \frac{L_d \cdot \alpha_{d1}(A_{d1} \cdot pi_d + \alpha_{d1} \cdot B_{d1} \cdot e_f)}{p(p + \alpha_{d1})}$$

$$\psi_{d1} = L_d \cdot A_{d1} \cdot i_d - \alpha_{d1} \int (\psi_{d1} - L_d \cdot B_{d1} \cdot e_f)\, dt \quad .(4.7)$$

Similarly, from Eqn. (4.6),

$$\psi_{d2} = L_d \cdot A_{d2} \cdot i_d - \alpha_{d2} \int (\psi_{d2} - L_d \cdot B_{d2} \cdot e_f)\, dt \quad .(4.8)$$

From Eqns. (3.19) and (4.4),

$$\psi_{d1} + \psi_{d2} = \left[\frac{x_d(p)}{\omega_o} - \frac{x_d}{\omega_o} \right] i_d + \frac{G(p)}{\omega_o} \cdot e_f \quad . . .(4.9)$$

The coefficients of Eqns. (4.7) and (4.8) can be obtained by substituting Eqns. (C.2) and (C.3) [Appendix 'C'], (4.5) and (4.6) in Eqn. (4.9) and dividing both the denominator and numerator of right-hand side by $(\ell_f \cdot L_{kd} + \ell_{kd} \cdot L_{md})$. The denominator of the resulting expression is

$$p^2 + \frac{(r_{kd} \cdot L_f + r_f \cdot L_{kd})}{(\ell_f \cdot L_{kd} + \ell_{kd} \cdot L_{md})}\, p + \frac{r_f \cdot r_{kd}}{(\ell_f \cdot L_{kd} + \ell_{kd} \cdot L_{md})}$$

which on factorisation and simplification gives

$$\alpha_{d1},\ \alpha_{d2} = \frac{(T_1 + T_2) \mp \sqrt{T_1^2 + T_2^2 - 2T_1 \cdot T_2 + 4L_{md}^2 / r_f \cdot r_{kd}}}{2T_1 \cdot T_3} \quad . .(4.10)$$

Solving the identity resulting from Eqn. (4.9), the constants and coefficients of p and p^2 can be obtained as below:

$$A_{d1} = -\frac{x_d - x_d''}{x_d} \cdot \frac{\alpha_{d1}}{(\alpha_{d1} - \alpha_{d2}) T_1 \cdot T_3} + \frac{x_{md}^2}{\omega_o \cdot x_d} \cdot \frac{r_f + r_{kd}}{r_f \cdot r_{kd}} \cdot \frac{1}{(\alpha_{d1} - \alpha_{d2}) T_1 T_3}$$

. . .(4.11)

$$A_{d2} = \frac{x_d - x_d''}{x_d} \circ \frac{\alpha_{d2}}{(\alpha_{d1}-\alpha_{d2})\text{[illegible]}} - \frac{x_{md}^2}{\omega_o \cdot x_d} \cdot \frac{r_f + r_{kd}}{r_f \cdot r_{kd}} \cdot \frac{1}{(\alpha_{d1}-\alpha_{d2})T_1 \cdot T_3} \quad \ldots (4.12)$$

$$B_{d1} = \frac{x_{md}}{x_d} \cdot \frac{(\alpha_{d1} \cdot T_{kd} - 1)}{(\alpha_{d1} - \alpha_{d2})T_1 \cdot T_3 \cdot \alpha_{d1} \cdot r_f} \quad \ldots (4.13)$$

$$B_{d2} = \frac{x_{md}}{x_d} \cdot \frac{(-\alpha_{d2} \cdot T_{kd} + 1)}{(\alpha_{d1} - \alpha_{d2})T_1 \cdot T_3 \cdot \alpha_{d2} \cdot r_f} \quad \ldots (4.14)$$

Eqn. (4.4) re-arranged for representation on the analogue computer becomes

$$i_d = \frac{\omega_o}{x_d} \left[\psi_d - \psi_{d1} - \psi_{d2} \right] \quad \ldots (4.15)$$

where ψ_{d1} and ψ_{d2} are given by Eqns. (4.7) and (4.8) respectively.

(c) Eqn. (3.21)

From Eqn. (C.5), Appendix 'C',

$$\psi_q = \left\{ L_q - \left[\frac{L_{mq}^2 \cdot p}{r_{kq} + (L_{mq} + \ell_{kq})p} \right] \right\} \cdot i_q$$

It may be expanded to

$$\psi_q = \left\{ \left[L_q - \frac{L_{mq}^2}{L_{mq} + \ell_{kq}} \right] + \frac{r_{kq}}{(L_{mq} + \ell_{kq})p} \left[\frac{L_{mq}^2 \cdot p}{r_{kq} + (L_{mq} + \ell_{kq})p} \right] \right\} \cdot i_q \quad \ldots (4.16)$$

By definition[45],

$$\left[L_q - \frac{L_{mq}^2}{(L_{mq} + \ell_{kq})}\right] = \ell_a + \frac{L_{mq} \cdot \ell_{kq}}{(L_{mq} + \ell_{kq})} = \frac{x_q''}{\omega_o} \qquad \ldots (4.17)$$

which on substitution into Eqn. (4.16) and by suitable re-arrangement gives

$$\Psi_q = \frac{x_q''}{\omega_o} \cdot i_q - \frac{1}{T_{qo}''}\int \Psi_q \, dt + \frac{x_q}{\omega_o \cdot T_{qo}''}\int i_q \, dt \qquad \ldots (4.18)$$

Eqn. (4.18) re-arranged for analogue computer solution would be

$$i_q = \frac{\omega_o}{x_q''} \cdot \Psi_q + \frac{\omega_o}{x_q'' \cdot T_{qo}''}\int \Psi_q \, dt - \frac{x_q}{x_q'' \cdot T_{qo}''}\int i_q \, dt \qquad \ldots (4.19)$$

(d) Eqn. (3.29)

Eqn. (3.29) re-arranged for solution on the computer becomes

$$p^2\delta = -\frac{\omega_o^2}{4H}(\Psi_d \cdot i_q - \Psi_q \cdot i_d) + \frac{\omega_o}{2H} \cdot T_t \qquad \ldots (4.20)$$

where T_t can easily be represented on a computer by Eqn. (3.27).

The re-arranged Eqns. (4.2), (4.3), (4.7), (4.8), (4.15), (4.19) and (4.20) form the mathematical model. Their simultaneous solution renders it possible to study any mode of asynchronous operation and resynchronisation of a laminated rotor synchronous machine.

4.5 Procedure for practical solutions

4.5.1 Analytical solution

Using Eqns. (B.16) and (B.17) [Appendix 'B'], output torque pulsations and mean asynchronous torque can be calculated by using appropriate bus-bar voltage E and the values of the operational admittances Y_a, Y_b, Y_c and Y_d derived from Eqns. (B.11) and (3.21) for a range of slip values. The effect of different time-constants and various values of discharge resistor can be studied by substituting appropriate time-constants into these equations. The behaviour of the machine with an external reactance between the machine terminals and the infinite bus-bar can be studied by combining the external reactance with the armature leakage reactance and modifying accordingly all the machine constants[45,70,71].

Field open-circuit condition can be studied by taking field resistance as infinite i.e. field time-constant as zero. For conditions with the field excited, total torque may be calculated as described in Section B.1.2.

Slip pulsations can be calculated by substituting appropriate values into Eqn. (B.25).

This method lends itself, quite readily, to solution on a digital computer provided the assumptions adopted in arriving at the various equations can be justified or improved methods found to incorporate the various non-linear factors involved. Recently some literature has been published in Russia[72,73,74] and Hungary[21,75] for the determination of response characteristics, but this either gives approximate representation or requires actual tests on the machine which are not always feasible. Further, because the external reactance and the armature leakage reactance are lumped together, it is not possible to calculate the voltage fluctuations at the machine terminals.

4.5.2 Use of the micro-machine

The micro-machine consists of a three-phase wound stator with a set of rotors of different types, for example, cylindrical or salient-pole, laminated or solid, with or without damper bars, end rings, etc. Some rotors also have auxiliary windings on the direct and quadrature axes for the study of various phenomena. For the study of individual machine behaviour and investigating new problems it is very useful and convenient. Due to the number of model machines required and the cost involved, their use is, in general, limited to small-system studies.

With suitably designed micro-machine good simulation of large machines is possible. In order to check the reliability of the analogue computer model, a selected number of tests were carried out on a micro-machine using a laminated salient-pole rotor. The rotor had damper bars with complete end rings between the direct and quadrature axis bars forming a squirrel cage. The tests correspond to a few out of the extensive set of studies performed on the analogue computer. For these tests, output power, current, terminal voltage and slip were measured or recorded.

Details of the micro-machine are given in Section A.2 and a comparison of the results is made in Section 4.6.

4.5.3 Mechanisation of the equations for solution by analogue computer

Fig. 4.1 shows an outline diagram for the simultaneous solution of Eqns. (4.2), (4.3), (4.7), (4.8), (4.15), (4.19) and (4.20) on the TR48 analogue computer. All factors such as scales, signs and other considerations involved in obtaining the solution of the numerous simultaneous equations are omitted from this diagram. For the studies performed, a mathematical model of the micro-machine mentioned in Section 4.5.2 was set up. Various studies were performed by suitably adjusting the attenuator settings and making alterations to the patch diagram where necessary.

It is quite easy to represent the following modes of operation.

i) No excitation, field shorted on itself. This condition is represented by putting $e_f = 0$ in Eqns. (4.7) and (4.8).

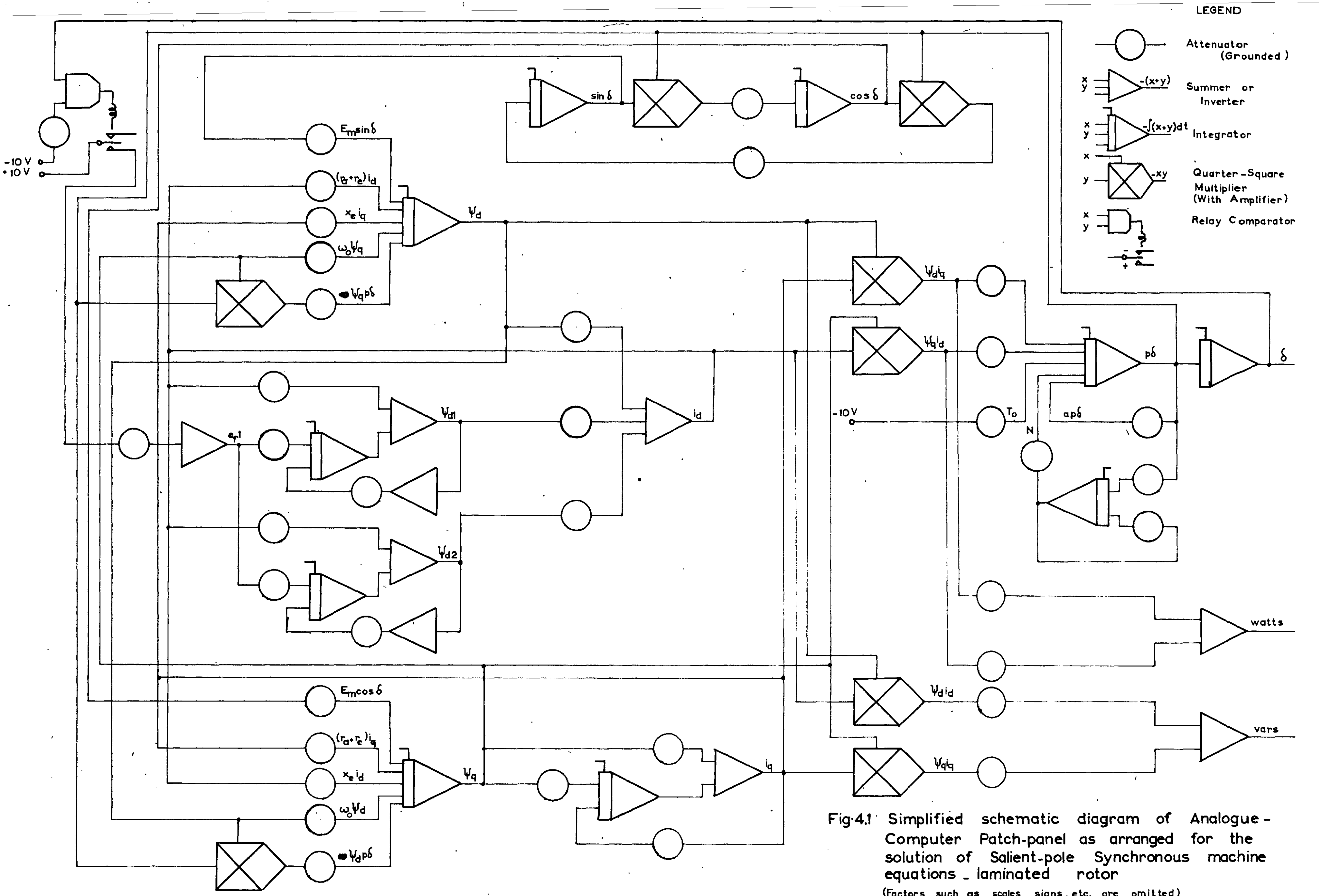
Different time-constants were studied simply by changing the coefficients of these two equations.

ii) Field open circuit i.e. $r_f = \infty$. In this case, the values of coefficients α_{d1}, α_{d2}, A_{d1} and A_{d2} given by Eqns. (4.10), (4.11) and (4.12) reduce to

$$\alpha_{d1} = {}^{1}/_{2T_3} \qquad \ldots(4.21)$$

$$\alpha_{d2} = \infty \qquad \ldots(4.22)$$

$$A_{d1} = -\, {}^{x_{md}^2}/_{x_d} \cdot x_{kd} \qquad \ldots(4.23)$$



Fig·4.1 Simplified schematic diagram of Analogue-Computer Patch-panel as arranged for the solution of Salient-pole Synchronous machine equations _ laminated rotor

(Factors such as scales, signs, etc. are omitted)

$$A_{d2} = \frac{x_{md}^2}{x_d \cdot X_{kd}} - 1 \quad ...(4.24)$$

Eqn. (4.8) in the light of Eqn. (4.22) reduces to

$$\psi_{d2} = 0 \quad ...(4.25)$$

iii) Field closed and excited. This condition was simulated by adjusting the setting of relevant attenuators according to the required excitation. Using a comparator relay, the field can be boosted - if desired - at any preset moment in the slip cycle.

iv) Transmission line or external reactance between the machine terminals and the infinite bus-bar. Representing the external reactance or the transmission line by a resistance (r_e) and reactance (x_e)[75], (Fig. 4.2), Eqns. (3.12) and (3.13) are modified to

$$e_{dm} = E_m \cdot \mathrm{Sin}\delta - x_e \cdot i_q - r_e \cdot i_d = p\psi_d + \omega_o \psi_q - \psi_q \cdot p\delta + r_a \cdot i_d \quad .(4.26)$$

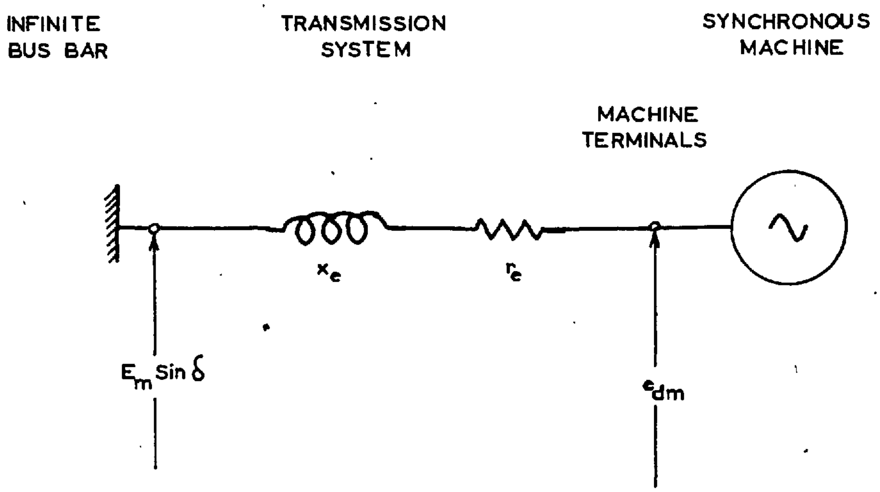
$$e_{qm} = E_m \cdot \mathrm{Cos}\delta + x_e \cdot i_d - r_e \cdot i_q = -\omega_o \psi_d + \psi_d \cdot p\delta + p\psi_q + r_a \cdot i_q \quad .(4.27)$$

For this condition, the patch diagram was modified to correspond to Eqns. (4.28) and (4.29) given below [instead of Eqns. (4.2) and (4.3)].

$$p\psi_d = E_m \cdot \mathrm{Sin}\delta - x_e \cdot i_q - (r_e + r_a) i_d - \omega_o \psi_q + \psi_q \cdot p\delta \quad ..(4.28)$$

$$p\psi_q = E_m \cdot \mathrm{Cos}\delta + x_e \cdot i_d - (r_e + r_a) i_q + \omega_o \psi_d - \psi_d \cdot p\delta \quad ..(4.29)$$

v) Infinite bus-bar at different voltages. This



Fig·4·2 Representation of Transmission system on the Analogue Computer requires changing the value of E_m in Eqns. (4.2) and (4.3) to the required per-unit value.

vi) Moment of inertia. Changing the value of H in Eqn. (4.20) to the required value, effect of moment of inertia can be studied.

vii) Effect of speed-governor and its characteristics. In the present series of studies, only a velocity governor represented by a single time-constant[25] [Eqn. (3.28)] was simulated. Typical constants[2,77,78] for speed-governors fitted to hydraulic turbines were used and the effect of varying the droop characteristics was studied.

The first step in carrying out any set of studies was to let the computer run with the selected conditions of operation. Each of these runs was carried to a point where the slip oscillations became repetitive. By making use of the 'hold' facility on the computer, outputs of various integrating units were read and noted down for a complete slip cycle. Values from these records were then used in making 'initial condition' settings for all subsequent runs for that study. By repeating the same run, any desired quantity was recorded by an X-Y plotter.

Records of watts and VArs were taken by mechanising the following two equations:

$$\text{Watts} = -\frac{\omega_o}{2}(\psi_d \cdot i_q - \psi_q \cdot i_d) \quad \ldots (4.30)$$

$$\text{VArs} = \frac{\omega_o}{2}(\psi_d \cdot i_d + \psi_q \cdot i_q) \quad \ldots (4.31)$$

The terminal voltage of the machine was recorded by simulating the following equations:

$$e_{dm} = E_m \cdot \operatorname{Sin}\delta - x_e \cdot i_q - r_e \cdot i_d \qquad \ldots (4.32)$$

$$e_{qm} = E_m \cdot \operatorname{Cos}\delta + x_e \cdot i_d - r_e \cdot i_q \qquad \ldots (4.33)$$

$$e_t = \sqrt{(e_{dm}^2 + e_{qm}^2)/2} \qquad \ldots (4.34)$$

4.6 Comparison of results

The mean asynchronous operation characteristics, derived by three different methods, viz.,

i) analytical solution
ii) micro-machine
iii) analogue computer

described in Section 4.5 for a salient-pole synchronous machine under different conditions of operation, are shown in Figs. 4.3 to 4.8. The various curves given in these figures clearly show that, on the whole, the results obtained on the analogue computer are more realistic and closer to the practical values than those obtained by the analytical solution of Section 4.3, which is based on a number of assumptions. As a further check on the dependability of the computer results, mean current is plotted in Fig. 4.9 against mean torque for three different conditions. Results obtained on the computer are considered to be quite reasonable and justify this method of studying the behaviour of a laminated rotor synchronous machine during asynchronous operation (Chapter 6). This gives confidence to the study of resynchronisation (Chapter 8) by the method detailed in Section 4.4.

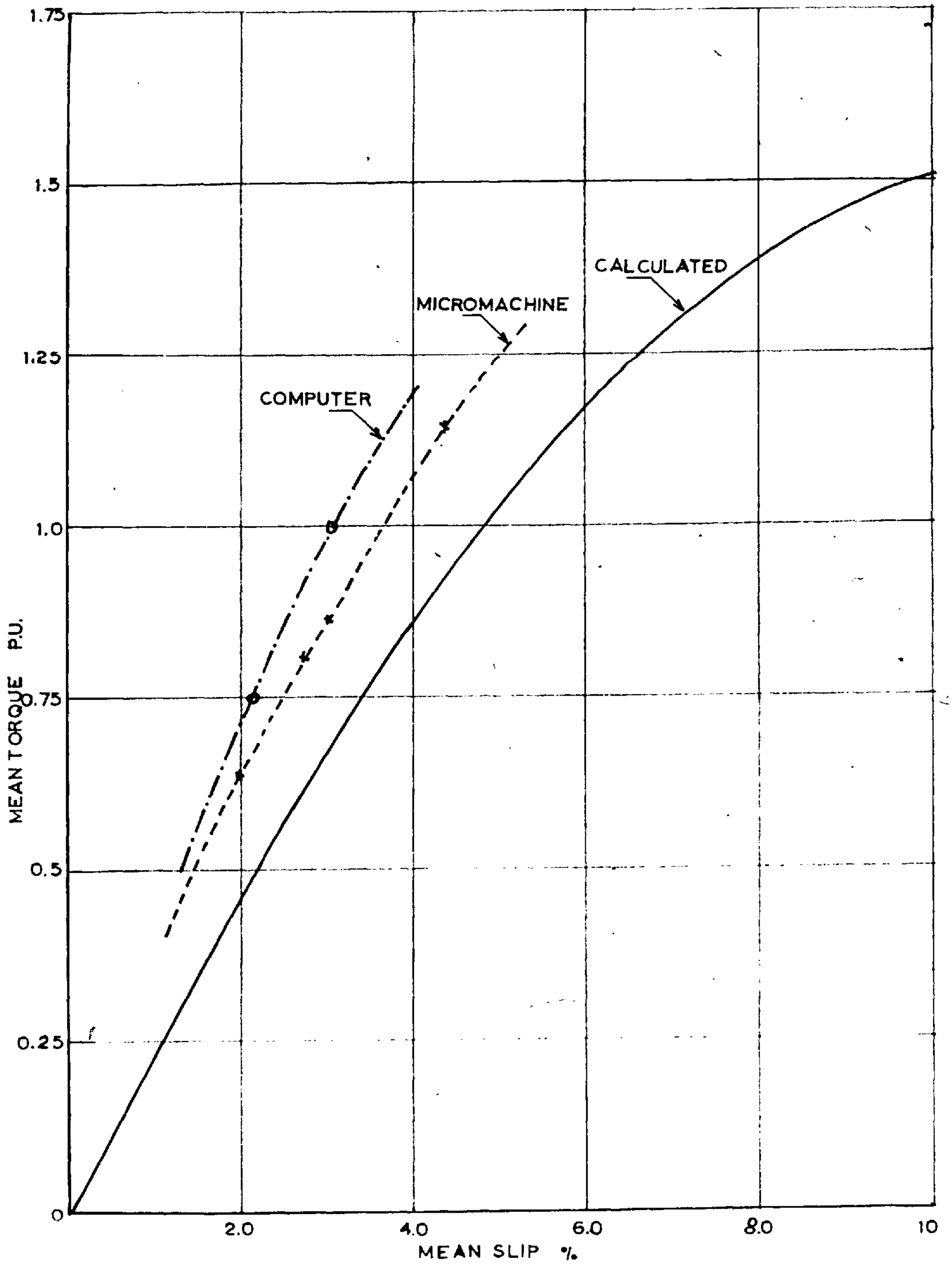
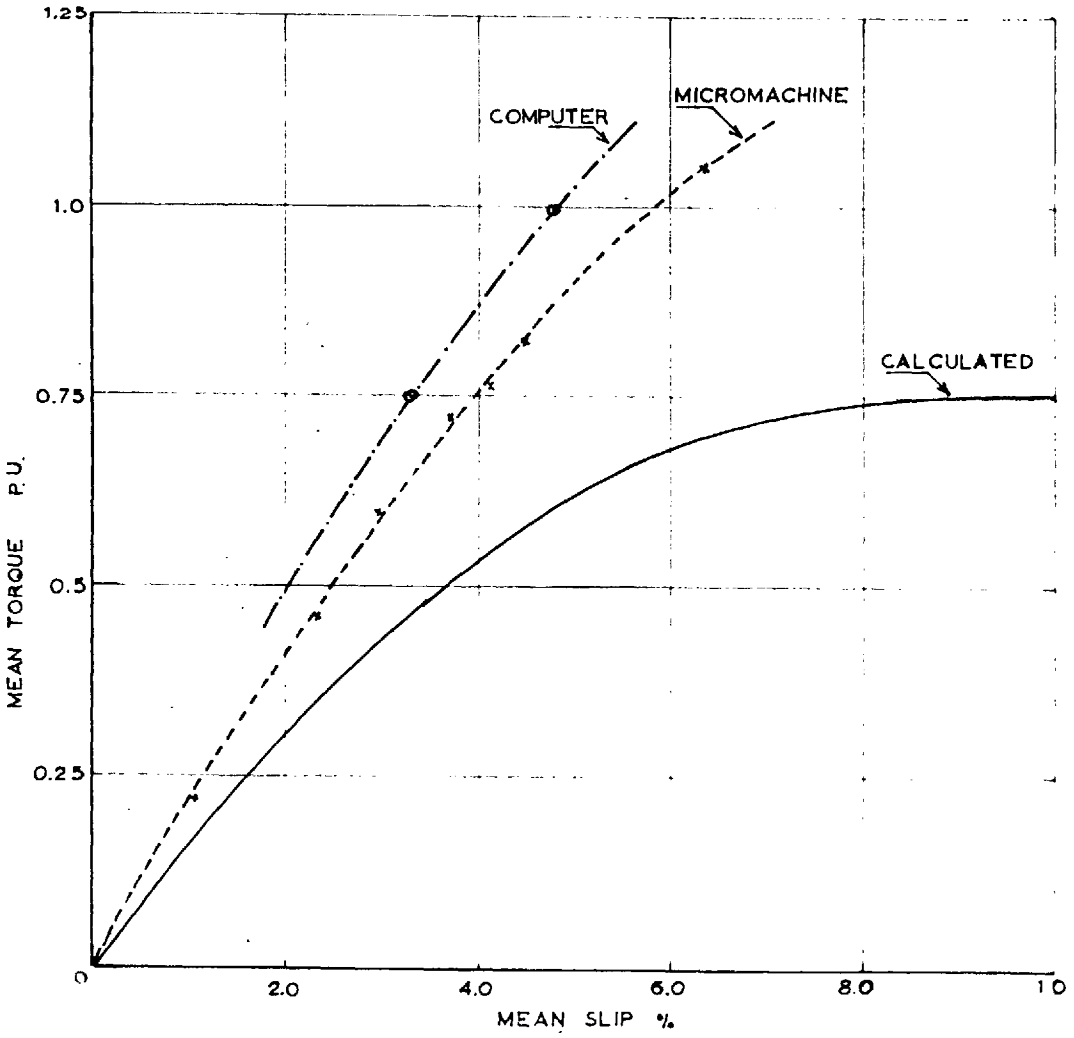


Fig.4.3 Asynchronous mean Torque-slip characteristics

Field open, $x_e=0$, $e_{bus}=1.0$ p.u., Laminated rotor



Fig·4.4 Asynchronous mean Torque–slip characteristics

Field open, x_e = ~~1.2~~ p.u., e_{bus}=1.0 p.u., Laminated rotor

0·12 p.u.

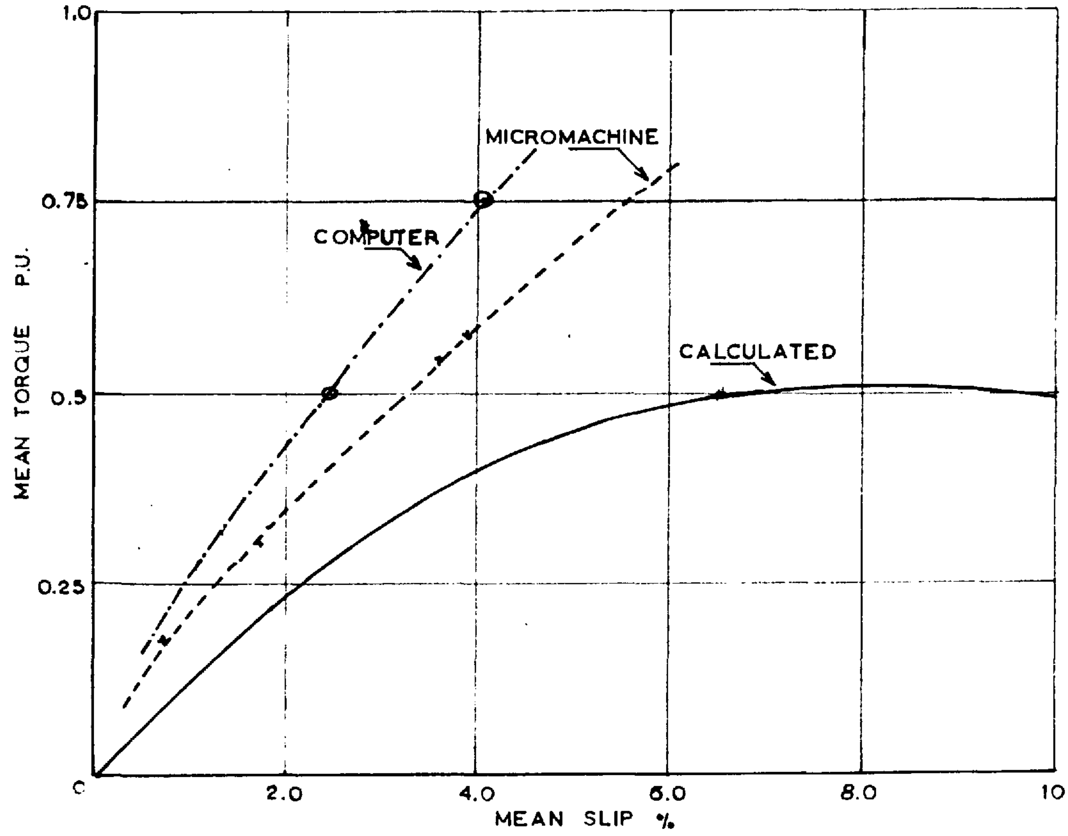
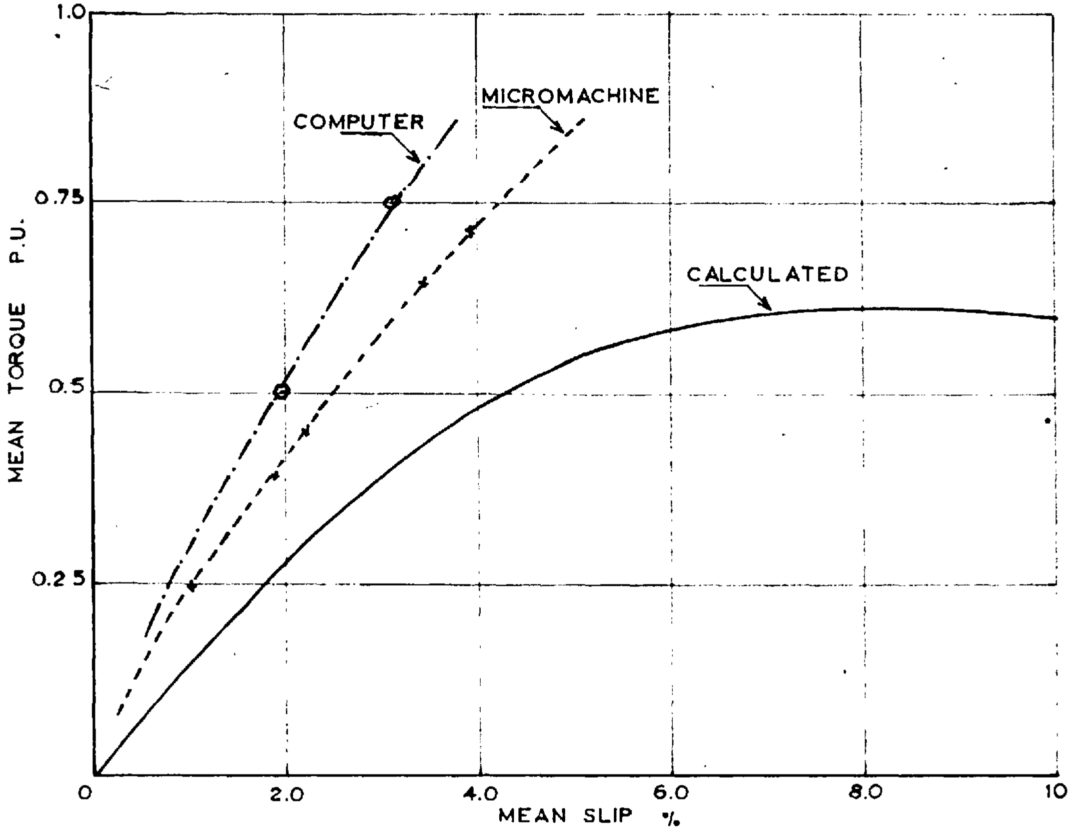


Fig.4.5 Asynchronous mean Torque-slip characteristics

Field open, $x_e = 0.2$ p.u., $e_{bus} = 1.0$ p.u.

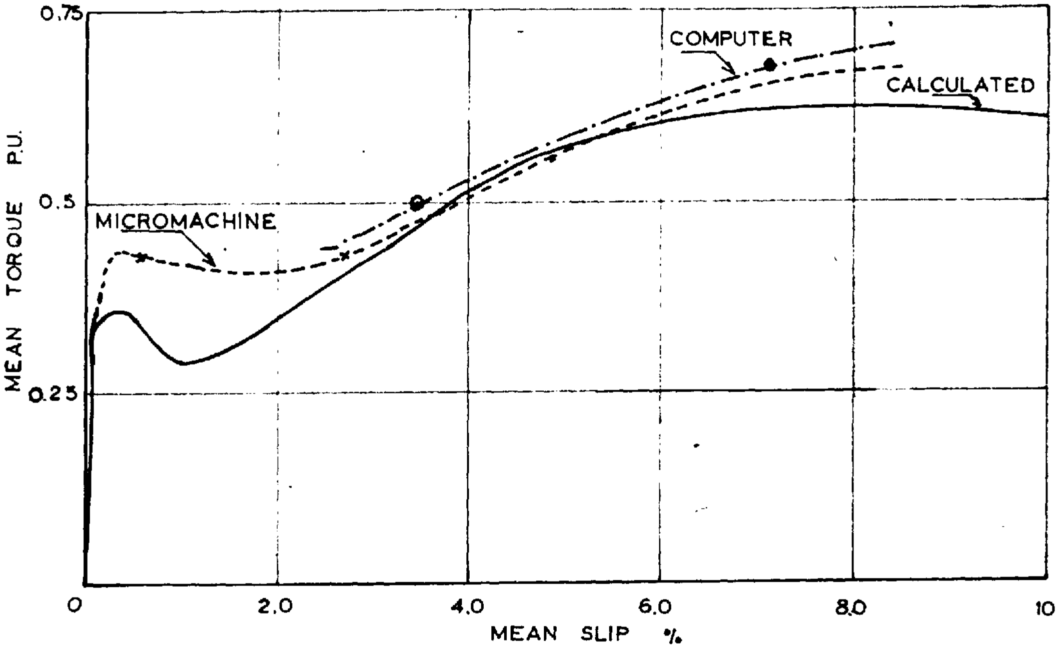
Laminated rotor



Fig·4.6 Asynchronous mean Torque_slip characteristics

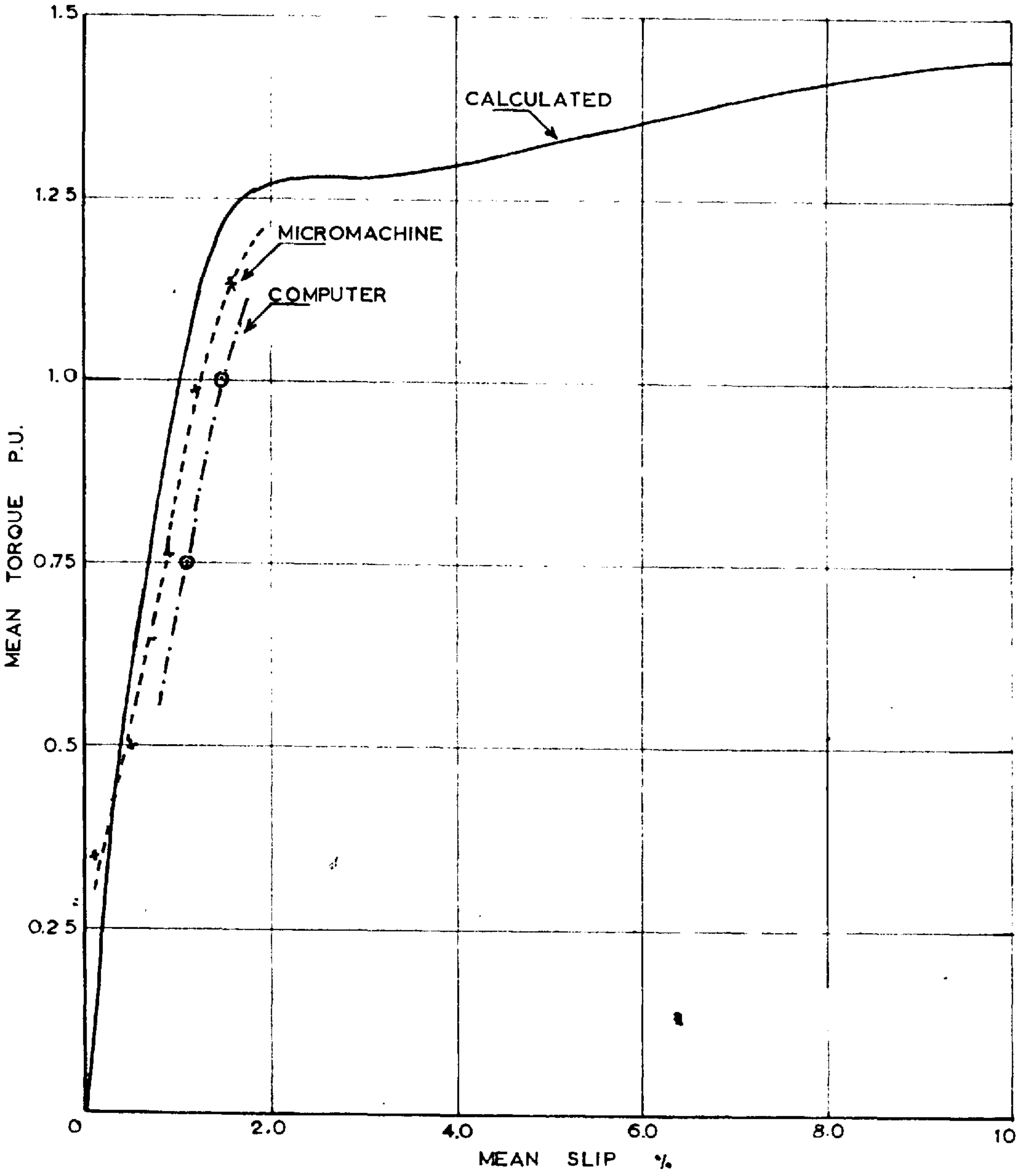
Field open, $x_e = 0.2$ p.u., $e_{bus} = 1.1$ p.u.

Laminated rotor



Fig·4.7 Asynchronous mean Torque – slip characteristics

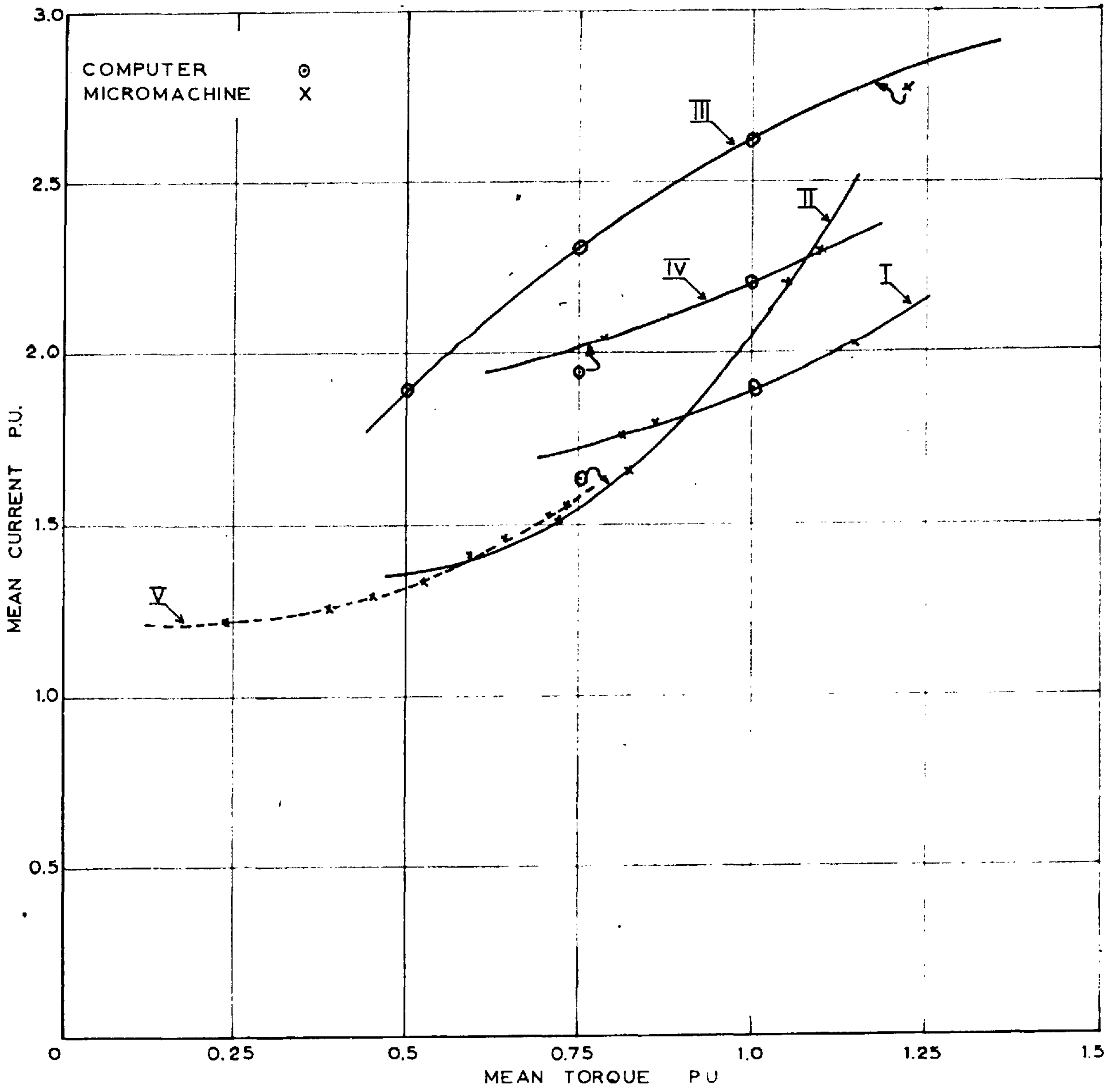
Field Shorted, $T'_{do} = 4.425$ Secs., $x_e = 0.2$ p.u., $e_{bus} = 1.0$ p.u.
Laminated rotor



Fig·4.8 Asynchronous mean Torque–slip characteristics

Field shorted, $T'_{do} = 0.885$ secs., $x_e = 0.0$ p.u., $e_{bus} = 1.0$ p.u.

Laminated rotor



Fig·4.9 Variation of line current with asynchronous torque under different conditions of operation

Laminated rotor

I. Field open
$x_e = 0$, $e_{bus} = 1.0$ p.u.

II. Field open
$x_e = 0.12$ pu., $e_{bus} = 1.0$ pu.

III. Field shorted on itself
$r_f = 0.00089$ pu., $x_e = 0$, $e_{bus} = 1.0$ pu.

IV. Field excited
$r_f = 0.00089$ pu $x_e = 0$, $e_{bus} = 1.0$ pu

V. Field open
$x_e = 0.2$ pu, $e_{bus} = 1.1$ pu

A number of parameters required to calculate the coefficients of different terms in Eqns. (4.7) and (4.8) could not be found by any direct test[50] and had to be calculated by indirect procedures from the various expressions for standard time-constants[45] where-in these parameters occur. Some of these parameters can be calculated from more than one expression and the values differ slightly, depending upon the assumptions involved in arriving at that expression. By a suitable choice of expressions from which these parameters should be derived, results obtained from the analogue computer can give even better correlation with the practical results than those shown in Figs. 4.3 to 4.9.

CHAPTER 5

SIMULATION OF SOLID ROTOR MACHINE

5.1 Introduction

Laminated rotor machines are generally provided with damper bars, with or without end rings, to provide a damping effect in case the rotor speed departs from synchronous speed. Unlike laminated rotors, damping action in solid rotors is produced by the eddy currents induced in various parts of the rotor body. The main solid-iron rotor body contributes much more to the total damping action than the metal wedges[40] which have a much smaller effective cross-section.

Because of the complicated distribution of the eddy currents in the rotor, their damping circuits cannot simply be represented by a single coil on each axis as in Section 4.2. Attempts have been made in the past to calculate the effect of eddy currents in a synchronous machine[79,80,81,82] based mostly on consideration of a rotating flux in a uniform air gap. Some of these investigators also developed methods to take account of the variation of permeability. For studying the asynchronous operation of synchronous machines, none of these approaches is realistic, because flux in the rotor body reverses periodically as the rotor slips.

In solid rotor ~~machines~~ machin, eddy currents may result in pronounced 'skin effect'. Thus the magnetising characteristic tends to be highly non-linear. To investigate effects involving magnetic saturation, a number of authors[20,28,40] have recently made use of the limiting non-linear magnetic theory[83]. This theory uses an idealised rectangular curve to represent the magnetisation curve of rotor material, as shown in Fig. 5.1. All these authors have worked out expressions for the impedance of the rotor using various simplifying assumptions.

The expression derived by Bharali and Adkins[40] is based on minimum assumptions and is also particularly amenable for use in a mathematical model. Representation of the damping circuit and the development of the mathematical model is described in the following sections. To check the viability of the method adopted, certain full scale tests conducted by the C.E.G.B. on their system were simulated.

5.2 Representation of the damping circuit

5.2.1 General expression

Representation of synchronous machines by equivalent circuits, one each for the two axes, has been mentioned in Section 3.7. One branch in each of the two equivalent circuits given in Fig. 3.2 represents the rotor damping circuit for that axis. To allow for the effect of eddy currents in the solid-rotor body, impedances of these two branches are represented by variable complex impedances Z_{kd} and Z_{kq}. The expression for Z_{kd} has been derived in Appendix 'D' and is given by

$$Z_{kd} = \frac{640}{9\pi^2} \cdot k_v \cdot k_i \cdot \frac{w^2}{\ell} \cdot \frac{\rho \cdot B_s}{\varnothing_m} \cdot \frac{1}{s} \cdot \varepsilon^{j26.6^\circ} \qquad \ldots(5.1)$$

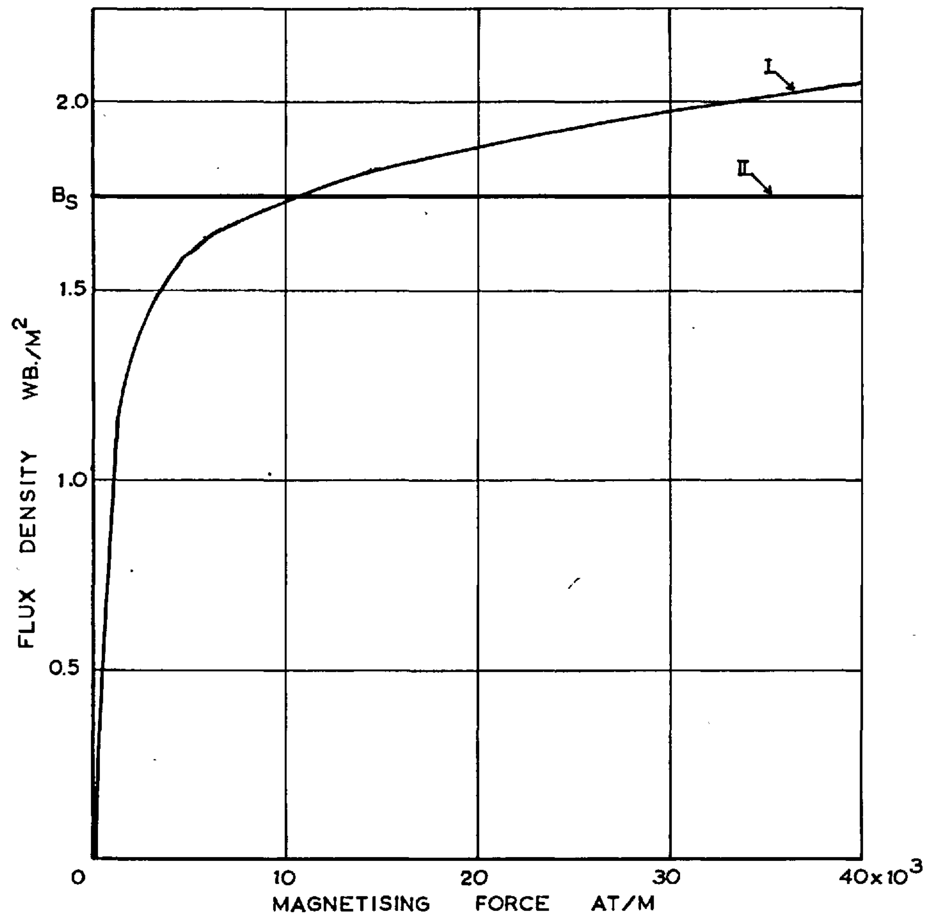


Fig.5.1 Magnetisation curve for forged steel

I. Actual curve

II. Non-linear approximation

which in the case of a laminated rotor machine is expressed in the form

$$Z_{kd} = \frac{r_{kd}}{s} + j\omega_o \cdot \ell_{kd} = \frac{r_{kd}}{s} + jx_{kd} \qquad \ldots (5.2)$$

On the basis of the experimental results, it has been suggested (Appendix 'D') that the value of quadrature axis rotor impedance be taken equal to that of the direct axis impedance as given by Eqn. (5.1). In the case of cylindrical rotor machines, this assumption is considered quite reasonable and is confirmed by the virtual lack of pulsations during asynchronous operation with open field.

5.2.2 Considerations involved in calculating numerical values

Eqn. (5.1) renders it possible to calculate, from the physical dimensions of a rotor, the damping effects produced by rotor eddy currents. To obtain numerical results, it is, however, necessary to estimate the effective length 'ℓ' as well as the approximate value of B_s, both of which are somewhat indefinite.

For the direct axis, the length is taken equal to the peripheral length in the iron of the path passing below the teeth.

The value of B_s has to be determined on an empirical basis. The value of B corresponding to normal flux would be too low for B_s, since that would mean that the flux would always penetrate to the centre at the maximum value. Various proposals[40,83,84] have been made for the appropriate value to be taken. A value about 30°/o above the normal value was found to give best results while checking this theory on some large machines[40]. Because of mutually cancelling effects, selection of a suitable value of B_s is, however, not very critical.

In practice, machines are generally connected to a source of fixed voltage through a high impedance. Because of the lower effective voltage at the machine terminals, the effect of B_s is further decreased.

Having fixed the appropriate value of B_s, the calculation of Z_{kd} can be made for a definite value of ϕ. Because of the stator leakage and transformer reactance drops, the flux varies slightly with load. A correction has been made for this effect by estimating the terminal voltage for each condition studied and then correcting the value of ϕ used in calculating the rotor impedances.

5.3 Mathematical model

5.3.1 General

Keeping in view the general observations made in Section 4.4.1 regarding the usefulness of studying the problem of asynchronous operation and resynchronisation with the help of a mathematical model, it was considered desirable to simulate the solid rotor machine in addition to the laminated rotor machine. Damper circuits in the solid rotor have a variable complex impedance as described above, instead of a single valued impedance as was assumed in the case of the laminated rotor. It is, therefore, not possible to use the same mathematical model as adopted in Section 4.4, and a completely different approach, described below, has been adopted.

5.3.2 Explanation of the adopted method

The problem of asynchronous operation and resynchronisation for a solid-rotor synchronous machine can be studied in full detail by the simultaneous solution of Eqns. (3.12), (3.13), (3.20), (3.22) and (3.29). Out of these, Eqns. (3.20) and (3.22) cannot be treated in their corresponding form given by Eqns. (3.19) and (3.21) respectively, as was the case with the laminated rotor machine. Instead Eqns. (3.14) to (3.18), from which Eqns. (3.20) and (3.22) are derived, can be represented by the two equivalent circuits shown in Fig. 3.2. Employing TR48 as a direct analogue[85], it is possible to synthesise the mathematical model from these two equivalent circuits in conjunction with Eqns. (3.12), (3.13) and (3.29).

The method described in Ref. 85 is applicable directly to obtain the solution of ordinary linear differential equations with constant coefficients. In the case of solid rotor machines, one branch in each of the two equivalent circuits contains terms which are functions of a system variable, and, therefore, cannot be represented in the ordinary manner. These branches have been simulated in the mathematical model by an alternative approach. The approach adopted highlights still further the two axis theory.

Since the two axes are at right angles to each other, corresponding axis quantities such as e_d and e_q or i_d and i_q have a time phase relation of 90 degrees with each other. This was shown to be a valid representation (Figs. 5.2 and 5.3) from the analysis of full scale tests conducted by the C.E.G.B. on a 30 MW turbogenerator set at Goldington in 1960 and also by the analogue computer studies performed in the present work. This phase relationship remains unaltered even when the wave-form of these quantities is far from sinusoidal during certain asynchronous operating conditions. Since the rotor impedance on the two axes has been assumed equal in phase and magnitude (Section 5.2.1), the property of a constant phase relationship has been used in developing the mathematical model for the present case.

Putting $p = js\omega_o$, it will be observed that the two equivalent circuits, shown in Figs. 3.2(a) and D.3 are identical. From Eqn. (5.1), by expansion of the exponential term,

$$Z_{kd} = \frac{640}{9\pi^2} \cdot k_v \cdot k_i \cdot \frac{w^2}{\ell} \cdot \frac{\rho B_s}{\emptyset_m} \cdot \frac{1}{s} \left[\text{Cos}\,26.6 + j\text{Sin}\,26.6\right] \quad \ldots(5.3)$$

$$\text{or} \quad sZ_{kd} = 0.894Z_{d1} + j0.448Z_{d1} \quad \ldots(5.4)$$

where

$$Z_{d1} = \frac{640}{9\pi^2} \cdot k_v \cdot k_i \cdot \frac{w^2}{\ell} \cdot \frac{\rho \cdot B_s}{\emptyset_m} \quad \ldots(5.5)$$

= constant, for particular conditions of operation.

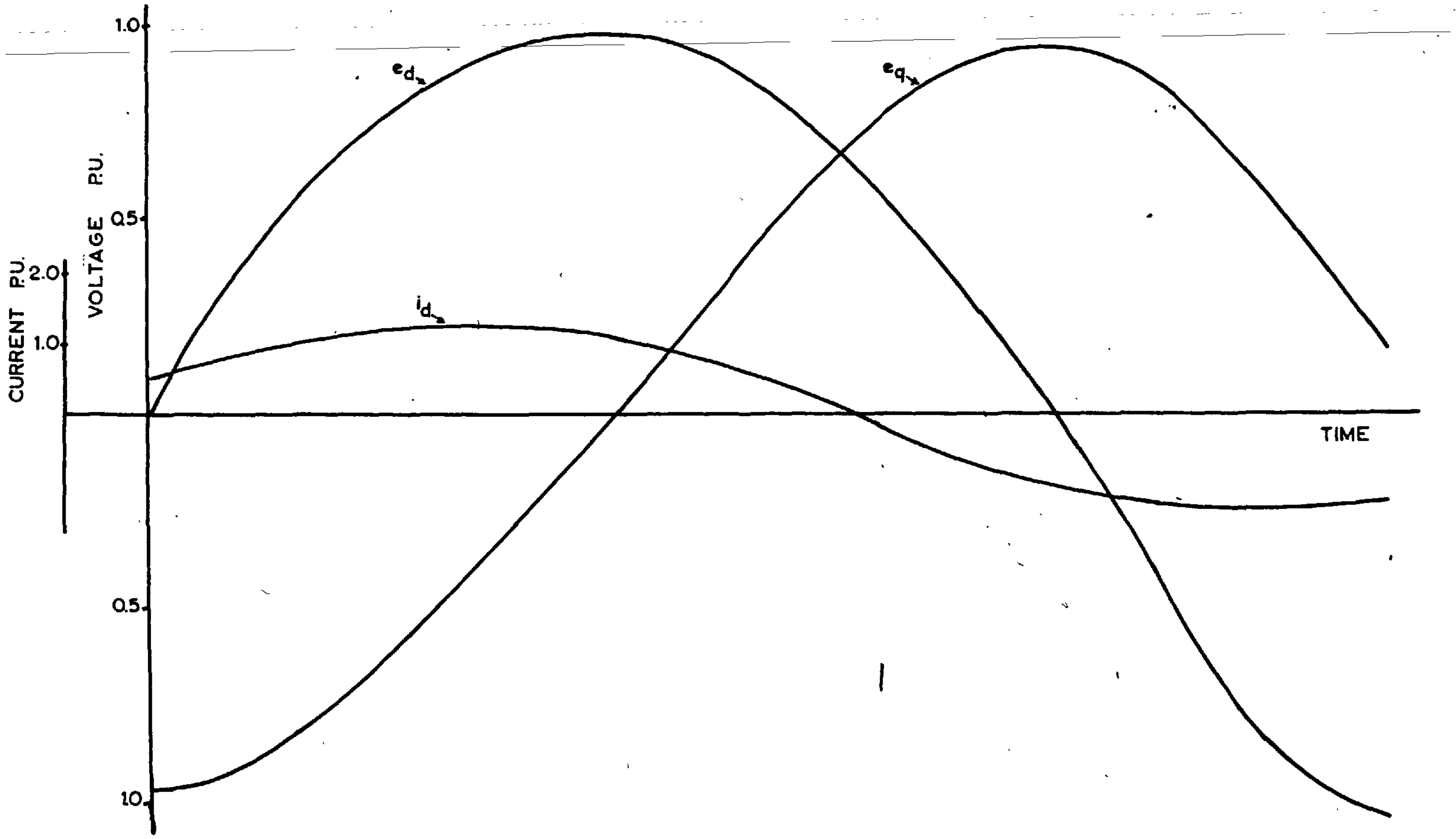


Fig. 5.2 Axis-voltages and current
Goldington 30 M.W. Turbo-alternator
Asynchronous running test
Field open 21 M.W. Load

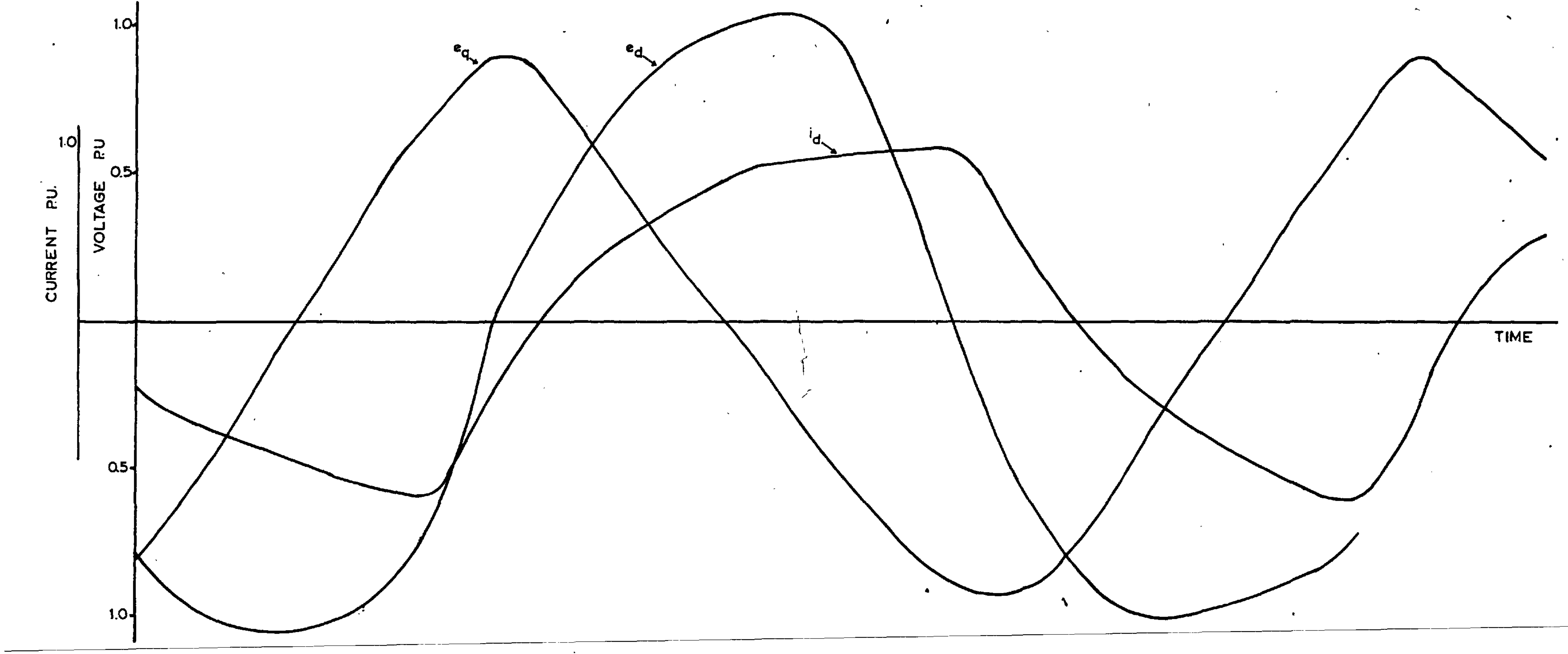


Fig. 5.3 Axis-voltages and current
Goldington 30 M.W. Turbo-alternator
Asynchronous running test
Field shorted through discharge resistor
21 M.W. Load

Comparing Figs. 3.2(a) and D.3, sZ_{kd} may be written as

$$sZ_{kd} = r_{kd}(j\omega) + p\ell_{kd}(j\omega) \qquad \ldots(5.6)$$

From Eqns. (5.1) and (5.6), therefore,

$$r_{kd}(j\omega) = 0.894\, Z_{d1} = F \text{ (say)} \qquad \ldots(5.7)$$

and $p\ell_{kd}(j\omega) = j\,0.448\, Z_{d1} = jG \text{ (say)}$ ...(5.8)

Similarly, the quadrature axis rotor-circuits can be represented by

$$r_{kq}(j\omega) = Z_{d1} \cdot \mathrm{Cos}\, 26.6^{\circ} \qquad \ldots(5.9)$$

and $p\ell_{kq}(j\omega) = j\, Z_{d1} \cdot \mathrm{Sin}\, 26.6^{\circ}$ ...(5.10)

Using Eqns. (5.7) to (5.10), the following equations can be written to simulate the two equivalent circuits shown in Fig. 3.2.

i) Direct axis

$$p\psi_d = \ell_a \cdot pi_d + L_{md} \cdot p(i_d + i_{kd} + i_f) \qquad \ldots(5.11)$$

$$e_{kd} = sZ_{kd} \cdot i_{kd} + L_{md}p(i_d + i_{kd} + i_f) = 0 \qquad \ldots(5.12)$$

$$e_f = (r_f + \ell_f p)i_f - sZ_{kd} \cdot i_{kd} \qquad \ldots(5.13)$$

ii) Quadrature axis

$$p\psi_q = \ell_a \cdot pi_q + L_{mq}p(i_q + i_{kq}) \qquad \ldots(5.14)$$

$$e_{kq} = sZ_{kq} \cdot i_{kq} + L_{mq}p(i_q + i_{kq}) \qquad \ldots(5.15)$$

5.3.3 Formulation of the mathematical model

Eqns. (3.12), (3.13), (3.29) and (5.11) to (5.15) set up for simultaneous solution on an analogue computer form a mathematical model for the study of asynchronous operation and resynchronisation of a solid-rotor synchronous machine. Of these, the first three equations need to be re-arranged as described in Section 4.4.2. Modifications necessary in Eqns. (5.11) to (5.15) to make them also suitable for simulation are given below.

(a) Eqns. (5.11) and (5.14)

By re-arranging and integrating both sides, the following suitable form is obtained:

$$i_d = \frac{1}{L_d} \cdot \Psi_d - \frac{L_{md}}{L_d} \cdot i_{kd} - \frac{L_{md}}{L_d} \cdot i_f \qquad \ldots (5.16)$$

$$i_q = \frac{1}{L_q} \cdot \Psi_q - \frac{L_{mq}}{L_q} \cdot i_{kq} \qquad \ldots (5.17)$$

(b) Eqns. (5.12) and (5.15)

Re-arranging Eqn. (5.12),

$$L_{md} \cdot p i_{kd} = -L_{md} \cdot p(i_d + i_f) - sZ_{kd} \cdot i_{kd} \qquad \ldots (5.18)$$

Substituting $sZ_{kd} = (F + jG)$ from Eqns. (5.6) to (5.8), Eqn. (5.18) becomes

$$L_{md} \cdot p i_{kd} = -L_{md} \cdot p(i_d + i_f) - (F + jG) i_{kd} \qquad \ldots (5.19)$$

which may be put in the alternative form,

$$L_{md} \cdot pi_{kd} = -L_{md} \cdot p(i_d + i_f) - F \cdot i_{kd} + G \cdot i_{kq} \quad \ldots (5.20)$$

Substituting for pi_d from Eqn. (5.11) in Eqn. (5.20) and re-arranging,

$$pi_{kd} = -\frac{L_d}{\ell_a \cdot L_{md}}\left[F \cdot i_{kd} - G \cdot i_{kq}\right] - \frac{1}{\ell_a} \cdot p\psi_d - pi_f \quad \ldots (5.21)$$

Integrating Eqn. (5.21), gives

$$i_{kd} = -\frac{L_d}{\ell_a \cdot L_{md}}\int \left[F \cdot i_{kd} - G \cdot i_{kq}\right] dt - \frac{1}{\ell_a} \cdot \psi_d - i_f \quad \ldots (5.22)$$

Similarly, Eqn. (5.15) can be written as

$$pi_{kq} = -\frac{L_q}{\ell_a \cdot L_{mq}}\left[F \cdot i_{kq} + G \cdot i_{kd}\right] - \frac{1}{\ell_a} \cdot p\psi_q \quad \ldots (5.23)$$

Integrating Eqn. (5.23), gives

$$i_{kq} = -\frac{L_q}{\ell_a \cdot L_{mq}}\int \left[F \cdot i_{kq} + G \cdot i_{kd}\right] dt - \frac{1}{\ell_a} \cdot \psi_q \quad \ldots (5.24)$$

(c) <u>Eqn. (5.13)</u>

Rewriting and substituting for $sZ_{kd} \cdot i_{kd}$ in the same way as described for Eqn. (5.12), Eqn. (5.13) can be written in the alternative form as

$$pi_f = \frac{1}{\ell_f}\left[e_f - r_f \cdot i_f + F \cdot i_{kd} - G \cdot i_{kq}\right] \quad \ldots (5.25)$$

5.4 Procedure for practical solutions

5.4.1 Large machines

5.4.1.1 Tests without speed governor

Certain records of asynchronous running tests conducted by the C.E.G.B. in 1960 on a 30 MW turboalternator in Goldington power station and a 60 MW set in Marchwood power station were available. The various parameters and dimensions of these two machines and system conditions at the time of the tests, as far as known, are given in Appendix 'A'. Using these conditions and keeping in view the considerations mentioned in Section 5.2.2, constants for the various equations forming the mathematical model were calculated and the tests simulated on the analogue computer. In the full scale tests, the turbine speed-governor was set at its maximum value, thus making it ineffective for the range of slips encountered. Studies on the mathematical model have accordingly been done without simulation of the governor characteristic and a constant mechanical input was assumed.

5.4.1.2 Tests with speed-governor and voltage regulator

In addition to the above tests, a further series of tests which were conducted on a 120 MW set at Staythorpe 'B' generating station during June, 1962[46] have been simulated. All the necessary data of this machine is given in Appendix 'A'. In this test series, the automatic voltage regulator and the turbine speed governor were both in use. Due to the non-availability of sufficient elements on the TR48 analogue computer, it has not been possible to simulate these tests fully. However, two of these tests have been simulated in a slightly modified form.

In one of the tests, the machine was pulled out of synchronism by suddenly switching three 132/275 KV supergrid transformers from parallel to series connection thereby simulating the sudden disconnection of one circuit of a nominally-loaded 100 mile 400 KV double circuit line. During the ensuing out-of-step operation, the automatic voltage regulator maintained an effectively constant excitation and the speed-governor reduced the load on the set. In the analogue computer studies, out-of-step operation was initiated by the same means i.e. suddenly increasing the reactance between the machine terminals and the infinite bus, but due to the absence of a speed-governor simulator, the mechanical torque was gradually reduced by hand to the real test value in such a way that the maximum slip attained was approximately the same as in actual test conditions. This of course, gave a very crude regulation during the transient period till the machine settled down to a steady operation.

In a second test, asynchronous operation was started by manual tripping of the main field switch and shorting the field through a discharge resistor. The supergrid transformers were operated in parallel throughout. After steady asynchronous operation was attained, resynchronisation was attempted by applying field excitation at random. Steady asynchronous operation and resynchronisation has only been simulated on the analogue computer without taking into account the effect of turbine speed-governor and automatic voltage regulator during the process of resynchronisation.

5.4.2 Micro-machine

Studies performed on the analogue computer were also repeated on a micro-machine using a solid cylindrical rotor. All the necessary details of the set used are given in Appendix 'A'.

A good deal of experimental work in connection with operational impedances of the solid rotor was carried out by Bharali[48]. The same rotor as used by Bharali has been used in the present studies. The theoretical derivation of the expression for the rotor impedance, as worked out in Appendix 'D', is based on an idealised, static electro-magnetic model and a semi-infinite slab of iron.

The result of assuming a semi-infinite slab is to neglect end effects. This assumption is reasonable in the case of modern large turboalternators having a high length to diameter ratio (about 5 to 6[86]) for the rotor. For the micro-machine, this ratio is very small - 0.543 for the rotor used - and end effects cannot be neglected. Correction factors have been suggested[87] to account for the increase in the length of the eddy current path. In the present case, the length of the end path was added to the axial length of the rotor using a correction factor

$$K_1 = 1 + 0.312\,\tau/w \qquad \ldots(5.26)$$

$$= 1.45 \text{ for the rotor used.}$$

The assumption of an idealised condition leads to the effect of space harmonics being neglected. However, because of the relatively small air-gap and wide slot opening, a considerable amount of space harmonics are present. Presence of space harmonics at sub-synchronous speed results in increased secondary reactance. A similar effect was observed by Gibbs[80] in small induction motors and salient-pole synchronous motors. He suggested that the secondary reactance be increased by a factor of between 1.0 to 1.35.

Measurements made during operational impedance tests[48] on the present rotor showed that the phase angle of the rotor impedance is 45° compared to 26.6° as worked out by the theory based on simplifying assumptions. According to this, the correction factor for this rotor works out to be 2 instead of 1.0 to 1.35 as mentioned above. Values of rotor reactance used in the analogue computer studies were the corrected values given by

$$\begin{aligned} X_{kd}(\text{corrected}) &= G(\text{corrected}) = a \cdot X_{kd} \\ &= \frac{1}{2} \cdot a \cdot R_e\left[Z_{kd}\right] = F \qquad \ldots (5.27) \end{aligned}$$

where a = 2 in this case.

5.4.3 Solution by analogue computer

Fig. 5.4 shows an outline diagram for the simultaneous solution of Eqns. (4.2), (4.3), (4.20), (5.16), (5.17), (5.22), (5.24) and (5.25) on the TR48 analogue computer, all factors such as scales, signs etc. having been omitted. Mathematical models of the machines described in Sections 5.4.1 and 5.4.2 were set up for the various studies.

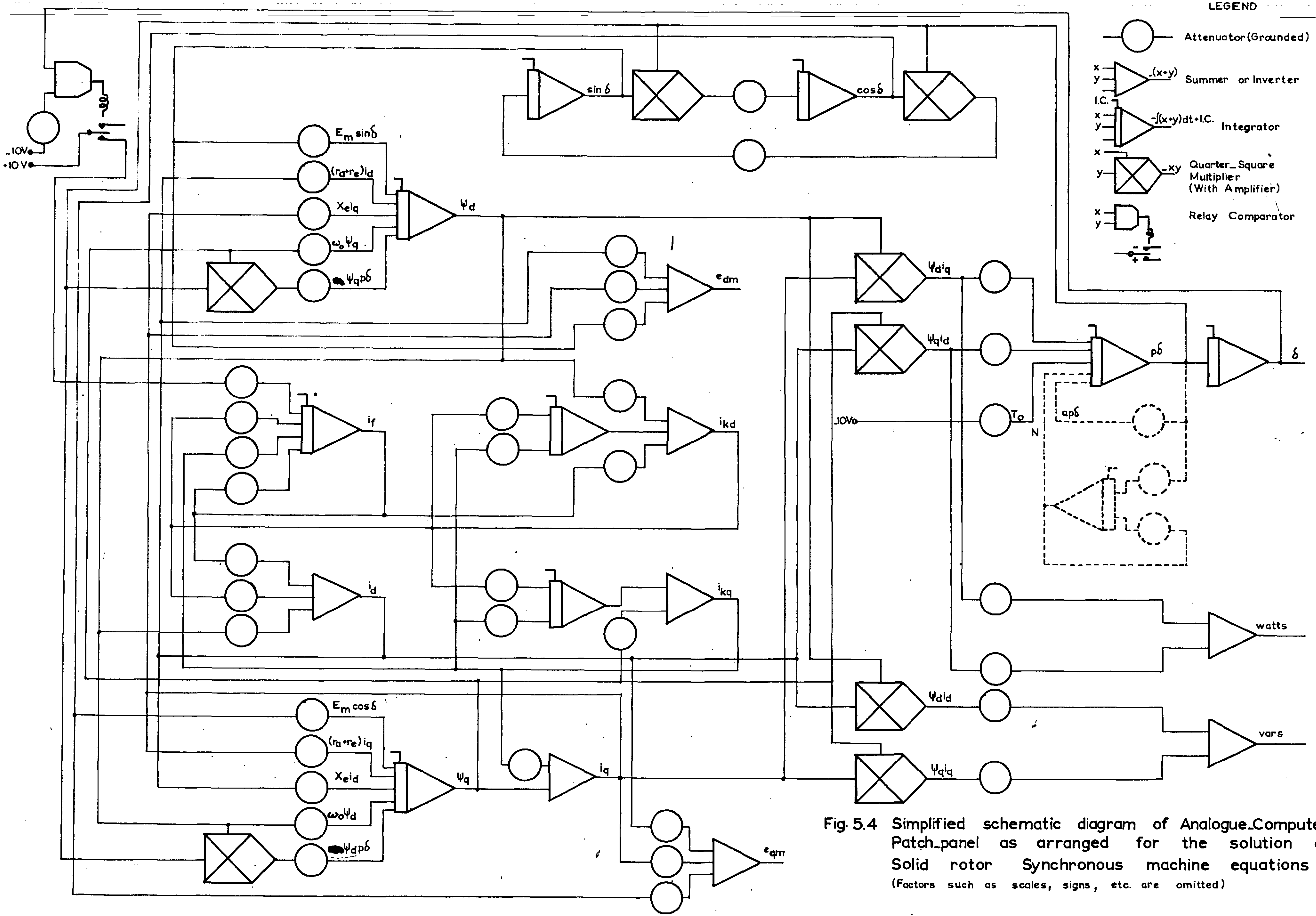


Fig. 5.4 Simplified schematic diagram of Analogue_Computer Patch_panel as arranged for the solution of Solid rotor Synchronous machine equations
(Factors such as scales, signs, etc. are omitted)

Procedure for carrying out the studies in the present case is in general the same as for the laminated rotor machine described in Section 4.5.3. Asynchronous operation with field open is studied by disconnecting the section simulating Eqn. (5.25) on the patch panel and connecting it only when applying field excitation for resynchronisation. A field shorted through a discharge resistance is easily simulated by putting $e_f = 0$ and using the total value of field resistance plus discharge resistor instead of r_f in Eqn. (5.25) and by readjusting the setting of relevant potentiometers at the instant of the application of excitation.

5.5 Comparison of results

The validity of the mathematical model for a solid rotor machine has been verified by simulating asynchronous running tests conducted on three large turbo-alternators and a micro-machine with a solid cylindrical rotor. The results obtained on the simulator gave a reasonable correlation with the actual test results for the four machines of widely varying proportions. On this basis, this model is considered a sufficiently reliable tool to be employed for the study of asynchronous operation and resynchronisation (Chapters 6 and 8) of a solid rotor synchronous machine.

The results obtained in each individual case are briefly discussed below.

5.5.1 Tests on a 60 MW turboalternator

Figs. 5.5 to 5.9 show a comparison of the values obtained from the analogue computer with the test results for a 60 MW set at Marchwood. Fig. 5.5 shows the corresponding values of the mean asynchronous torque against mean slip for four tests with field open and Fig. 5.6 shows the corresponding values for asynchronous operation with the field shorted through a discharge resistor. The mean stator current versus mean slip for the field open circuit condition is shown in Fig. 5.7. For the condition of field closed through a discharge resistor in Fig. 5.8. Fig. 5.9 shows the pulsations of stator current for one of the four tests plotted in Fig. 5.8.

It should be pointed out that the bus-bar voltage varied appreciably from test to test. The test points would not, therefore, be expected to be on a smooth curve, as would be the case with constant voltage operation.

In Figs. 5.5 to 5.9, values obtained by Chalmers[20] have also been plotted for comparison. A study of these figures shows that the mathematical model can be used to predict within a reasonable margin (±5 %) the operating characteristics of a large machine. The results obtained by this method are certainly an improvement over those predicted by the Chalmers method.

5.5.2 Tests on a 30 MW set

As a further check on the efficacy of the method suggested, asynchronous tests conducted on a 30 MW turbo-

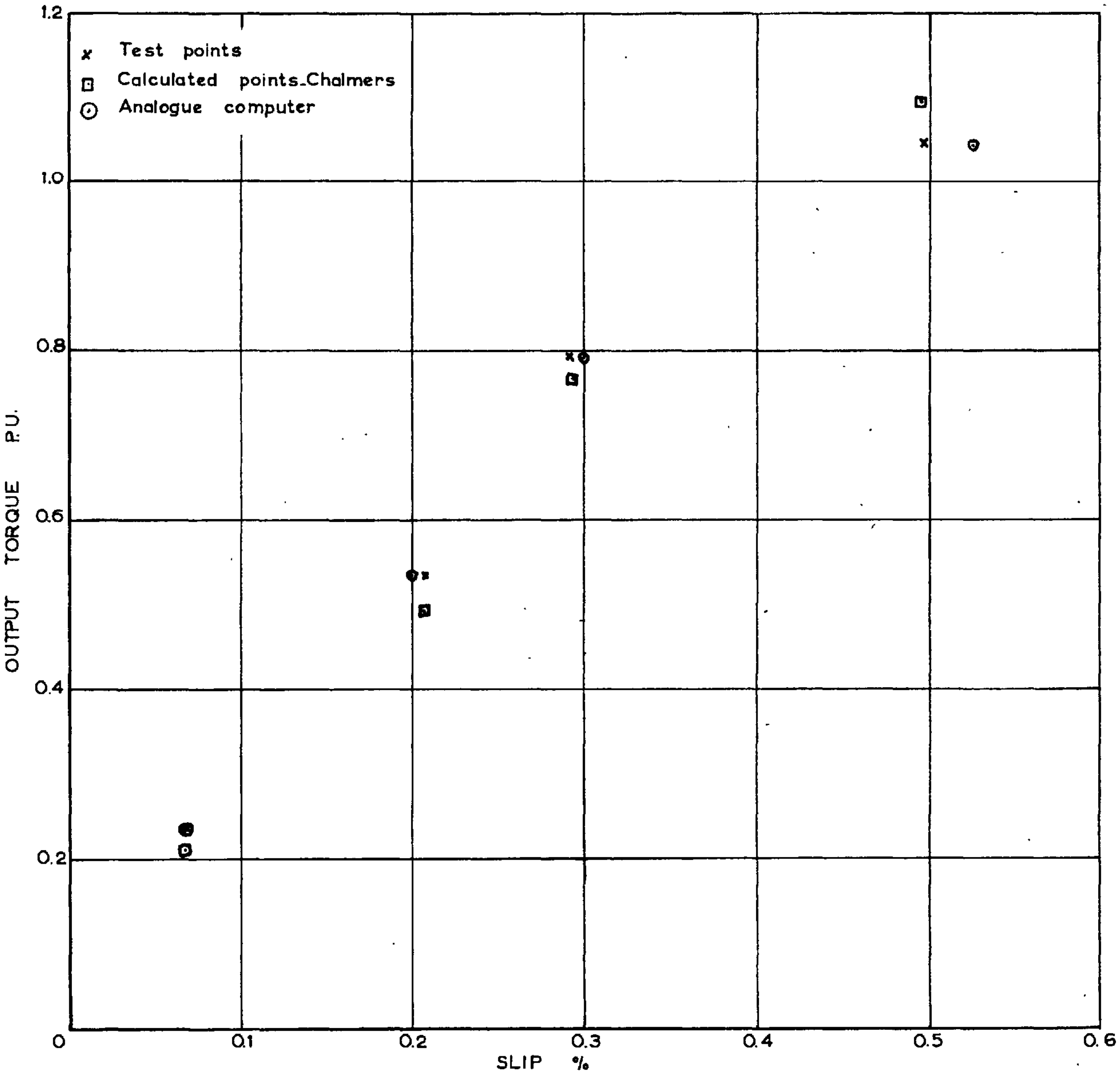


Fig. 5.5 Variation of output torque with slip

60 M.W. Marchwood machine , Field open

Asynchronous running tests

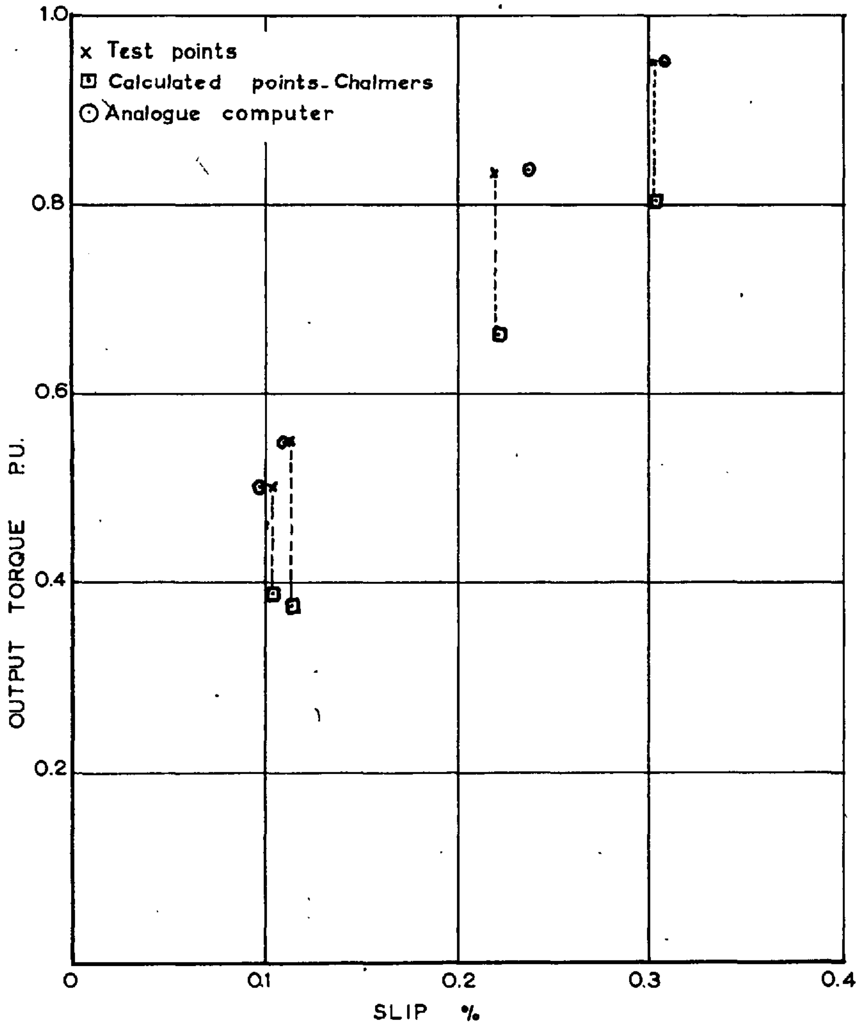


Fig. 5.6 Variation of output torque with slip
60 M.W. Marchwood machine asynchronous running tests
Field shorted through discharge resistor

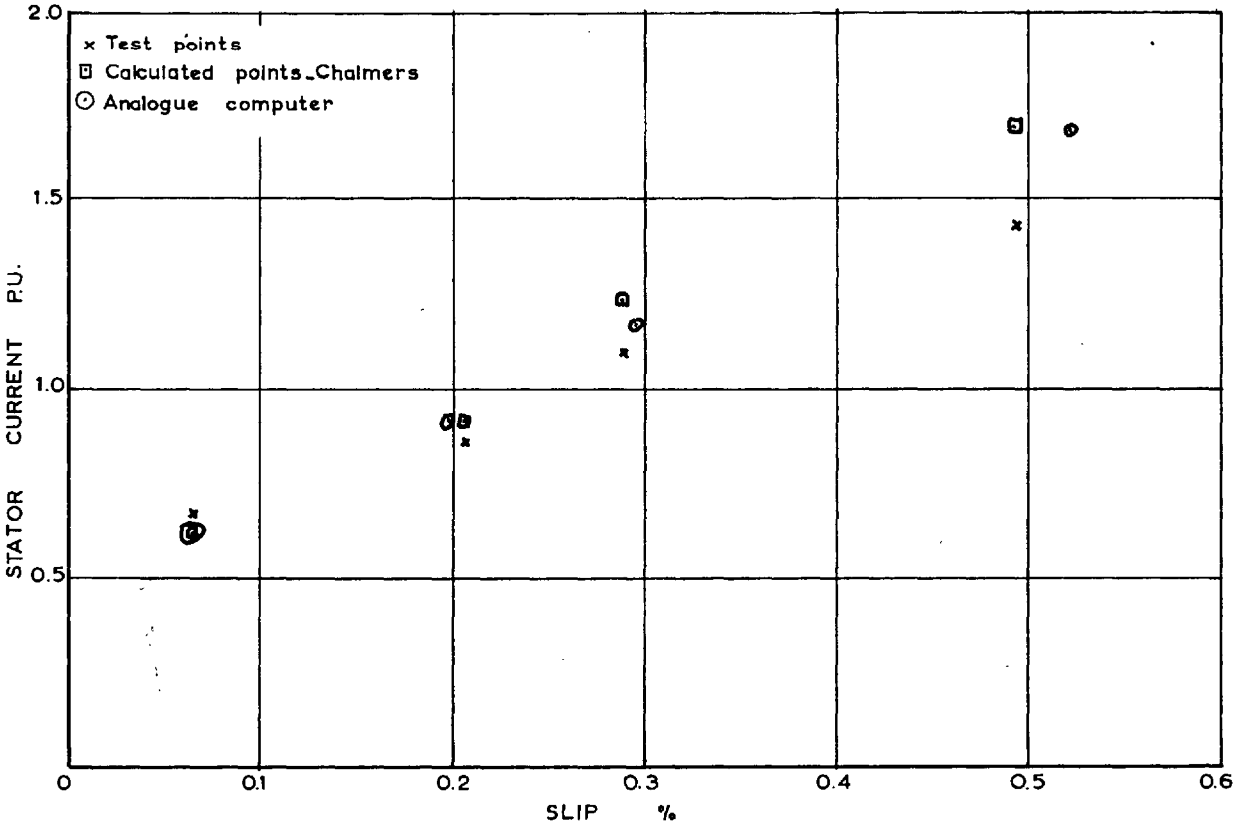


Fig. 5.7 Variation of stator current with slip

60 M.W. Marchwood machine asynchronous running tests

Field open

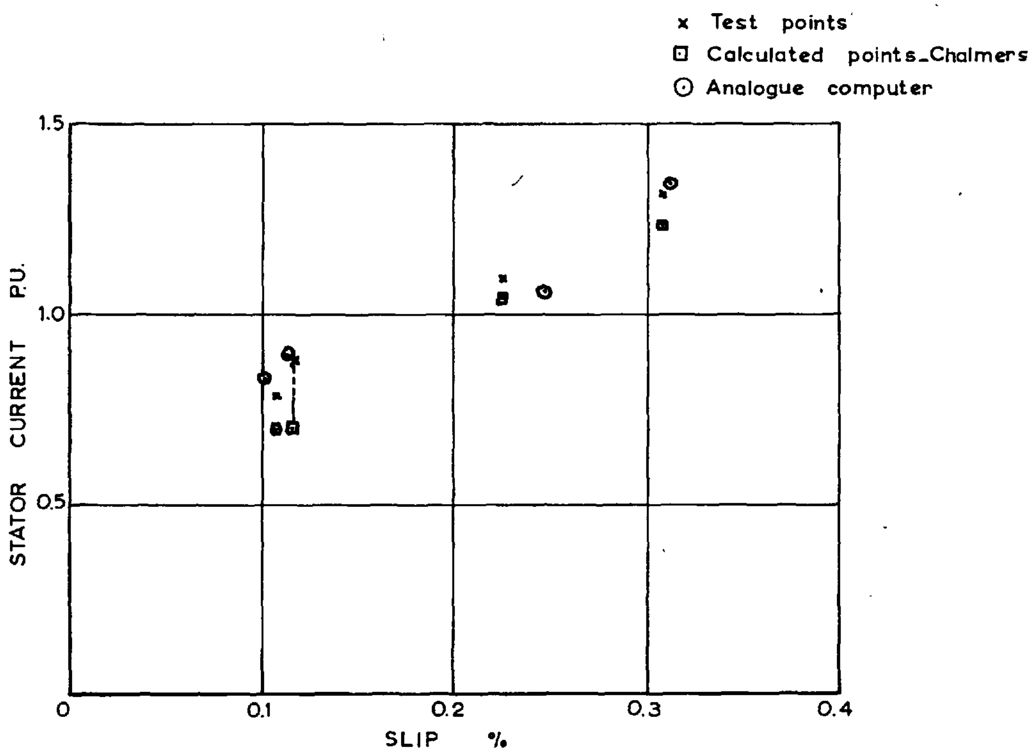


Fig. 5.8 Variation of stator current with slip

60 M.W. Marchwood machine asynchronous running tests

Field shorted through discharge resistor

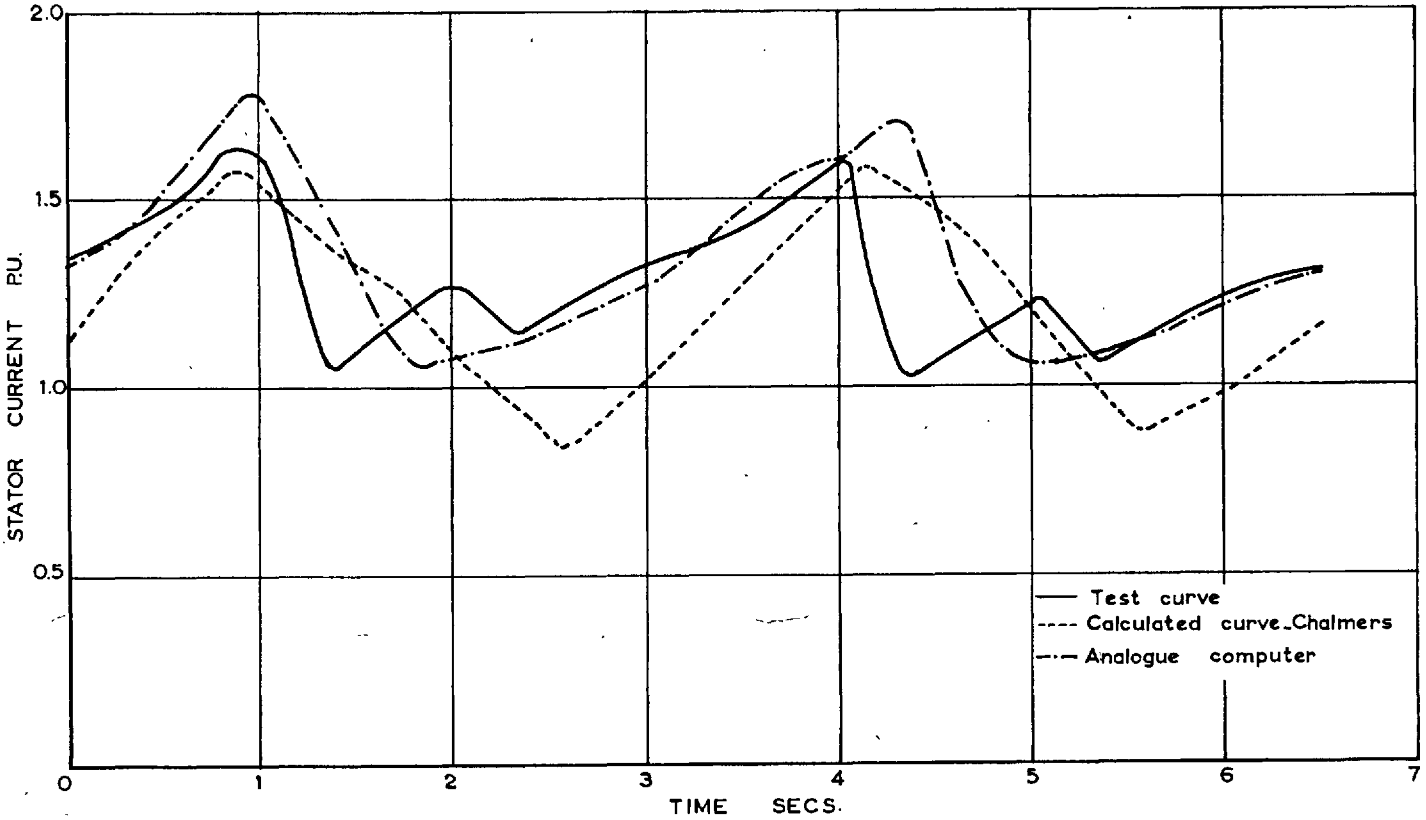


Fig. 5.9 Pulsation of stator current with time

60 M.W. Marchwood machine asynchronous running tests

Field shorted through discharge resistor

Output torque _ 0.932 p.u., Slip _ 0.31 %

alternator at Goldington power station were also simulated on the analogue computer. Results obtained from the simulation are given in Figs. 5.10 to 5.13. Actual test results[40] are also plotted in these figures for comparison. It is shown by Figs. 5.10 and 5.11 that the variation between the theoretical and actual test results lies within ±10% except in one case. Full information about the system conditions at the time of the tests was not available for the present studies. In view of this, the degree of agreement obtained is considered reasonable to justify the adoption of the proposed method in the further study of the problem.

5.5.3 Tests on a 120 MW turbo-alternator

In 1962, a series of tests was conducted on a 120 MW set at Staythorpe 'B' power station. Out of this series, one out-of-step running test and one test for asynchronous operation with attempted resynchronisation has been simulated on the analogue computer. Due to the lack of full information on the turbine speed-governor and the automatic voltage regulator, and non-availability of computer elements, these tests could be simulated only approximately. The results obtained are tabulated in Tables 5.1 and 5.2, and keeping in view the drastic simplifications involved, correlation obtained seems satisfactory.

5.5.4 Tests on a micro-machine

For a fuller study of the problem of asynchronous operation and resynchronisation, a large number of tests

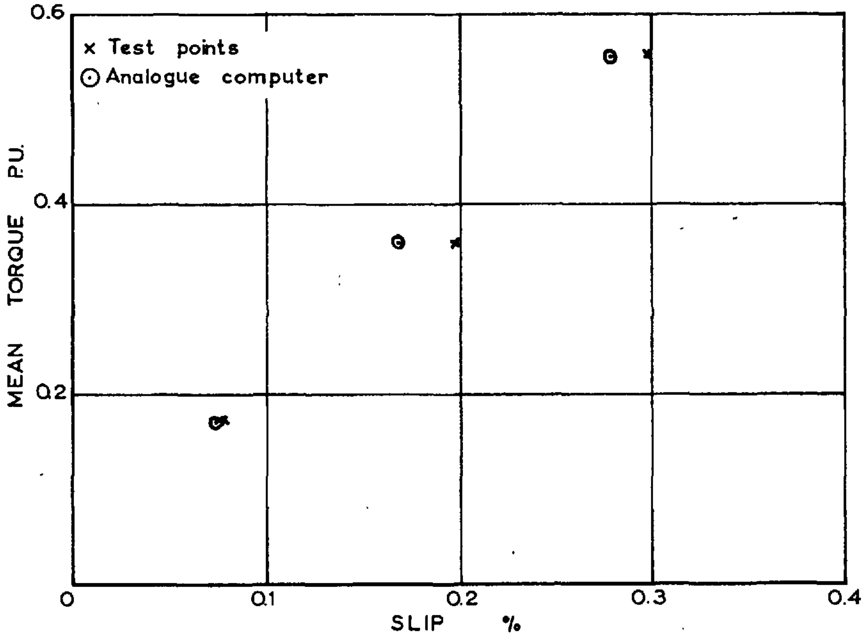


Fig. 5.10 Variation of mean torque with slip

30 M.W. Goldington machine asynchronous running tests

Field open

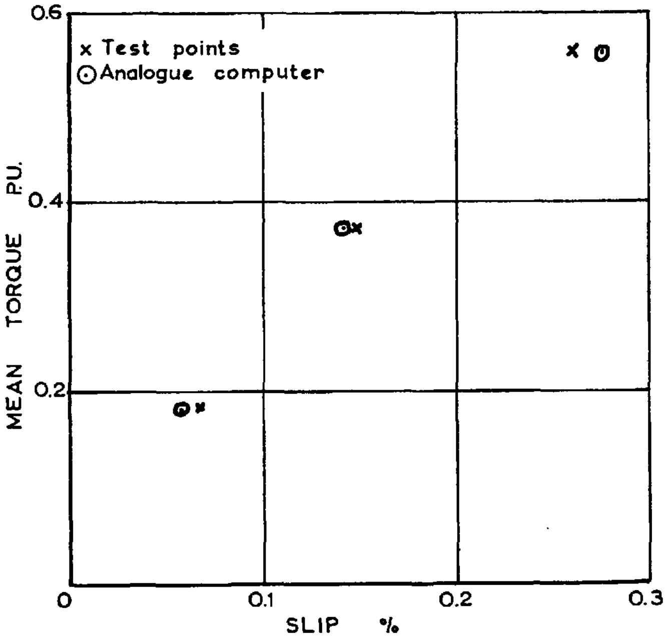


Fig. 5.11 Variation of mean torque with slip

30 M.W. Goldington machine asynchronous running tests

Field shorted through discharge resistor

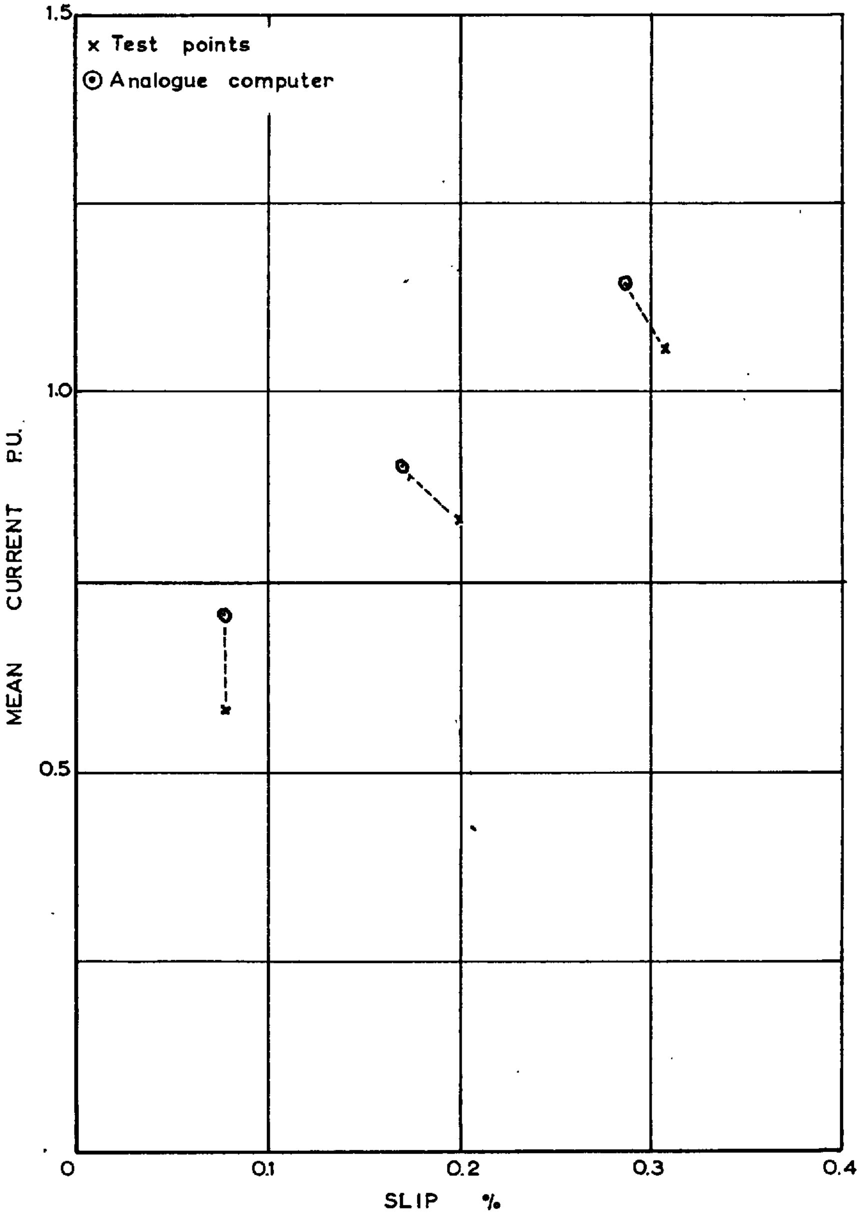


Fig. 5.12 Variation of mean current with slip

30 M.W. Goldington machine asynchronous running tests

Field open

Corresponding points plotted for same output torque

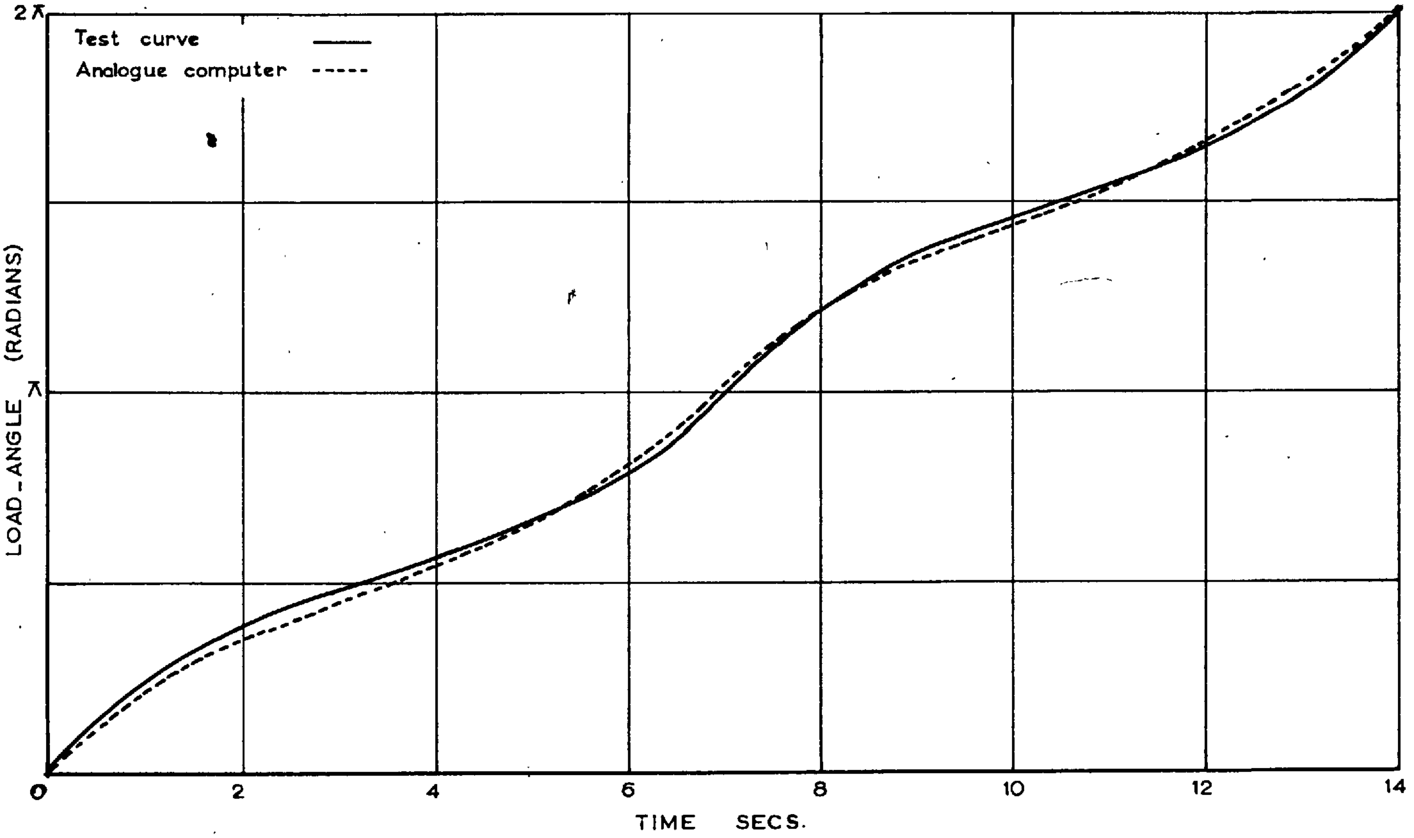


Fig. 5.13 Variation of load_angle with time

30 M.W. Goldington machine asynchronous running tests
Field shorted through discharge resistor

were conducted on a micro-machine and simultaneously simulated on the mathematical model. Figs. 5.14 to 5.16 show a comparison of the mean torque-slip characteristics obtained from the machine and the computer. Fig. 5.17 shows the mean stator current obtained by the two methods. Further details of the studies on the micro-machine and their comparison with the analogue computer results are given in Chapter 8 on resynchronisation. It will suffice to mention here, that a very good agreement has also been obtained in this case.

Table 5.1

Out-of-step running with approximately constant excitation

	Parameter	Staythorpe Test results	Analogue Computer results
1.	Mean rotor slip %	4.5	4.08
2.	Maximum stator current p.u.	1.15	1.255
3.	Maximum variation of MW output p.u.	+0.733 to -0.567	+0.56 to -0.27
4.	Maximum variation of MVAR p.u.	0.45 lead to 0.27 lag	0.73 lead to 0.03 lag
5.	Maximum variation of stator terminal voltage p.u.	0.19 to 0.82	0.13 to 0.73
6.	Maximum rotor current during disturbance p.u.	1.72	1.642

Table 5.2

Asynchronous operation and attempted resynchronisation

	Parameter	Test results	Analogue Computer results (see note)
1.	Mean value of slip %	2.0	1.56
2.	Mean value of MVAR p.u.	0.72	0.64
3.	Mean level of stator terminal voltage p.u.	0.53	0.61
4.	Magnitude of fluctuations in MW output p.u.	+0.8 to +0.33	+0.88 to +0.27
5.	Magnitude of fluctuations in stator current p.u.	1.01 to 1.436	1.03 to 1.52
6.	Magnitude of fluctuations in MVAR p.u.	0.673 to 0.767 lead	0.5 to 0.74 lead
7.	Maximum variation of MW output during attempted resynchronisation at $\delta = 135^\circ$ p.u.	+1.12 to -0.5	+1.32 to -0.3
8.	Maximum variation of generator stator voltage during attempted resynchronisation at $\delta = 135^\circ$ p.u.	0.35 to 0.75	0.26 to 0.81

Note: Analogue computer results in Table 5.2 relate to steady asynchronous operation at 0.52 p.u. (78 MW) output.

Attempted resynchronisation is fully discussed in Section 8.11.

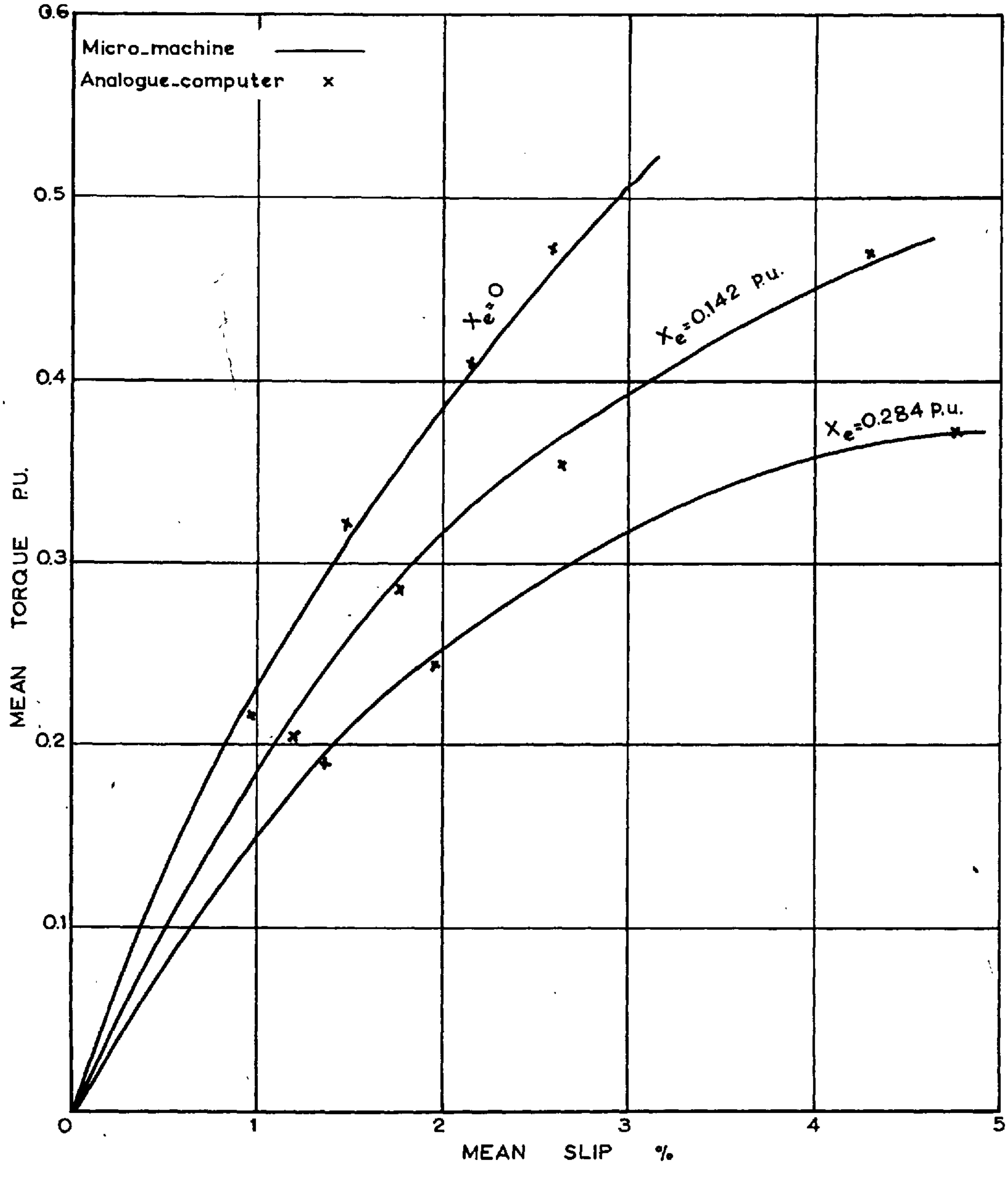


Fig. 5.14 Mean torque_slip characteristics

Micro_machine with solid rotor asynchronous running tests
Field open

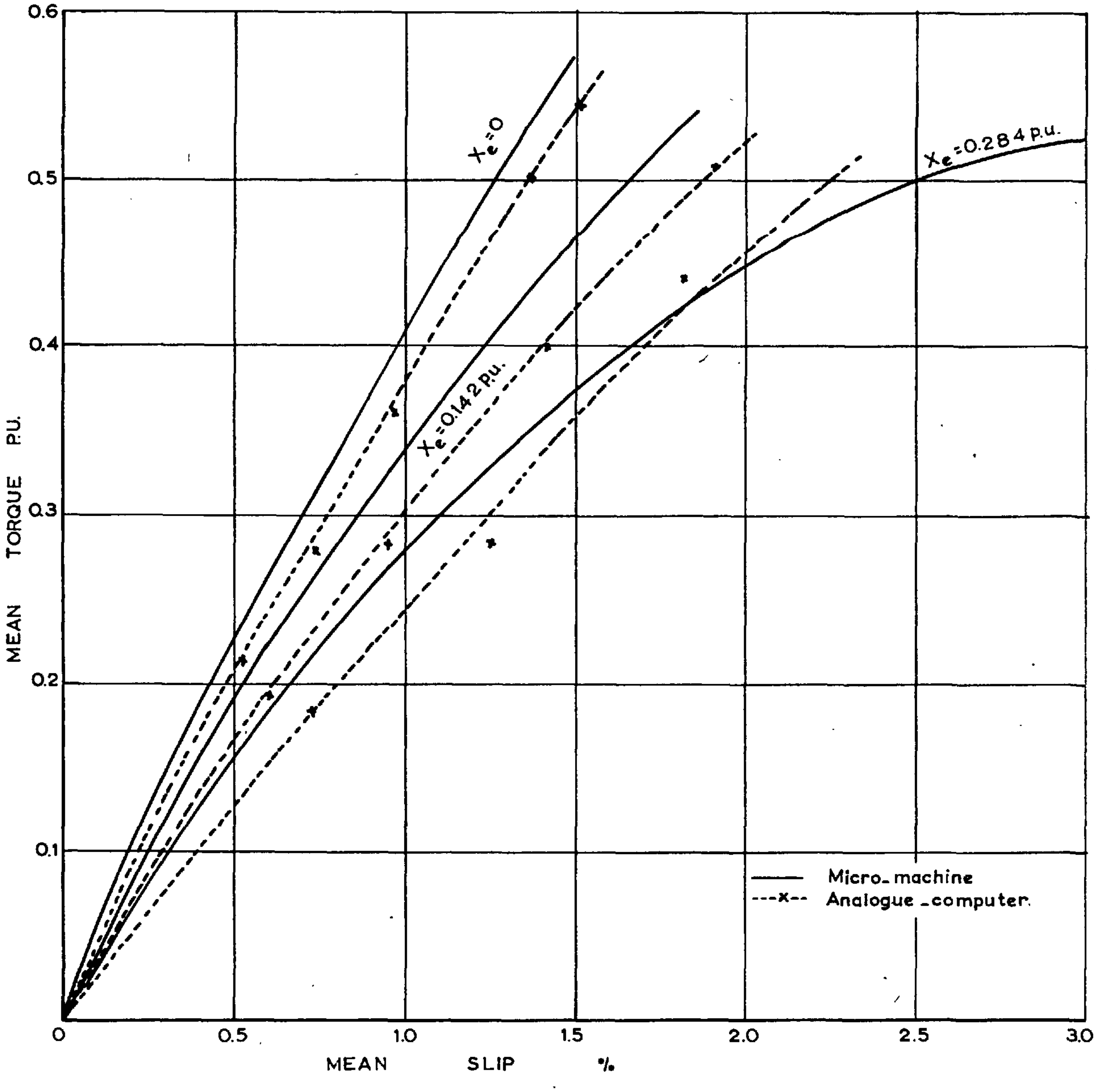


Fig. 5.15 Asynchronous mean torque_slip characteristics

Micro_machine with solid rotor

Field shorted through discharge resistor

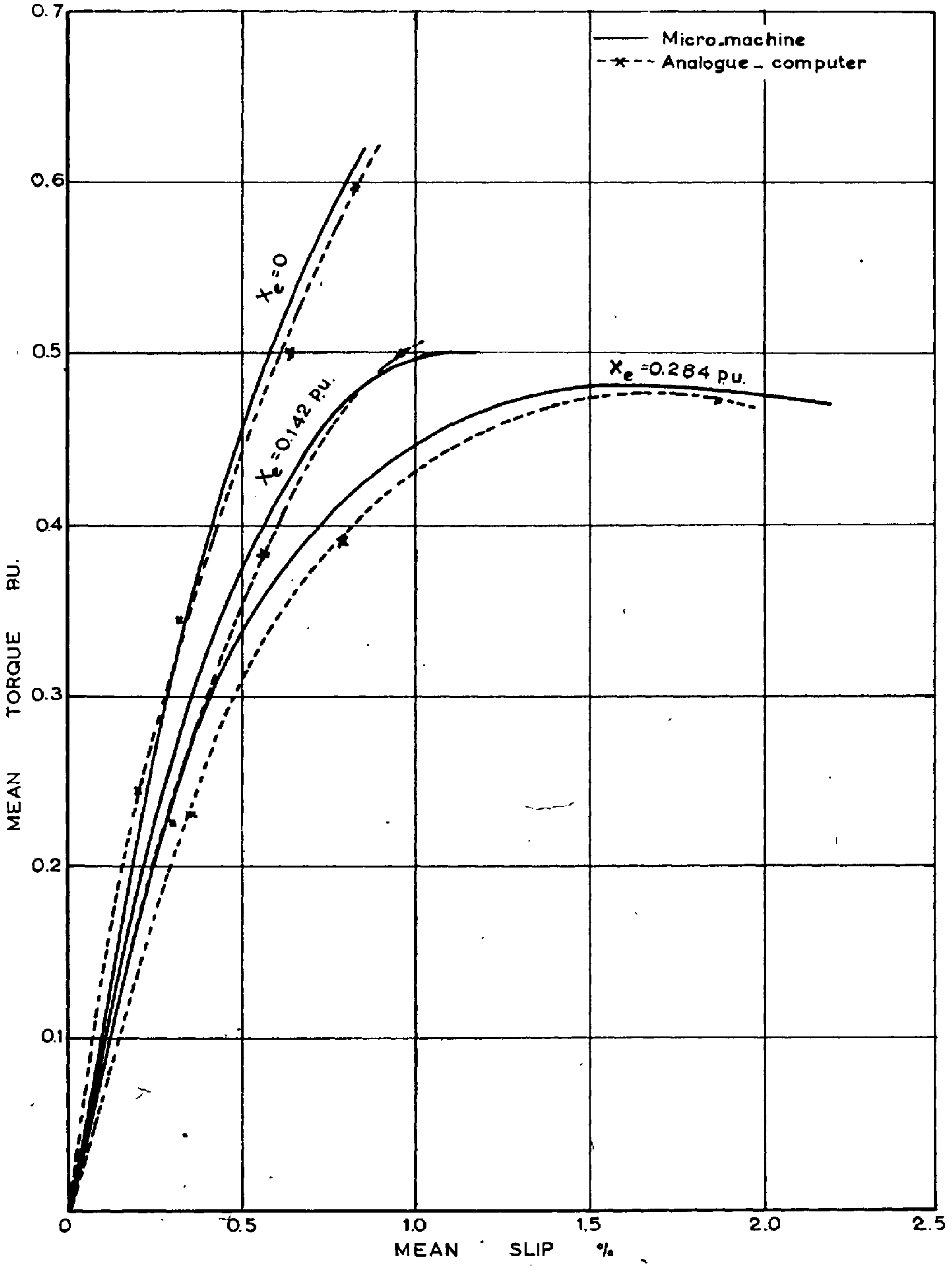


Fig. 5.16 Asynchronous mean torque-slip characteristics

Micro-machine with solid rotor

Field excited

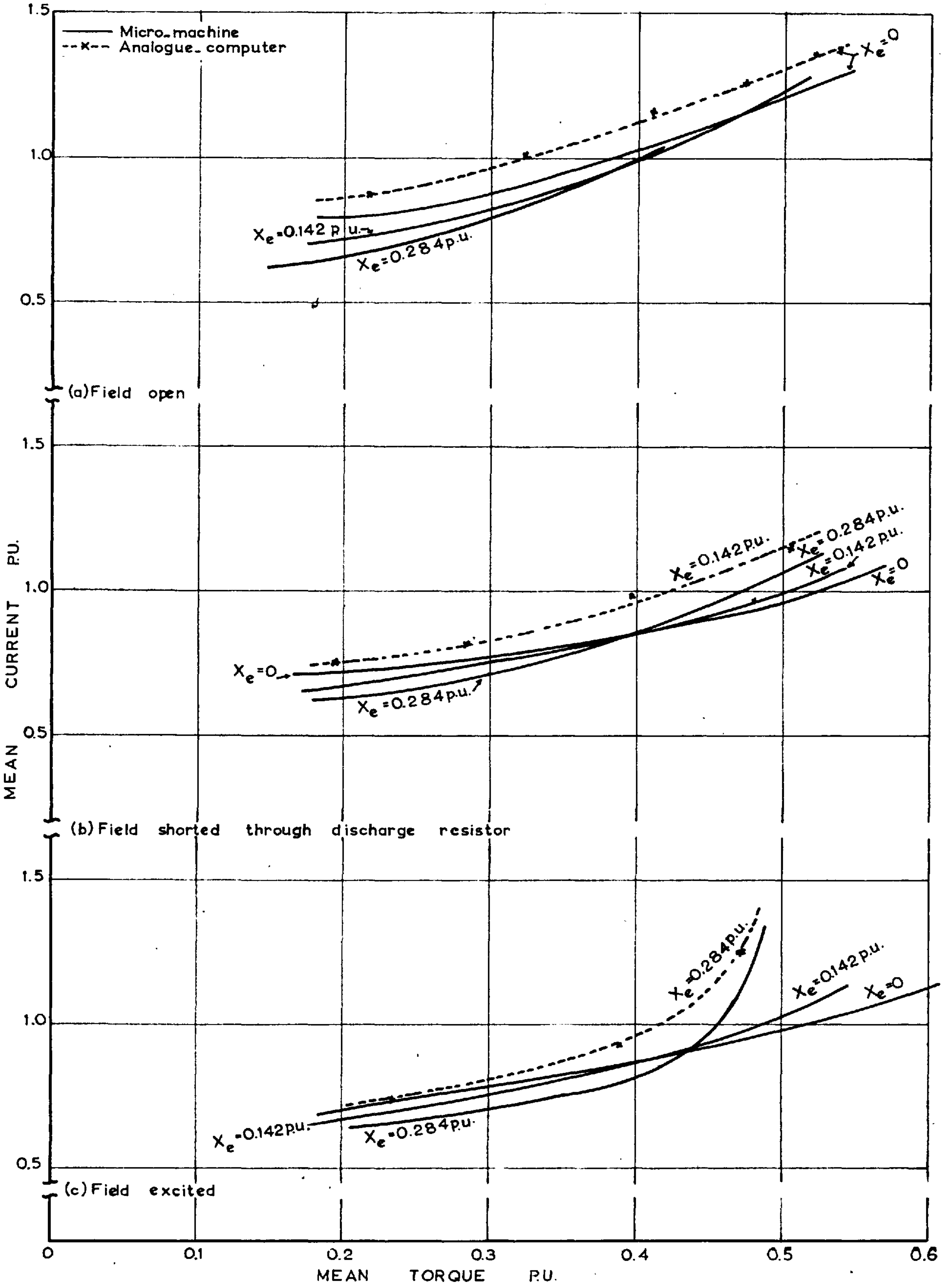


Fig. 5.17 Variation of stator current with asynchronous torque

Micro-machine with solid rotor

CHAPTER 6

BEHAVIOUR DURING ASYNCHRONOUS OPERATION

6.1 General

During asynchronous operation, the power and electrical torque developed in a synchronous machine depend not only on the load angle, but also on the time rate of change of the load-angle. Torque 'T' can then, as an approximation, be considered to be made up of a synchronous component and an asynchronous component.

$$T = T_s + T_{as} \qquad \ldots(6.1)$$

The synchronous component T_s will be present only when field excitation is present during asynchronous operation. Its magnitude depends on the constants applicable to synchronous operation, on the applied voltage, excitation and the load angle. The asynchronous component T_{as} depends on the asynchronous constants, the applied voltage, the load angle δ and its time rate of change i.e. the slip s.

A marked asymmetry exists between the direct and quadrature axes of a machine with salient-pole rotor. In comparison, asymmetry is very slight, and in some cases, may even be absent in the case of machines with cylindrical rotor. Due to asymmetry on the rotor, the watts and VArs components of the asynchronous volt amps pulsate about a mean value during asynchronous operation. Because of these variations in power, there are constant oscillations of speed (slip) about a fixed average value.

Operating as a generator, the machine will always run at super-synchronous speeds as an induction generator. As a motor it will run at sub-synchronous speeds as an induction motor. The asynchronous power supplied is generated by virtue of the induced rotor currents - which depend on the slip.

Under asynchronous conditions, VArs demand is met by the system to which the machine is connected. These VArs consist of two components, namely;

a) magnetising component, i.e. reactive volt amps required for magnetisation,

b) asynchronous component, i.e. VArs taken by the shunt reactance, as the machine under these conditions can be represented by an equivalent circuit containing series and shunt branches like the equivalent circuit of an ordinary induction machine.

Because of the comparatively large air-gaps of the normal synchronous machines, magnetising VArs demand of these machines is large. This results in the current being higher when compared with the values reached during normal synchronous operation for the same power output. This excessive VAr demand can produce a large voltage reduction at the machine terminals as well as in the system, which can cause difficulties. In addition, the magnitude of the VAr pulsations about the mean value is important, since these pulsations can cause fluctuations of the system voltage over a wide area.

6.2 Studies performed

To study the effect of various parameters, modes of machine operation and the system conditions, extensive studies have been performed for a laminated salient-pole rotor and a solid cylindrical rotor by setting up appropriate mathematical models on an analogue computer. Results from the computer have also been compared with the results obtained under appropriate conditions on micro-machines using corresponding rotors. The various asynchronous studies carried out are enumerated below.

i) No excitation, field shorted on itself with different time constants. These studies could also be interpreted as studies with field closed through a discharge resistor having various values.

ii) Open circuit field.

iii) Field closed and excited.

iv) Machine connected to an infinite bus through external reactance of various values.

v) Infinite bus at various fixed voltages.

vi) Variation of moment of inertia of the machine.

vii) Effect of speed-governor and its characteristics.

6.3 Pulsations in various quantities

Eqn. (B.21) for torque and Eqn. (B.25) for slip can both be split into three parts contributing separately to the total instantaneous torque and slip. The parts of these two equations which are independent of load-angle (δ) give the mean torque and mean slip, and do not contribute to the pulsations. The second part, which is proportional to the load-angle is present only when the field is excited and generates pulsations at slip frequency. The third part of these equations produces twice the slip frequency pulsations in all quantities.

In physical terms, this can be explained easily. The damper circuits are generally assumed to be symmetrically distributed about the two axes. The field, shorted on itself or through a discharge resistor, is also symmetrically distributed about the two axes. Thus the pulsations are caused only by the variation of reluctance as each rotor pole slips with respect to the stator mmf wave. The field, open or shorted, is symmetrical over every 180 electrical degrees and would, therefore, cause pulsations at twice the slip frequency. However, in the case of the excited field, synchronous torque proportional to Sinδ is produced. This torque pulsates at slip frequency, causing pulsations which dominate the comparatively weak double frequency pulsations caused by the variations in reluctance.

A few representative records of asynchronous operation obtained on the analogue computer are given in Figs. 6.1 to 6.32 and the various quantities shown in these figures are tabulated in Table 6.1. Figs. 6.1 to

Table 6.1

a) Laminated rotor micro-machine

Slip versus load-angle Watts versus load-angle	Figs. 6.1 to 6.6, 6.8 to 6.11 & 6.13
VArs versus load-angle	Figs. 6.4, 6.8 to 6.11 & 6.13
Load-angle versus time	Figs. 6.10 & 6.11
Effect of variation of moment of inertia	Fig. 6.7
Loss of synchronism and steady asynchronous operation	Fig. 6.12
Effect of speed-governor	Fig. 6.13
Line current versus load-angle	Figs. 6.14, 6.18 & 6.19
Line current versus time	Figs. 6.14 to 6.17

b) Solid rotor micro-machine

Slip versus load-angle Slip versus time Load-angle versus time Watts versus time VArs versus time	Figs. 6.20 to 6.24
Field current versus time	Figs. 6.22 to 6.24
Line current versus time	Figs. 6.25 to 6.32

6.32 clearly show that all quantities pulsate exactly as described in the preceding paragraph. It is also observed from these figures that during operation with the field excited all the quantities fluctuate much more violently than in either of the other two modes of operation

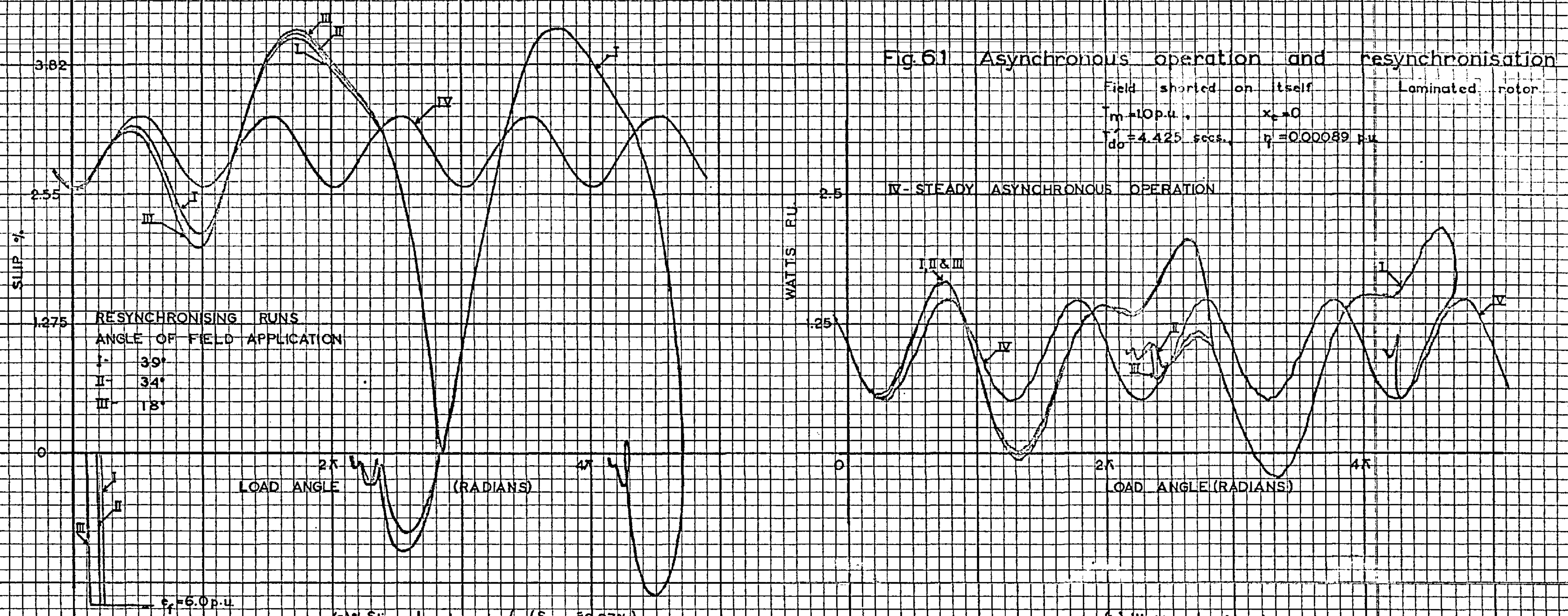


Fig. 6.1 Asynchronous operation and resynchronisation

Field shorted on itself Laminated rotor

T_m = 1.0 p.u., x_e = 0

T'_{do} = 4.425 secs., r_f = 0.00089 p.u.

(a) % Slip – Load-angle δ (S_{mean} = 2.97%)

(b) Watts – Load-angle

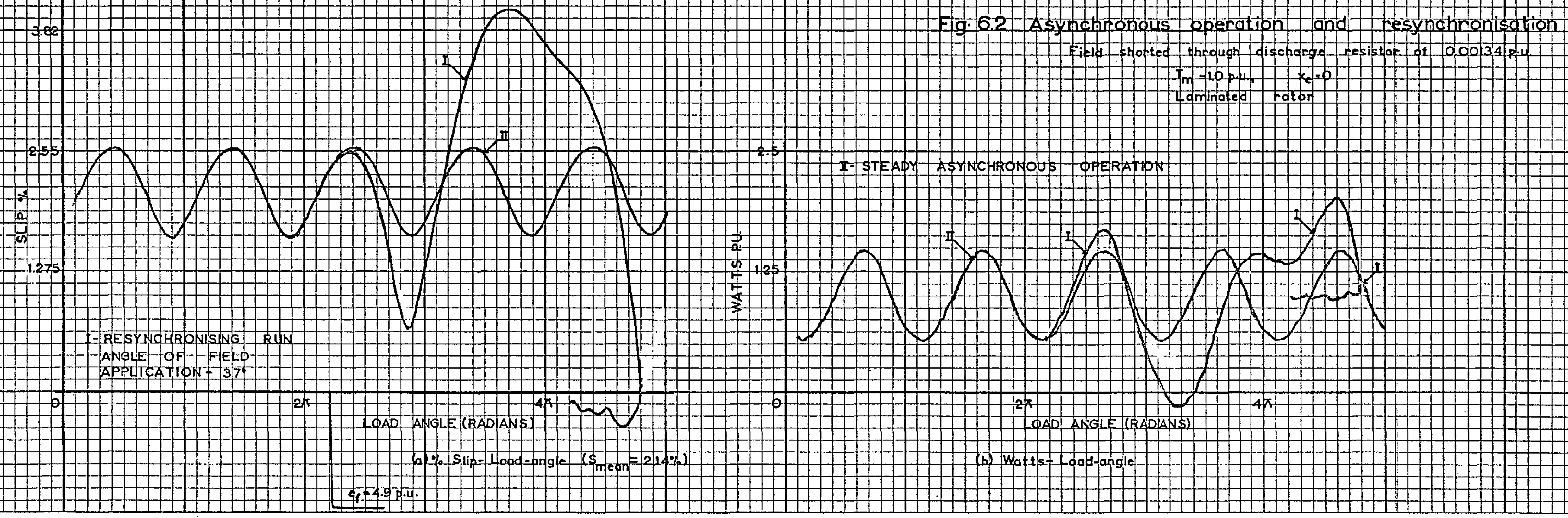


Fig. 6.2 Asynchronous operation and resynchronisation

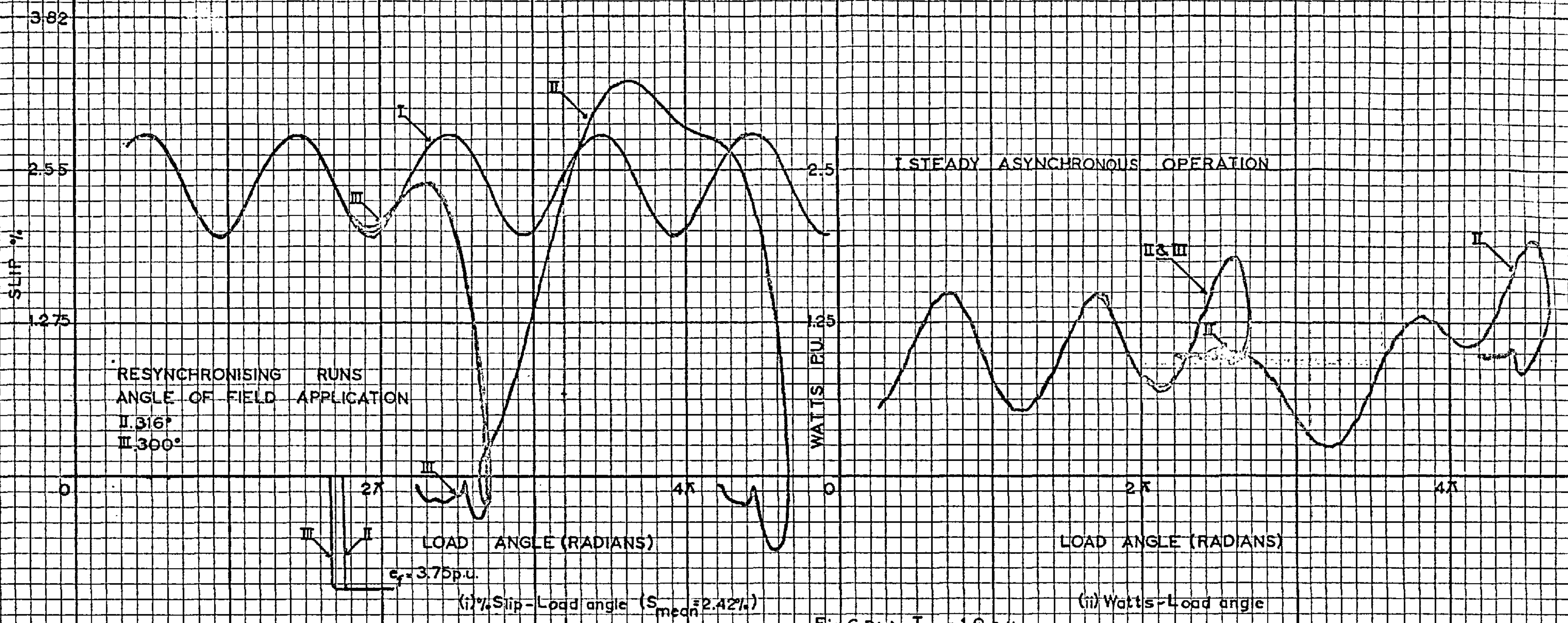
Field shorted through discharge resistor of 0.00134 p.u.

T_m = 1.0 p.u., x_e = 0

Laminated rotor

(a) % Slip – Load-angle (S_{mean} = 2.14%)

(b) Watts – Load-angle



(i) % Slip - Load angle ($S_{mean} = 2.42\%$)

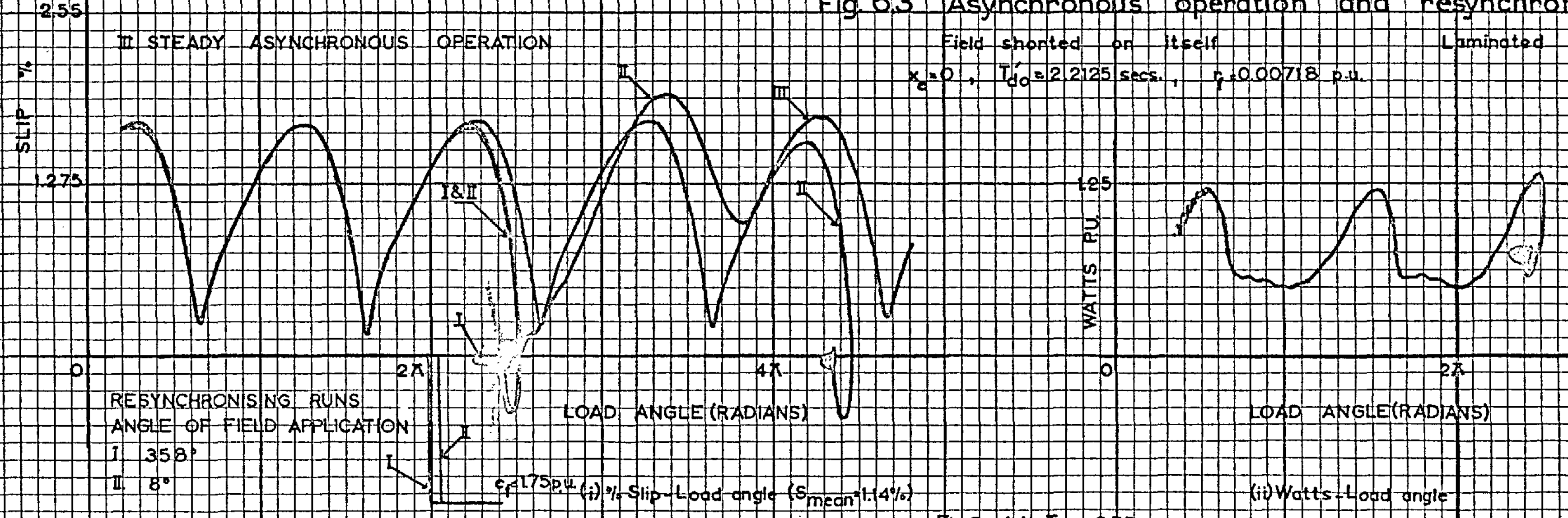
(ii) Watts - Load angle

Fig. 6.3(a) $T_m = 1.0$ p.u.

Fig. 6.3 Asynchronous operation and resynchronisation

Field shorted on itself Laminated rotor

$x_e = 0$, $T'_{do} = 2.2125$ secs., $r_f = 0.00718$ p.u.



(i) % Slip - Load angle ($S_{mean} = 1.14\%$)

(ii) Watts - Load angle

Fig. 6.3(b) $T_m = 0.75$ p.u.

Fig. 6.4 Asynchronous operation and resynchronisation
Field shorted through discharge resistor   Laminated rotor
T_m = 0.5 p.u., x_e = 0.12 p.u., e_{bus} = 0.9 p.u.

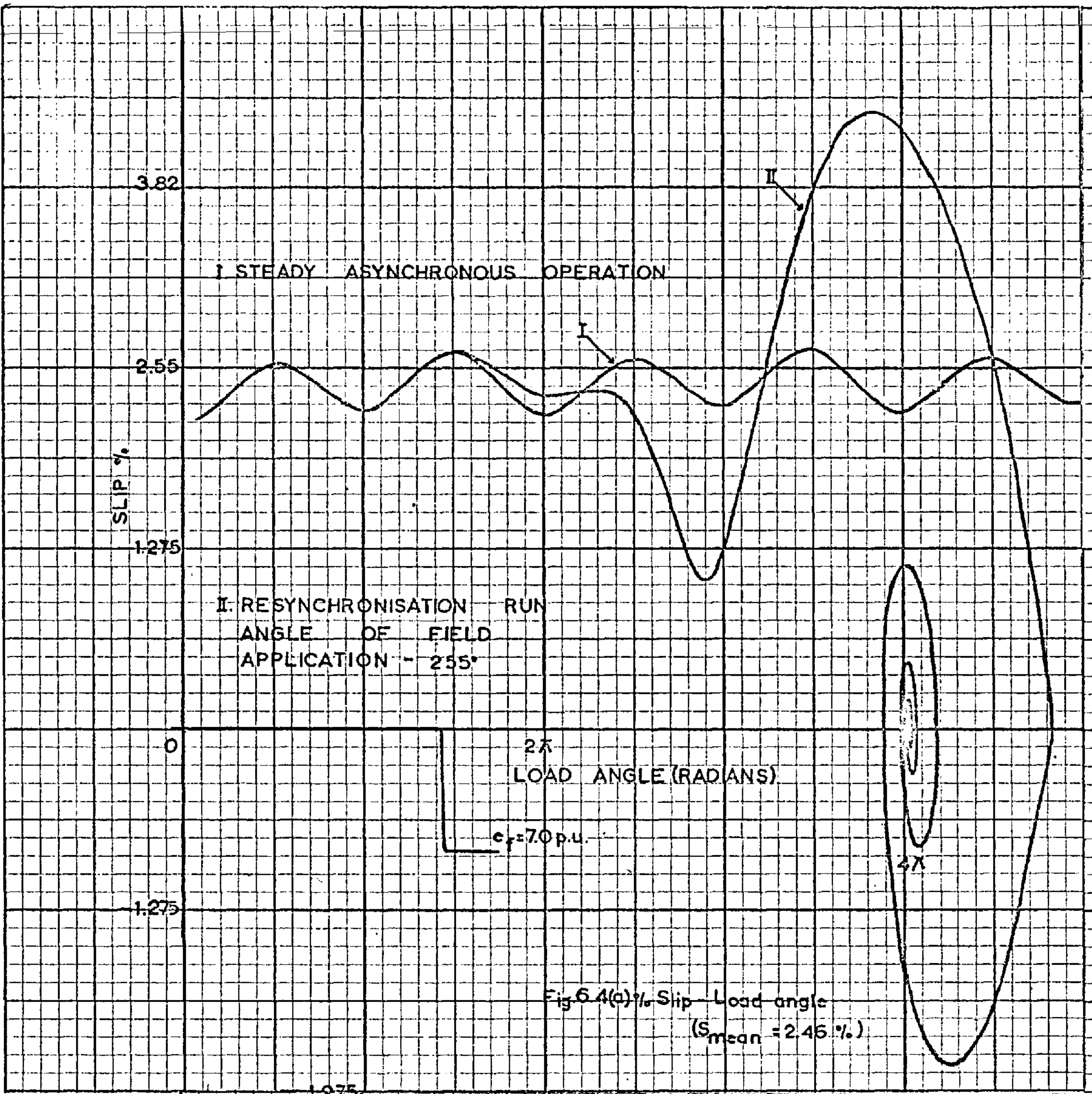


Fig. 6.4(a) % Slip – Load angle
(S_{mean} = 2.46 %)

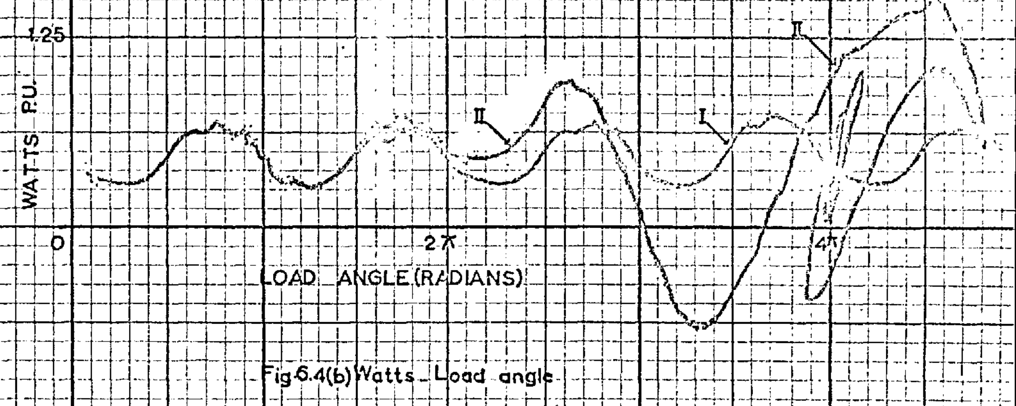


Fig. 6.4(b) Watts – Load angle

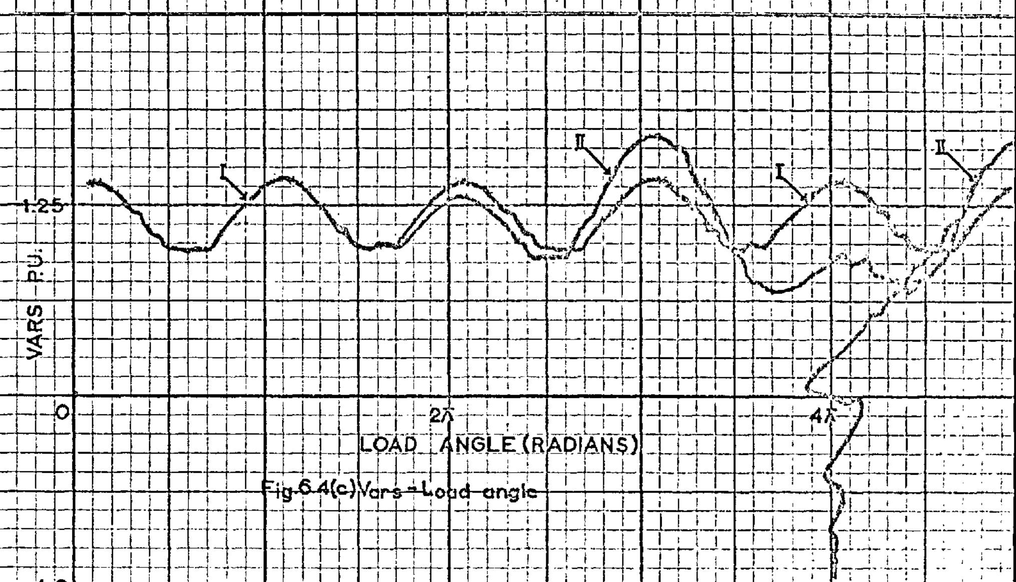
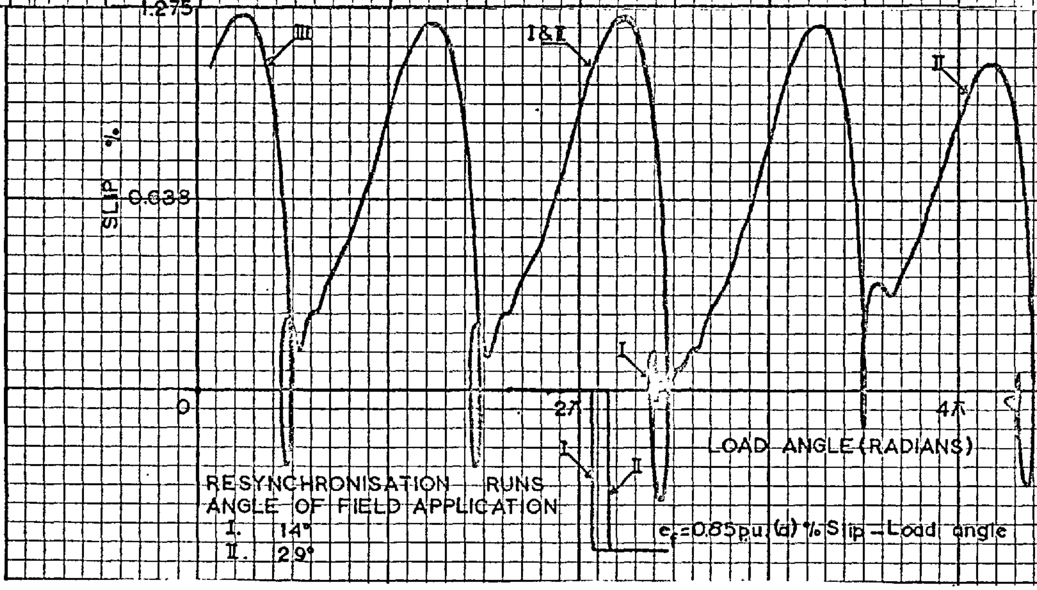
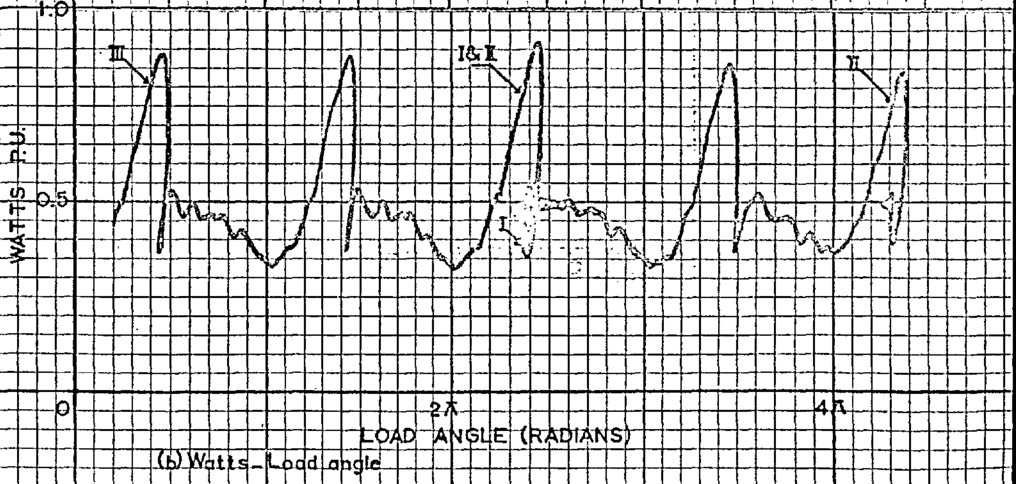


Fig. 6.4(c) Vars – Load angle



(a) % Slip – Load angle



(b) Watts – Load angle

Fig. 6.5 Asynchronous operation and resynchronisation
Field shorted on itself   Laminated rotor
T_m = 0.5 p.u., x_e = 0, T'_{do} = 4.425 secs, r_f = 0.00089 p.u.

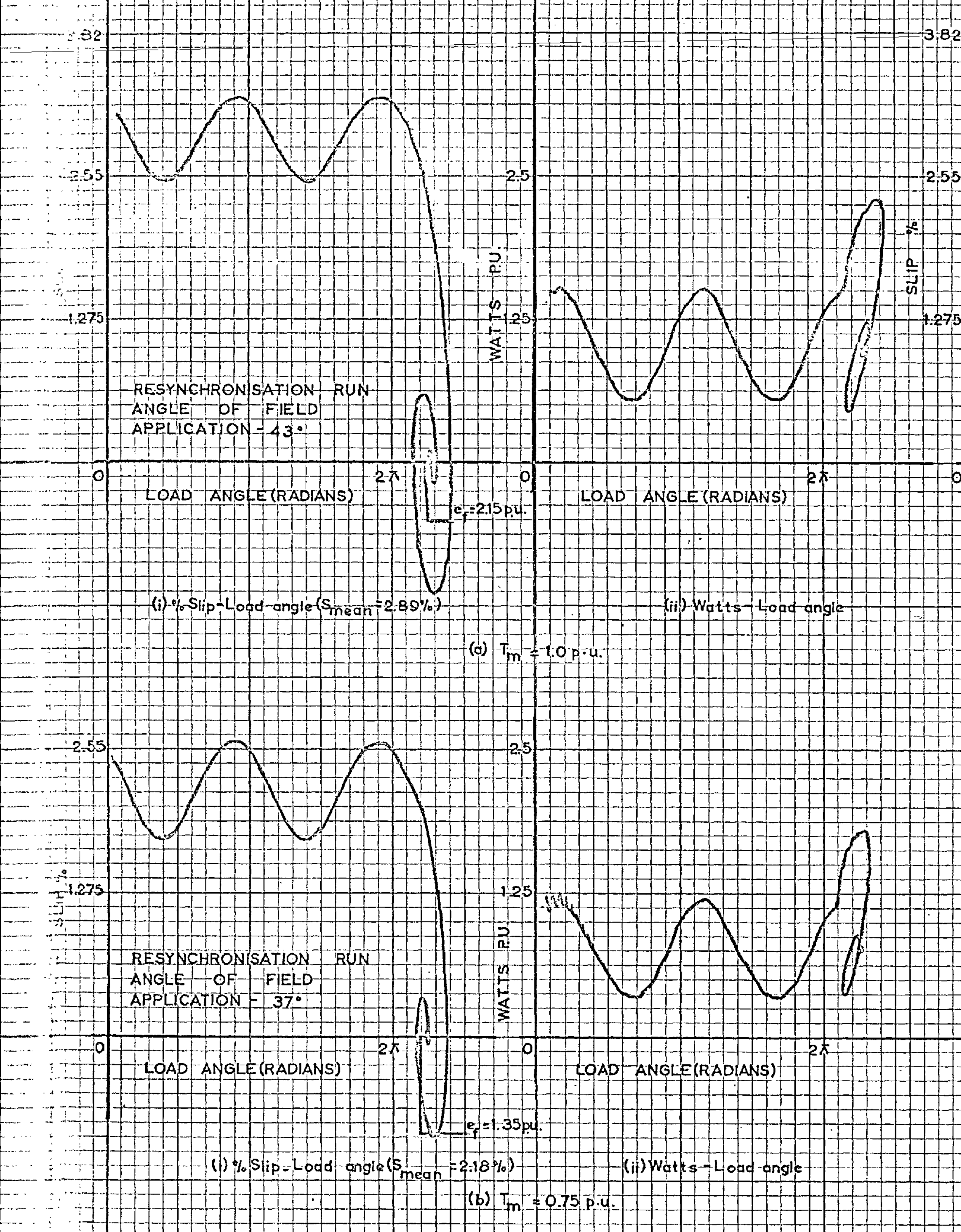


Fig. 6.6 Asynchronous operation and resynchronisation

Field open, $x_e = 0$ Laminated rotor

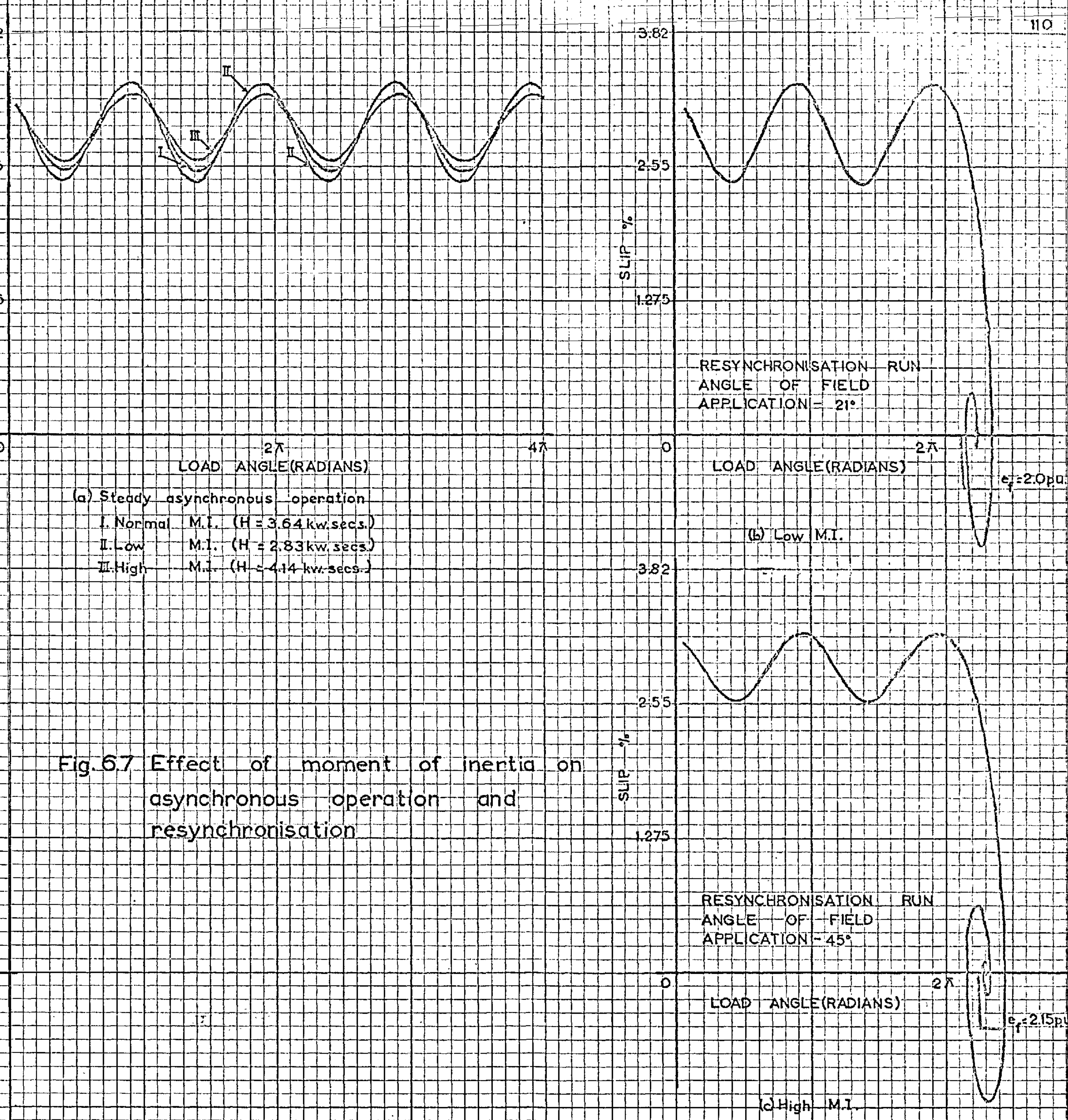
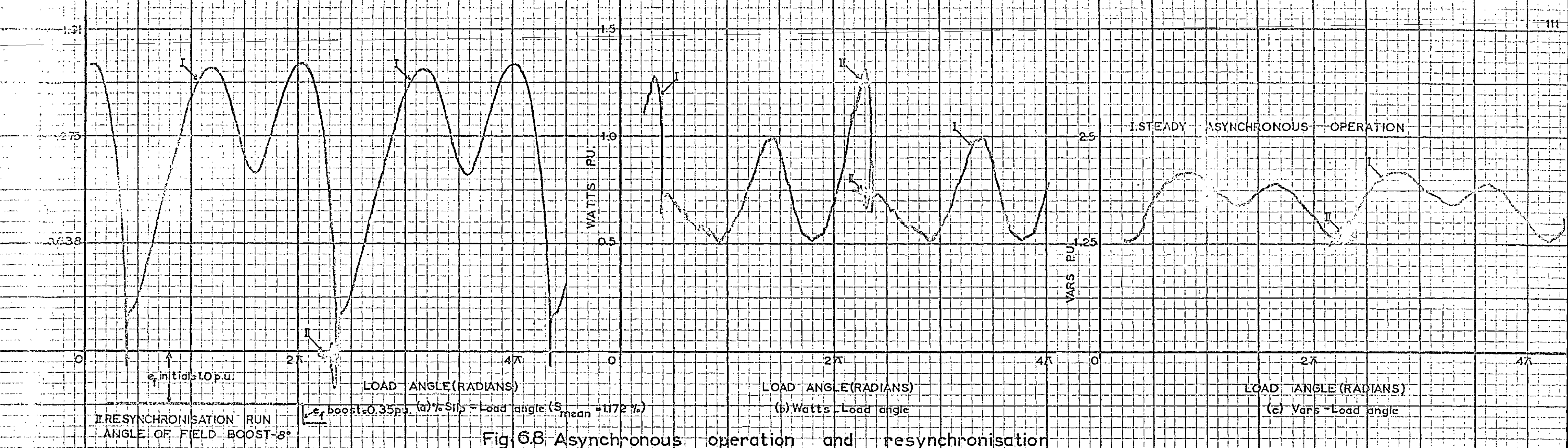


Fig. 6.7 Effect of moment of inertia on asynchronous operation and resynchronisation



(a) % Slip – Load angle (S_{mean} = 1.172 %)

(b) Watts – Load angle

(c) Vars – Load angle

Fig. 6.8 Asynchronous operation and resynchronisation

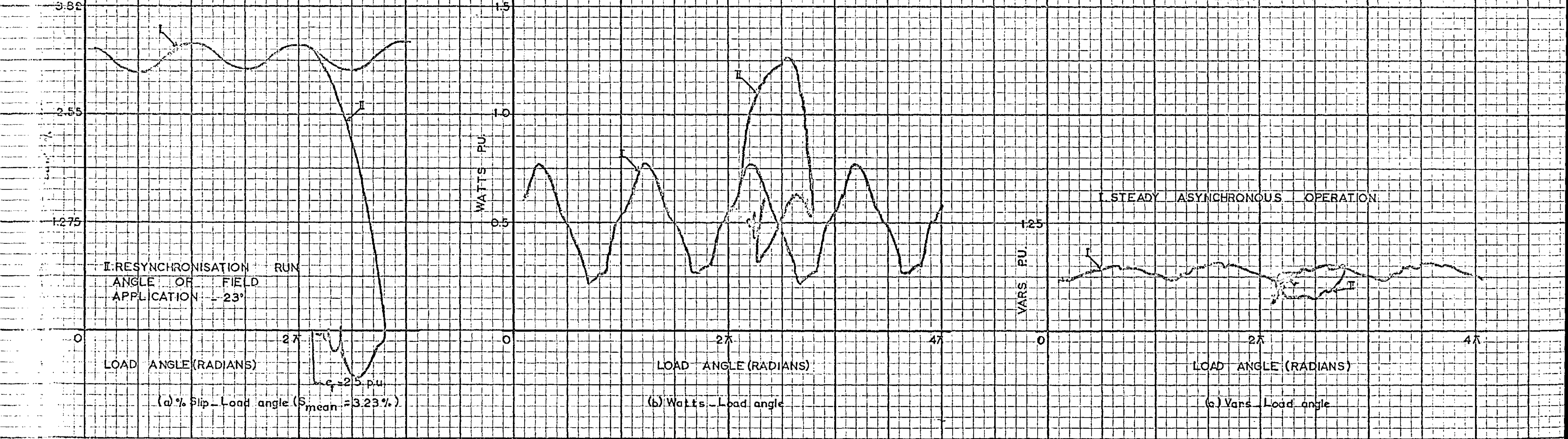
Field excited, T_m = 0.75 p.u., e_f initial = 1.0 p.u., x_e = 0

Laminated rotor

Fig. 6.9 Asynchronous operation and resynchronisation

Field open, T_m = 0.5 p.u., e_{bus} = 1.0 p.u., x_e = 0.3 p.u.

Laminated rotor



(a) % Slip – Load angle (S_{mean} = 3.23 %)

(b) Watts – Load angle

(c) Vars – Load angle

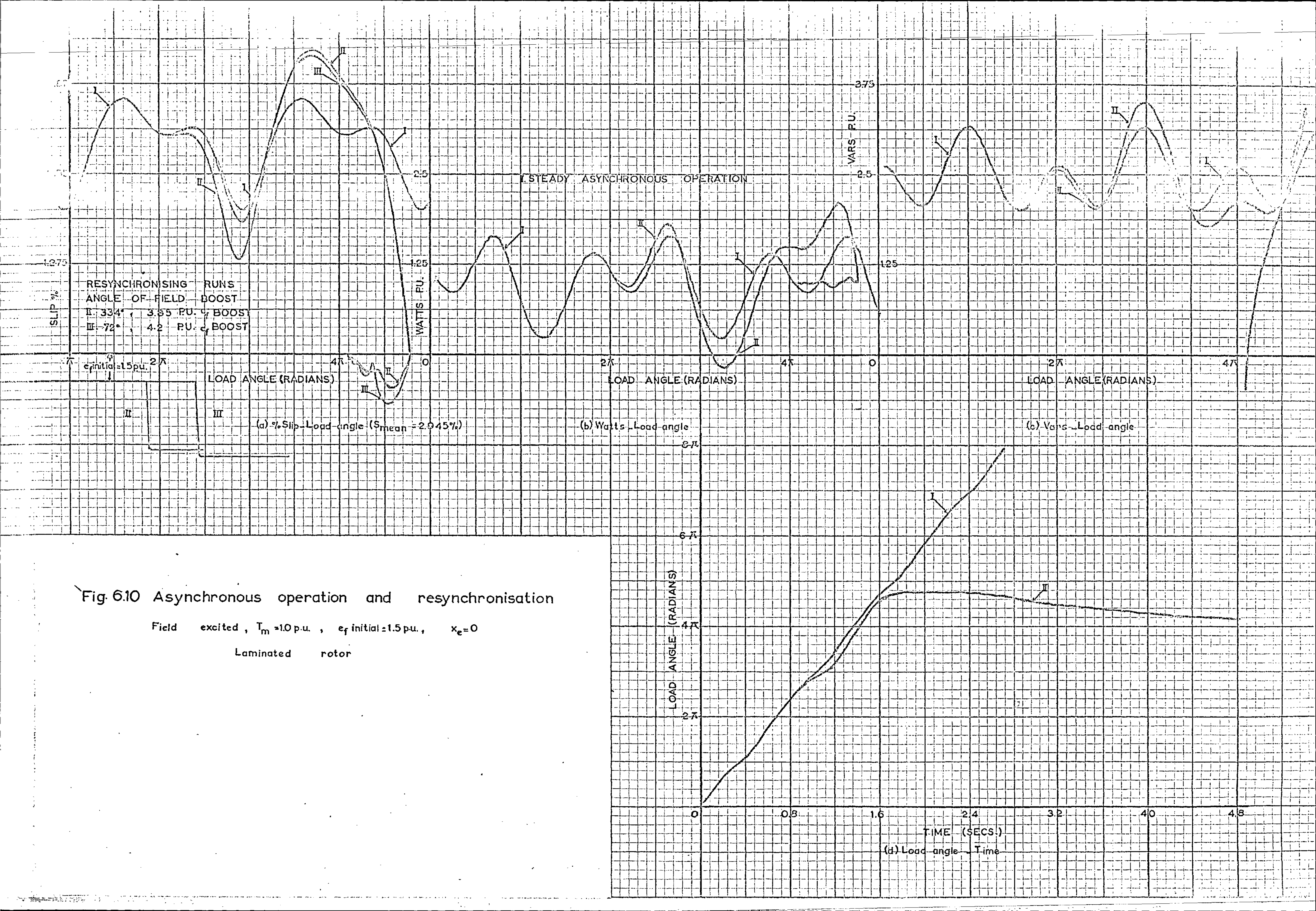
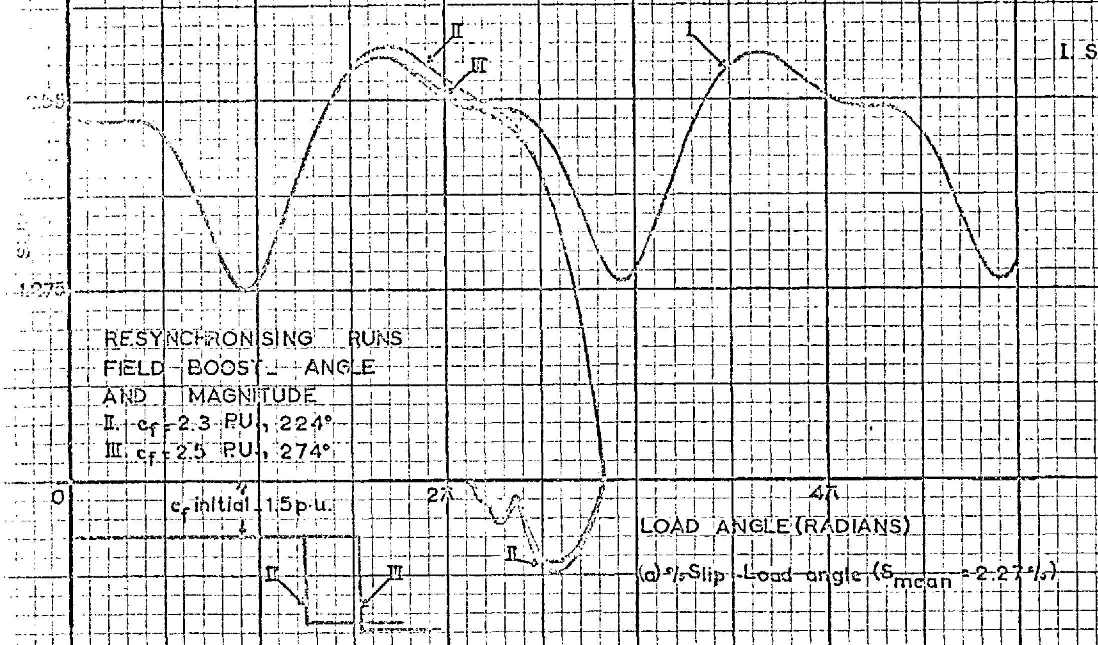


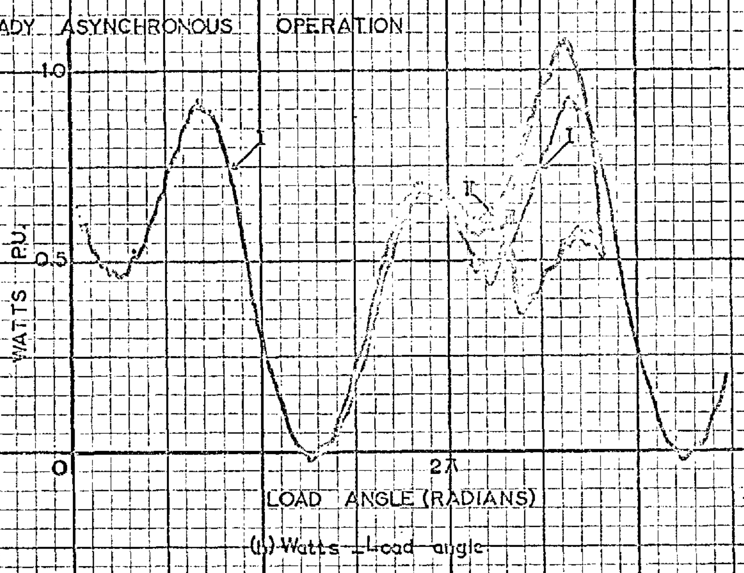
Fig. 6.10 Asynchronous operation and resynchronisation

Field excited , T_m = 1.0 p.u. , e_f initial = 1.5 p.u. , $x_e = 0$

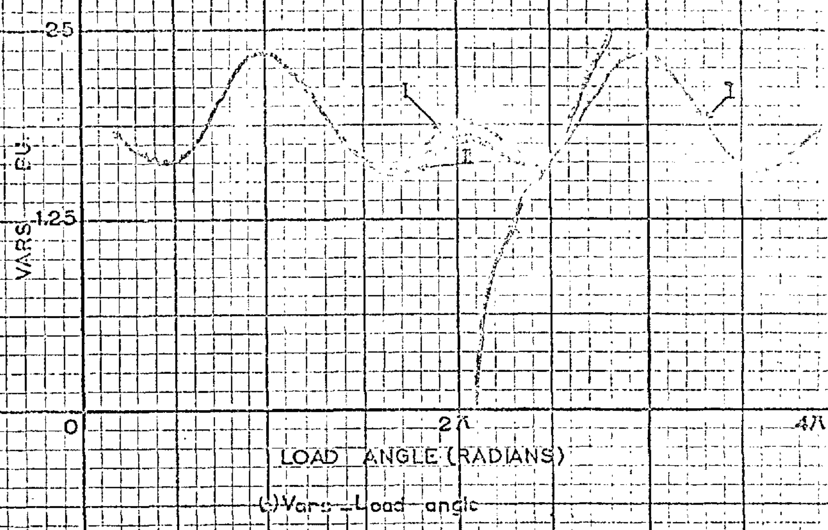
Laminated rotor



(a) % Slip - Load angle (S_{mean} = 2.27 %)



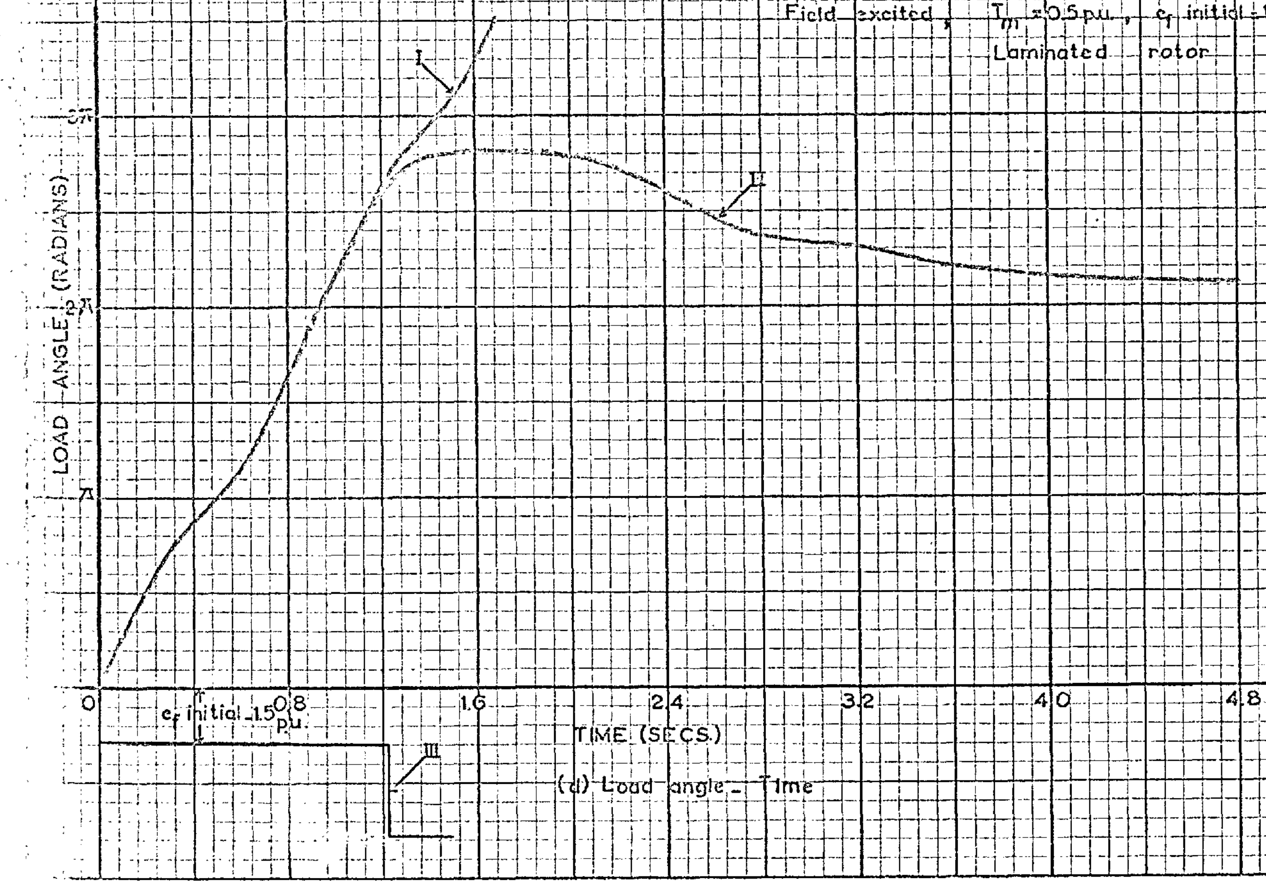
(b) Watts - Load angle



(c) Vars - Load angle

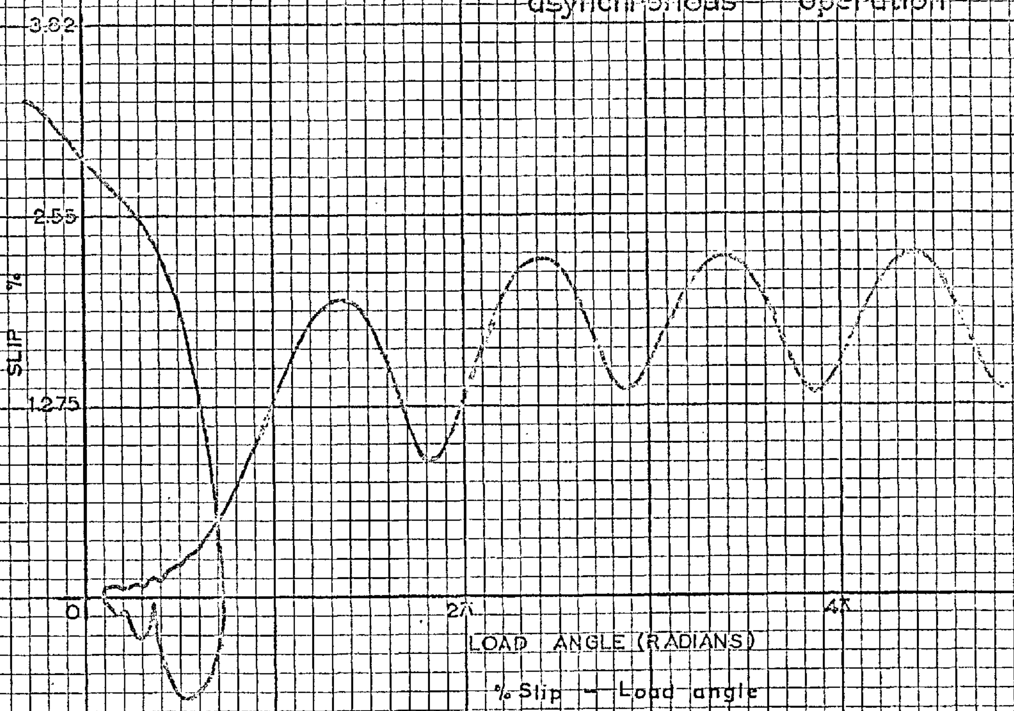
Fig. 6.11 Asynchronous operation and resynchronisation

Field excited, T_m = 0.5 p.u., e_f initial = 1.5 p.u., x_e = 0.12 p.u.
Laminated rotor



(d) Load angle - Time

Fig. 6.12 Loss of synchronism and steady asynchronous operation



% Slip - Load angle

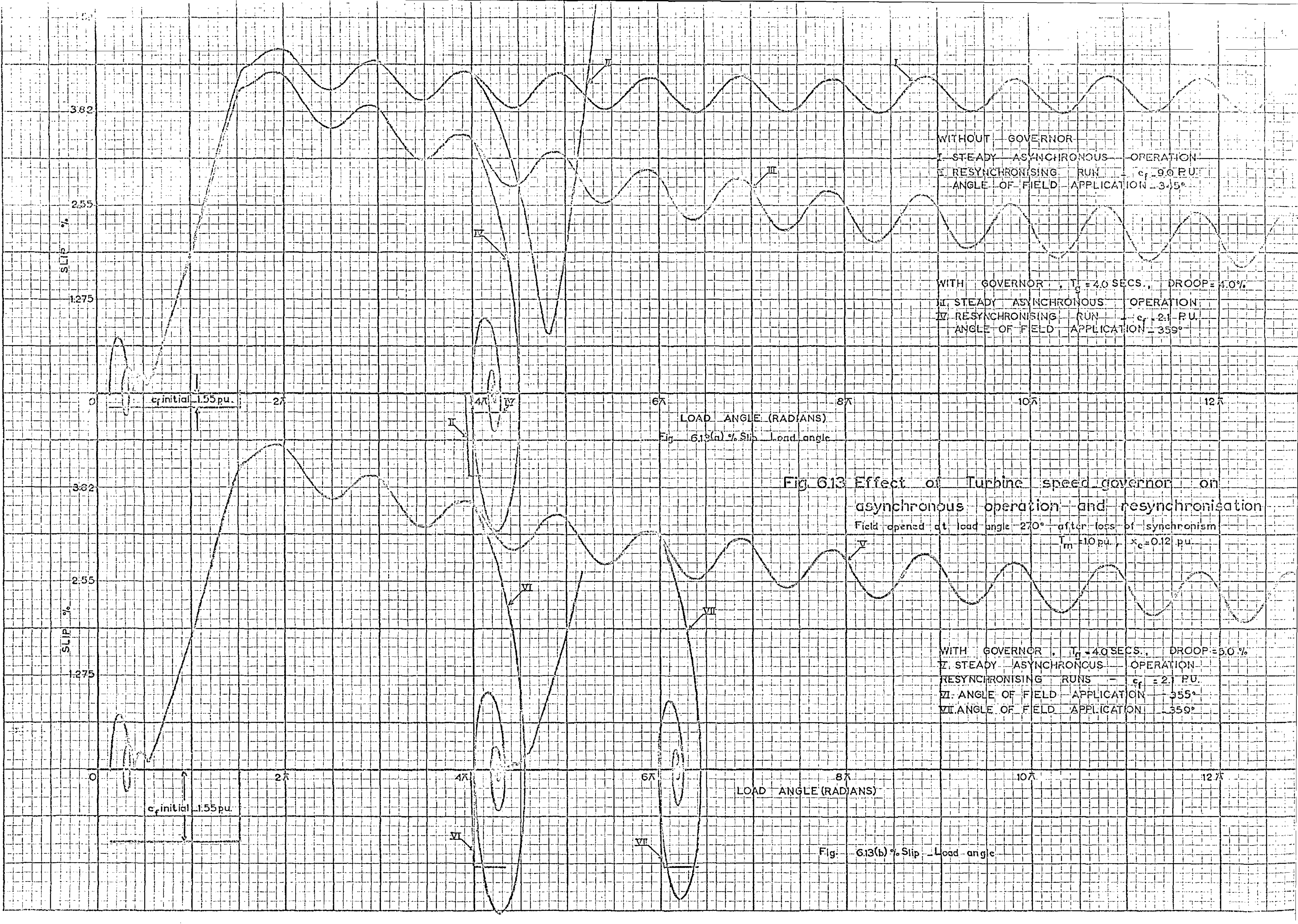


Fig. 6.13(a) % Slip _ Load angle

Fig. 6.13 Effect of Turbine speed governor on asynchronous operation and resynchronisation

Field opened at load angle 270° after loss of synchronism

T_m = 1.0 p.u., x_c = 0.12 p.u.

Fig. 6.13(b) % Slip _ Load angle

Fig. 6.13(c) Watts _Load angle (Governor T_g = 4.0 secs., Droop = 4.0%)

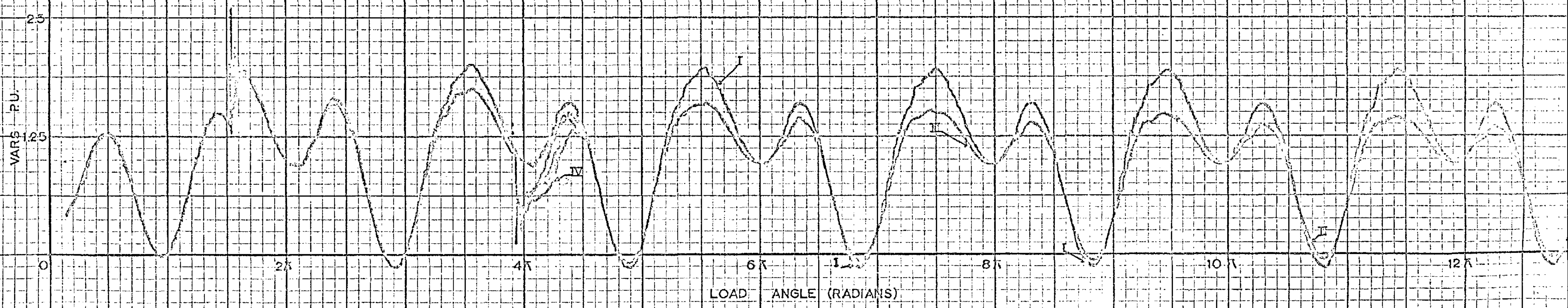
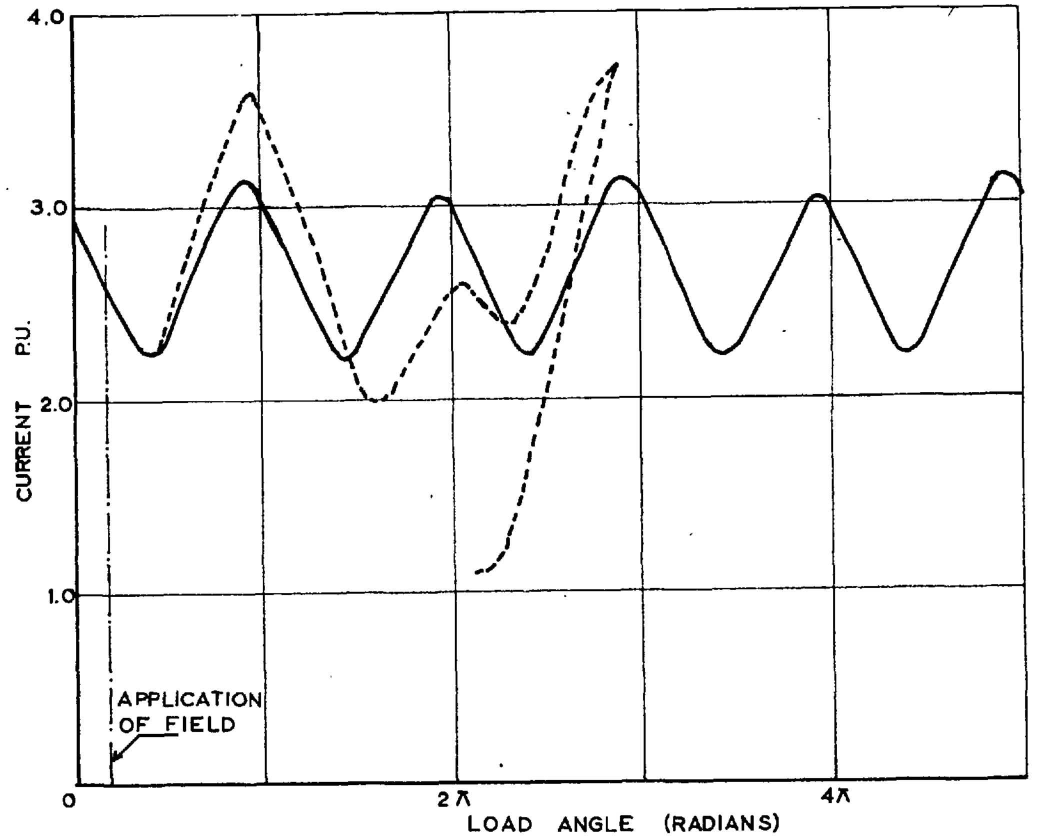
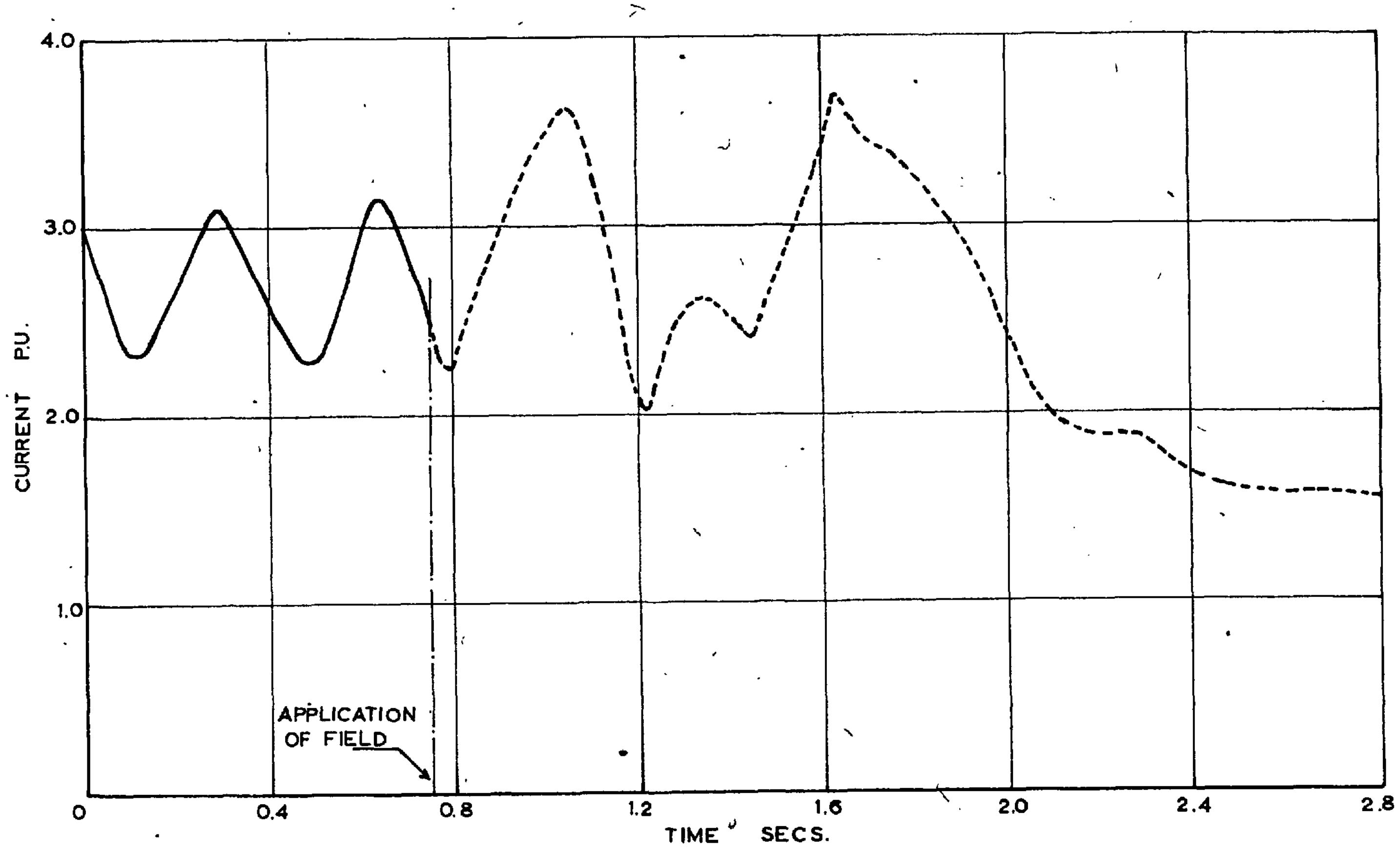


Fig. 6.13(d) Vars _Load angle (Governor T_g = 4.0 secs., Droop = 4.0%)

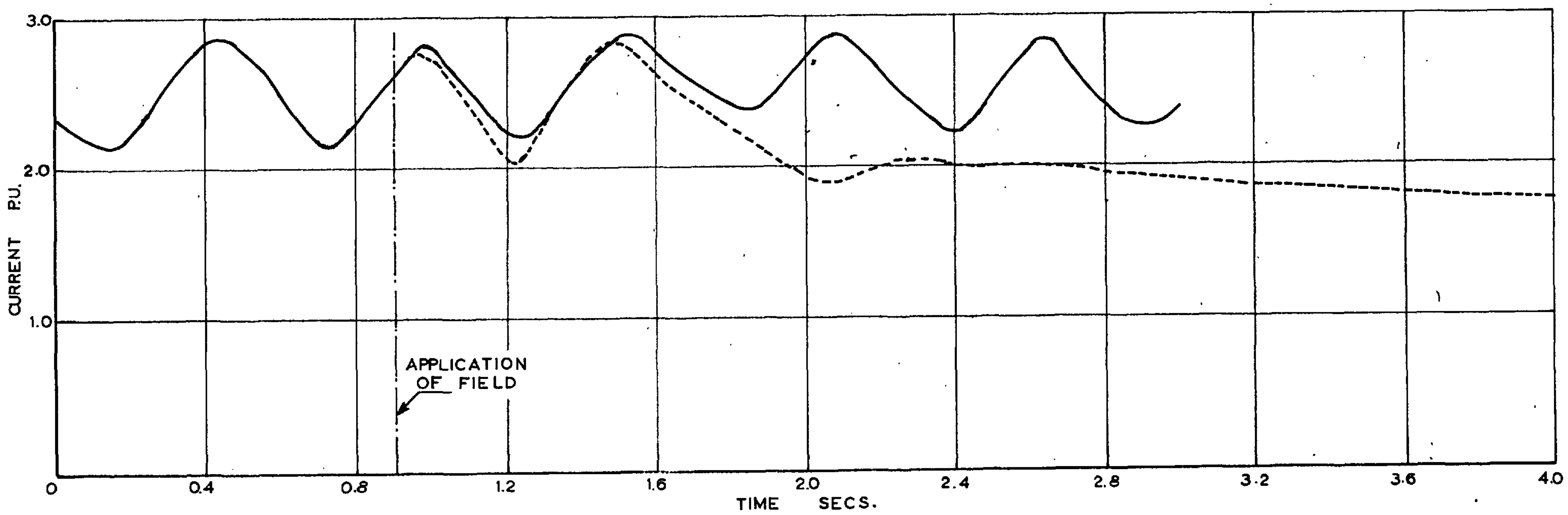


Fig·6.14(a) Variation of line current with load-angle



Fig·6.14(b) Variation of line current with time

Field shorted on itself, T_m=1.0p.u., r_f =0.00089 p.u., x_e=0, Laminated rotor

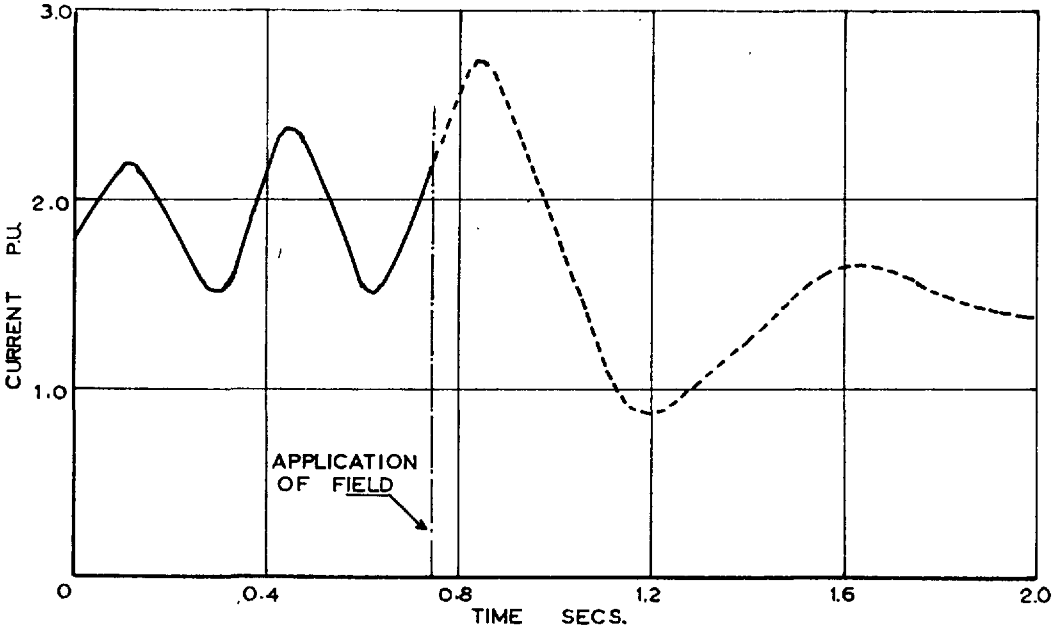


Fig·6.15 Variation of line current with time

Field shorted on itself, T_m =0·75 p.u., r_f =0·00089 pu, x_e=0, Laminated rotor

Steady asynchronous operation ———

Resynchronisation - - - - -

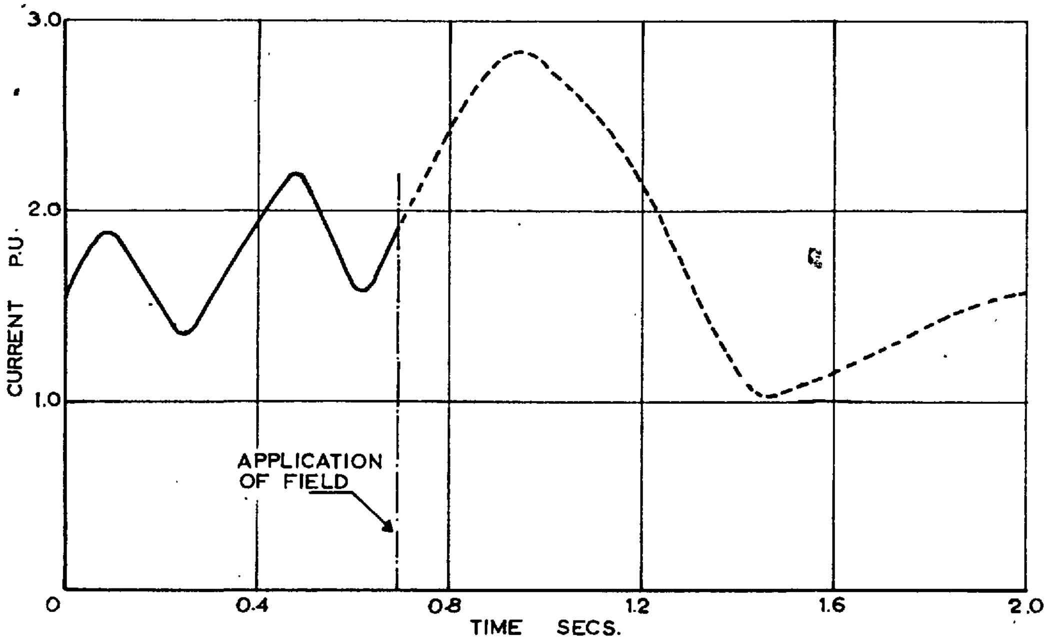


Fig·6.16 Variation of line current with time

Field open , T_m =1.0 p.u. , x_e =0 , Laminated rotor

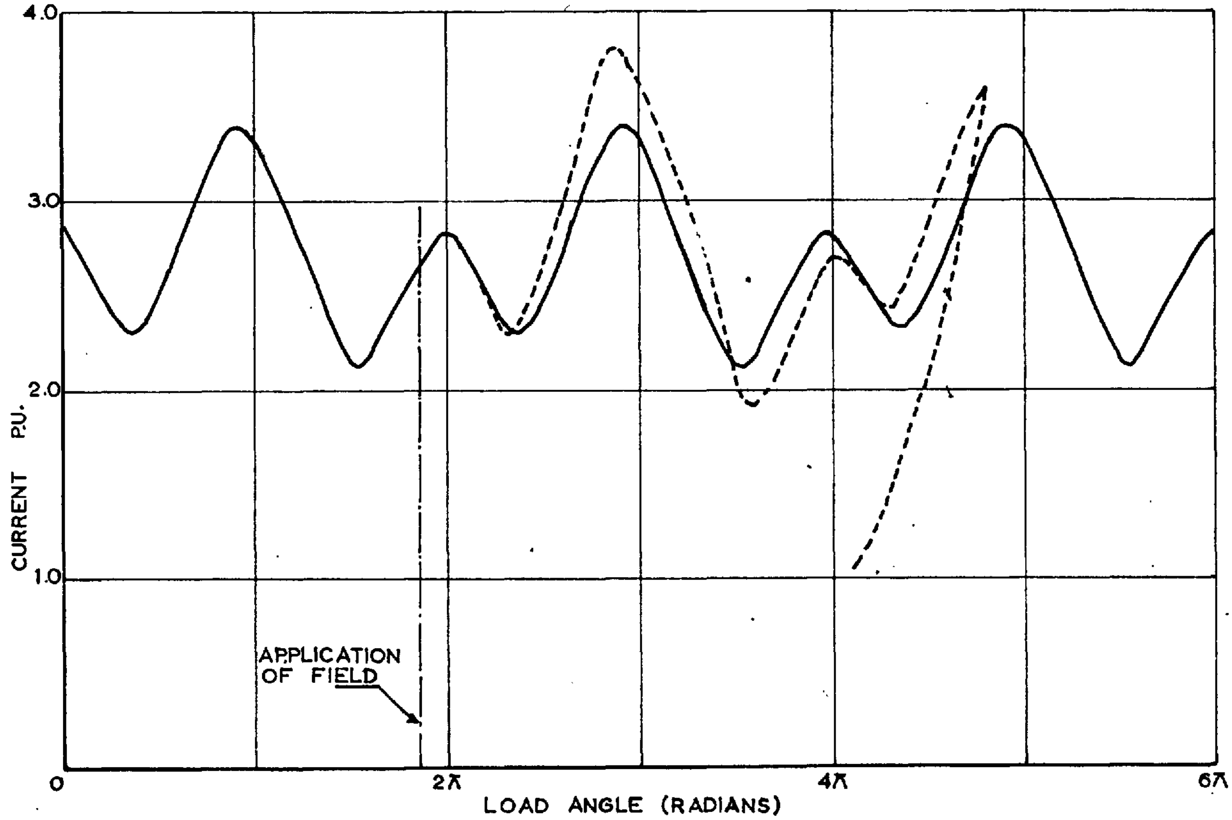
Steady asynchronous operation ————

Resynchronisation - - - - - -



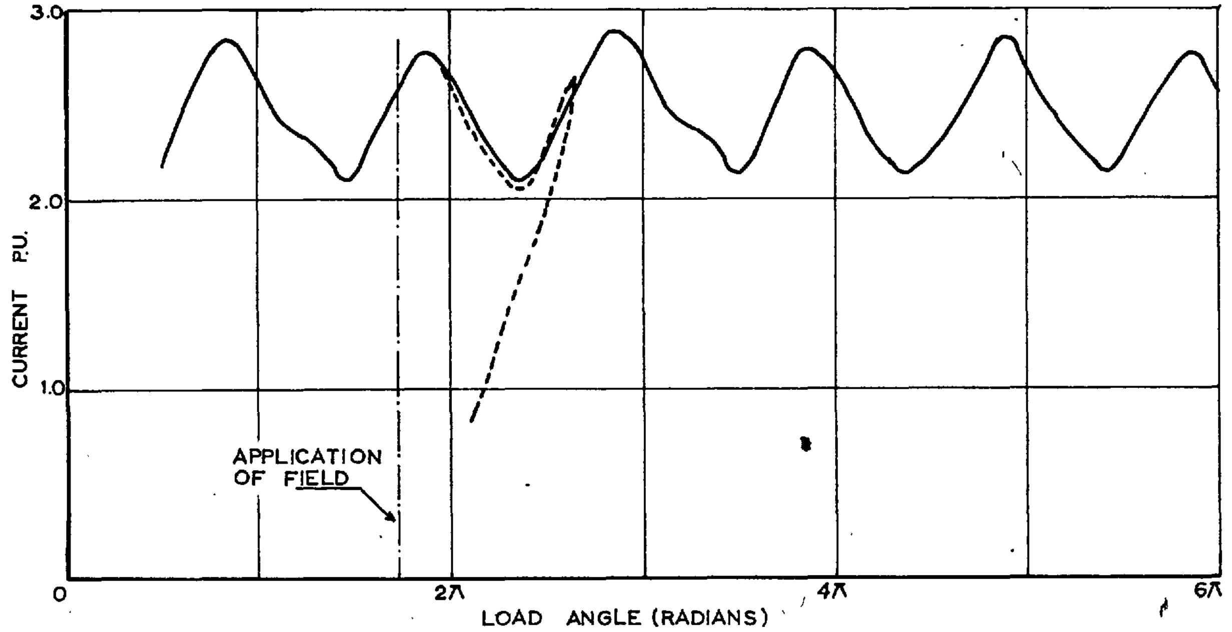
Fig· 6.17 Variation of line current with time

Field open , T_m =0·75 p.u. , x_e =0·12 p.u. , Laminated rotor



Fig·6.18(a)Variation of line current with load_angle

Field excited, $T_m = 1.0$ p.u., $x_e = 0$, Laminated rotor

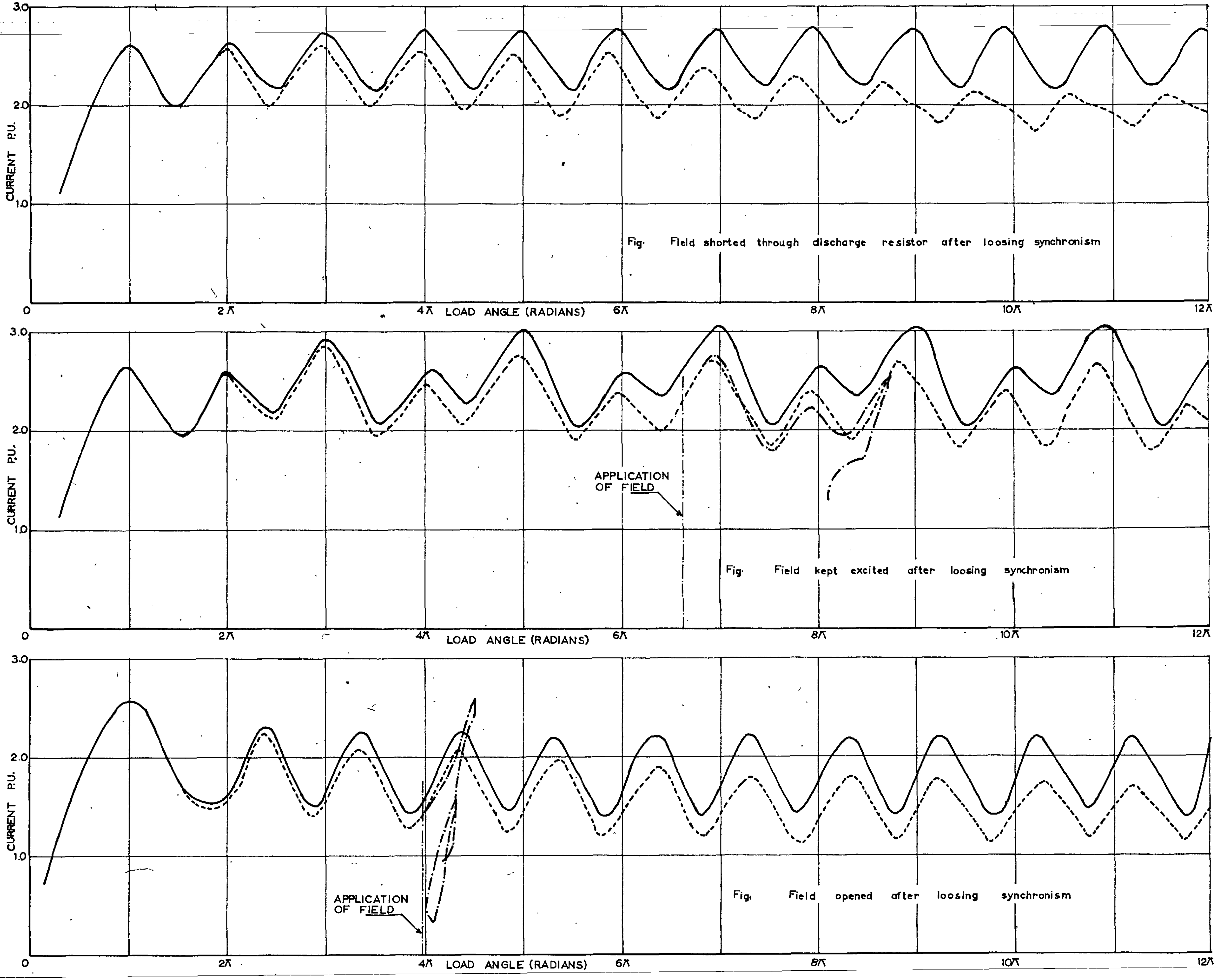


Fig·6.18(b)Variation of line current with load-angle

Field excited, $T_m = 0.75$ p.u., $x_e = 0$, Laminated rotor

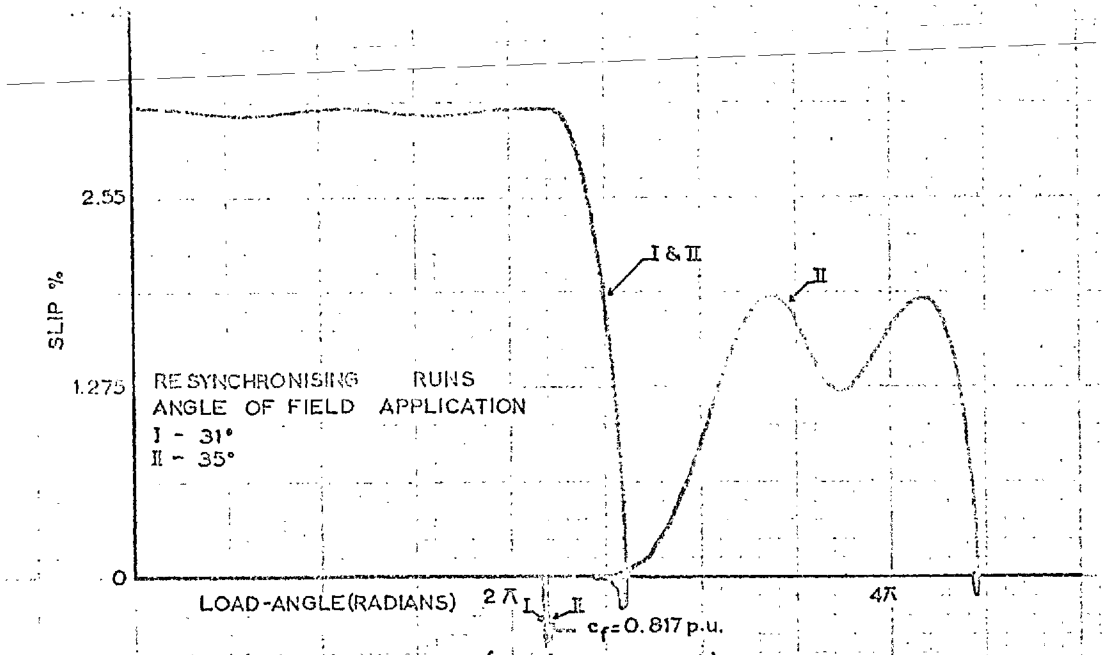
Steady asynchronous operation ———

Resynchronisation -------

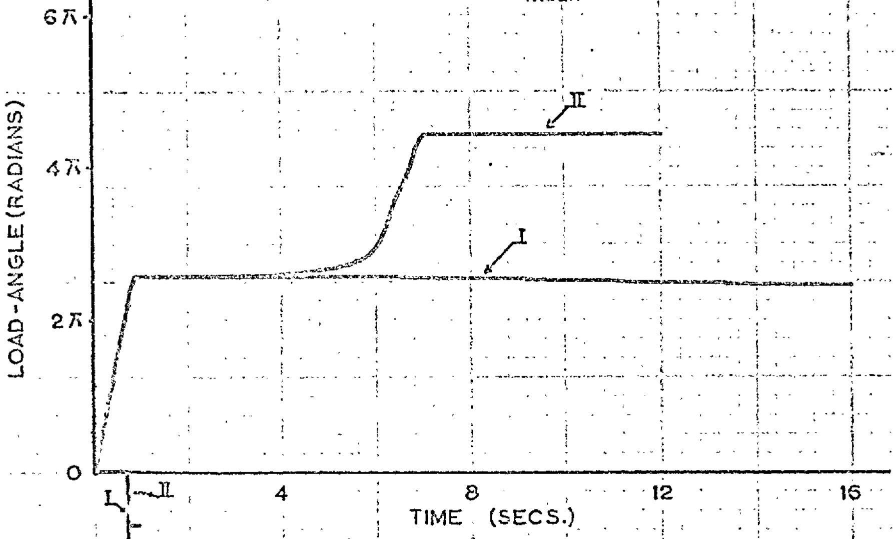


Fig·6.19 Variation of line current with load-angle as affected by turbine speed-governor action after loss of synchronism

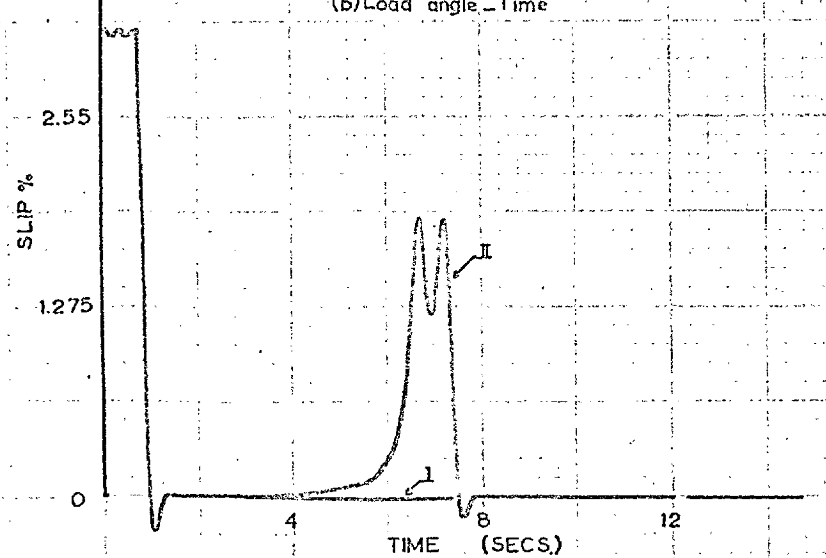
T_g = 4.0 secs., Droop = 4 %
T_m = 1.0 p.u., x_e = 0.12 p.u.
Laminated rotor
Without governor ————
With governor - - - - - - -
Resynchronisation —·—·—



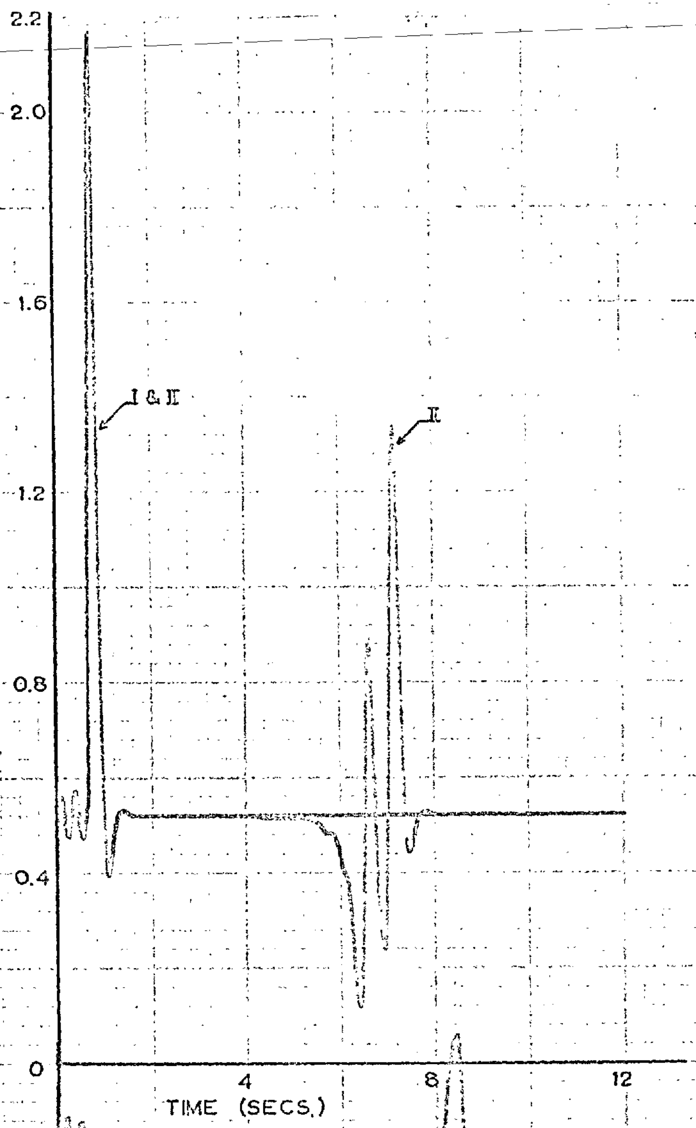
(a) % Slip – Load angle δ ($S_{mean} = 3.12\%$)



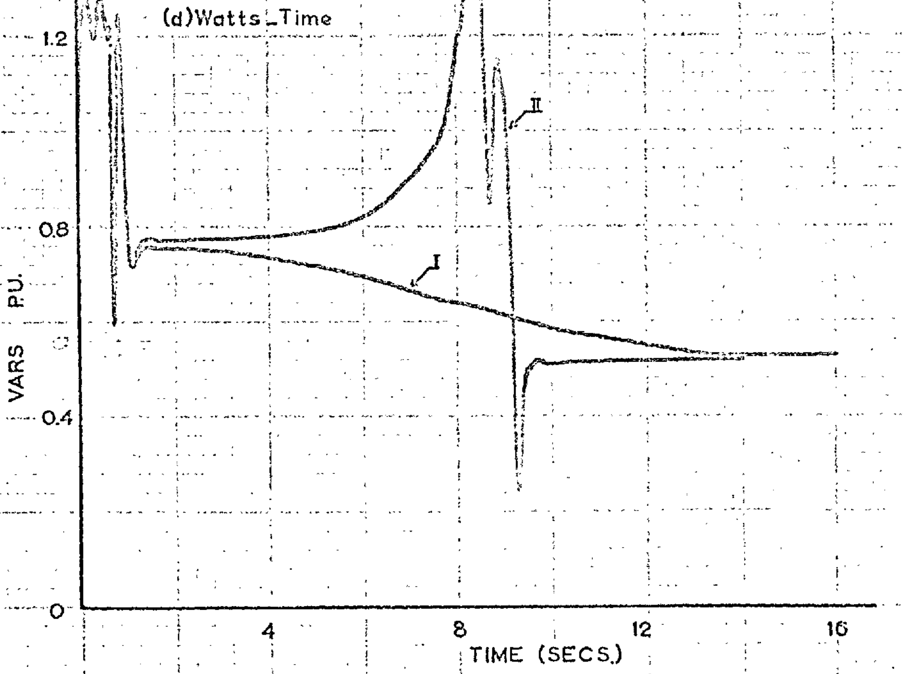
(b) Load angle – Time



(c) % Slip – Time



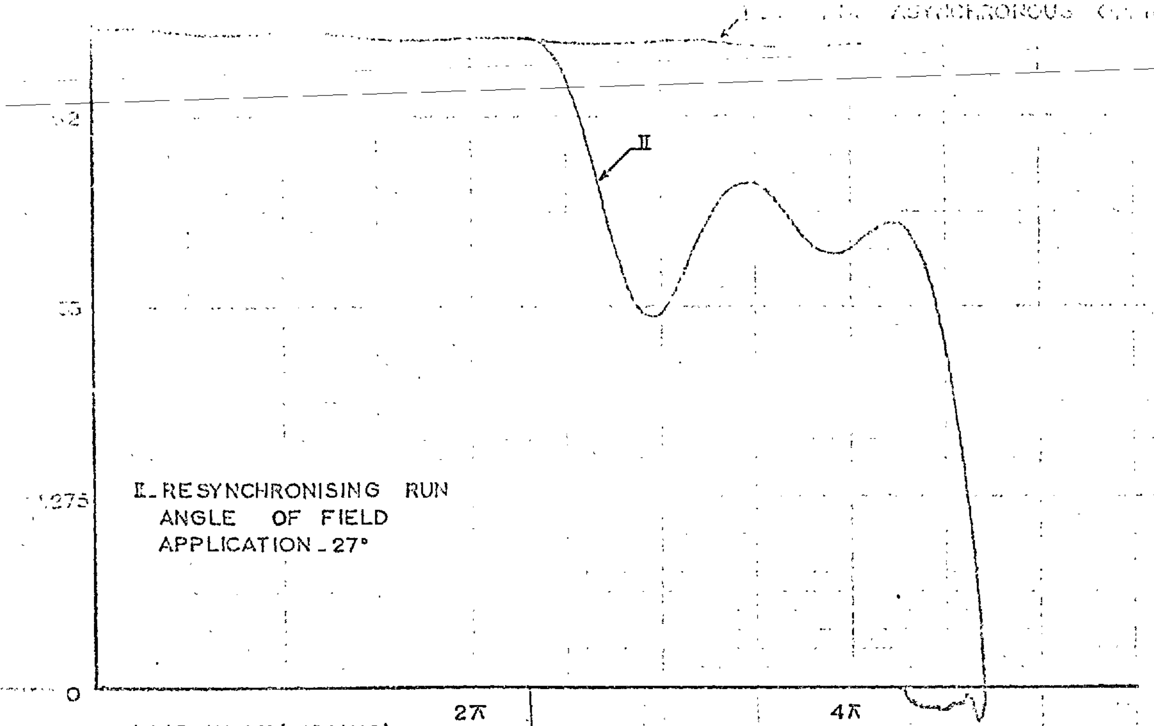
(d) Watts – Time



(e) Vars – Time

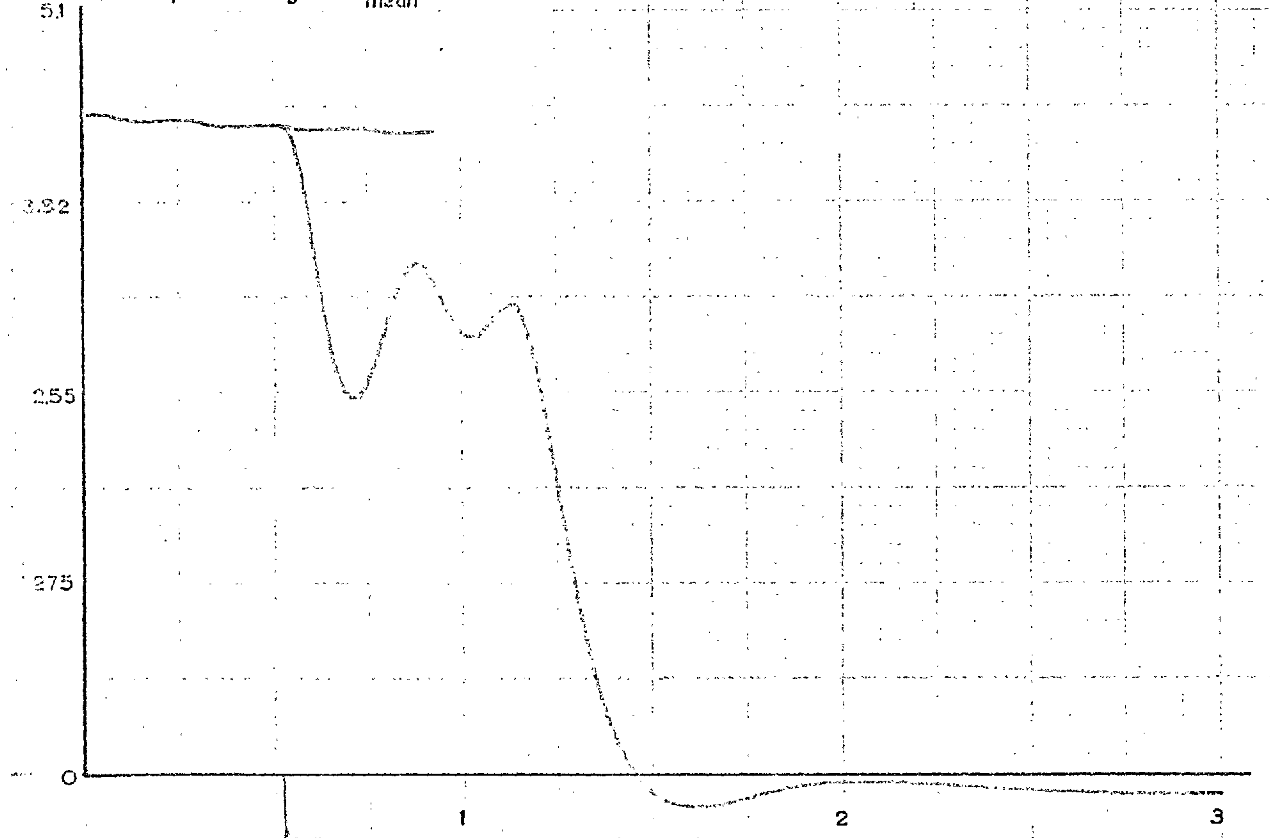
Fig. 6.20 Asynchronous operation and resynchronisation

Field open Solid rotor
$T_m = 0.522$ p.u. $X_e = 0$

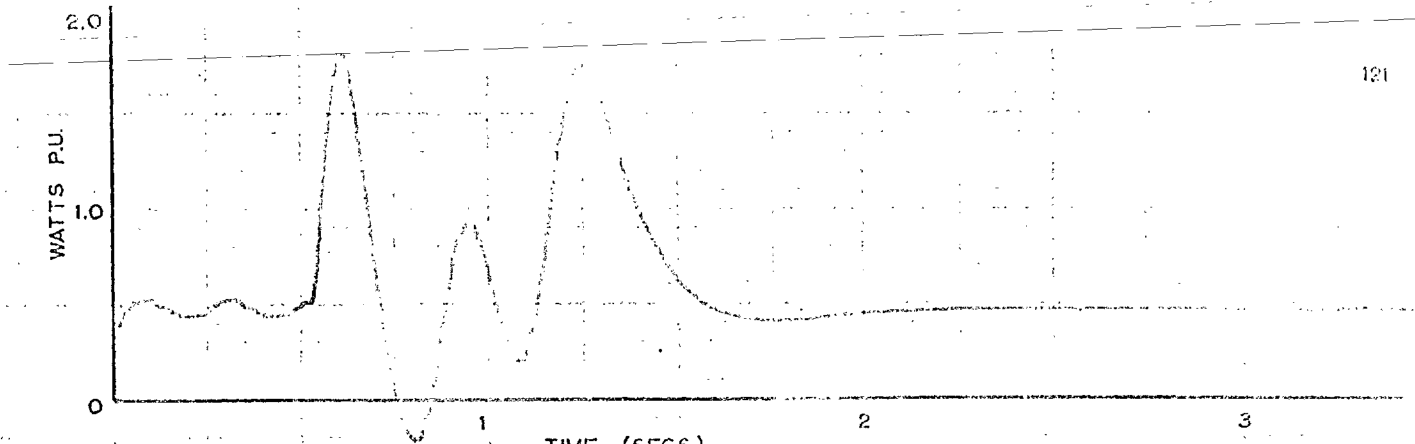


LOAD ANGLE (RADIANS)
(a)% Slip-Load angle δ (S_{mean}=4.335%)

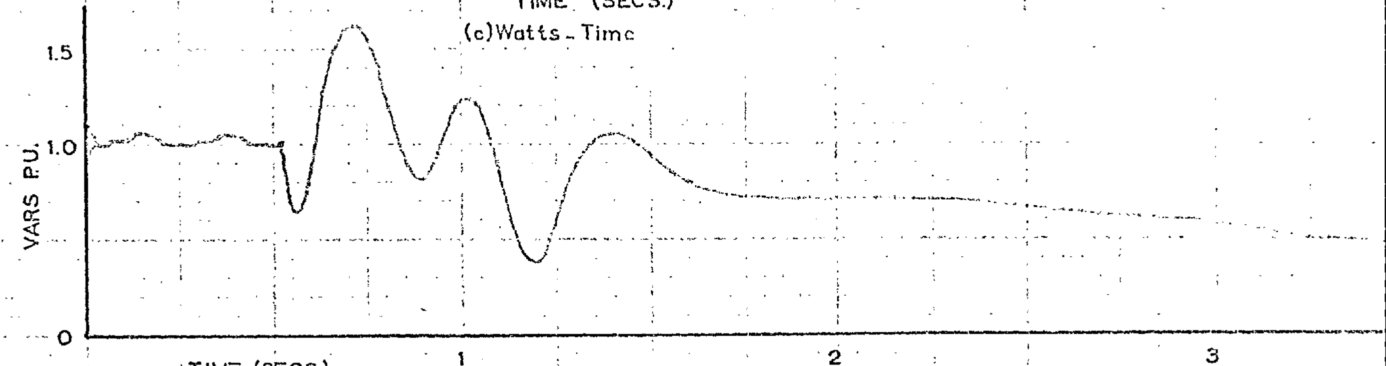
c_f = 1.0 p.u.



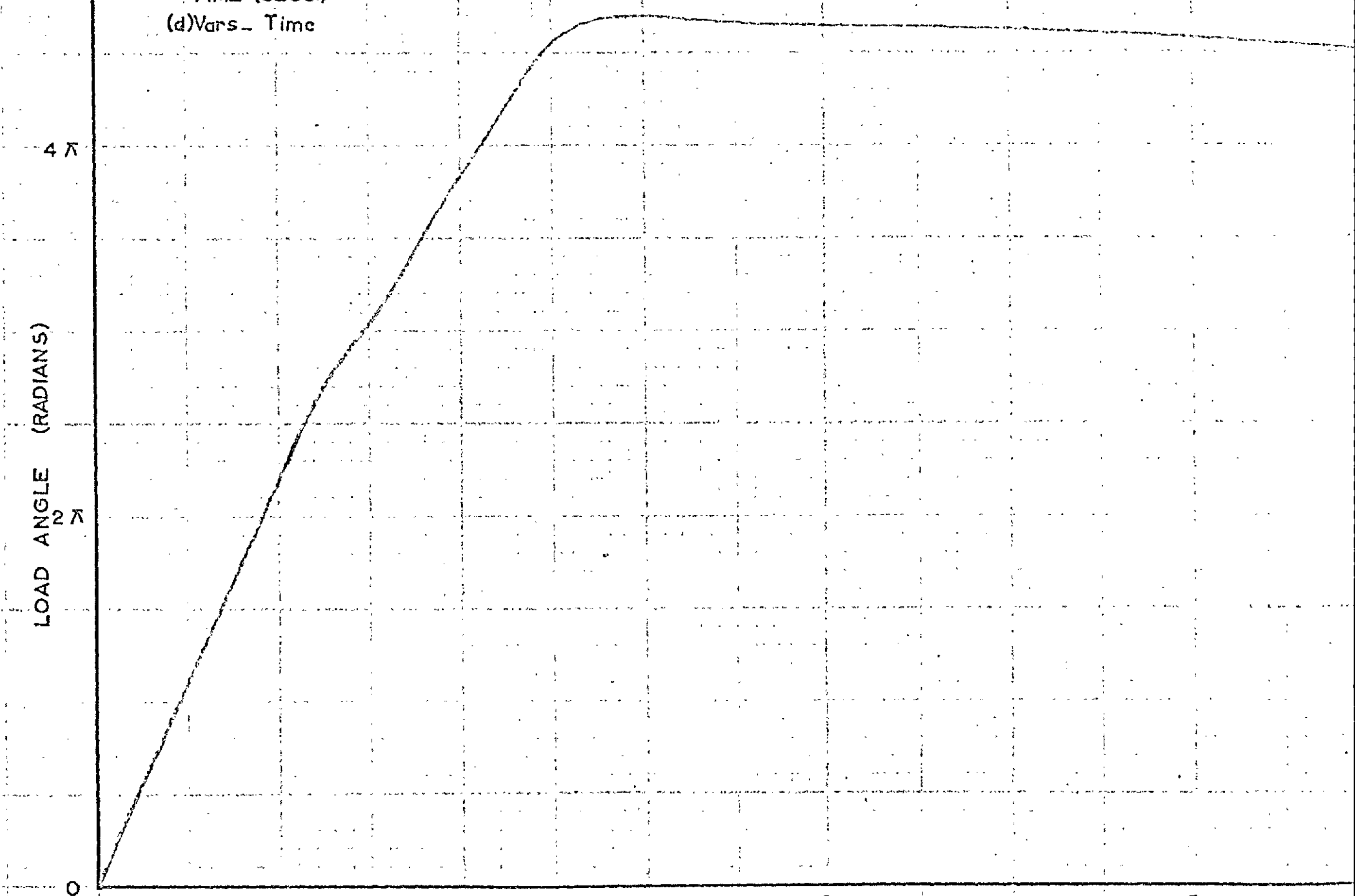
TIME (SECS.)
(b)% Slip-Time



TIME (SECS.)
(c)Watts-Time



TIME (SECS.)
(d)Vars-Time



1 TIME (SECS) 2 3
(e) Load angle-Time

Fig. 6.21 Asynchronous operation and resynchronisation

Field open Solid rotor
T_m =0.47 p.u. X_e =0.142 p.u.

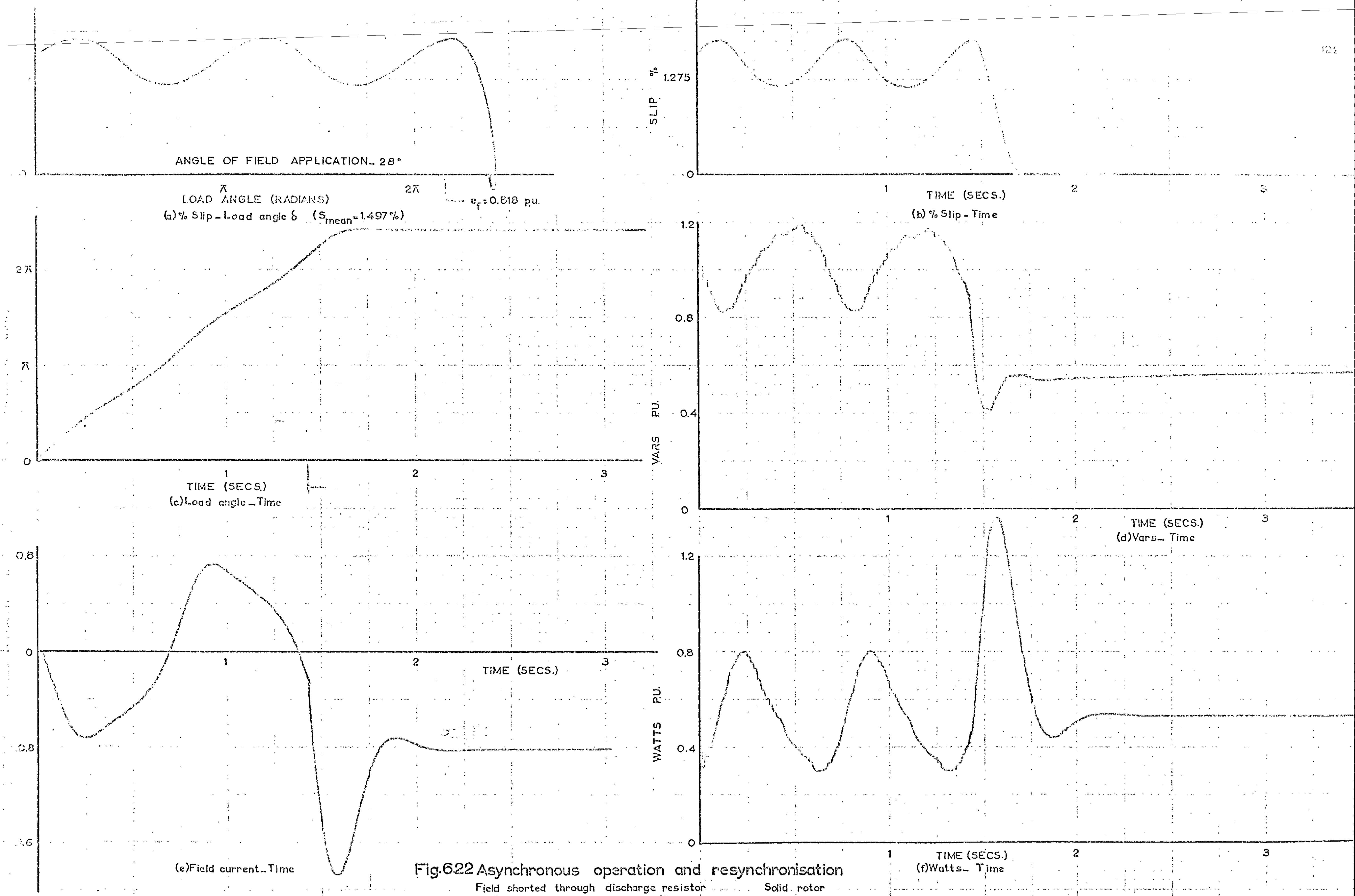
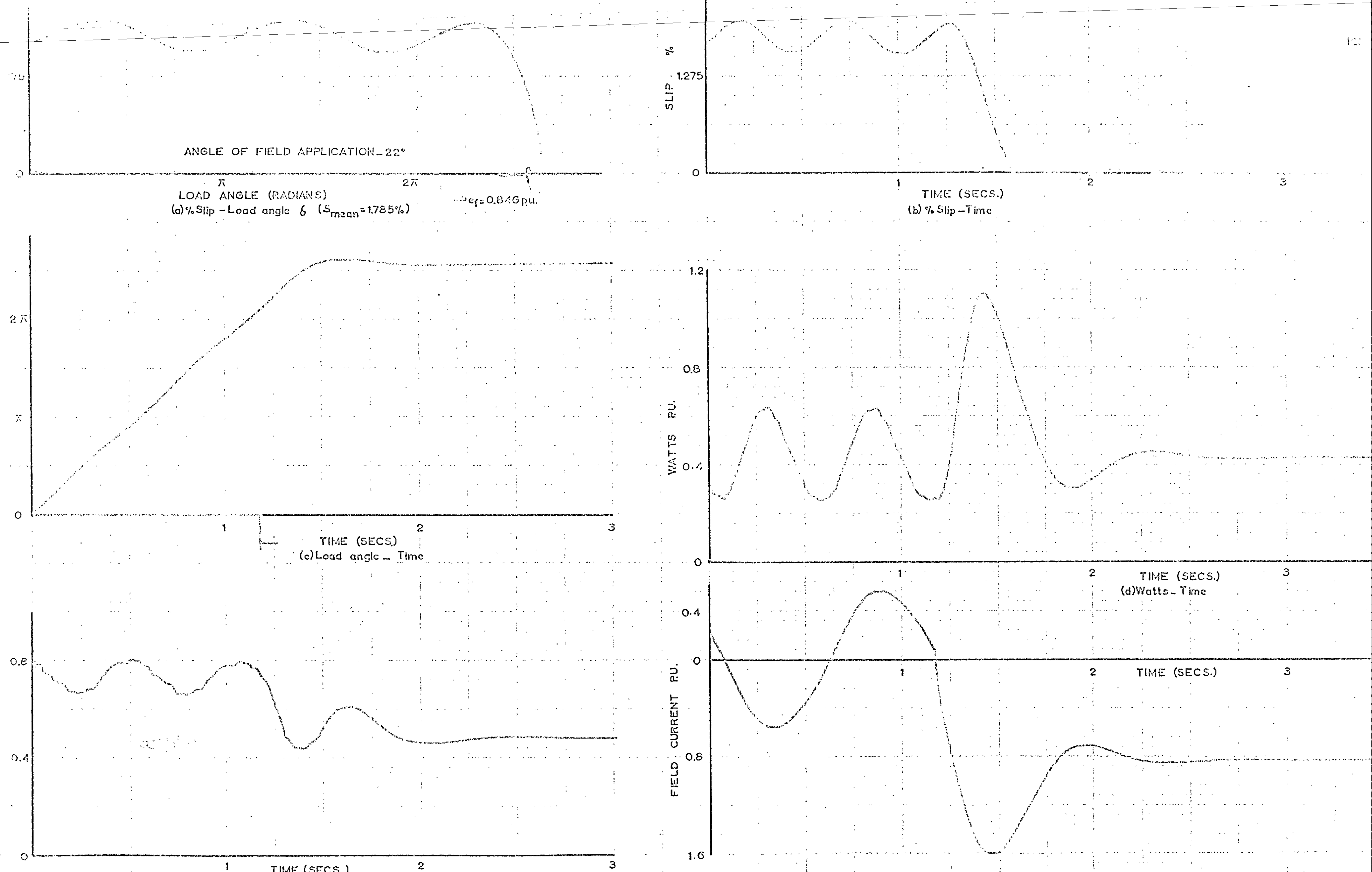


Fig. 6.22 Asynchronous operation and resynchronisation

Field shorted through discharge resistor Solid rotor
T_m = 0.544 p.u. $X_e = 0$



(a) % Slip - Load angle δ (S_{mean}=1.785%)

(b) % Slip - Time

(c) Load angle _ Time

(d) Watts _ Time

(e) Vars _ Time

(f) Field current _ Time

Fig.6.23 Asynchronous operation and resynchronisation

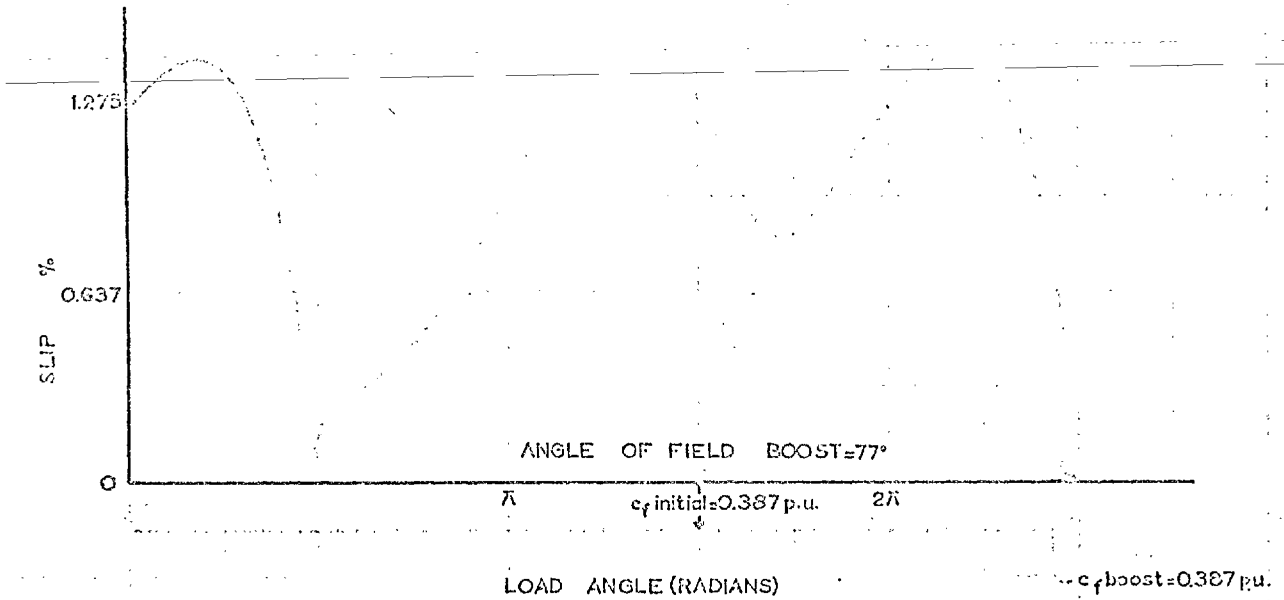
Field shorted through discharge resistor Solid rotor

T_m =0.442 p.u. X_e=0.284 p.u.

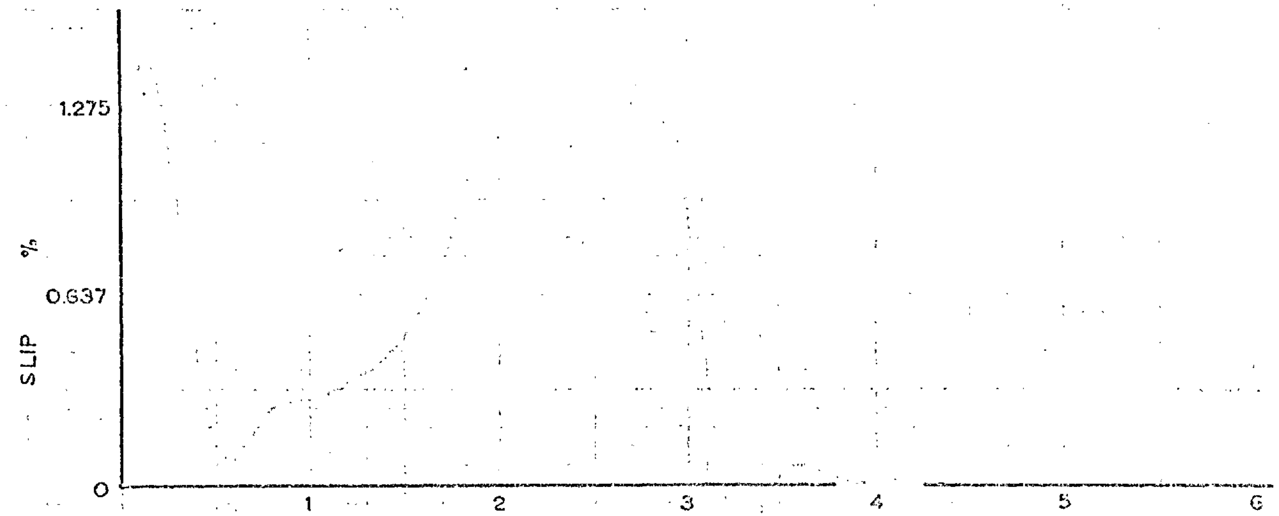
Fig.6.24 Asynchronous operation and resynchronisation

Field excited Solid rotor

T_m =0.496 p.u. c_f initial=0.387 p.u. X_c =0.142 p.u.

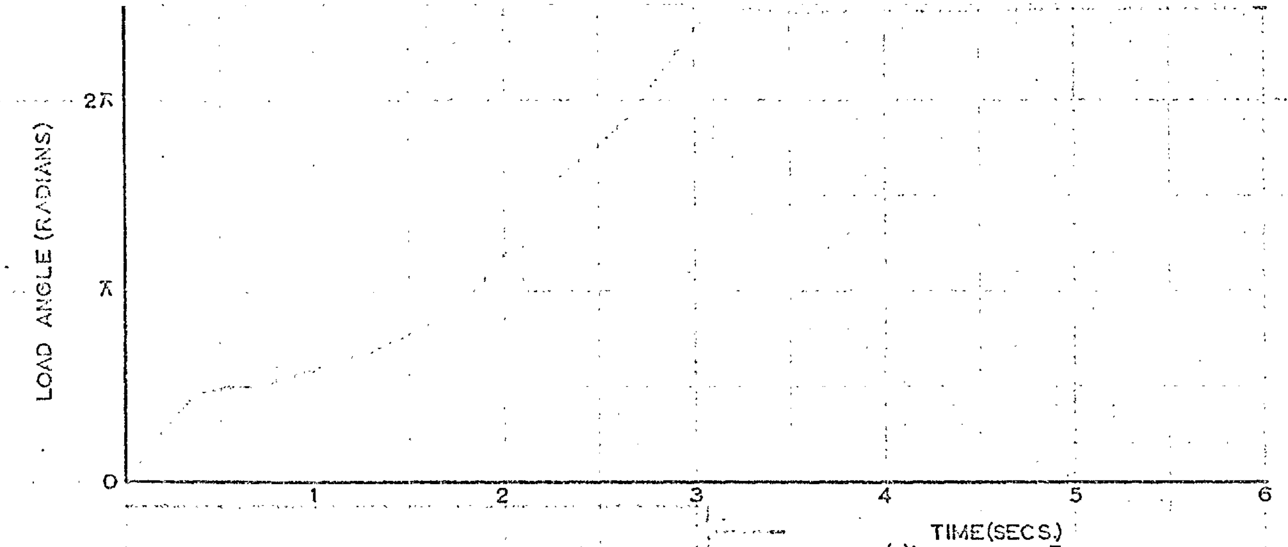


(a)%Slip-Load angle (S_{mean}=0.982%)

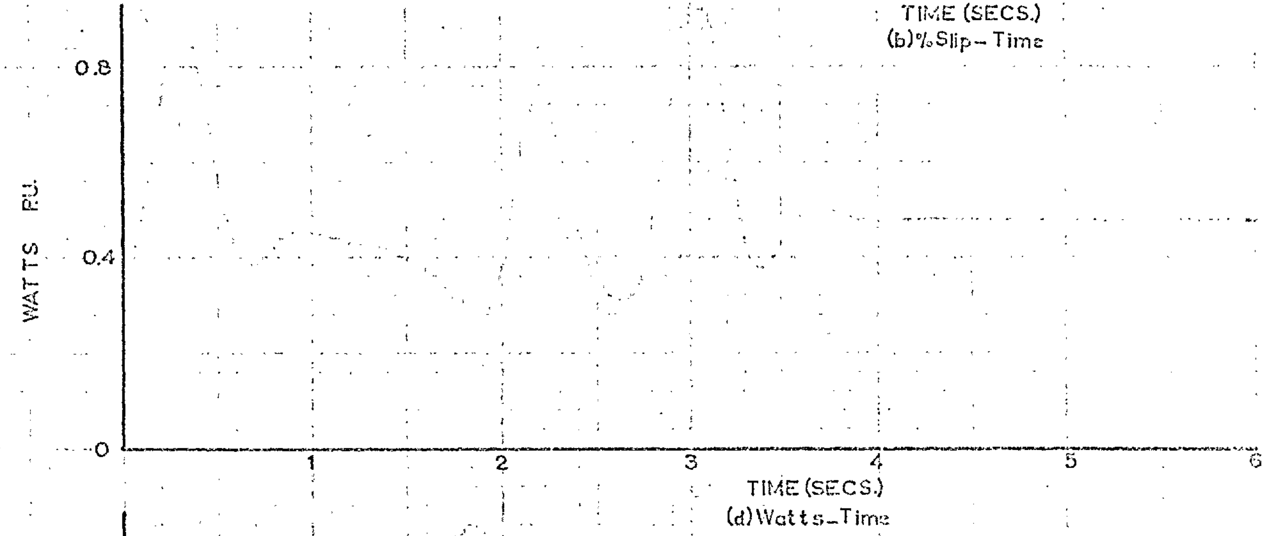


TIME (SECS.)

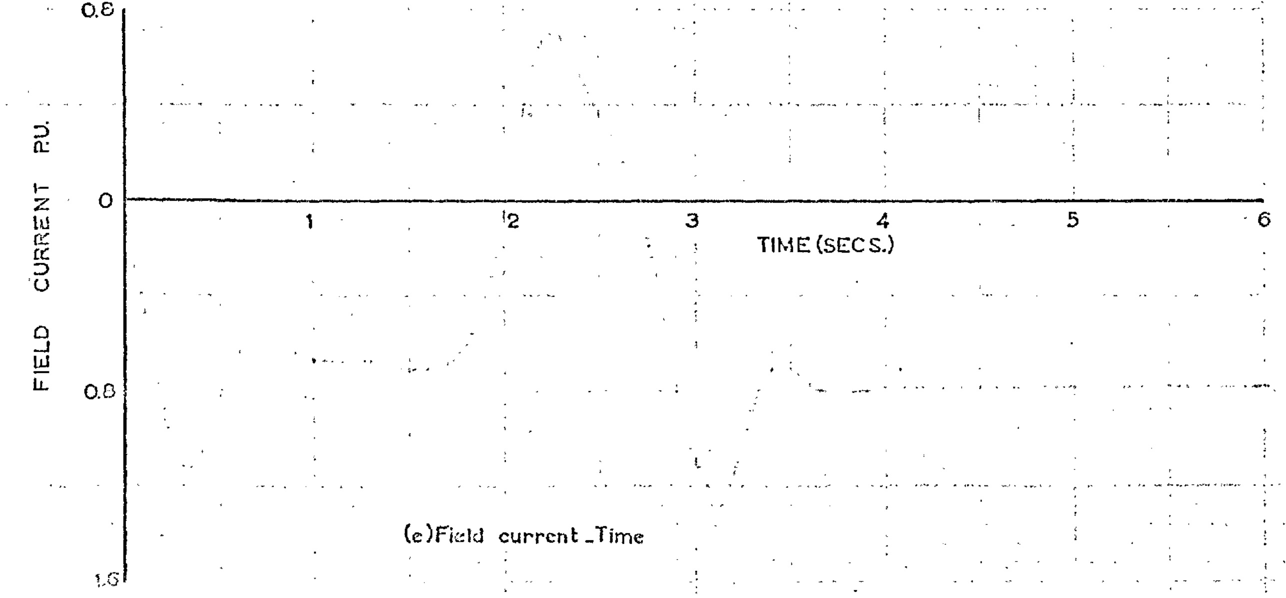
(b)%Slip-Time



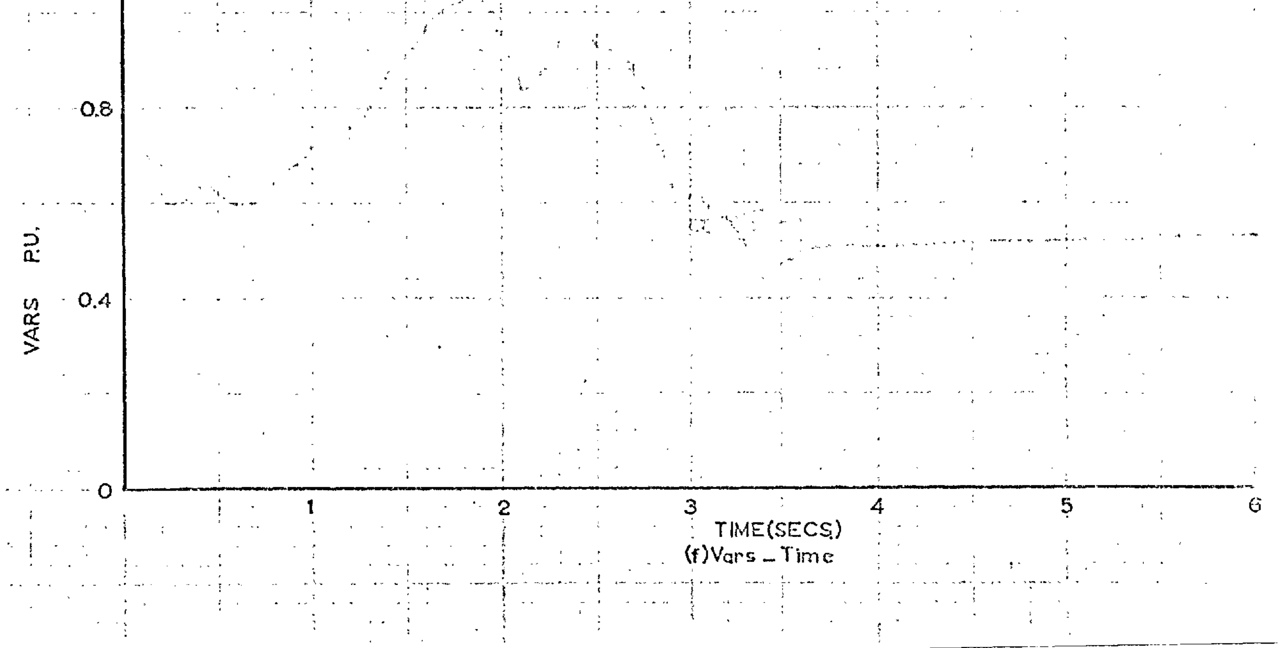
(c)Load angle-Time



(d)Watts-Time



(e)Field current-Time



(f)Vars-Time

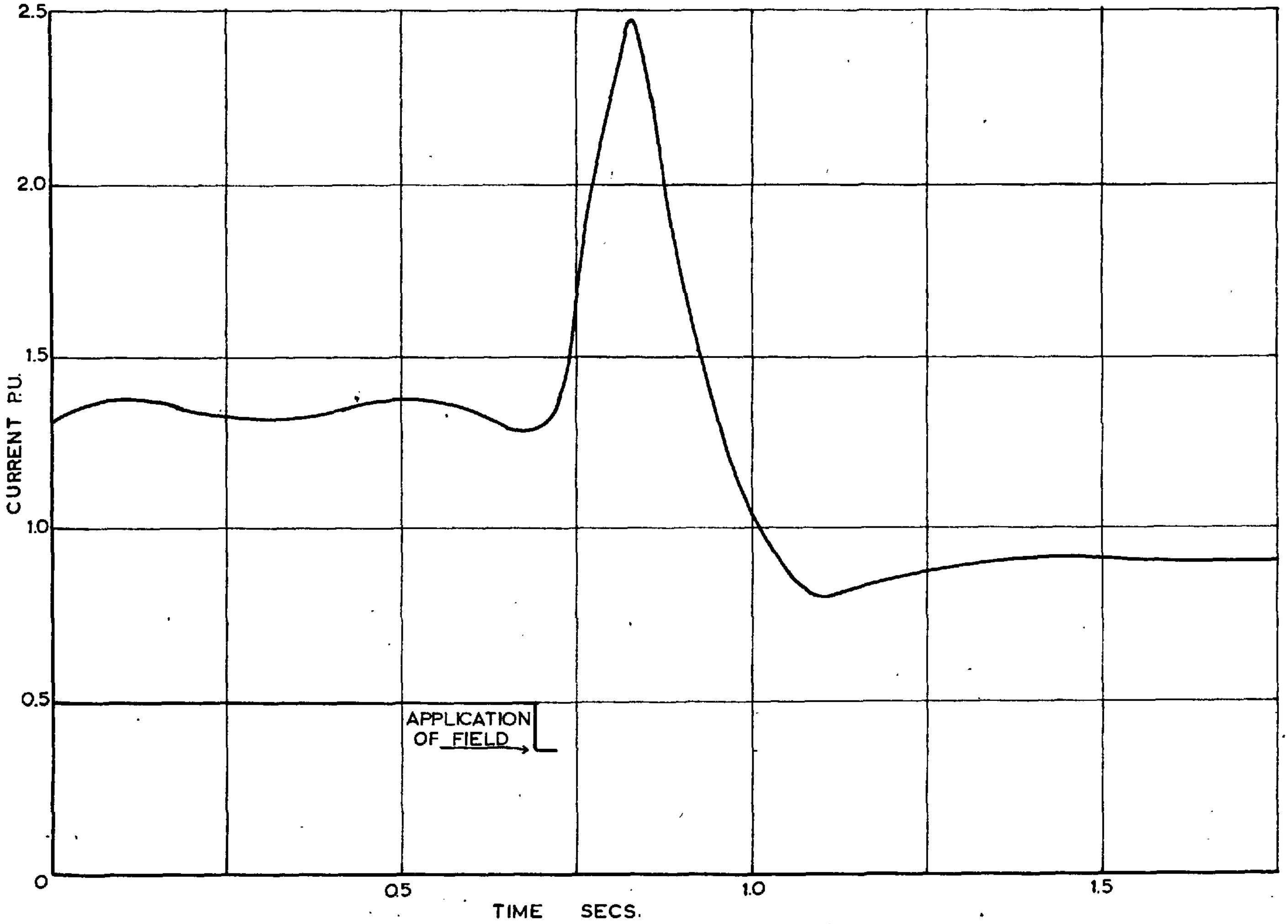


Fig. 6.25 Variation of line current with time

Solid rotor . Field open , $T_m = 0.522$ p.u. , $x_e = 0$

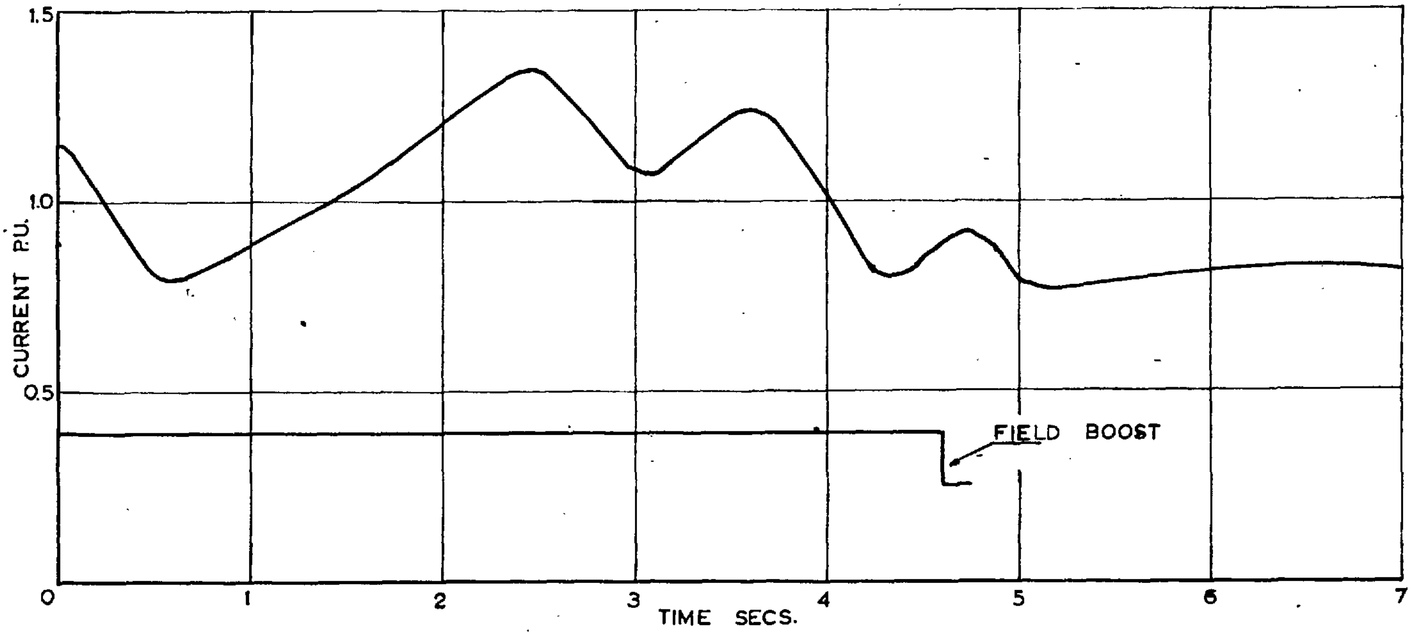


Fig 6.26 Variation of line current with time

Solid rotor , Field excited , $T_m = 0.496$ p.u., $x_e = 0$

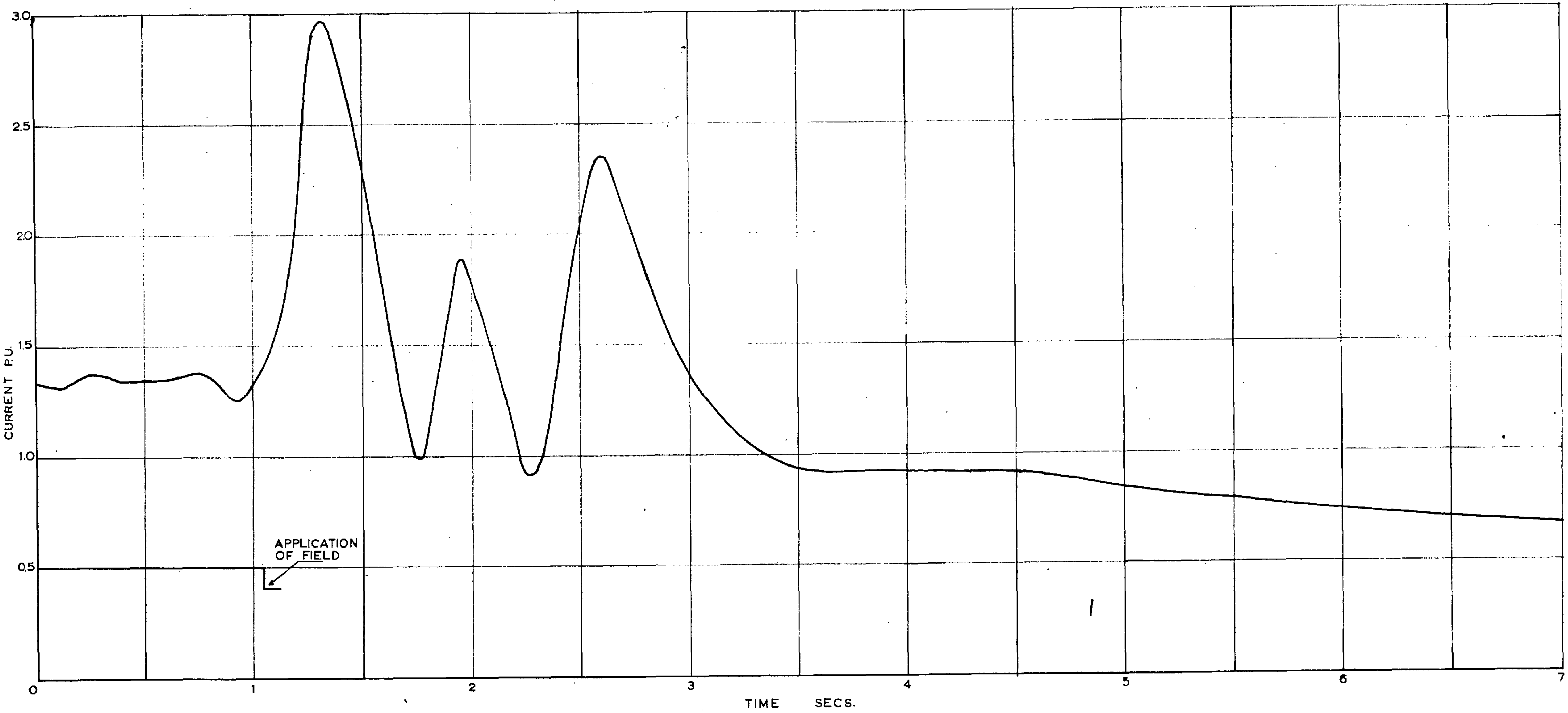
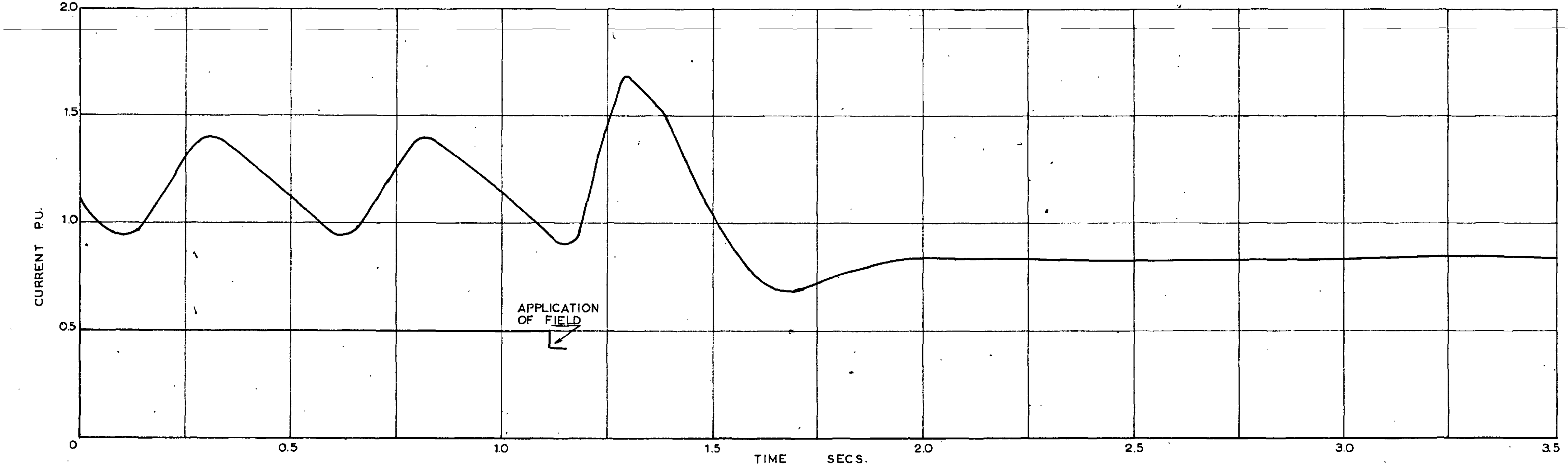
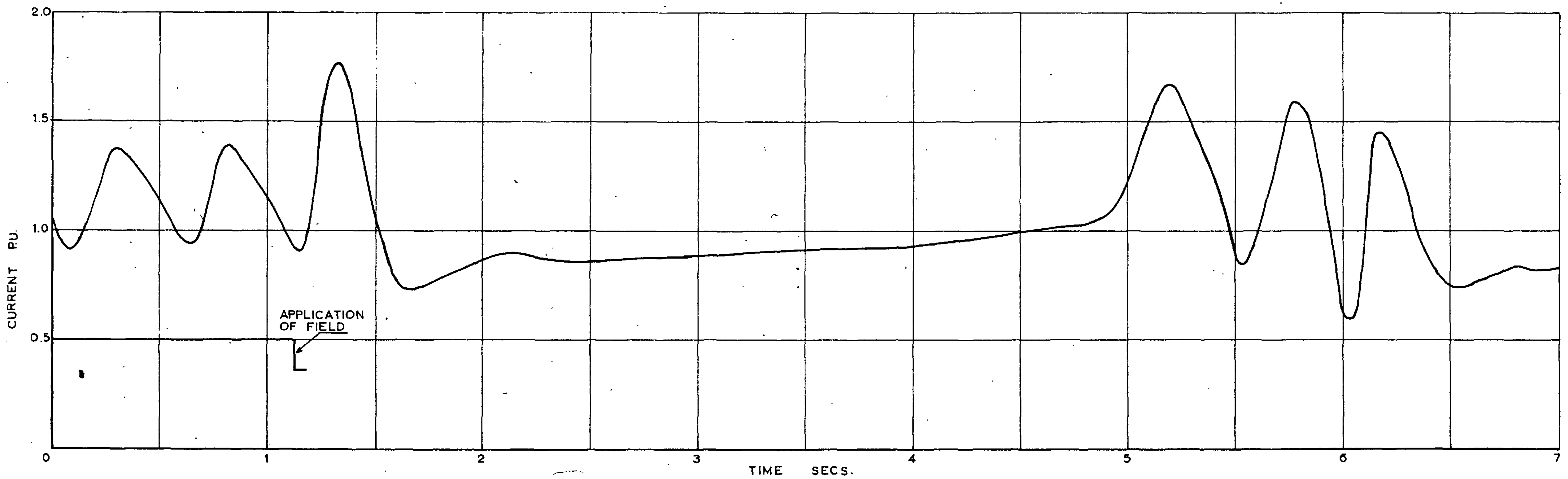


Fig. 6.27 Variation of line current with time

Solid rotor, Field open, $T_m = 0.47$ p.u., $x_e = 0.142$ p.u.



(a) Field applied at $\delta = 28°$, resynchronisation successful



(b) Field applied at $\delta = 34°$, resynchronisation unsuccessful

Fig. 6.28 Variation of line current with time

Figure shows effect of delay in applying field excitation

Solid rotor, Field shorted through discharge resistor, $T_m = 0.509$ p.u., $x_e = 0.142$ p.u.

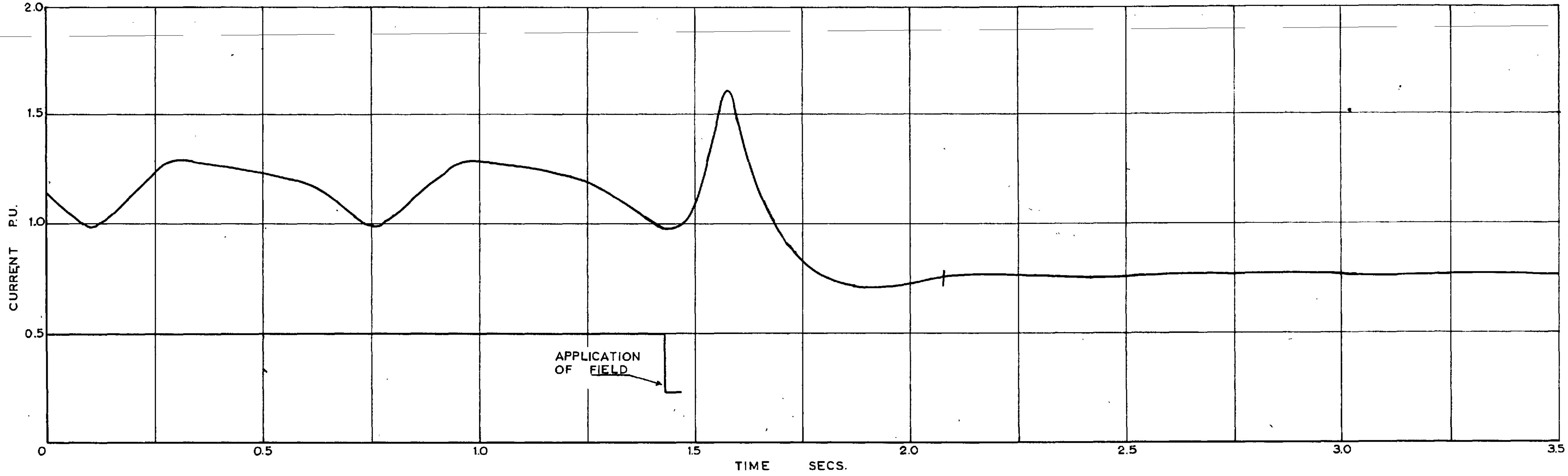


Fig. 6.29 Variation of line current with time

Solid rotor, Field shorted through discharge resistor, $T_m = 0.544$ p.u., $x_e = 0$

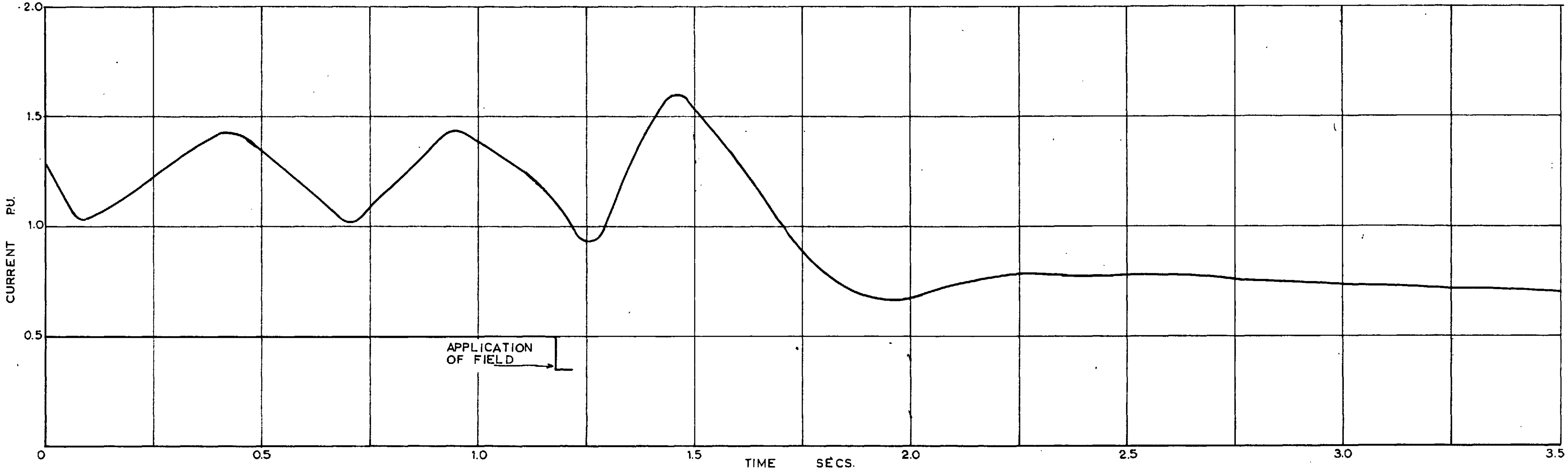


Fig. 6.30 Variation of line current with time

Solid rotor, Field shorted through discharge resistor, $T_m = 0.442$ p.u., $x_e = 0.284$ p.u.

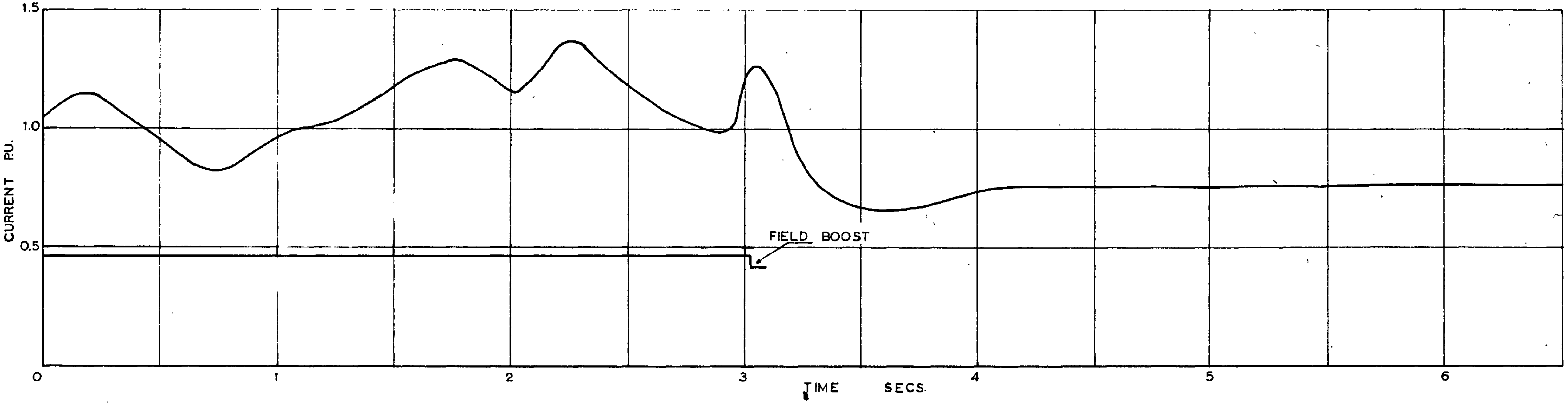


Fig. 6.31 Variation of line current with time

Solid rotor, Field excited, T_m =0.496 p.u., x_e =0.142 p.u.

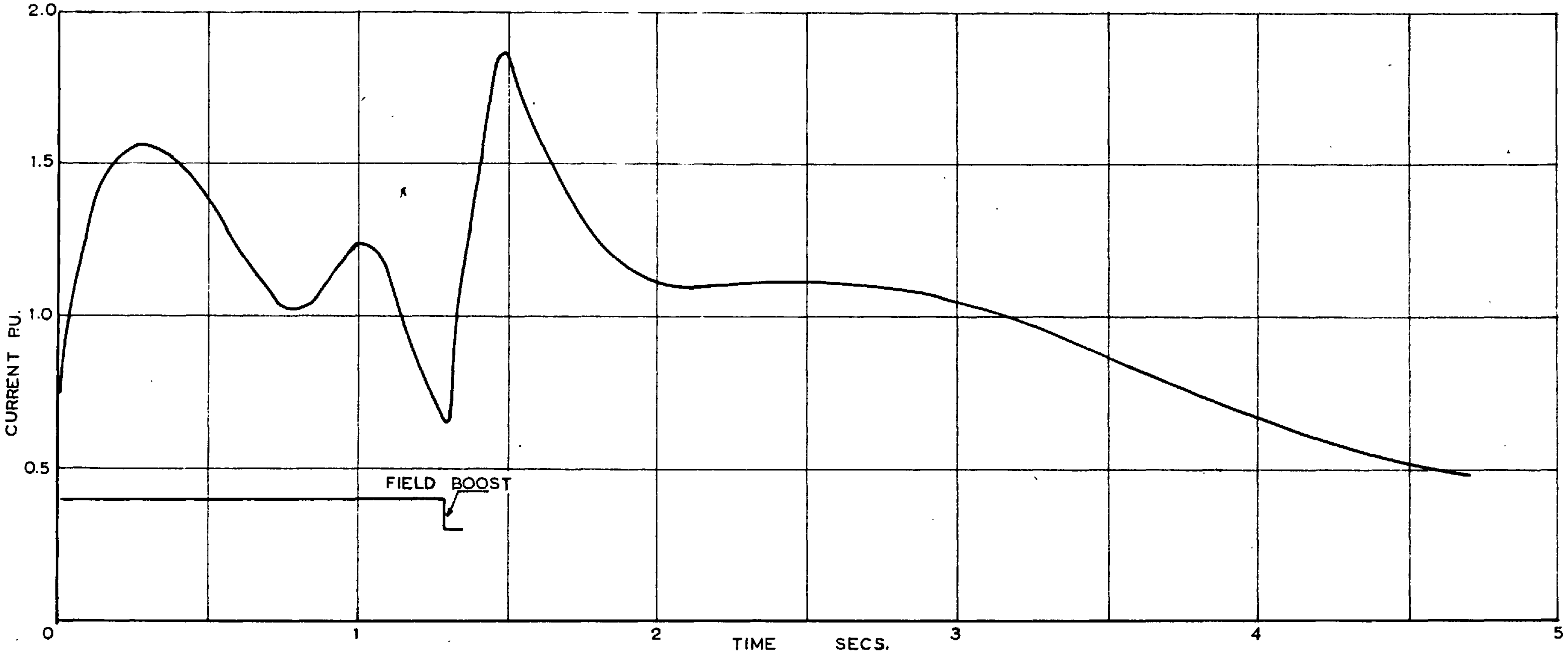


Fig. 6.32 Variation of line current with time

Solid rotor, Field excited, T_m =0.471 p.u., x_e =0.284 p.u.

i.e. (i) with field open and (ii) field shorted and unexcited. This is brought out even more clearly in Figs. 6.33 to 6.38 where the maxima and minima are plotted against the mean of a number of experimental quantities.

6.3.1 Slip pulsations

The magnitude of slip pulsations is inversely proportional to the mean slip, as for example, at a mean slip of 2.18 % [Fig. 6.6(b)], the slip varies between 1.75 % and 2.62 %, whereas at a mean slip of 3.23 % (Fig. 6.9), the variation is only between 3.06 % and 3.38 %. This fact is more clearly shown in Figs. 6.39 and 6.40 where the fluctuation in slip $\left[(S_{max} - S_{min})/S_{mean}\right]$ has been plotted against mean slip for a large number of cases. It will be noticed from these figures, that the amplitude of slip fluctuations drops rapidly with increase in speed. This is because the rotor, due to its high moment of inertia, cannot follow the variations in torque that the various factors tend to produce.

At very low values of slip, i.e. most of the studies with slips below 1.0 %, fluctuations were found to be so large, that in certain cases, the machine even went into the motoring region for a brief interval of time during each slip cycle. At these intervals, the machine tended to lock, but after a brief interval of synchronous motion again went into the next slip cycle. Examples of this are shown in Figs. 6.5, 6.8 and 6.24.

From Eqn. (B.25), variations in slip were expected to be sinusoidal, but at low values of slip (the only range

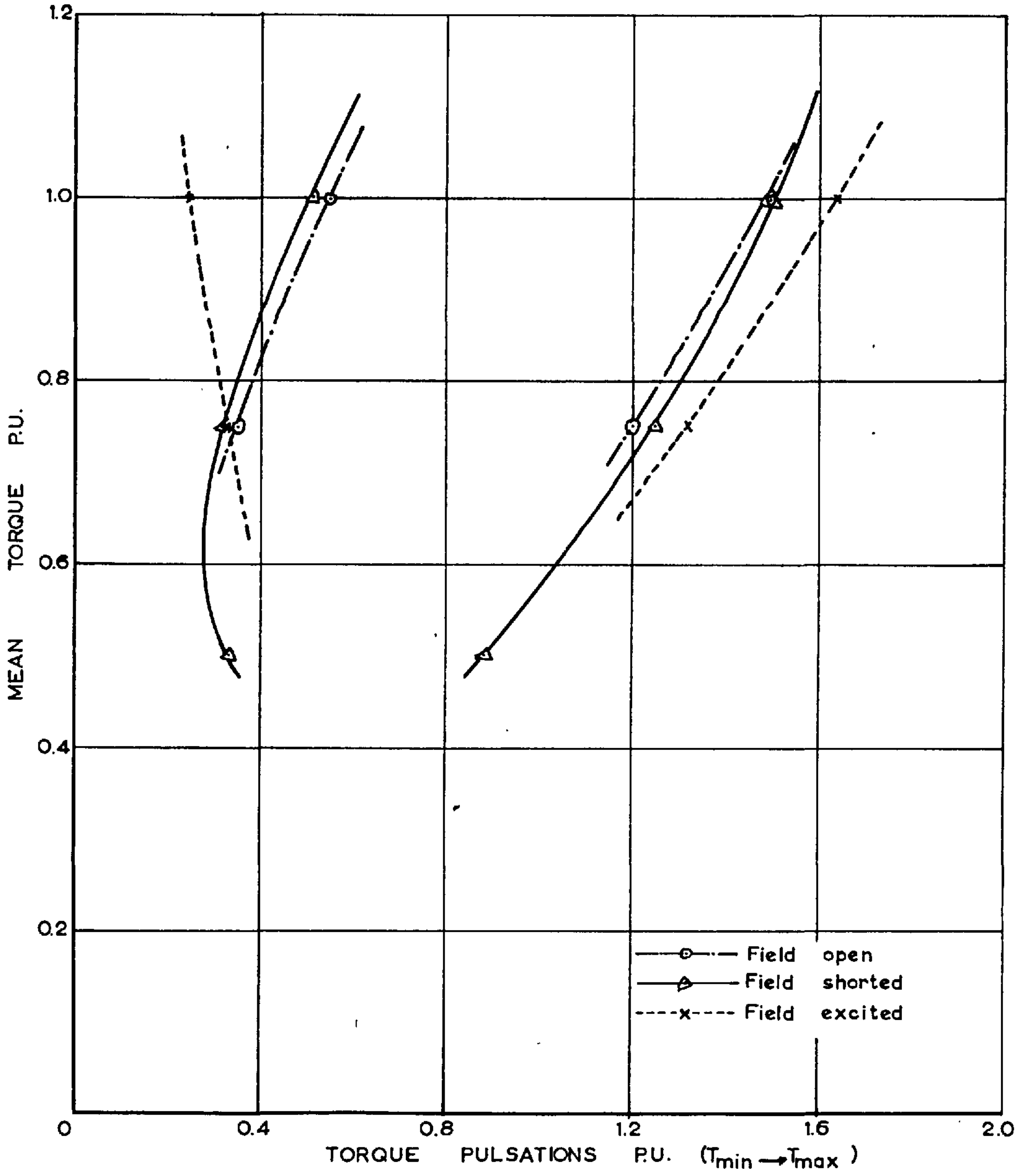


Fig. 6.33 Effect of field connection on magnitude of torque pulsations

Micro_machine with laminated rotor

Asynchronous operation study on analogue computer

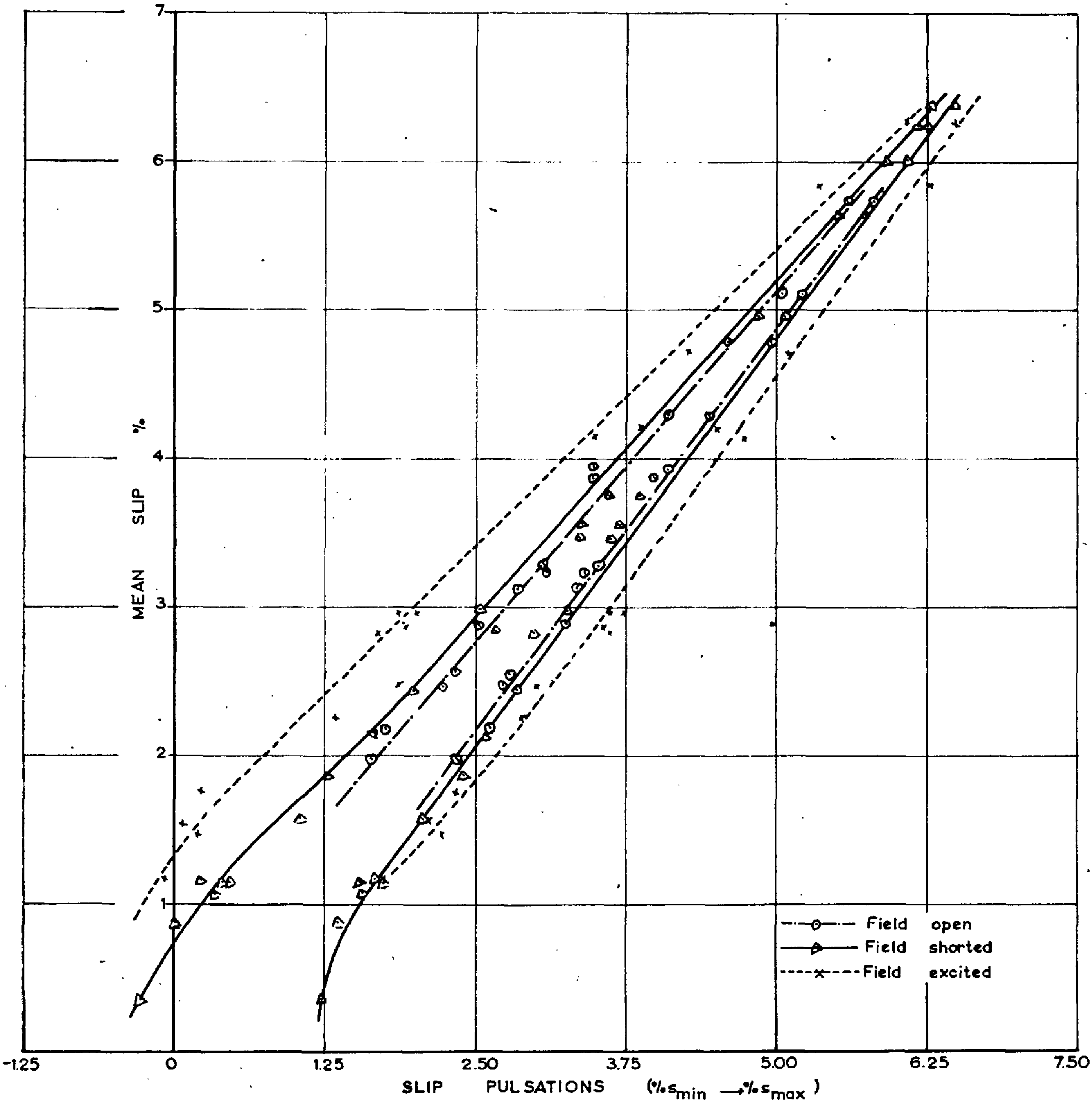


Fig. 6.34 Effect of field connection on magnitude of slip pulsations

Micro_machine with laminated rotor

Asynchronous operation study on analogue computer

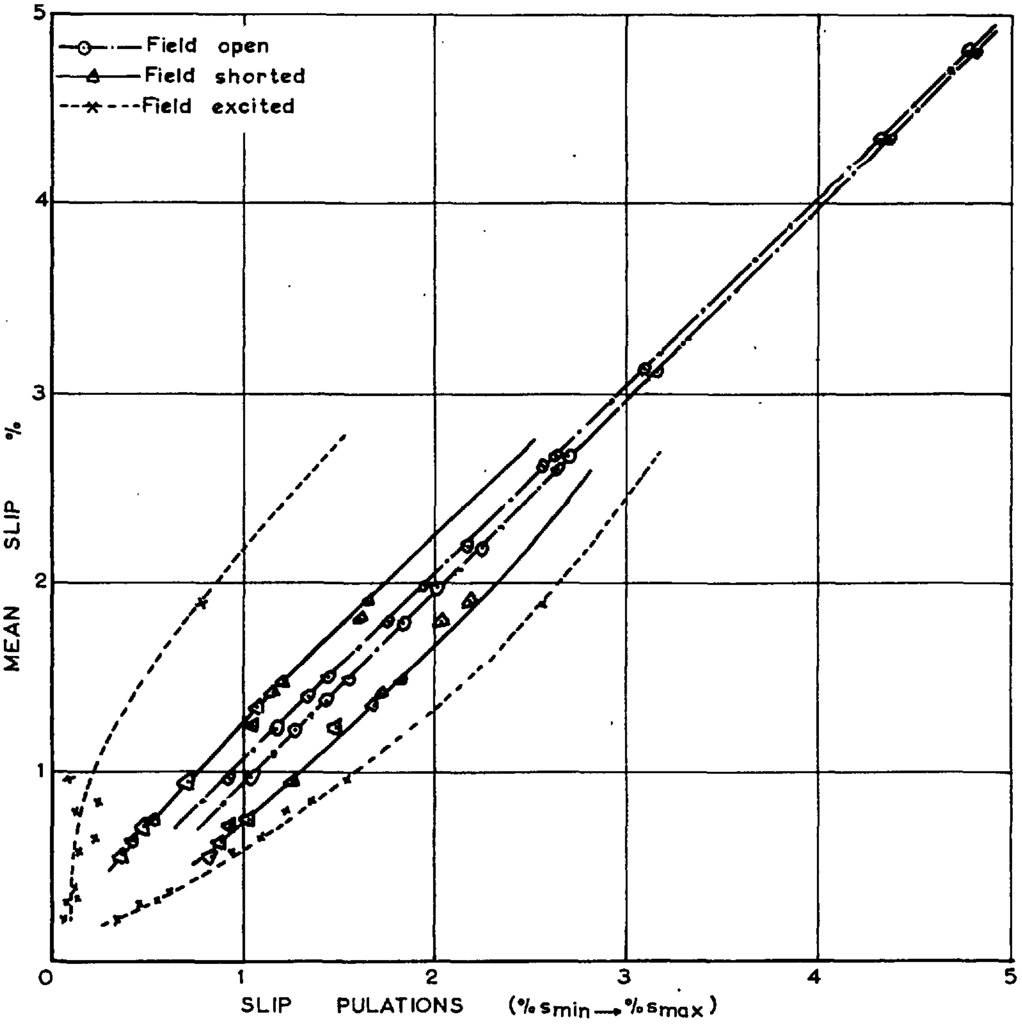


Fig. 6.35 Effect of field connection on magnitude of slip pulsations

Micro-machine with solid rotor

Asynchronous operation study on analogue computer

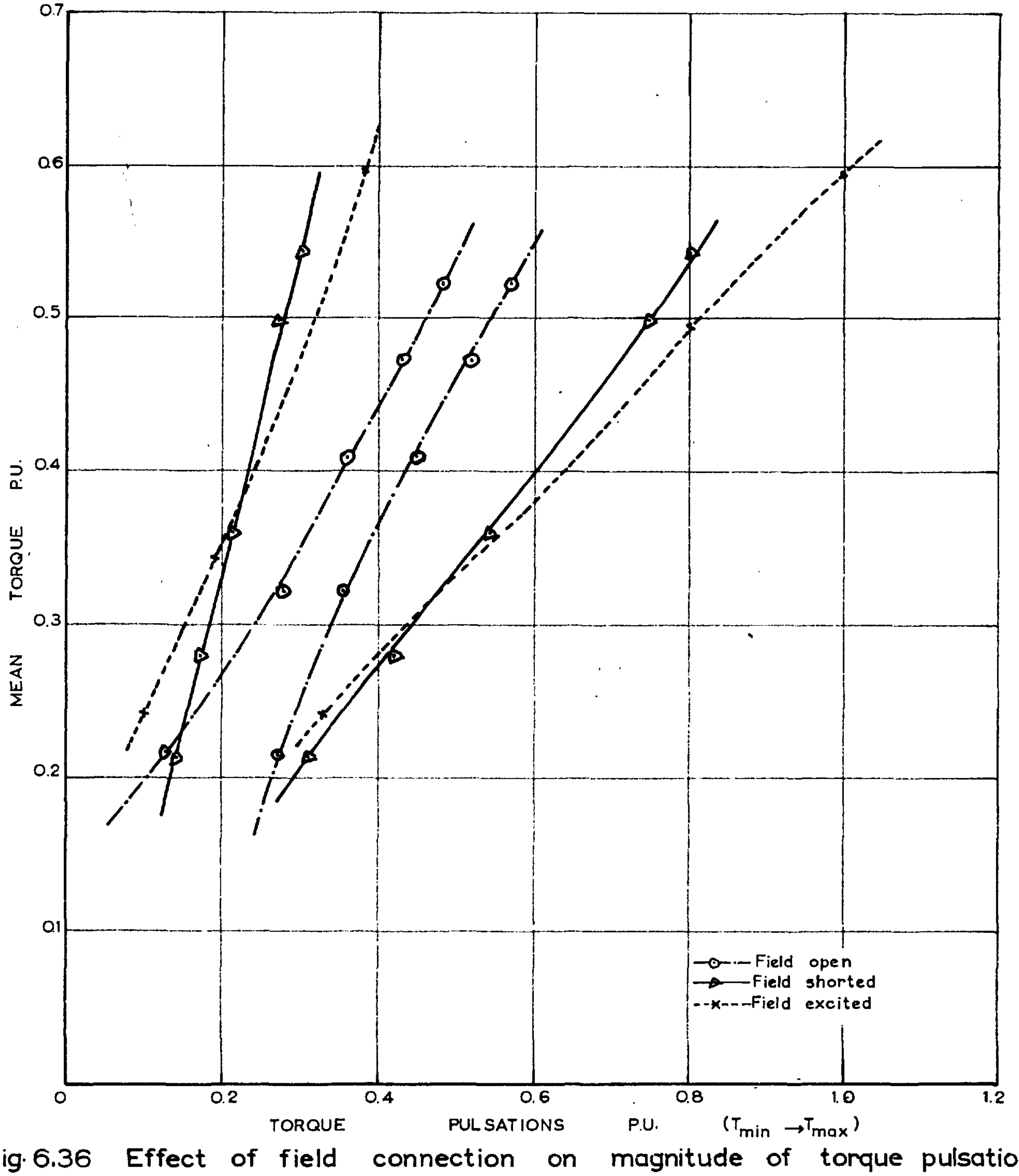


Fig. 6.36 Effect of field connection on magnitude of torque pulsations

Micro-machine with solid rotor
Asynchronous operation study on analogue computer

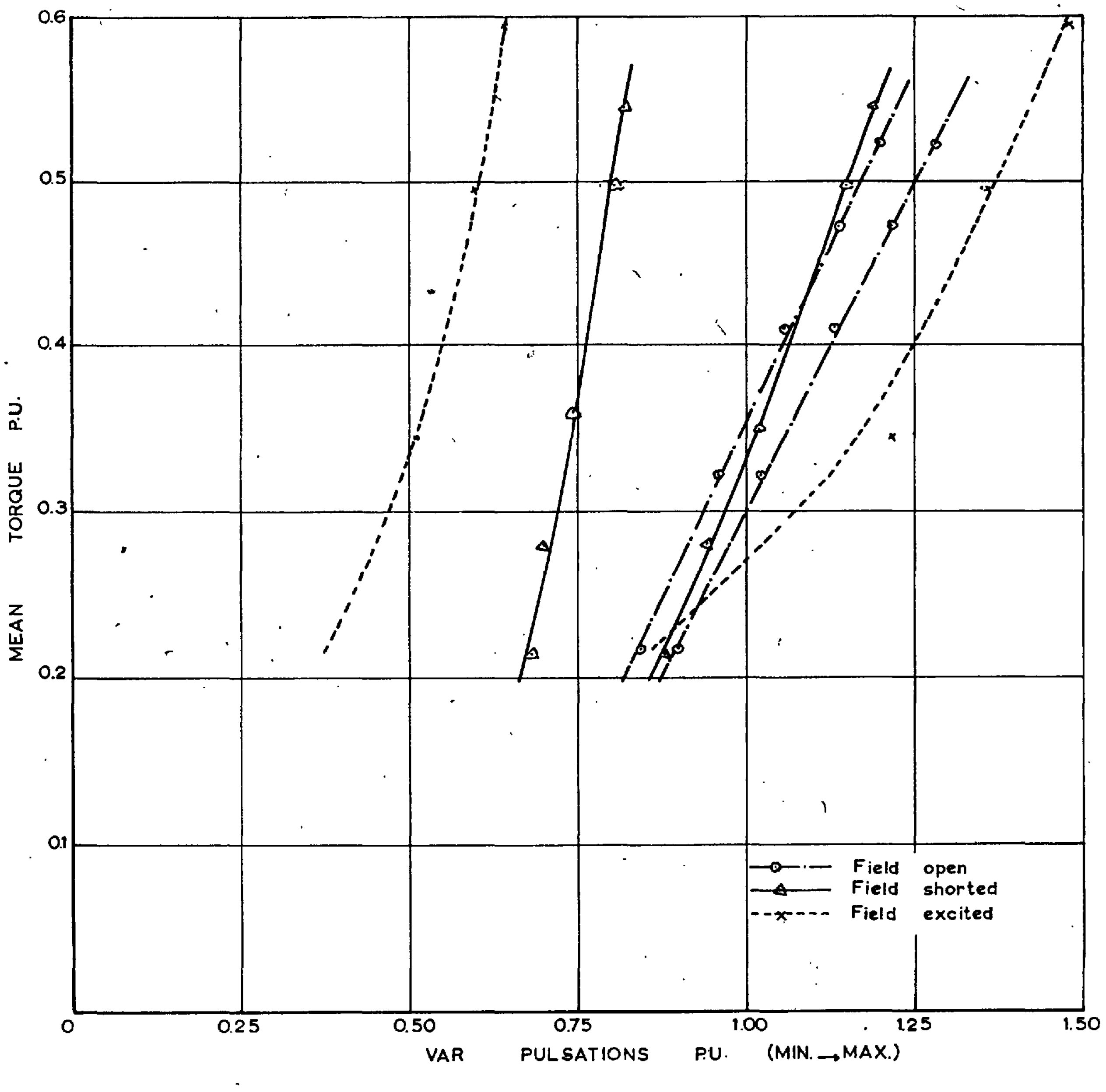


Fig. 6.37 Effect of field connection on magnitude of VAr pulsations

Micro-machine with solid rotor

Asynchronous operation study on analogue computer

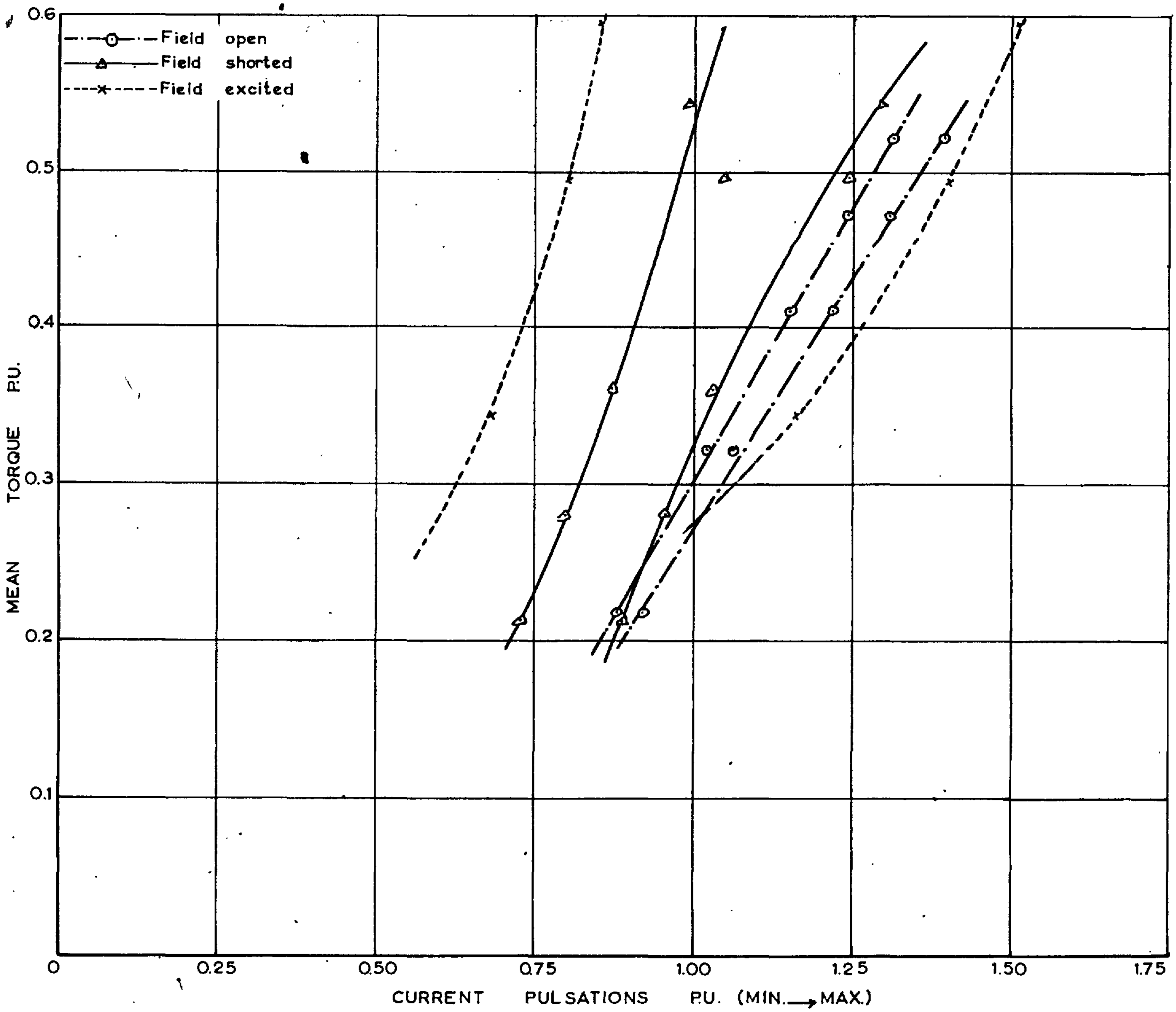


Fig. 6.38 Effect of field connection on magnitude of current pulsations

Micro_machine with solid rotor

Asynchronous operation study on analogue computer

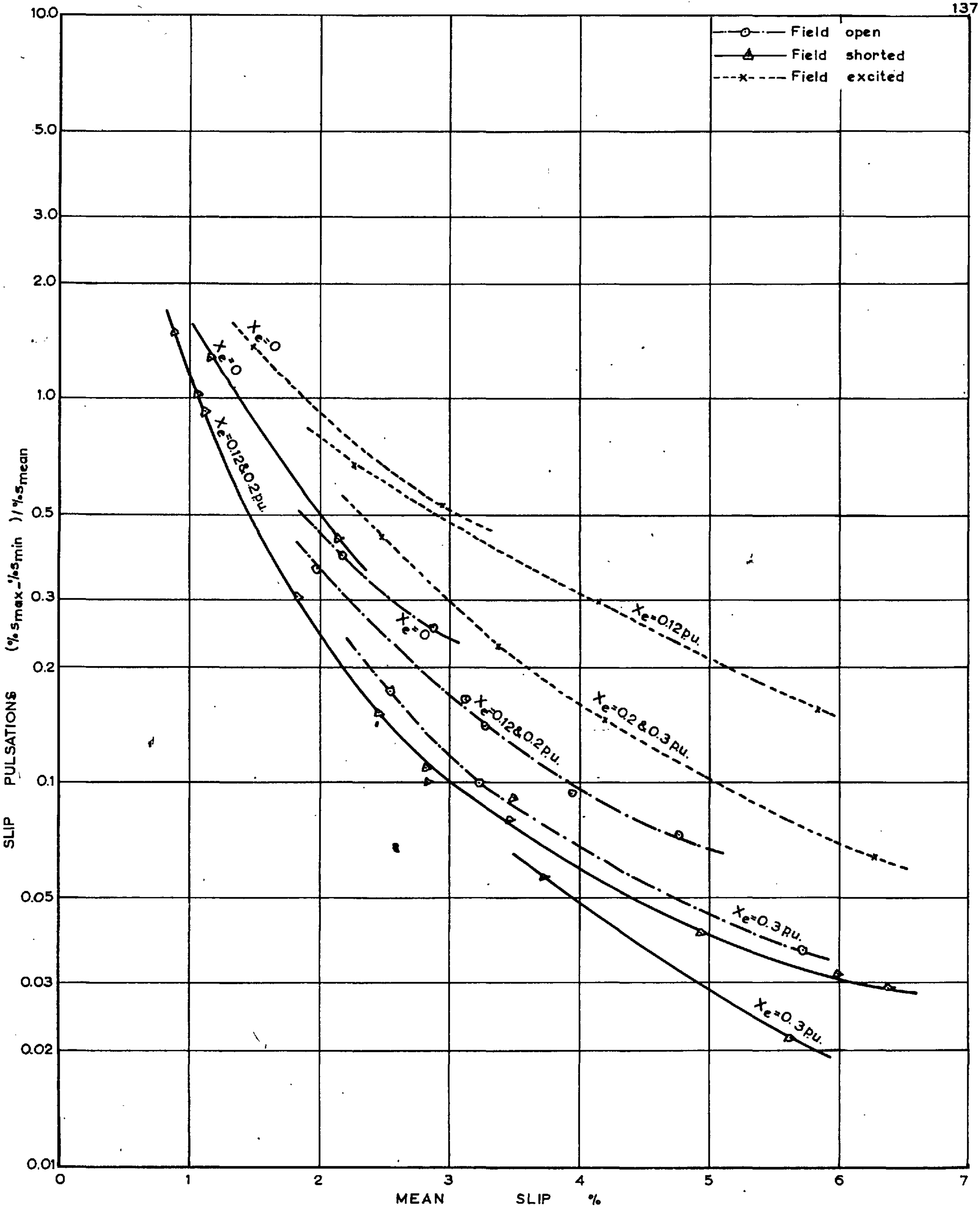


Fig. 6.39 Effect of different modes of field connection on asynchronous operation

Analogue computer study of micro-machine with laminated rotor

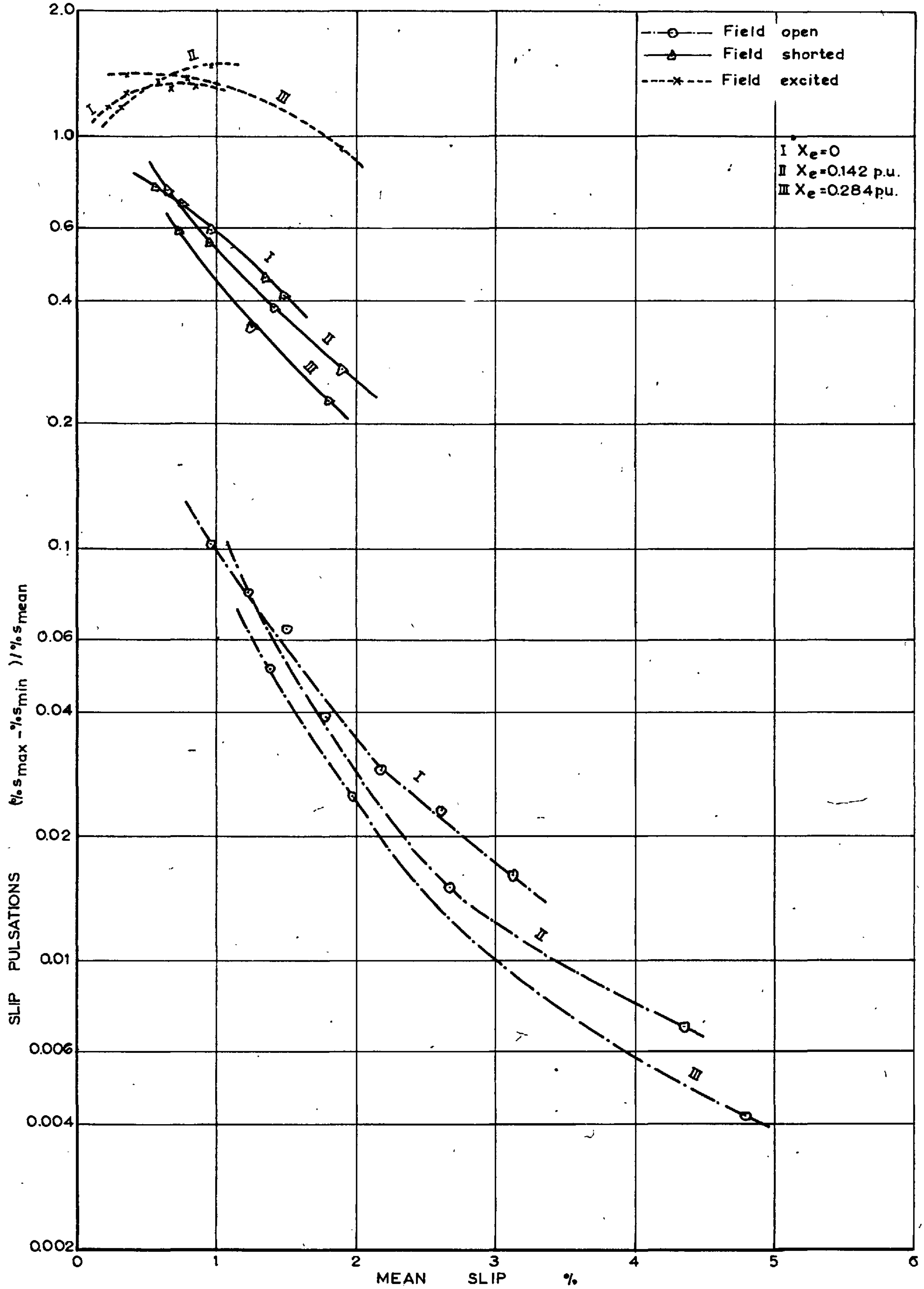


Fig. 6.40 Effect of different modes of field connection on asynchronous operation

Analogue computer study of micro_machine with solid rotor of importance for a practical study of resynchronisation as shown in Chapter 8) pulsations are far from sinusoidal. Also at these low values, the concept of mean slip on which the entire analytical solution of Section 4.3 is based, cannot be justified.

With the field excited, the amplitude of pulsations depends directly on the value of the synchronous component of torque, i.e. the magnitude of excitation maintained. Also in this case, the slip has its minimum value at an angle δ very near to 180° in every slip cycle, if the asynchronous torque is comparatively small. In other cases, the point of minimum slip will depend upon the proportional contribution of field winding and damper winding towards the total asynchronous torque.

6.3.2 Pulsations in watts and VArs

Pulsations in both these quantities in general follow the same pattern as that of slip. The magnitude of variation depends directly on the output of the machine and the slip. Operation with the field open produces the lowest magnitude of variations and with the field excited, the most violent fluctuations as shown in Figs. 6.36 and 6.37.

More external reactance increases the average slip for the same power output, with corresponding smaller magnitude of slip pulsations. This reduction in slip pulsations is directly reflected in the fluctuations of watts and VArs, and the machine runs comparatively smoothly.

With small magnitudes of slip, every time the slip passes through a minimum value or passes through the brief interval of synchronous type of motion mentioned in Section 6.3.1, there is a violent fluctuation in the active power, followed by a less violent fluctuation in the VArs as shown in Figs. 6.5, 6.8 and 6.24. The tendency to lock is caused by the reluctance torque set up due to the saliency effect of the rotor. It is, therefore, particularly marked in machines with salient-pole rotors and to a much smaller extent in cylindrical rotor machines.

This phenomena has also been observed in the form of damped oscillations during full scale tests conducted by the C.E.G.B. on a 120 MW generator at Uskmouth 'B' power station in August 1963[88]. When the instantaneous slip is moving to its minimum value, the reluctance torque tends to pull the machine into synchronism with a high acceleration. The rotor releases a large amount of kinetic energy in a comparatively short time, thereby causing a big jump in the active power output [Eqn. (3.25)]. This has only an indirect and, therefore, a minor influence on the VArs which are primarily affected by the system conditions. Reluctance torque fluctuates at twice the slip frequency, and, therefore, a big jump in power will take place twice every slip cycle. Also the magnitude of reluctance torque being comparatively small will produce a significant effect on pulling the machine into synchronism only at small values of slip.

In the case of large machines, this sudden jump will be accompanied by rotor oscillations caused by the semi-rigid mechanical system comprising the shaft, coupling, turbine rotor and the entrapped fluid. The frequency of these damped oscillations will depend upon the natural period of oscillation of the mechanical system conjointly with the entrapped fluid.

6.3.3 Pulsations in current

Figs. 6.14 to 6.19 and 6.25 to 6.32 show the fluctuations in current under various modes of operation. Pulsations are almost sinusoidal at twice the slip frequency for the high slip values experimented with during operation on open or shorted field, but depart from sinusoidal at the low values of slip. During operation with excited field, both the fundamental and twice the slip frequency components are present in the pulsations, the fundamental components being by far the dominant of the two. Also the pulsations are far more violent in this mode of operation than in either of the other two cases.

It was observed that with the field open, the pulsations in general have the minimum magnitude as shown in Fig. 6.38. Also, additional external reactance has a slight effect in reducing the magnitude of the fluctuations, and this can be attributed directly to the higher slips and smaller variations in speed produced thereby, as already mentioned in Section 6.3.1.

6.4 Mean torque-slip characteristics

Figs. 6.41 to 6.44 show curves relating mean torque and mean slip during steady asynchronous operation for a machine connected to an infinite bus through various

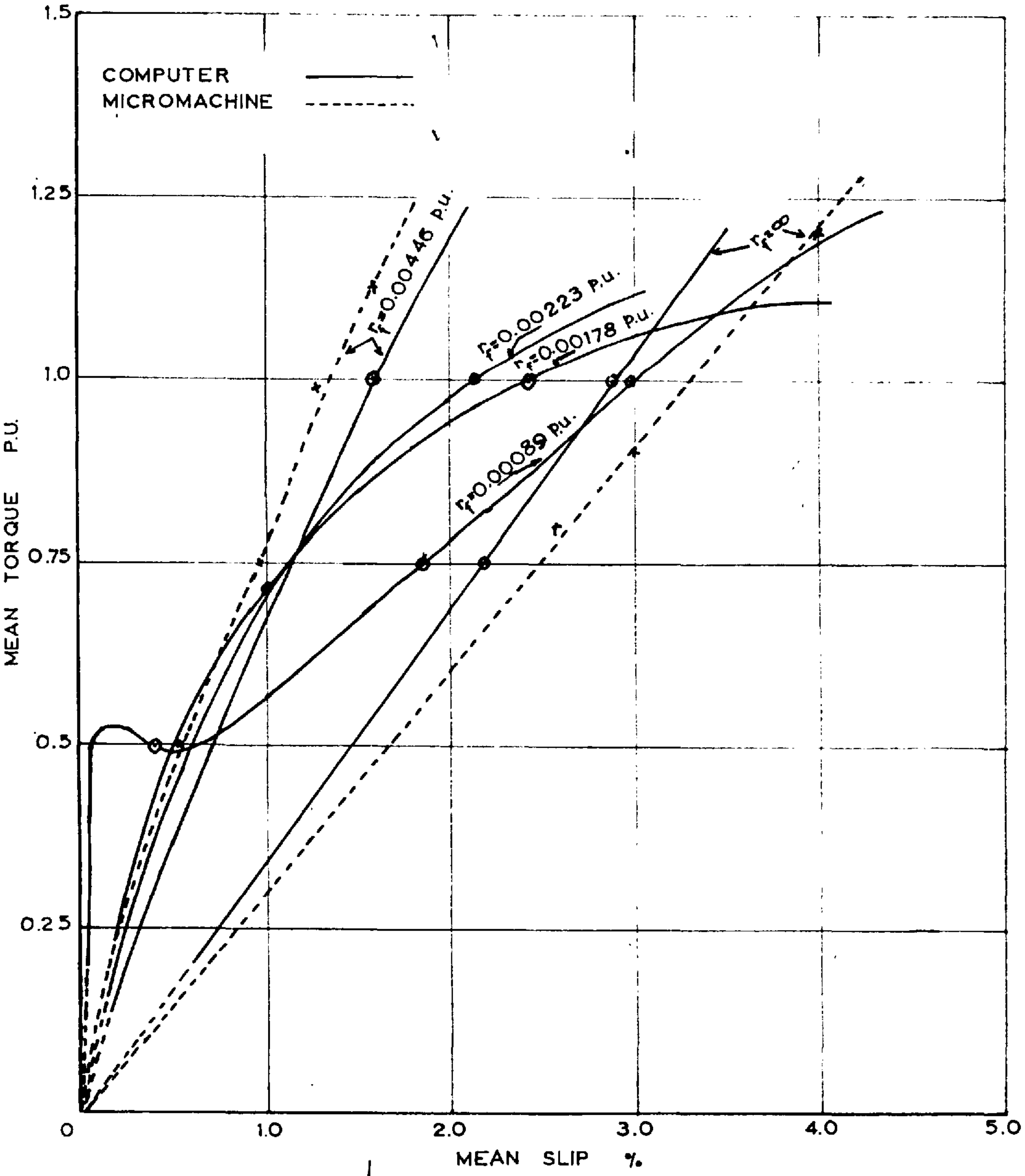


Fig.6.41 Asynchronous mean Torque-slip characteristics

x_e=0 e_{bus}=1.0 p.u. Laminated rotor

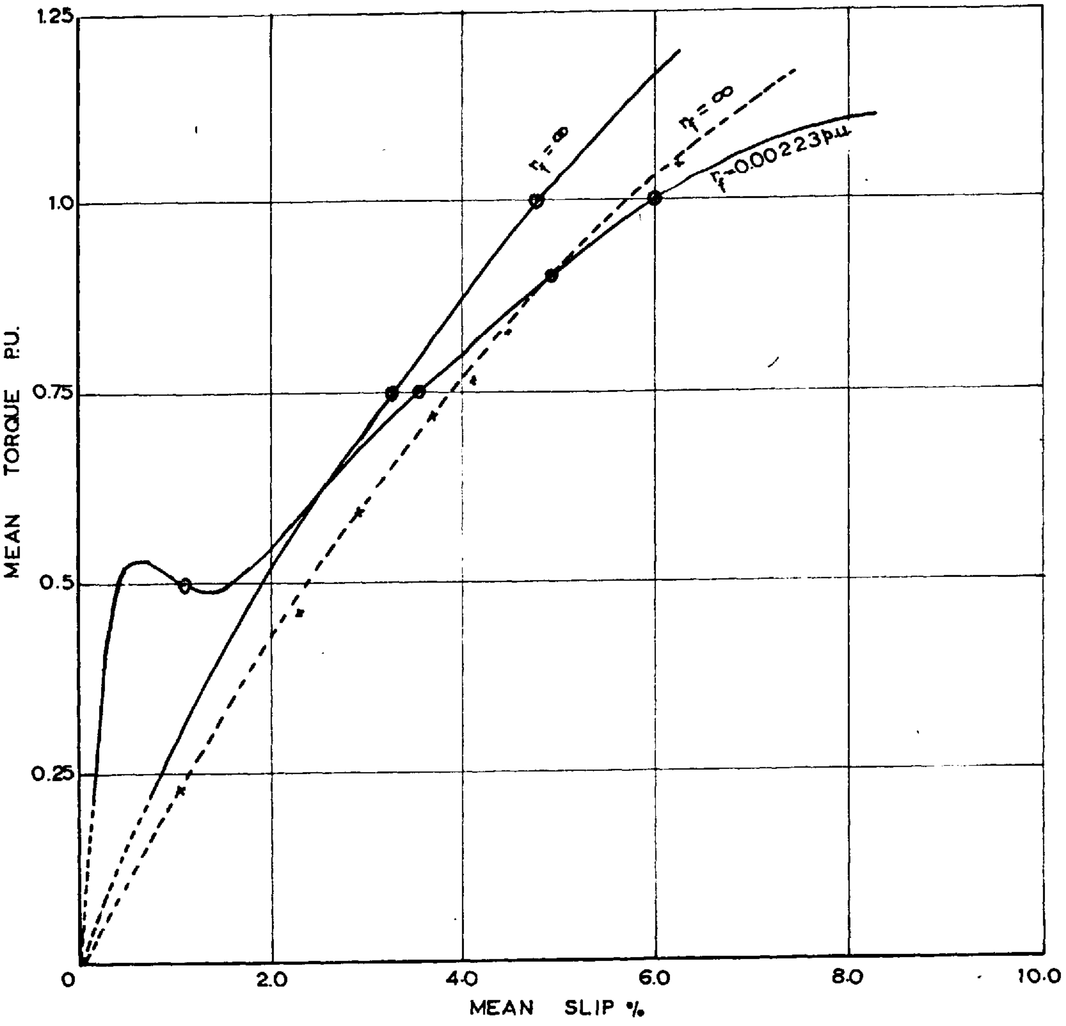


Fig. 6.42 Asynchronous mean torque-slip characteristics

$x_e = 0.12$ p.u. $e_{bus} = 1.0$ p.u. Laminated rotor

Computer ————————

Micro-machine - - - - - - - - - - -

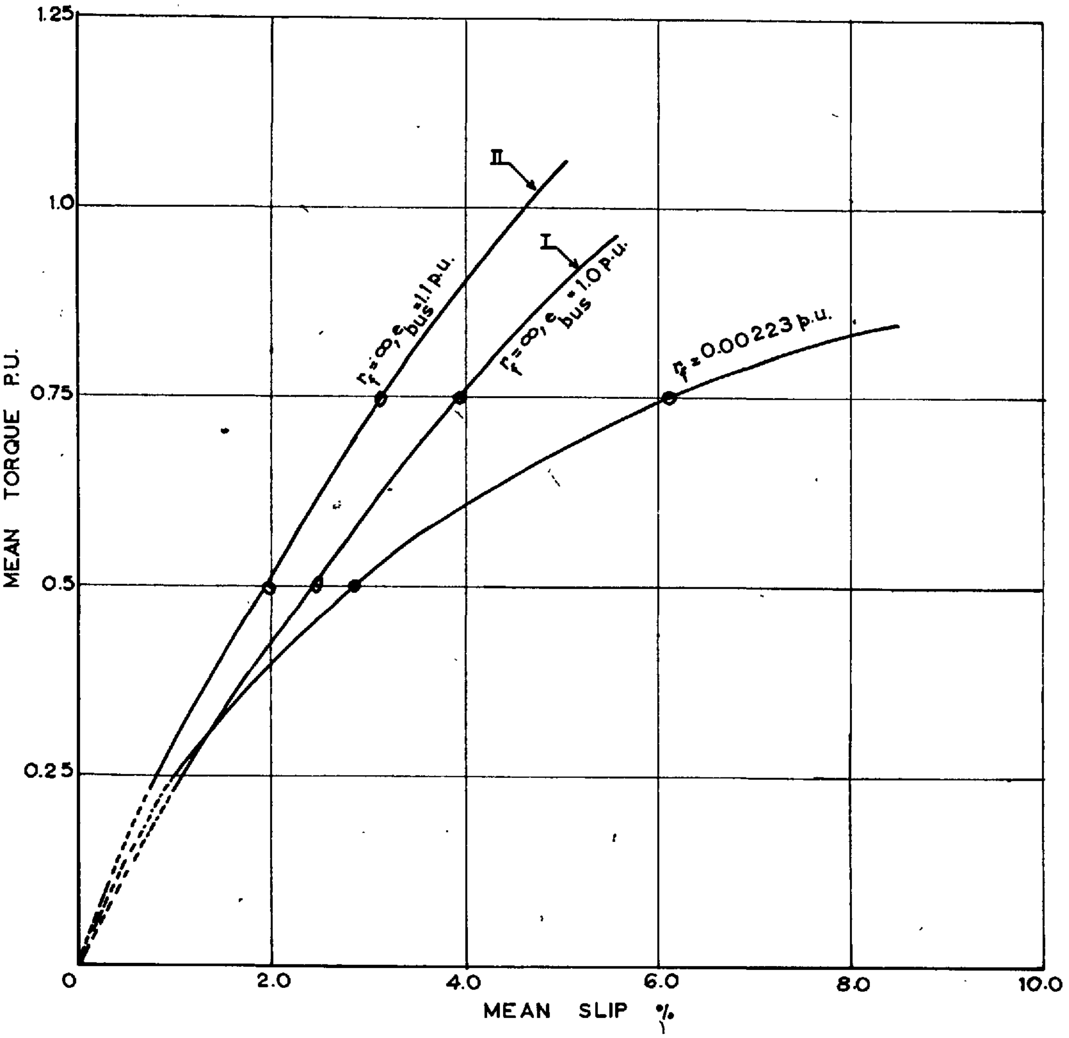


Fig.6.43 Asynchronous mean torque-slip characteristics

$x_e=0.2$ p.u. Laminated rotor

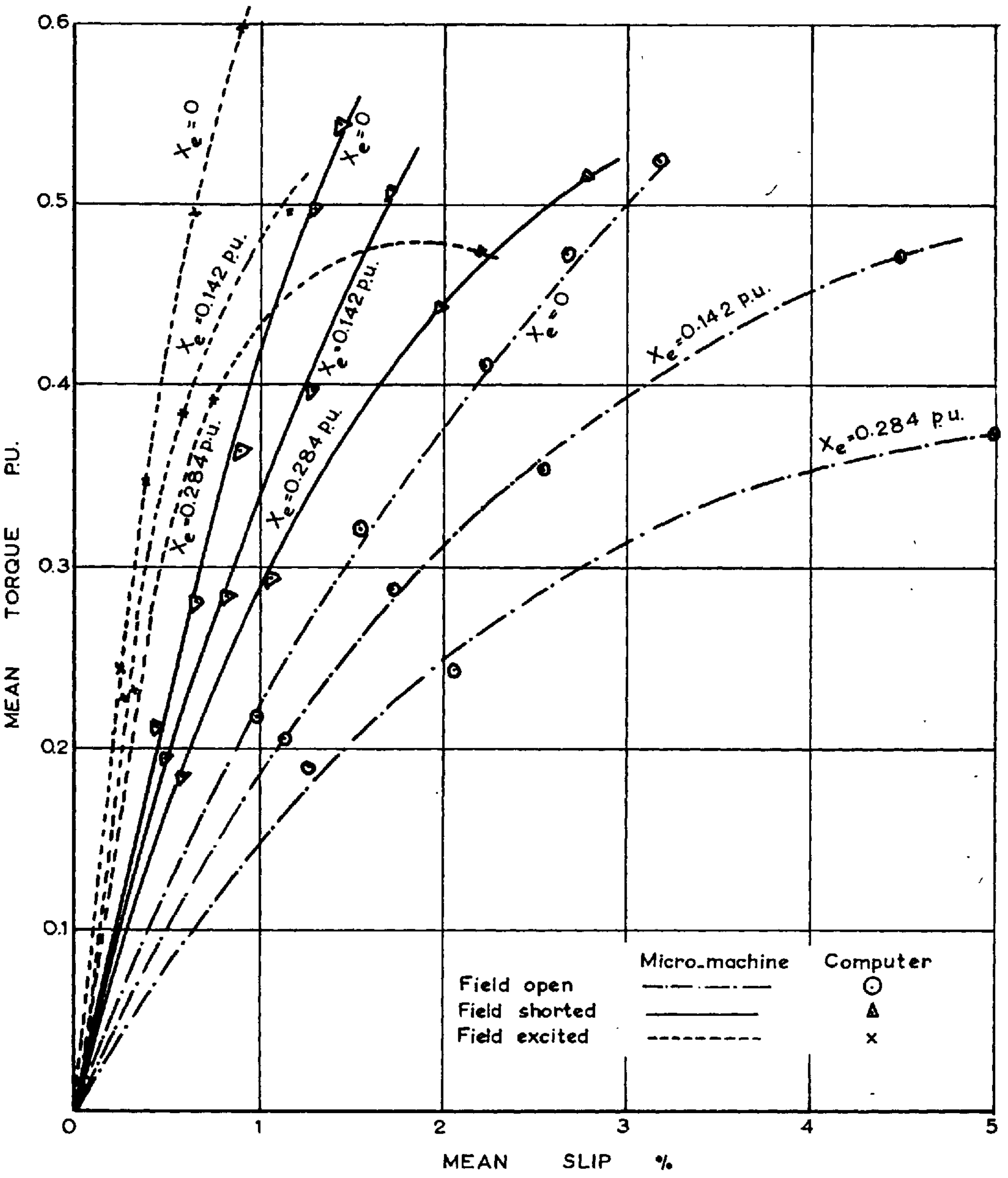


Fig. 6.44 Asynchronous mean torque_slip characteristics

Micro_machine with solid rotor

values of external reactance. Curves I and II in Fig. 6.43 also show the effect of bus-bar voltage on the asynchronous characteristics. A perusal of these curves shows that, particularly for small power outputs, operation with the field shorted on itself or through a discharge resistor is advantageous, in that slips are in general low compared to the open-circuit field condition. This is because the field winding, being generally of lower resistance than the damper circuits, is more effective at low slips when the damper circuit torque is low. At higher slips, the damper circuits become more important and the contribution from the field winding is of less significance. The advantage of the field shorted condition is almost completely lost at higher outputs or with high external reactance, even for low power outputs. These results are also corroborated by the investigations of Mehta and Adkins[44].

6.5 Reactive voltamps

6.5.1 General

Reactive voltamps demand of the machine during asynchronous operation under certain conditions, can be as high as 2 to 2.5 p.u. Figs. 6.45 to 6.47 show the effect of

i) watts output,
ii) external reactance
and iii) mode of field connection

on the VArs demand of solid rotor machines. The effect

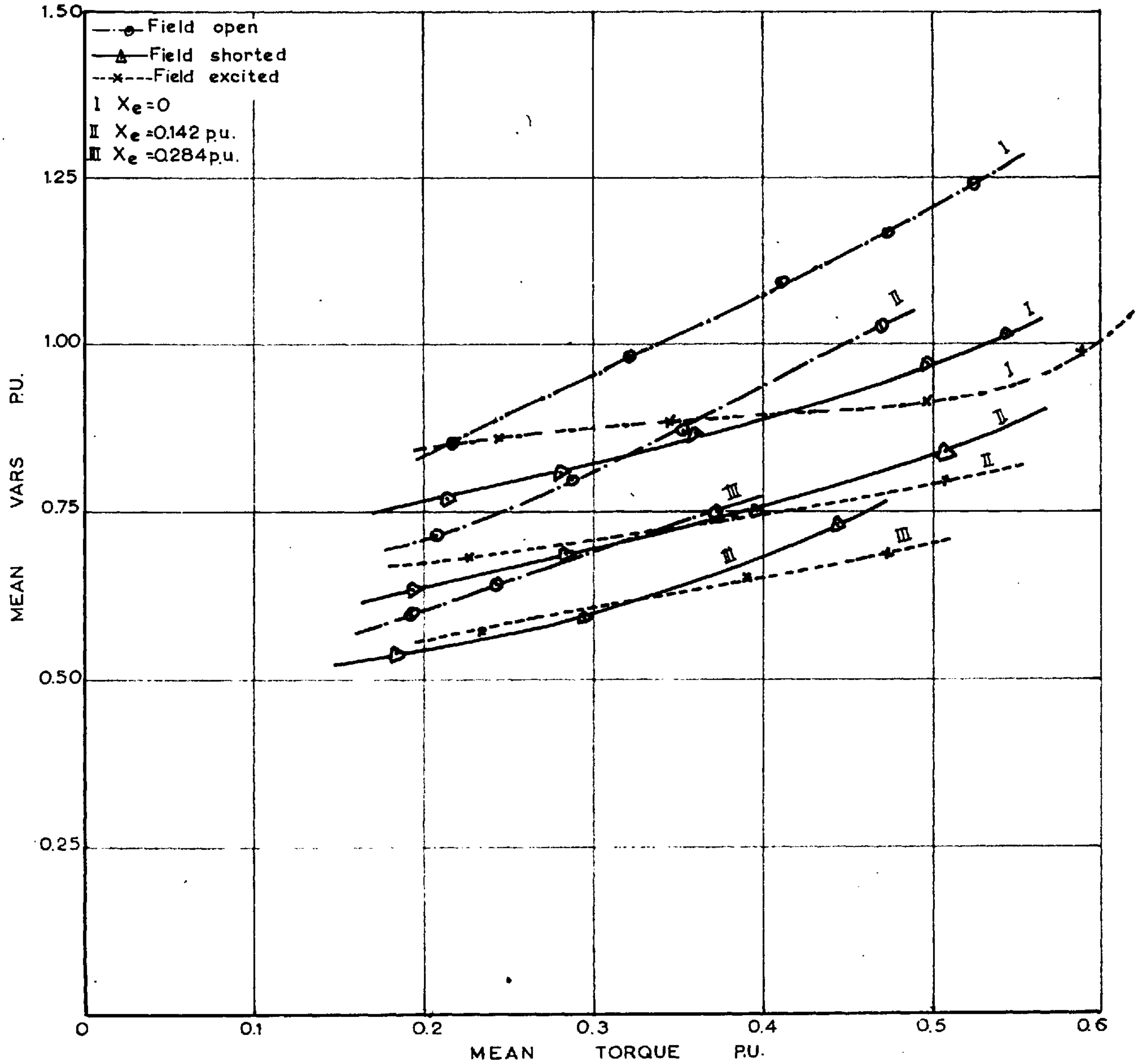


Fig. 6.45 Variation of mean VArs with torque

Micro-machine with solid rotor

Asynchronous operation study on analogue computer

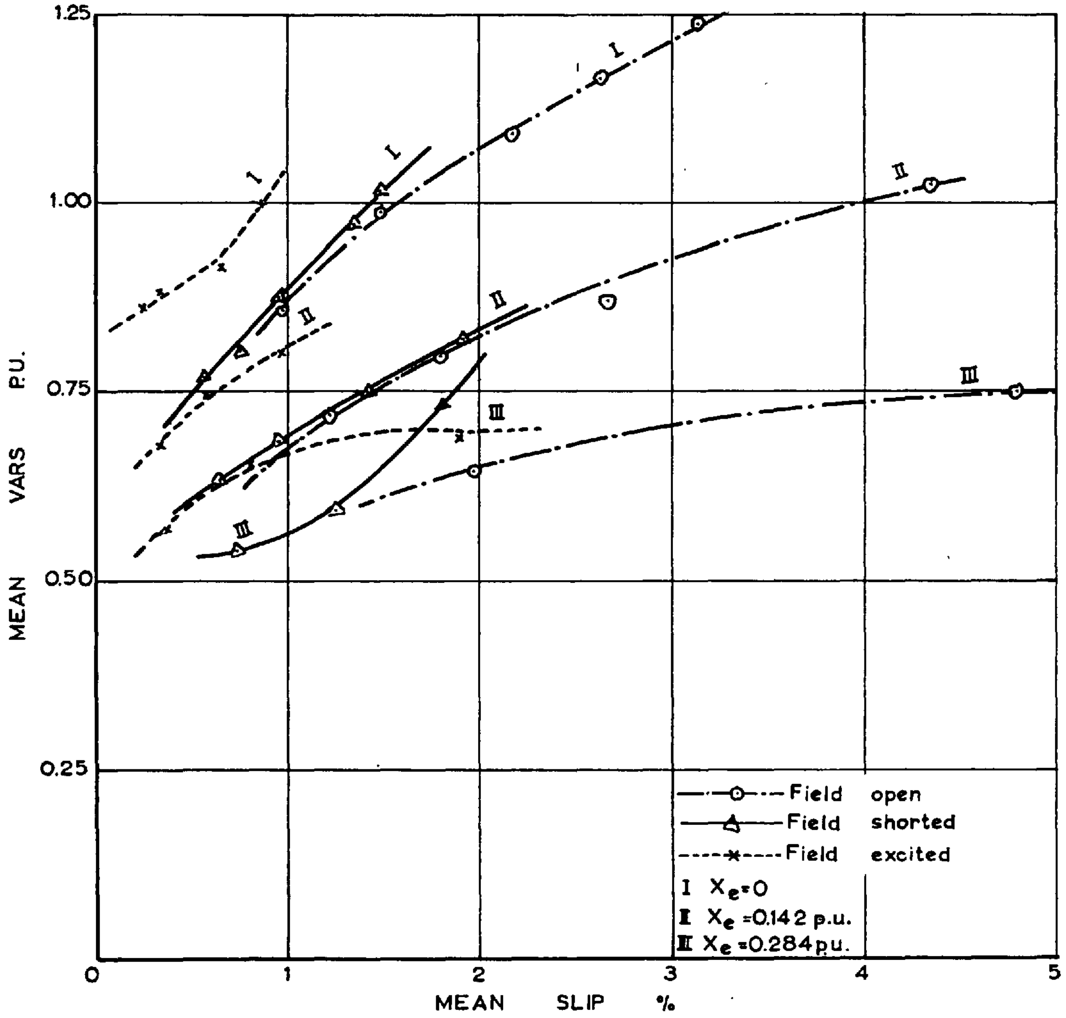


Fig. 6.46 Variation of mean VArs with slip

Micro-machine with solid rotor

Asynchronous operation study on analogue computer

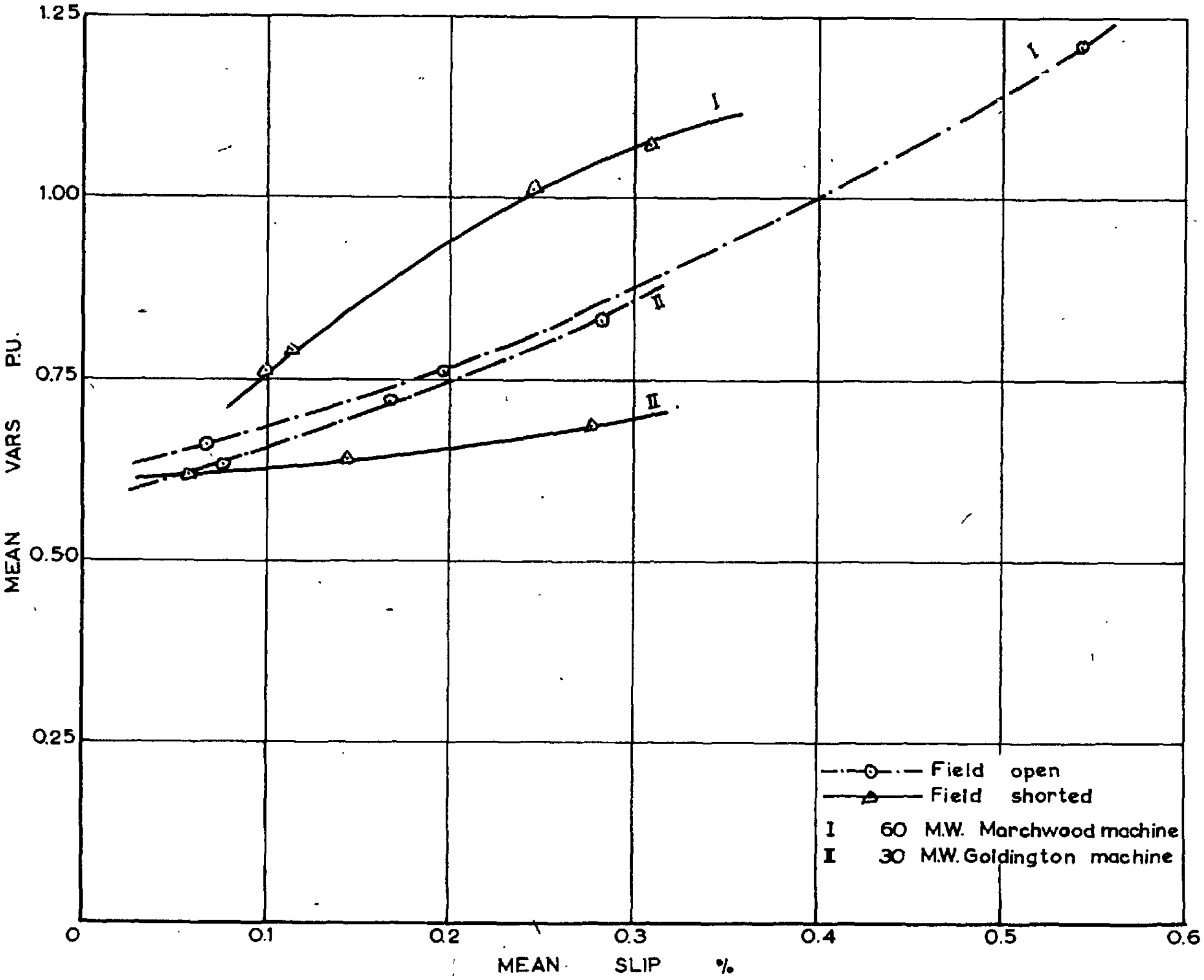


Fig. 6.47 Variation of mean VArs with slip

Asynchronous operation studies of large turbo-alternators on analogue computer of these factors is, in general, similar for solid and laminated rotors as discussed below.

6.5.2 Power output

Active power supplied by the machine has only a small effect on VArs demand, which tends to reduce with fall of watts output as shown by Figs. 6.37 and 6.45.

6.5.3 External reactance

The external reactance has a profound effect on the VArs demand, because of the reduction in the machine terminal voltage caused by high reactive current. Bus-bar voltage level has a similar effect. The higher the external reactance or lower the bus-bar voltage, the smaller will be the VArs intake as shown by Figs. 6.45 to 6.47.

6.5.4 Mode of operation with respect to field

A machine operating with excitation or with the field unexcited and shorted without a discharge resistor takes approximately the same VArs. The effect of introducing a discharge resistor in the field is to improve the power factor of the rotor currents with a corresponding reduction in VArs demand.

6.6 Current

6.6.1 General

Because of the large VArs demand of the machine as mentioned in Section 6.1, the armature current during asynchronous operation is also high. Figs. 4.9 and 5.17 show the variation of current with mean torque for a few cases. As can be seen, armature current during asynchronous operation can rise to as much as 2.5 p.u. depending upon a number of factors such as watts output, field connections, external reactance, bus voltage etc. Keeping in view the remarks made in Section 6.5.4, currents are a minimum in the case of operation with field open. Particularly at high values of power output, the external reactance has a marked effect in increasing the armature current.

A general conclusion that can be drawn from Figs. 4.9 and 5.17 is that if a machine can be allowed to run at upto 1.5 p.u. current for a short period of time, it is possible to obtain a power output of about 50 % of its rated capacity. This estimate of 50 % can be considered as a safe figure from the results of tests on various large machines as reported in the literature[18]. For smaller values of overload or longer duration of asynchronous operation, the output obtainable will be proportionately less. The value of current at which the machine can be allowed to operate under asynchronous conditions, however, depends upon a number of considerations, the effect of each of which has to be taken into account for each individual machine. Some of the points requiring consideration are mentioned hereunder.

6.6.2 Temperature rise

The temperature rise in different parts of the machine will depend upon the length of time for which machine will have to operate asynchronously before successful resynchronisation can be effected, the average load at which machine has been operating before the onset of the disturbance, the cooling system etc. It has generally been observed[12, 17, 21] that output during asynchronous operation is limited more by the heating of the stator than by that of the rotor.

It has been suggested that modern synchronous machines can be allowed to operate under asynchronous conditions for as long as 30 minutes if the stator current does not exceed 110 % of rated value[46,86]. With the stator currents as high as 130 % of normal, machines can be operated for about 2 minutes[86,89] without excessive temperature rise in either the stator or the rotor. Thus, although the temperature rise is the major limiting factor in allowing a machine to operate asynchronously, it is still feasible to operate modern machines in this regime with a view to resynchronisation by the scheme proposed in Chapters 7 to 9.

6.6.3 Terminal voltage

Depending upon the reactance between the machine terminals and the point of effectively constant voltage in the system, the voltage drop at the machine terminals will be directly proportional to the line current. Figs. 6.48 to 6.52 show the variation of terminal voltage for various

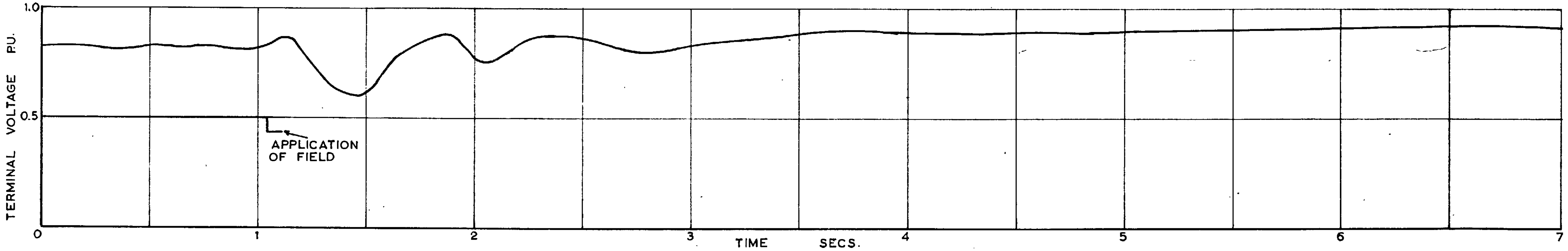
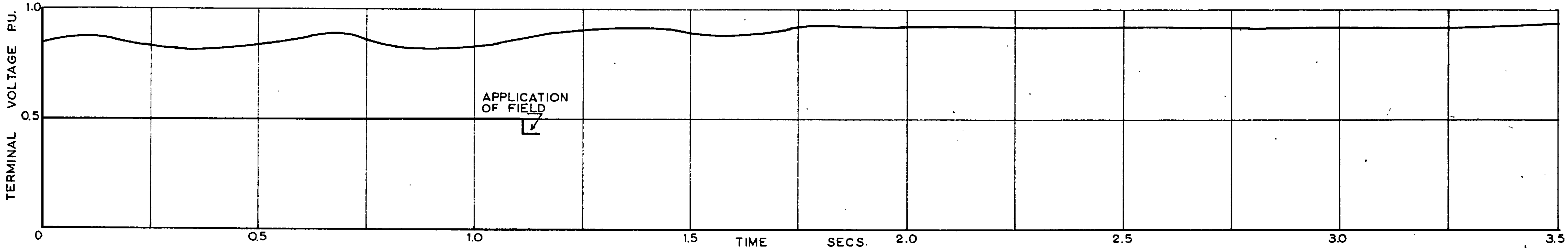
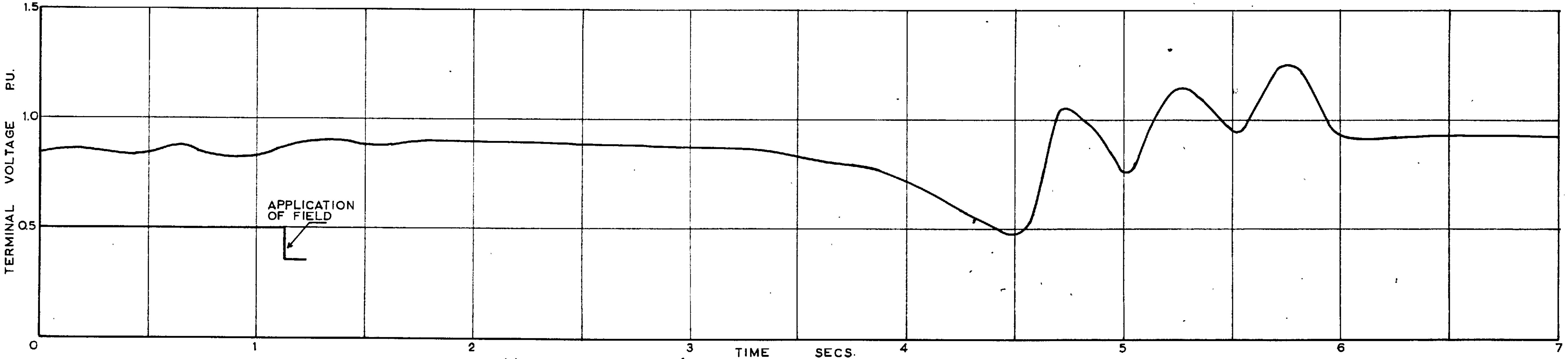


Fig. 6.48 Variation of terminal voltage with time

Solid rotor, Field open, $T_m = 0.47$ p.u., $x_e = 0.142$ p.u.



(a) Field applied at $\delta = 28°$, resynchronisation successful



(b) Field applied at $\delta = 34°$, resynchronisation unsuccessful

Fig. 6.49 Variation of terminal voltage with time

Figure shows effect of delay in applying field excitation

Solid rotor, Field shorted through discharge resistor, $T_m = 0.509$ p.u., $x_e = 0.142$ p.u.

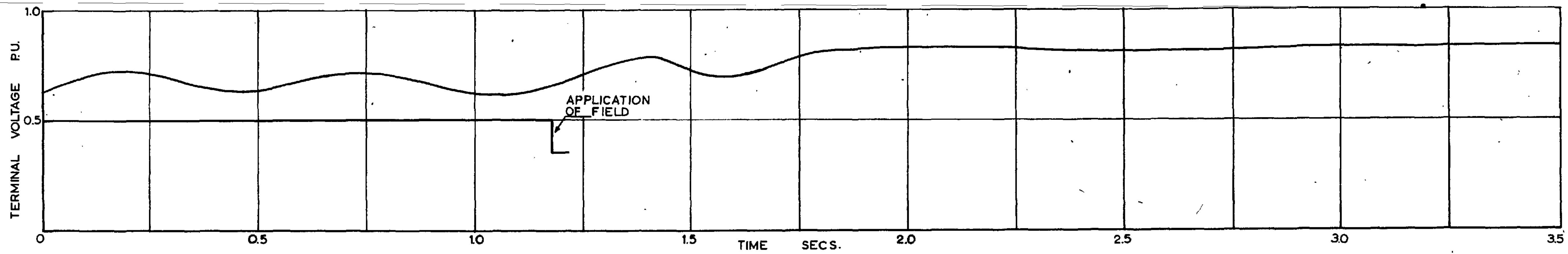


Fig. 6.50 Variation of terminal voltage with time
Solid rotor, Field shorted through discharge resistor, T_m =0.442 p.u., x_e=0.284 p.u.

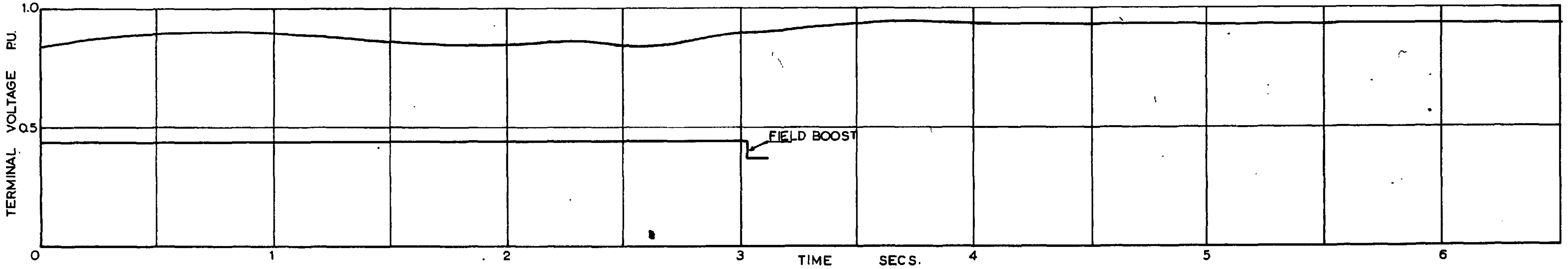


Fig. 6.51 Variation of terminal voltage with time
Solid rotor, Field excited, T_m =0.496 p.u., x_e=0.142 p.u.

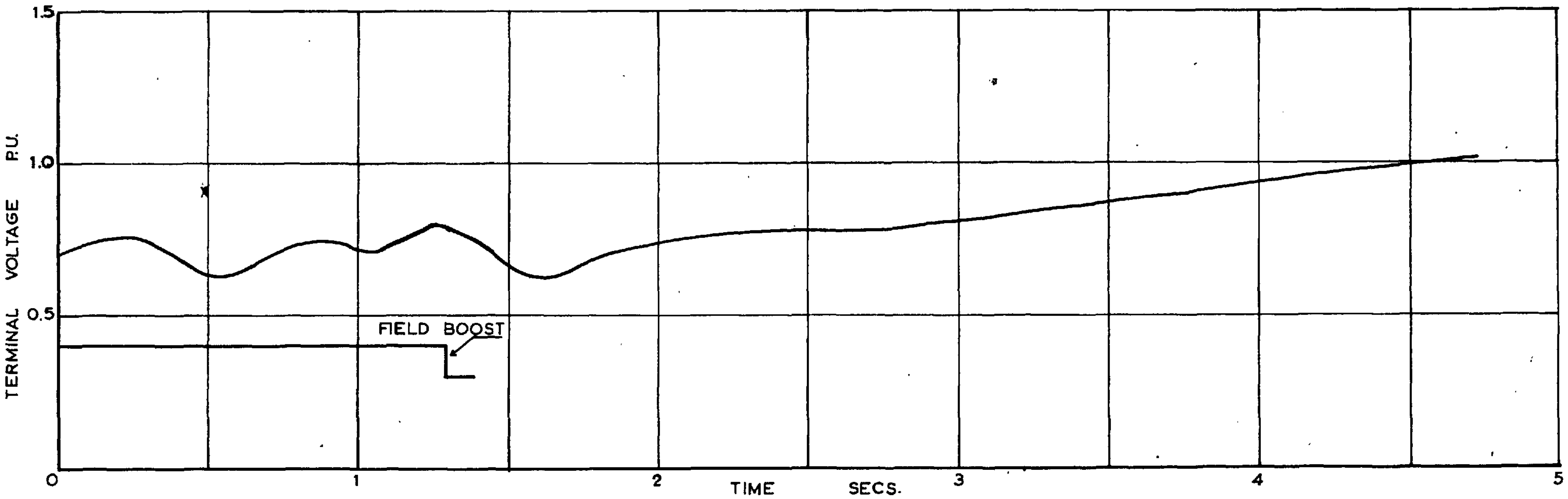


Fig. 6.52 Variation of terminal voltage with time
Field excited, Solid rotor, T_m =0.471 p.u., x_e=0.284 p.u.

loads and values of external reactance. As can be seen, in certain cases, the terminal voltage can drop considerably, thereby affecting the operation of various machine auxiliaries if connected as a unit system. Continuous operation of the machine auxiliaries under depressed conditions is vital for the operation of the machine, particularly in the present case where it is proposed that the machine be automatically brought back to synchronism and normal load in the minimum possible time.

The maximum load that can be supplied during asynchronous operation is, therefore, limited by the minimum terminal voltage required for the normal functioning of the auxiliaries. Figs. 6.48 to 6.52 show that the limit set by this requirement is less critical than that of temperature rise as discussed in Section 6.6.2 above.

6.6.4 Reactive voltamps

The system capability to supply the VAr demand of the machine and its effect on system stability in other branches also requires careful consideration. By incorporating automatic regulation and means to raise the excitation in the system[66] under fault conditions, it is possible to overcome this difficulty.

6.7 Effect of various factors on asynchronous operation

6.7.1 External reactance

Figs. 6.44, 6.53 and 6.54 show the effect of interposing external reactance between the infinite bus

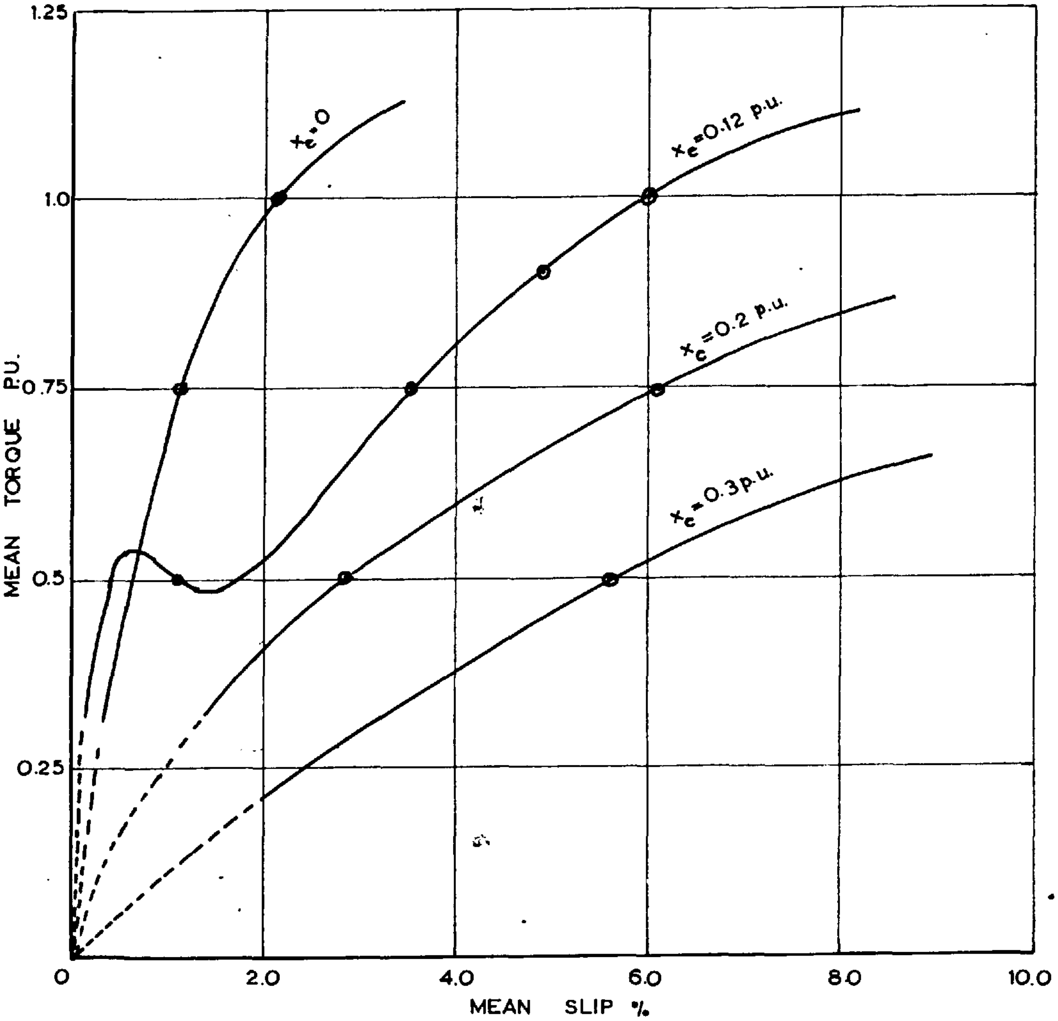


Fig. 6.53 Asynchronous mean torque-slip characteristics

Field shorted through discharge resistor

r_f (total) = 0.00223 p.u., e_{bus} = 1.0 p.u.

Laminated rotor

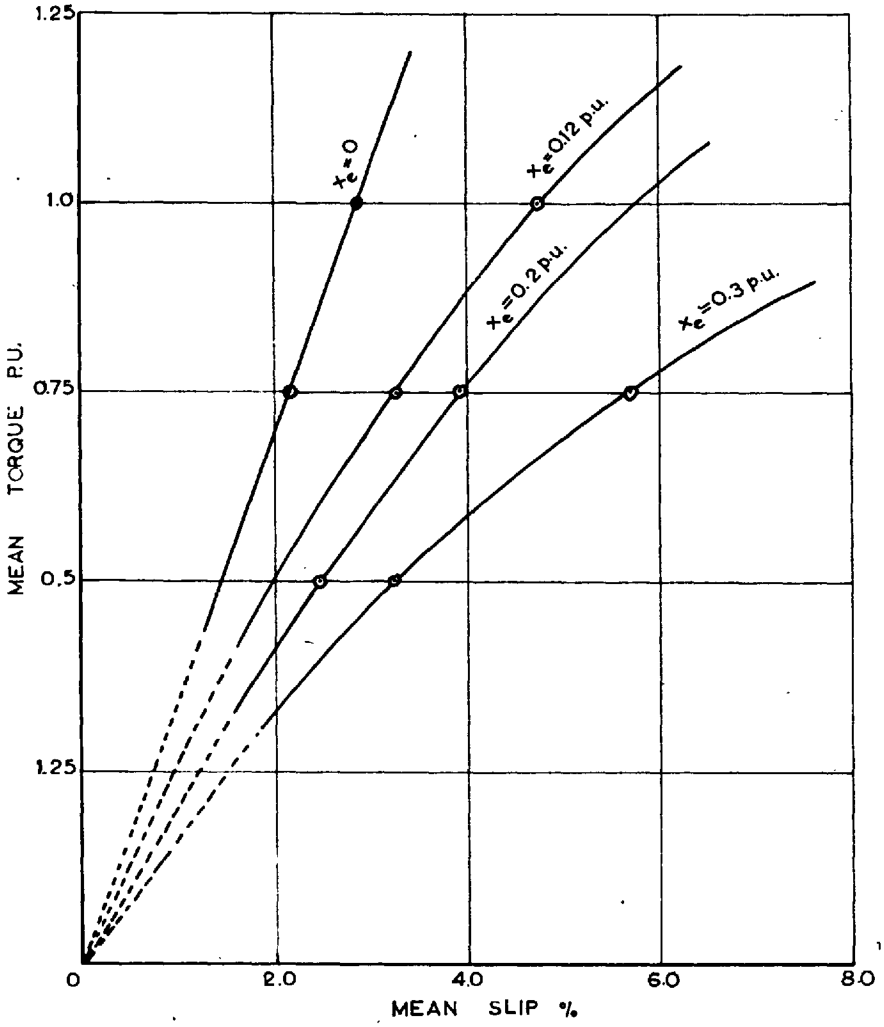


Fig. 6.54 Asynchronous mean torque-slip characteristics

Field open, $e_{bus}=1.0$ p.u.

Laminated rotor

and the machine terminals, on the torque-slip characteristics of a synchronous machine under different conditions of operation. Even a small value of external reactance reduces the asynchronous torque considerably, although its effect is comparatively more pronounced in the case of operation with field shorted than in the case of field open.

6.7.2 Bus-bar voltage

Fig. 6.55 shows the variation of slip with busbar voltage for a fixed power output. Higher bus voltage is very helpful in keeping the magnitude of slip within reasonable values. It will be shown in Chapter 8, that to be able to restore synchronism easily and successfully, it is essential that the slip be within certain limits. By the use of automatic voltage regulators and boosting the excitation on the rest of the system, it is possible to raise the bus voltage to the highest values allowed within proper safety limits and thus keep the slips reasonably low. Raising the excitation on the machines located nearest to the machine running asynchronously will help to a very large extent in reducing the disturbance to the rest of the system.

6.7.3 Moment of inertia

The moment of inertia of the rotating parts has no influence on the mean torque-slip characteristics as is shown by Fig. 6.7. It does, however, affect the magnitude of the slip pulsations, a higher value tending

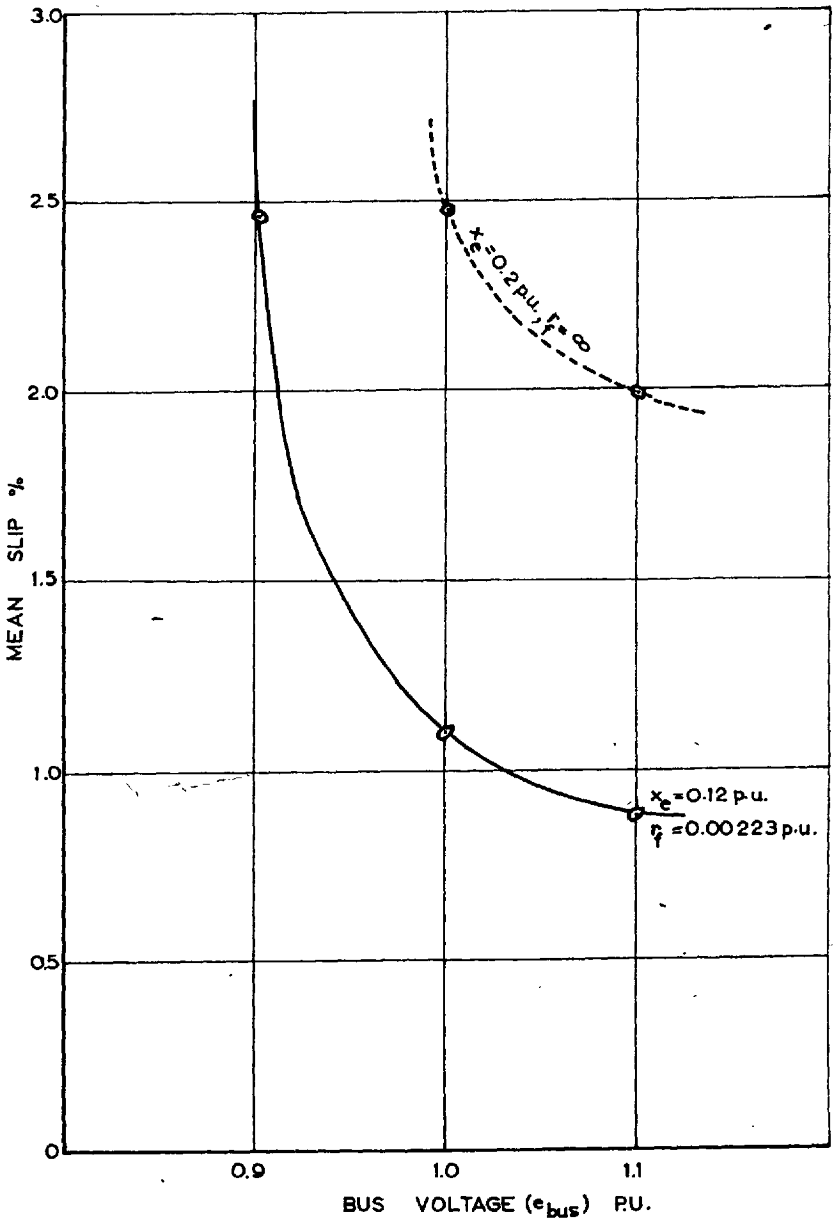


Fig. 6.55 Variation of slip with Bus voltage

T_m=0.5 p.u. , Laminated rotor

to smooth out the fluctuations and a lower moment of inertia increasing them. Although the effect of moment of inertia is small within the limits for which its value can be altered in a practical machine, nevertheless it does have some influence on the process of resynchronisation as is discussed later.

6.7.4 Turbine speed-governor

When a generator loses synchronism, its speed rises and the speed-governor comes into action to limit the speed increase by closing the inlet valve of the turbine. The machine ultimately settles down to steady asynchronous operation about the point of intersection of the generator torque-slip characteristics and the turbine governor characteristics as shown in Fig. 3.3. Because of the drooping nature of the turbine-governor characteristics, an alternator will, therefore, in practice, always generate less than its rated power output while operating asynchronously.

The behaviour of a simple speed governor and its effect on the ultimate slip and power output is shown in Fig. 6.13 for different governor characteristics. Although it is not easy to alter the droop of the governor characteristics during abnormal conditions which may occur suddenly in the system, the characteristics can easily be displaced (as shown by dotted lines in Fig. 3.3(a)) by sending an electrical signal to the speeder gear. Power output and machine slip can thus be controlled as desired. This control operation to bring the machine slip within the required limits may take between 5 and 10 seconds.

6.7.5 Automatic voltage regulator (AVR)

The voltage regulator is only effective when the field is closed and excited during asynchronous operation. In the literature, this mode of operation is sometimes also referred as 'out-of-step' operation. In the other two modes of operation i.e. field open and field shorted, the voltage regulator will be out of action and will come into play only when the excitation is reapplied for resynchronisation.

The AVR merely increases the magnitude of both the transient generating and motoring torques which occur alternately every half slip cycle during out-of-step operation, without materially contributing to the positive damping of the system. Because of the drop in machine terminal voltage, the AVR tries to boost the field excitation. Although this may tend to reduce the slip and increase the power output of the machine slightly, it will ~~considerably increase~~ tend to decrease the VAr demand. Also the fluctuations of various quantities will become very violent, thereby affecting the entire system. Furthermore, the voltage regulator will try to follow the slip frequency pulsations in the terminal voltage and should be stable in operation at all the reasonable slip frequencies likely to be encountered in practice.

Due to the non-availability of sufficient units on the TR48 computer, it was not possible to simulate and study the effect of the AVR. Also, because of the violent fluctuations set up in the system during out-of-step operation, operation with excited field is not very desirable and was, therefore, not studied in greater detail.

6.8 Comparison of operation with different field connections

In the present work, only the following three modes of field connection have been studied:

i) field excited,
ii) field unexcited and shorted,
iii) field open.

6.8.1 Field excited

a) Without materially affecting the mean power output, the pulsations in various quantities are at slip frequency and are very violent as shown in Figs. 6.8, 6.10, 6.11, 6.18, 6.19(b), 6.24, and 6.30 to 6.32. Thus there is much greater likelihood of the entire system getting disturbed and various auxiliary equipment such as speed-governor, voltage regulator, etc. becoming unstable.

b) Because of the lower effective field resistance compared to the case of the field shorted through a discharge resistor, the per-unit slip for the same p.u. power output could be higher in this case. (Fig. 6.41 shows the effect of various values of field resistance.)

c) Current and VAr demand are also, comparatively greater than in the other modes of operation.

All the undesirable effects associated with asynchronous operation are thus exaggerated in the case of out-of-step operation without gaining any advantage over other modes of operation.

6.8.2 Field unexcited and shorted

If the machine is operated asynchronously with the field unexcited and shorted either directly on itself or through a discharge resistor, then:

a) pulsations are at twice the slip frequency and less violent in magnitude than in the case of excited field.

b) without external reactance or at very low values of external reactance, output is generally higher than with field open, but the presence of external reactance has a comparatively greater effect. At the values of reactance likely to be met in practical systems, this advantage is only marginal.

c) current and VAr demand though smaller than in the case of out-of-step operation, are comparatively higher than the field open mode of operation.

There are two factors which govern the size of the discharge resistor in this mode of operation:

i) magnitude of current circulating in the field winding when supplying various outputs. The discharge resistor should have a suitable value to hold the current within safe limits under all conditions.

ii) as an ordinary induction machine, there is a critical value of effective field resistance (total resistance of field winding and discharge resistor) beyond which the torque-slip characteristic starts to drop. The discharge resistor should be of a value such as to keep the effective field resistance below this critical value for the particular machine under study.

6.8.3 Field open

Asynchronous operation with the field open tends to produce more favourable conditions of operation from almost every aspect. The magnitude of pulsations of practically all quantities is generally smaller than in all other modes of operation, thus giving much smoother operation. Although under certain conditions of operation, the power output has to be sacrificed by a few percent, the advantages gained under most conditions far outweigh this. In most conditions and particularly with external reactance in the circuit, VAr demand, current and slip are all smaller than in the corresponding other cases.

With the field open, a voltage proportional to slip is induced in the field winding. This voltage cannot be allowed to exceed the insulation level of the field winding and thus sets a limit to the maximum slip at which the machine may be allowed to operate asynchronously.

CHAPTER 7

RESYNCHRONISATION - THEORETICAL ANALYSIS

7.1 General

One of the taboos still lurking in the minds of most of the modern power system planners and operators is to stick to the outdated definition of system stability as that limit which keeps the synchronous machine in step with the system to which it is connected. Even though the possibility of restoring synchronism without taking a machine off the bus-bars, after it has lost synchronism following system disturbances, was considered as far back as 1931[90], it is only recently that this problem has started to attract more serious consideration.

Most of the investigators have studied resynchronisation on the basis of the instantaneous speed, during a slip cycle, touching or going below synchronous speed by virtue of pulsations in speed. In the present studies carried out on an analogue computer, it has been demonstrated decisively that for successful resynchronisation to be established, it is not at all essential that the machine speed should reach synchronous speed even momentarily during a slip cycle. In fact, by applying sufficient excitation at the proper instant, it is possible to pull a synchronous machine into synchronism from fairly large values of slip.

7.2 Theoretical explanation of resynchronisation process

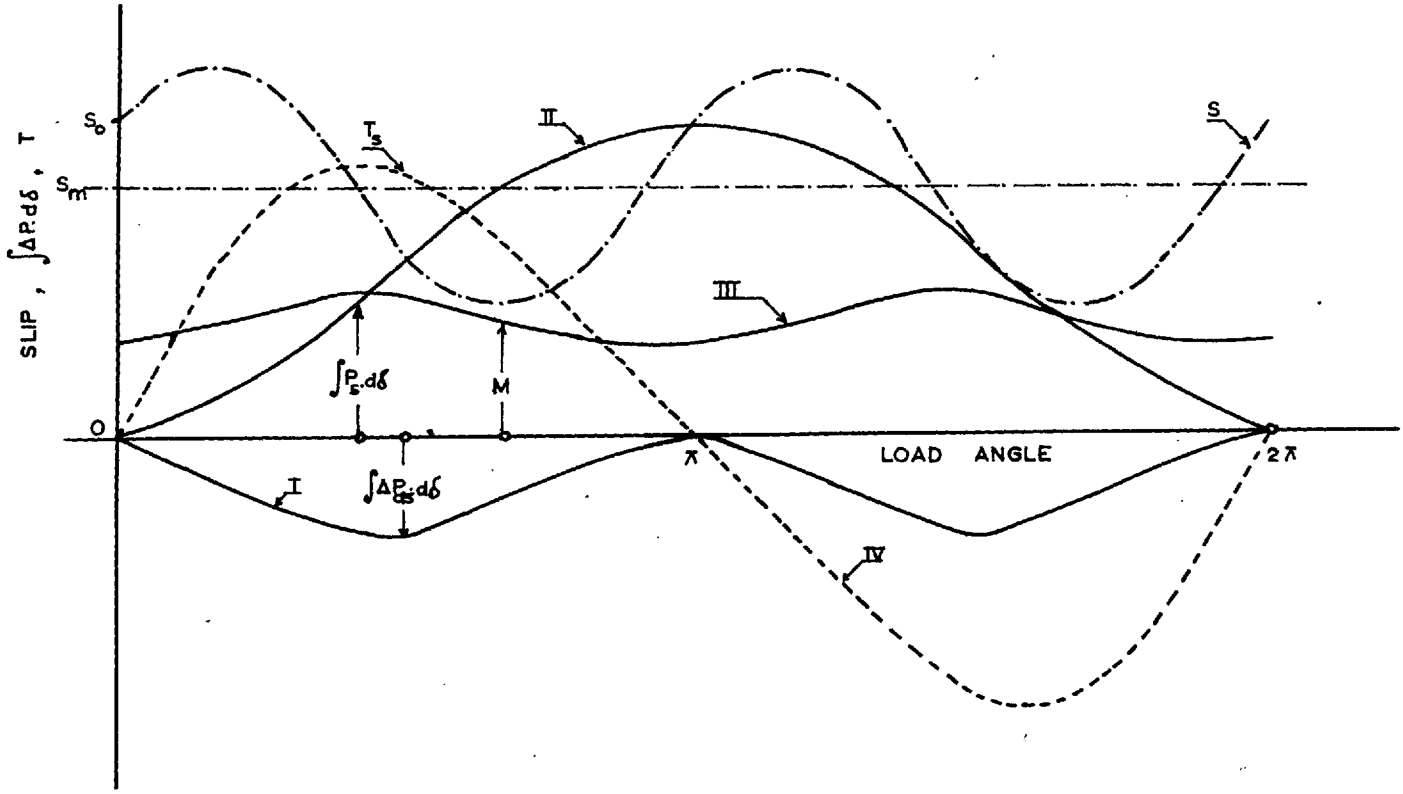
7.2.1 Physical description of the criterion for resynchronisation

Both steady state and transient stability of synchronous machines are generally explained in physical terms on the basis of the equal area criterion[33,91]. By extending this idea sufficiently further, the phenomena of falling out of synchronism and stable asynchronous operation can be explained quite simply. The mean point of steady asynchronous operation is determined by the trend of the mean torque-slip characteristics and the combined turbine speed-governor torque-speed characteristics as shown in Fig. 3.3 for the case of a generator, or the load torque-speed characteristics in the case of a motor. The point of intersection A [Fig. 3.3(a)] represents only the mean point of operation, as in practice both the speed and torque are pulsating about this point at the mean slip frequency.

By virtue of the increase in speed, a certain amount of kinetic energy $\Delta A = \int \Delta P \, dt$ is stored by the rotor. This stored energy varies with the variation of speed over a slip cycle and will at any instant 't' be given by the sum of the energies contributed between the interval 't_0' - the initial condition - and 't' by the following individual components:

i) net accelerating torque ΔT (Fig. 3.3(a)) produced due to the pulsations in slip (curve I, Fig. 7.1)

ii) synchronous torque present only with field excitation (curve II, Fig. 7.1)



Fig·7.1 Torque and Energy characteristics during asynchronous operation with field open or shorted

Machine will resynchronise any instant that
Ordinate of curve II becomes equal to the sum
of ordinates of curves I & III

(Figure not to scale)

iii) the quantity 'M' [Eqn. (7.11)] dependent on the initial and the instantaneous values of slip (curve III, Fig. 7.1).

If at any instant, the increase in kinetic energy (ΔA) becomes equal to zero, the rotor speed becomes equal to the synchronous speed and the machine attains a condition such that it may pull into synchronism. Most of the previous investigators[5,14,15,44,66] have studied the problem of resynchronisation on the basis of the instantaneous speed touching synchronous speed as a necessary condition and leaving it to resynchronise more by chance than by design.

A study of the components contributing to the stored kinetic energy of the rotor reveals that components (i) and (iii) depend on the design parameters of the machine, and thus cannot be controlled during the process of resynchronisation. Component (ii) is, however, very much under control and within the limits of the exciter and voltage regulator can be fully manipulated to influence resynchronisation. By applying sufficiently large excitation at a suitable instant in a slip cycle, it is possible to make the energy contributed by component (ii) equal and opposite to the combined energy contributed by components (i) and (iii) and thus resynchronise the machine before the load-angle δ reaches 180°.

In the case of a synchronous motor, the rotor speed is less than synchronous speed. Thus kinetic energy (ΔA) will be of opposite sign to that in the case of a generator. Otherwise the process of resynchronisation will be exactly the same.

7.2.2 Mathematical formulation of the criterion for resynchronisation

The relative motion of the synchronous machine is described by Eqn. (3.25) as

$$\Sigma\ T = \text{Accelerating torque} = \text{Input torque} - \text{output torque}$$

where, from Eqn. (3.26)

$$\text{Accelerating torque} = J \cdot d^2\delta/dt^2$$

Putting $s = d\delta/dt$,

$$\text{accelerating torque} = J \cdot \frac{ds}{d\delta} \cdot s \qquad \ldots (7.1)$$

According to the definition of per-unit quantities adopted earlier[45], the excess power P_t of the turbine is given by

$$P_t = T_t(1 - s) \qquad \ldots (7.2)$$

where, the input torque T_t is a complex function of time and speed, after allowing for the action of the speed-governor.

Output torque is the total sum of synchronous torque T_s and asynchronous torque T_{as}. The synchronous torque T_s and the synchronous power P_s are functions of the load-angle δ, while the asynchronous power P_{as} is a complex function of time, slip and the load-angle. In the per-unit system, power and torque are related by

$$P_s = T_s(1 - s) \qquad \ldots (7.3)$$

$$\text{and } P_{as} = T_{as} \qquad \ldots (7.4)$$

Using per-unit quantities and substituting Eqns. (7.1) to (7.4) into Eqn. (3.25) gives

$$J \cdot s \cdot \frac{ds}{d\delta} = \frac{P_t - P_s}{(1-s)} - P_{as} \qquad \ldots (7.5)$$

Rewriting the above equation,

$$J(1-s) \cdot s \cdot ds = \left[P_t - P_s - P_{as}(1-s) \right] d\delta \qquad \ldots (7.6)$$

and integrating, gives

$$J\left(\frac{s^2}{2} - \frac{s^3}{3}\right) + C = -\int_{\delta_o}^{\delta} P_s \cdot d\delta + \int_{\delta_o}^{\delta} \left[P_t - P_{as}(1-s) \right] d\delta \qquad .(7.7)$$

where C, additional stored kinetic energy of the rotor at $\delta = \delta_o$,

$$= - J\left(\frac{s_o^2}{2} - \frac{s_o^3}{3}\right) \qquad \ldots (7.8)$$

assuming the initial value of slip to be s_o at $\delta = \delta_o$.

The actual change of kinetic energy ΔA of the rotor from the state of synchronous operation to steady asynchronous operation can be written as

$$\Delta A = \frac{1}{2} J_o \left[\Omega^2 - \Omega_s^2 \right] = J\left(\frac{\Delta \omega^2}{2} + \Delta \omega\right)$$

$$= J\left(\frac{s^2}{2} - s\right) \qquad \ldots (7.9)$$

for the particular case of a generator, where the slip s is negative according to the sign convention adopted[45].

Substituting the value of C from Eqn. (7.8) in Eqn. (7.7) and rearranging,

$$J(\frac{s^2}{2} - s) = -\int_{\delta_o}^{\delta} P_s \cdot d\delta + \int_{\delta_o}^{\delta} \left[P_t - P_{as}(1-s)\right] d\delta + M \quad .(7.10)$$

$$\text{where } M = (\frac{s_o^2}{2} - \frac{s_o^3}{3} + \frac{s^3}{3} - s) \cdot J \quad . . .(7.11)$$

Putting $\left[P_t - P_{as}(1-s)\right] = \Delta P_{as}$, Eqn. (7.10) can be expressed in the form

$$\Delta A = \int_{\delta_o}^{\delta} \Delta P_{as} \cdot d\delta - \int_{\delta_o}^{\delta} P_s \cdot d\delta + M \quad . . .(7.12)$$

The three right-hand components of Eqn. (7.12) represent in mathematical terms the three components mentioned in Section 7.2.1. During steady asynchronous operation with or without the field, over one slip cycle i.e. $\delta = (\delta_o + 2\pi)$, the three right-hand components of Eqn. (7.12) would be

(a) $\int_{\delta_o}^{\delta} \Delta P_{as} \cdot d\delta = 0$

(b) $\int_{\delta_o}^{\delta} P_s \cdot d\delta = 0$

$$\text{(c)}\quad M = \int_{\delta_o}^{\delta} \left(\frac{s_o^2}{2} - \frac{s_o^3}{3} + \frac{s^3}{3} - s\right) \cdot J \cdot d\delta$$

$$= J\left(\frac{s_m^2}{2} - s_m\right)$$

where s_m is the mean slip.

For synchronous operation, the additional kinetic energy of the rotor would be equal to zero. Therefore, from Eqn. (7.12),

$$\Delta A = \int_{\delta_o}^{\delta} \Delta P_{as} \cdot d\delta - \int_{\delta_o}^{\delta} P_s \cdot d\delta + M = 0$$

$$\text{or} \int_{\delta_o}^{\delta} P_s \cdot d\delta = \int_{\delta_o}^{\delta} \Delta P_{as} \cdot d\delta + M \qquad \ldots(7.13)$$

The mathematical formulation of the criterion of resynchronisation as presented above, is, in general, very similar to the treatment of Venikov[66], but the philosophy of approach to the whole problem as adopted in these studies is entirely different.

The synchronous power P_s is a function of the load-angle and the magnitude of field excitation E_o, and for a salient-pole machine is given by the well-known equation[45]

$$P_s = \frac{E \cdot E_o}{x_d} \cdot \text{Sin}\,\delta + \frac{E^2}{2}\left(\frac{1}{x_q} - \frac{1}{x_d}\right) \text{Sin}\,2\delta \qquad \ldots(7.14)$$

In the case of the cylindrical rotor machine, the second term, proportional to Sin 2δ in Eqn. (7.14), is generally neglected, even though it is present in most cases.

The variation of P_s $\left[\text{Eqn. (7.14)}\right]$ and that of the expression

$$\int_{\delta_o}^{\delta} P_s \cdot d\delta$$

with δ as derived from Eqn. (7.14) is shown by the curves IV and II respectively in Fig. 7.1 and that of the two right-hand expressions of Eqn. (7.13) by curves I and III in the same figure. A study of Eqn. (7.13) in association with Eqn. (7.14) shows that by applying a sufficiently large magnitude of field excitation, it is possible to satisfy Eqn. (7.13), and when satisfied, the machine will synchronise. Fig. 7.1 is drawn with the initial condition for the start of the process of resynchronisation being taken as $\delta = 0^o$. Although, the process of resynchronisation can be started at any point in a slip cycle, values of δ_o of any practical importance will be in the neighbourhood of 0^o i.e. the start of a new slip cycle.

At a first glance, Eqn. (7.13) shows in a very simple mathematical form the condition for resynchronisation. It points to an easy straightforward method of studying the required magnitude and the most appropriate instant of application or boosting the field excitation. However, it soon proves to be illusory because of the following non-linear factors involved in practice.

i) Eqn. (7.14) as well as curves II and IV in Fig. 7.1 are all based on the assumption that the field is applied as a step function with zero time-constant, whereas the field has a finite time-constant and will take some time to build up to its full value. Curves II and IV (Fig. 7.1) will thus both be considerably modified and will be very difficult to calculate in a simple manner from Eqn. (7.14).

ii) During the process of resynchronisation, the speed is changing very fast and thus the two right-hand components of Eqn. (7.13), which vary with speed in a complex manner, will be extremely difficult to calculate unless some drastic simplifying assumptions are made.

The mathematical analysis given above is useful in the sense that the process of resynchronisation is made clearer in physical terms, but the solutions obtained by this method are of a doubtful value if applied to a practical problem because of the various non-linear factors involved. However, solution of these equations on an analogue computer as described in Section 7.3 is very simple. By this method, the effect of each factor is very easily taken into account without any simplifying assumptions.

7.3 Study of resynchronisation on an analogue computer

7.3.1 Nature of the problem

Resynchronisation can be studied by solving Eqn. (4.20) describing the motion of a synchronous machine. This equation is a non-linear differential equation of the second order for which no straightforward analytical solution exists. To investigate the conditions for resynchronisation, it is necessary to obtain a range of solutions for this equation with different system conditions. It has already been pointed out earlier that because of the highly complex and non-linear nature of the problem, step-by-step or numerical methods are not very suitable for its solution. Efforts to solve this equation by the methods of Non-Linear Mechanics[92,93] have been made by a few investigators[8,14,26]. These solutions relate the slip (which is the first derivative of the angle) with the angle and are called solutions in the phase plane. Solutions thus obtained are called trajectories of motion.

A realistic solution of Eqn. (4.20) in the present problem can only be obtained by a simultaneous solution of the set of Eqns. (4.2), (4.3). (4.7), (4.8), (4.15), (4.19) and (4.20) or Eqns. (4.2), (4.3), (4.20), (5.16), (5.17), (5.22), (5.24) and (5.25) for the two types of rotor and obtaining the solution in the form of phase-plane trajectories relating the slip ($p\delta$) with the load-angle (δ). To obtain a range of solutions with different system conditions and minimum simplifying assumptions, it was found convenient to use an analogue computer.

7.3.2 Mechanisation and procedure for the solution of the problem

Mechanisation of the equations for the study of resynchronisation is exactly as described in Sections 4.5.3 and 5.4.3. The main advantage of this method is that the study of asynchronous operation and resynchronisation under any condition of operation can be made with a single setting for both.

After taking the necessary records for the asynchronous operation under a certain condition, the required magnitude of excitation voltage given by the step functions $L_d \cdot B_{d1} \cdot e_f \cdot 1$ and $L_d \cdot B_{d2} \cdot e_f \cdot 1$ (laminated rotor) or

$$\frac{1}{\ell_f} \cdot e_f \cdot 1 \text{ (solid rotor)}$$

was introduced into the solution at the required point in the slip cycle and the subsequent resynchronisation process studied. In the case of asynchronous operation with different field connections, computation was stopped at the desired point in the slip cycle by making use of the 'hold' facility available in the computer. Changes, if any, required to be made in

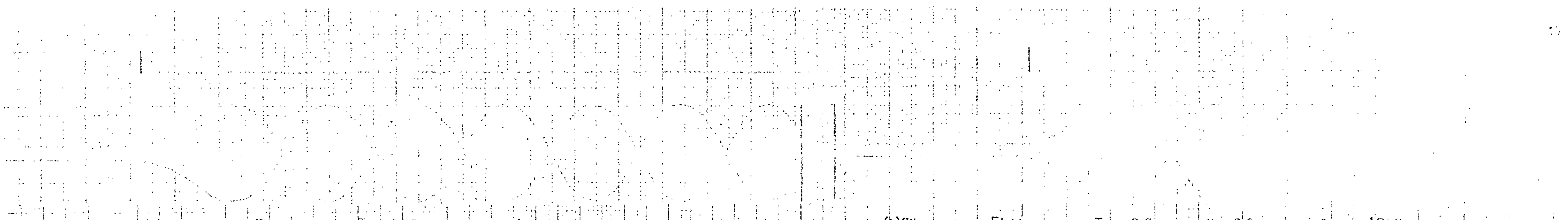
i) the patch panel in respect of different field connections as mentioned in Section 4.5.3, or
ii) attenuator settings necessitated by the removal of the discharge resistor

were made manually and excitation voltage introduced simultaneously. Computation was then allowed to proceed and the subsequent pulling into step studied and recorded.

7.3.3 Assumptions involved in the present studies

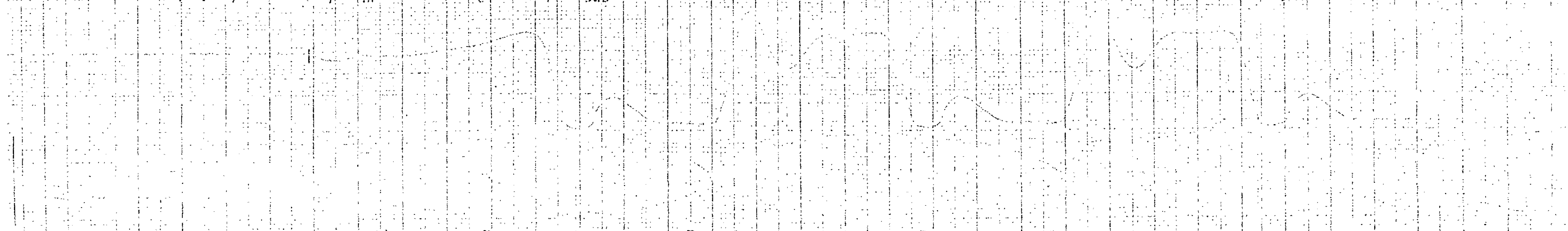
The above procedure for resynchronisation studies assumes that the machine is permitted to attain steady asynchronous operation before resynchronisation is attempted. To study how far this assumption is valid, a few runs were made by pulling the machine out of synchronism either by removing the excitation or by suddenly increasing the load under weak field conditions and noting the subsequent variation in slip. The results of these studies, shown in Figs. 6.12, 7.2 and 7.3, suggest quite conclusively that the machine can be said to have reached steady asynchronous operation after only one complete slip cycle from the time of loosing synchronism and hence the above assumption is quite justified. This is also confirmed by the records obtained from the asynchronous operation tests conducted on large machines. From this it can also be concluded that, provided certain other conditions mentioned subsequently are satisfied, it is possible to force the machine back into step in two slip cycles instead of requiring it to run asynchronously for a prolonged period of time.

One basic condition that is implicit in the entire study of resynchronisation is that the fault which initiated the system disturbance in the first instance has been cleared by the time resynchronisation is attempted and that the system will be capable of normal operation under the new conditions.



(a) Slip cycle, Field open, $T_m = 0.47$ p.u., $x_c = 0.25$ p.u., $e_{bus} = 1.1$ p.u.

(b) Slip cycle, Field open, $T_m = 0.6$ p.u., $x_c = 0.2$ p.u., $e_{bus} = 1.0$ p.u.



(c) Slip cycle, Field shorted on itself, $T_m = 1.15$ p.u., $x_c = 0$, $r_f = 0.00175$ p.u., $e_{bus} = 1.0$ p.u.

Fig. 7.2 Loss of synchronism and establishment of steady asynchronous operation (Paper speed 25 m.m./sec.)
Laminated rotor

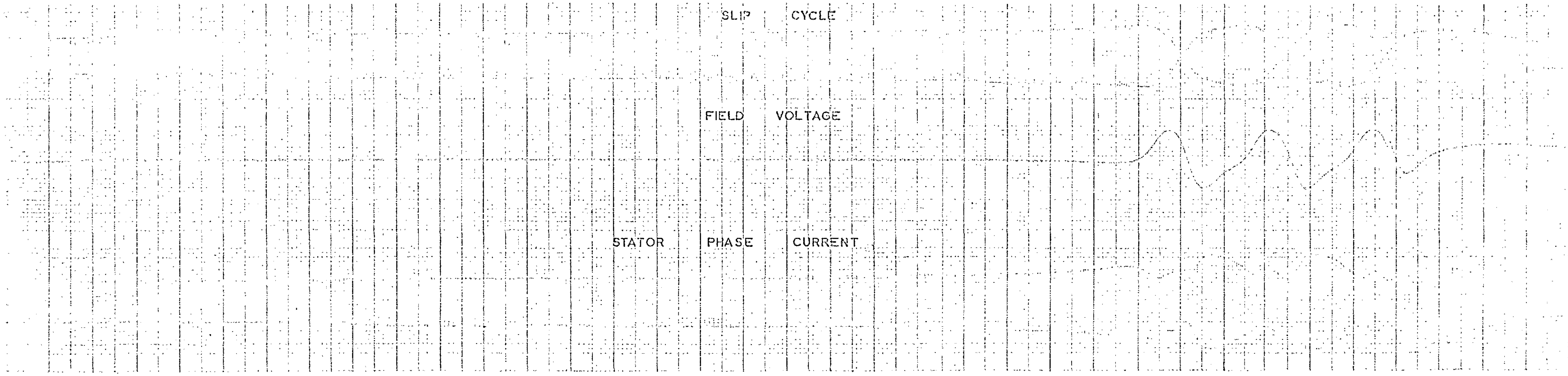


Fig. 7.3 Loss of synchronism and establishment of steady asynchronous operation (Paper speed 25 m.m./sec.)
Field excited, $T_m = 0.471$ p.u., $X_c = 0.284$ p.u., Solid rotor

CHAPTER 8

RESYNCHRONISATION - PRACTICAL INVESTIGATIONS

8.1 Criterion for resynchronisation

To study the effect of different factors, such as;

- i) machine parameters,
- ii) modes of operation with respect to field connections,
- iii) load on the machine,
- iv) auxiliary equipment characteristics, e.g. speed governor,
- v) system conditions, e.g. external reactance, busbar voltage, etc.,

a range of solutions for resynchronisation was obtained in the form of phase-plane trajectories. It is not possible to include in this thesis all the solutions obtained on the analogue computer. A representative selection of the more important solutions is given in Figs. 6.1 to 6.11, 6.13 and 6.20 to 6.24 and the effect of various factors are discussed below.

With the computer operating in a steady asynchronous state as described in Section 4.5.3, different values of excitation voltage were applied to find the minimum excitation required for resynchronisation for a certain run. The criterion for minimum excitation was fixed as that value which pulls the machine into synchronism within one slip cycle of application. After obtaining the minimum magnitude of field required, the instant of field application was delayed so as to obtain the optimum value of the load-angle at which the field must be applied or boosted to achieve synchronism under the above criterion.

The figures mentioned above show the solutions of phase plane trajectories for resynchronisation obtained on the analogue computer under the conditions described. For any higher excitation or any load-angle smaller than that shown in these figures, the machine will definitely resynchronise within one slip cycle of field application under the conditions of operation mentioned.

The reason for fixing the criterion for resynchronisation within one slip cycle is that with the discharge resistor removed from the field circuit after the application of excitation, the machine will, in most cases, develop less asynchronous torque. This will result in an increase in average slip. Therefore, if resynchronisation is not achieved within one slip cycle, there is a great likelihood of the machine passing through several slip cycles. As will be shown subsequently, this is very undesirable for the system.

8.2 Slip magnitude

A study of Eqn. (7.13) shows that the most important single quantity influencing resynchronisation from steady asynchronous operating state is the quantity 'M'. This quantity as given by Eqn. (7.11) is a function of slip, and thus slip would play the most significant part in resynchronisation.

Assuming a fixed mechanical input i.e. neglecting the effect of turbine torque-speed and governor characteristics, the electrical output must be increased to supply to the system some additional energy equal to the additional stored kinetic energy of the rotor. This transfer of rotor energy must take place in the time between the instant of application or boosting of the field and the instant the machine attains synchronous speed. Also, for the machine to remain in step, synchronous speed must be achieved before the load-angle reaches 180°. At low slips, the additional stored energy is comparatively small and the time available for resynchronisation (i.e. time for half slip cycle) is comparatively large. Thus at small values of slip, it would be quite easy to resynchronise the machine with the application of a small excitation with a small swing of power output.

However, at high values of slips a large amount of energy has to be pumped out of the machine electrically in a much shorter time. Thus it needs a proportionally much larger excitation and the swing in power while pulling into step will be large. The relation between the mean slip and the magnitude of field excitation required is not linear but parabolic as would be evident from the expression for 'M' [Eqn. (7.11)]. Figs. 8.1 and 8.2 show this effect by an average plot of a large number of studies made on both the analogue computer and the micro-machines. Because of the parabolic nature of the curves, Figs. ~~7.4~~ 8.1 and ~~7.5~~ 8.2 point to a critical value of slip beyond which it would be impossible to resynchronise. This was also shown by studies on both the computer and the micro-machines, and has also been suggested by Hano et. al.[29] A few cases where the slip was higher than the optimum and the machine

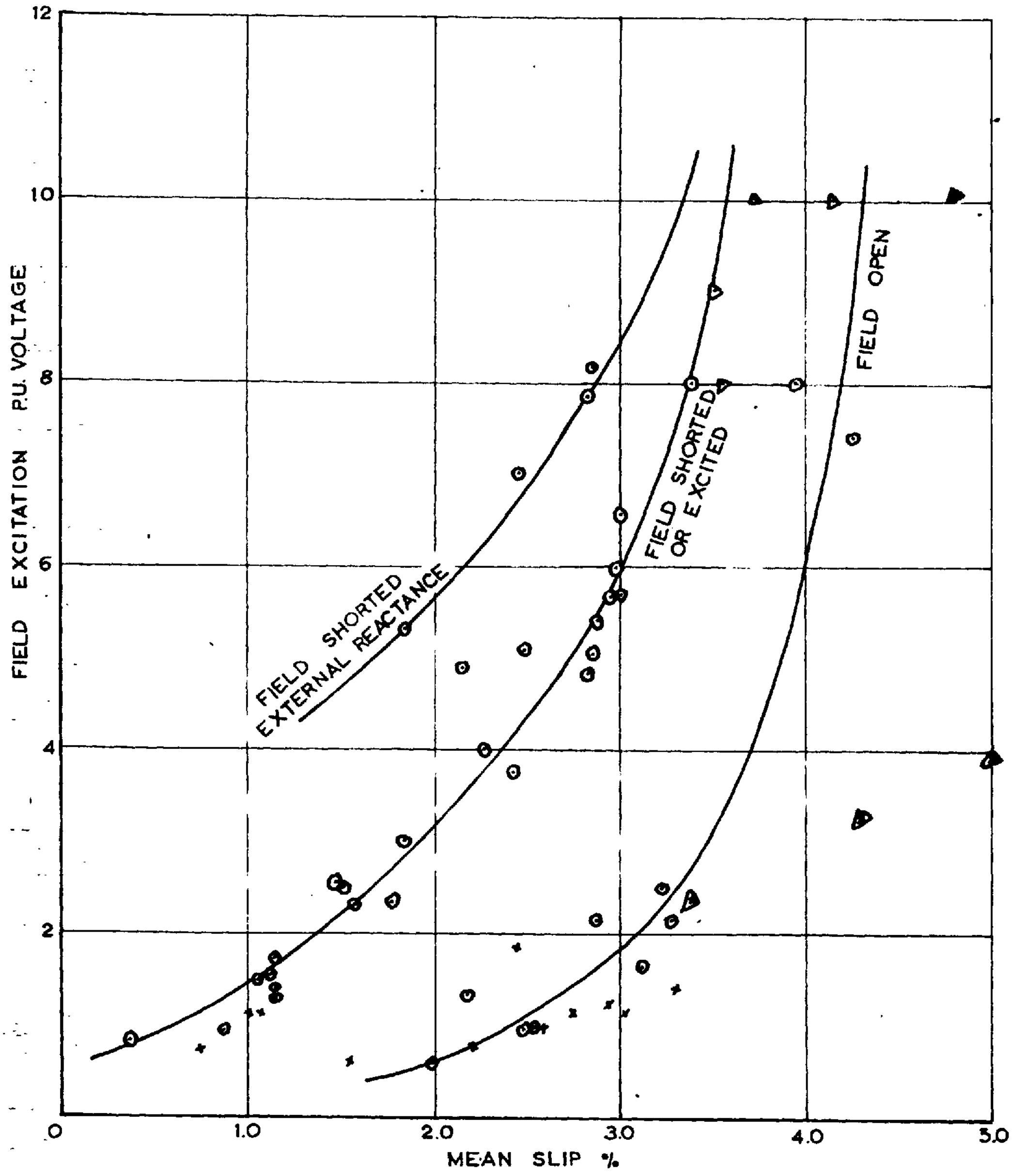


Fig 8.1 Effect of slip on the magnitude of field excitation required to resynchronise

Computer results:-	Resynchronisation achieved	⊙
	No resynchronisation achieved	▲
Micro-machine results:-	Resynchronisation achieved	×
	No resynchronisation achieved	⚠

Laminated rotor

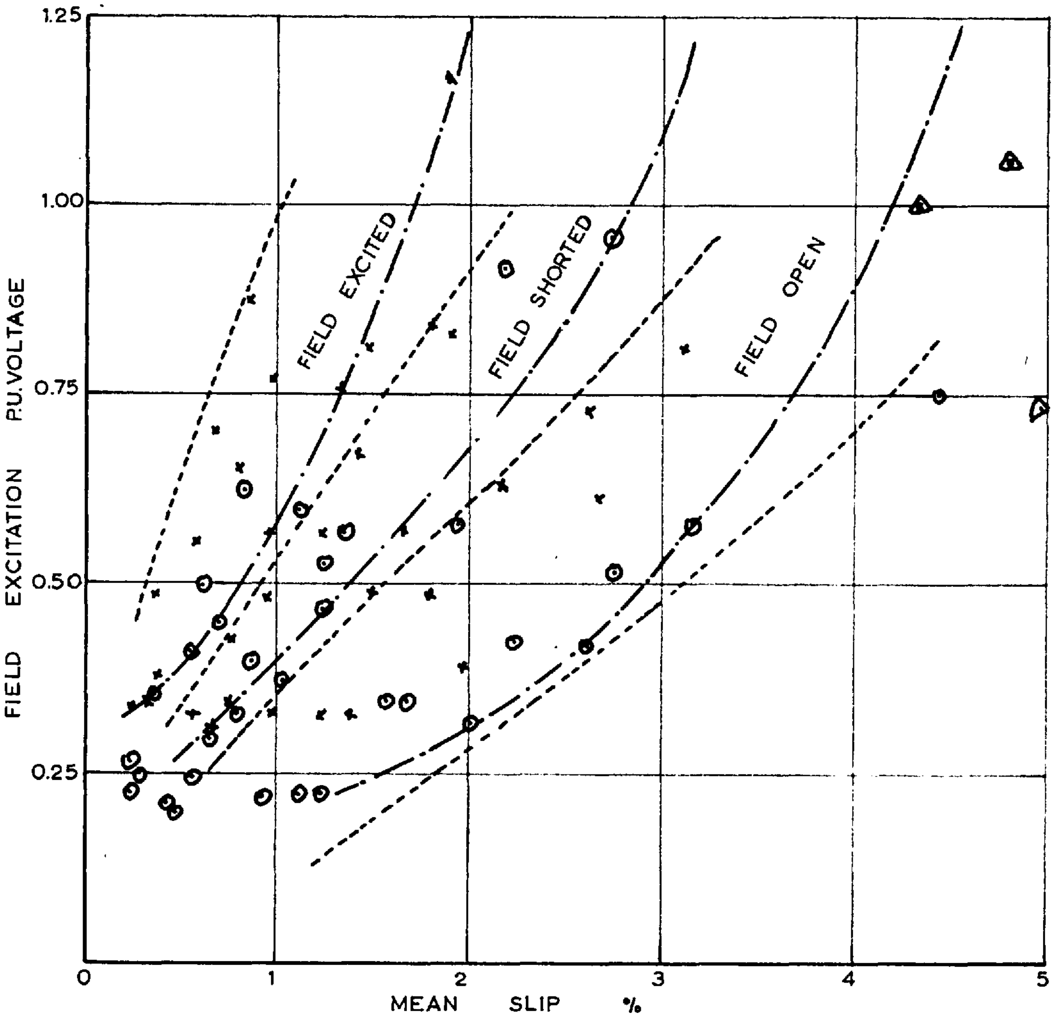


Fig. 8.2 Effect of slip on the magnitude of field excitation required to resynchronise

Micro_machine with solid rotor

Micro_machine results :- Resynchronisation achieved ⊙

No resynchronisation achieved △

Computer results :- Resynchronisation achieved ×

No resynchronisation achieved ⚠

failed to synchronise even for very high magnitudes of excitation are shown in Figs. 7.4 and 7.5.

Average curves for a particular group of studies have been drawn in Figs. 8.1 and 8.2, the scatter of the points showing chiefly the effect of the magnitude of slip pulsations. From this it can be safely concluded that the mean slip magnitude plays the major part in resynchronisation, other factors producing only marginal effects.

8.3 Magnitude of slip pulsations

Fig. 8.3 shows the effect which the magnitude of slip pulsations has over the value of excitation required to pull a machine into step. Large pulsations help towards resynchronisation and their effect is even more pronounced at higher slips than at lower slips. Thus all factors or modes of operation which in any way influence the magnitude of slip pulsations, as discussed in Chapter 6, would in a like manner also affect resynchronisation of the machine.

8.4 Angle of field application

After slip magnitude, the second most important factor influencing resynchronisation is the angle in the slip cycle at which the field is reapplied or boosted. According to the theory for resynchronisation as postulated above, the field should be switched in at the instant the load-angle passes through zero degrees or at any time after.

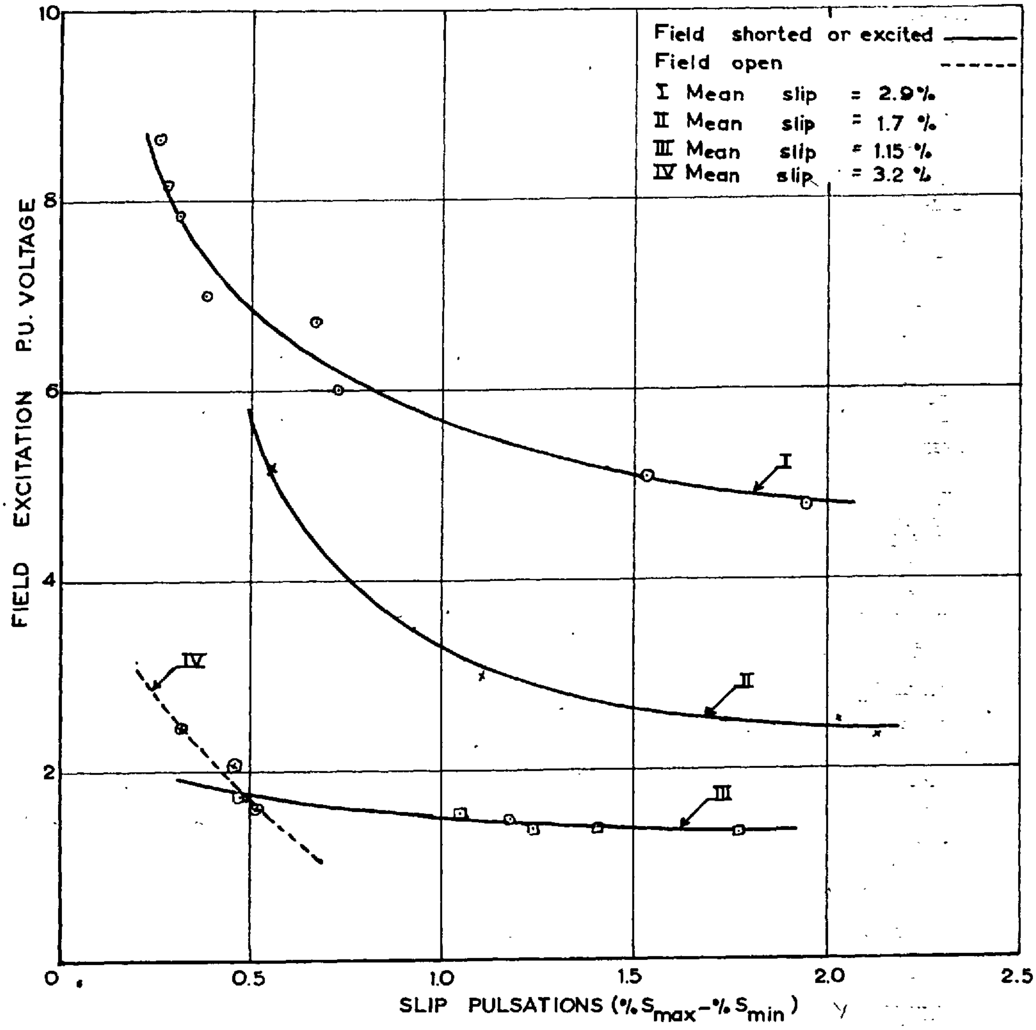


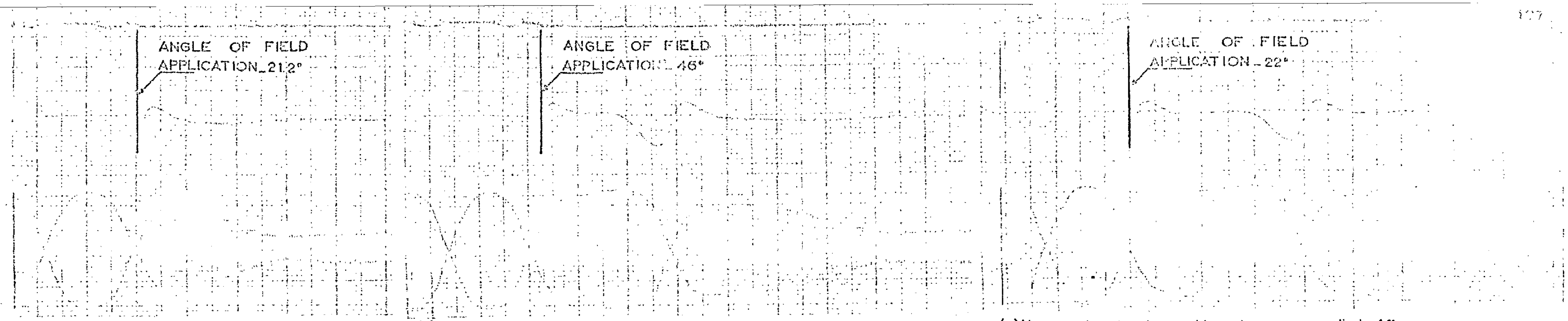
Fig.8.3 Effect of slip pulsations on the magnitude of field excition required to resynchronise

Laminated rotor

The amount of delay in switching is, however, subject to the condition that the equal area criterion described by Eqn. (7.13) and Fig. 7.1 is satisfied before the load-angle reaches 180°. Thus there is a limiting value of load-angle before which the excitation must be applied. This is clearly shown in Figs. 6.1 to 6.6, 6.8 to 6.11, 6.13, and 6.20 to 6.24 relating to the studies on the analogue computer and Figs. 8.4 to 8.13 relating to tests on the micro-machines. That this is so, is also shown by the studies carried out on a tidal power station in France[94].

Because of the non-linear nature of the whole problem as formulated by Eqn. (7.13), it is not possible to calculate the limiting value of the angle in a straight forward manner. The exact value would depend upon the system conditions at the time of resynchronisation and a number of other factors. The effect of the two most important factors is briefly discussed below.

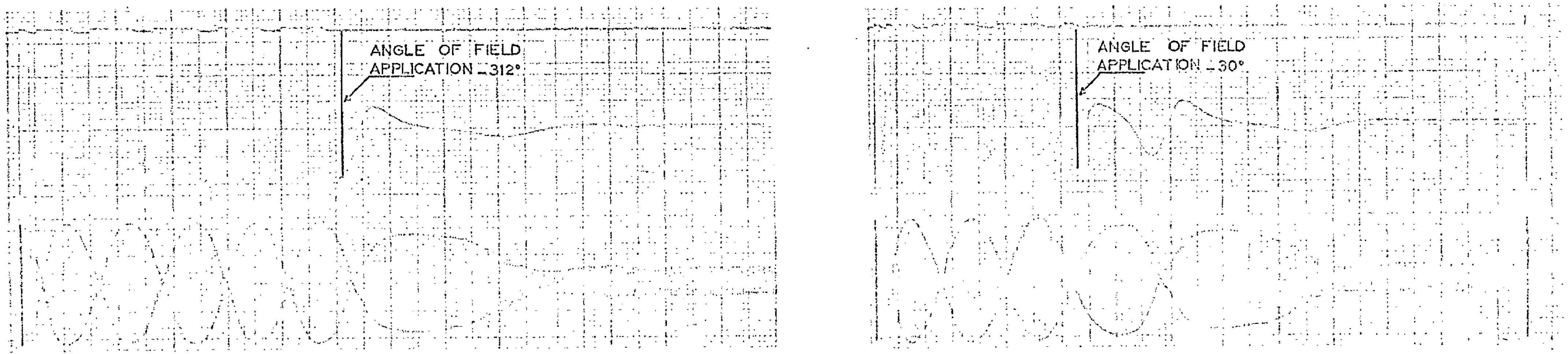
i) Time-constant of the field circuit. Because the field circuit has a finite time-constant, the field current cannot reach its full magnitude immediately at the instant of switching. Thus the synchronous torque component as given by Eqn. (7.14) would be modified. For a machine with a large time-constant, it takes a long time for the excitation to build up and though the machine starts to slow down almost immediately, the synchronous power supplied is not sufficient to bring it to synchronous speed by the time load-angle reaches 180°. After that the machine again starts to accelerate under the negative synchronous



(a) Synchronisation achieved, e_f applied=1.185 p.u.   (b) No synchronisation in one slip cycle, e_f applied =1.185 p.u.   (c) No synchronisation achieved , e_f applied =1.11 p.u.

Fig. 8.4 Resynchronisation on micro-machine

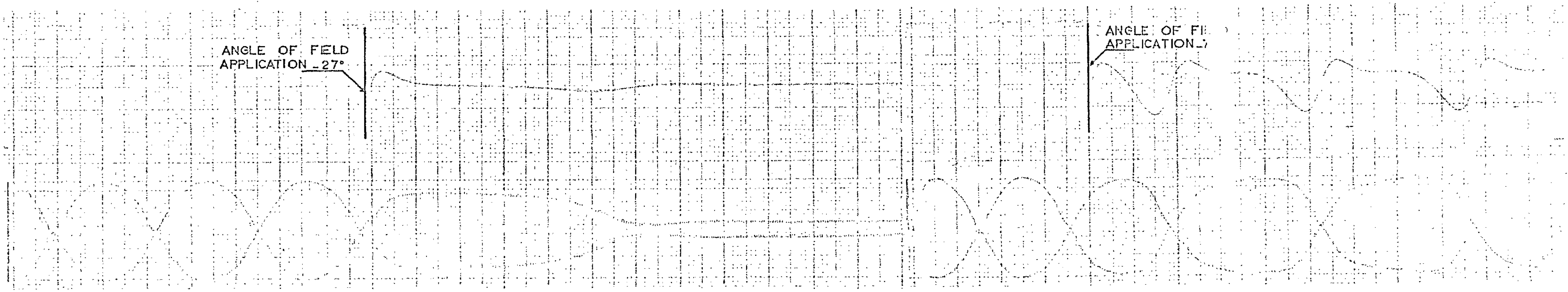
Field open, T_m =0.81 p.u., x_e=0 , e_{bus} =1.0 p.u. , Laminated rotor



(a) Synchronisation achieved   (b) No synchronisation in one slip cycle

Fig. 8.5 Resynchronisation on micro-machine

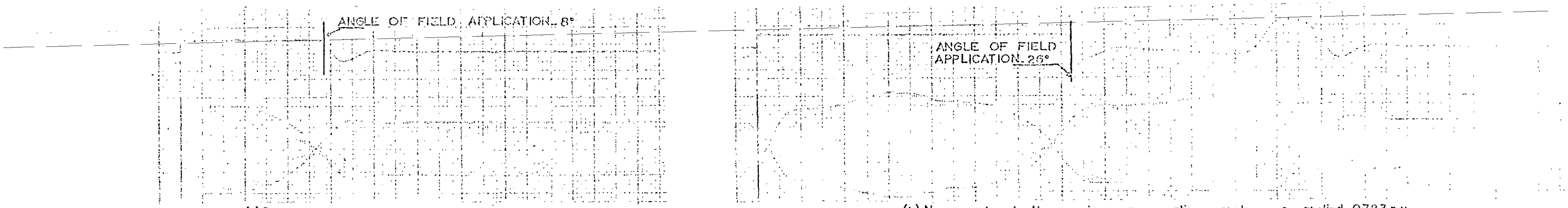
Field open, T_m =0.712 p.u., x_e=0.2 p.u., e_{bus}=1.1 p.u., e_f applied=2.025 p.u. , Laminated rotor



(a) Synchronisation achieved   (b) No synchronisation achieved

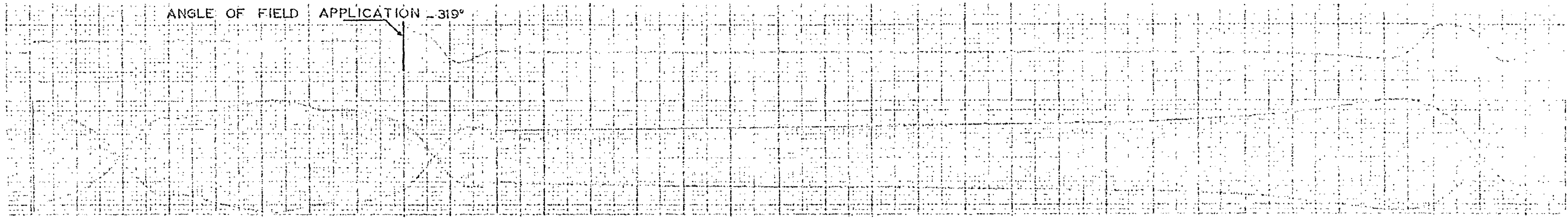
Fig. 8.6 Resynchronisation on micro-machine

Field open, T_m =0.452 p.u., x_e=0.2 p.u., e_{bus}=1.1 p.u., $e_f$applied=0.762 p.u. , Laminated rotor



(a) Synchronisation achieved, e_f applied = 0.723 p.u.

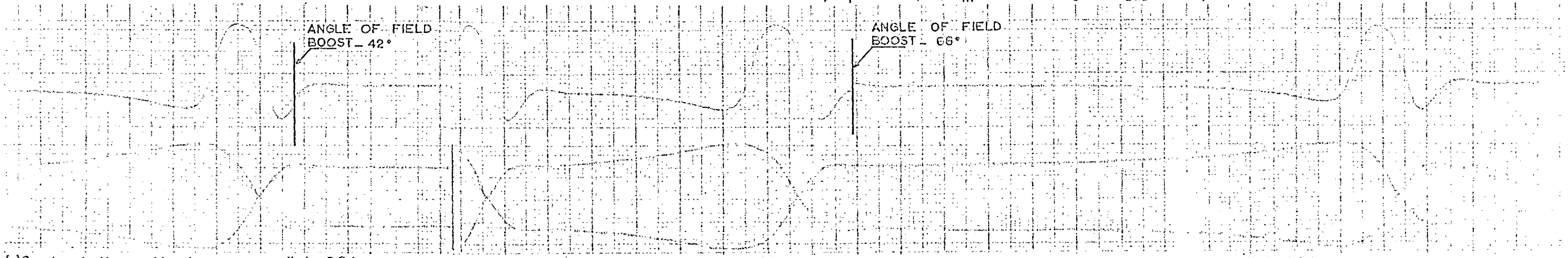
(b) No synchronisation in one slip cycle, e_f applied = 0.723 p.u.



(c) No synchronisation achieved, e_f applied = 0.675 p.u

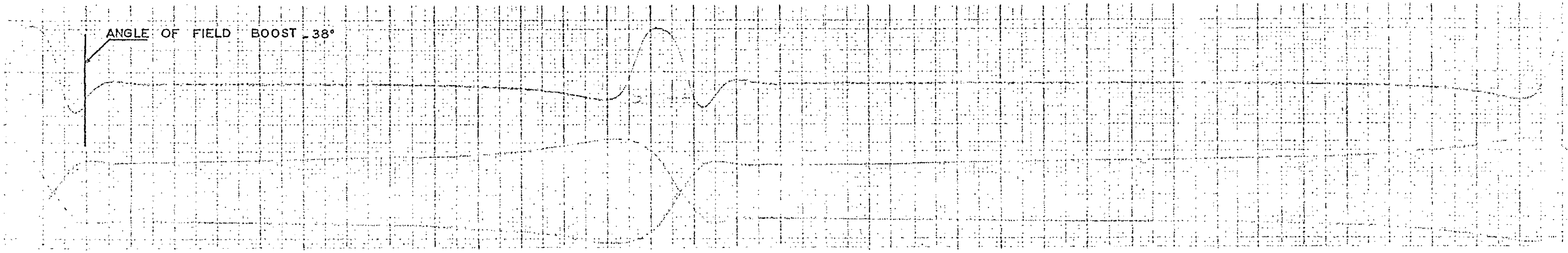
Fig. 8.7 Resynchronisation on micro_machine

Field shorted on itself, r_f = 0.00446 p.u., T_m = 0.843 p.u., x_e = 0, e_{bus} = 1.0 p.u., Laminated rotor



(a) Synchronisation achieved, e_f applied = 0.84 p.u.

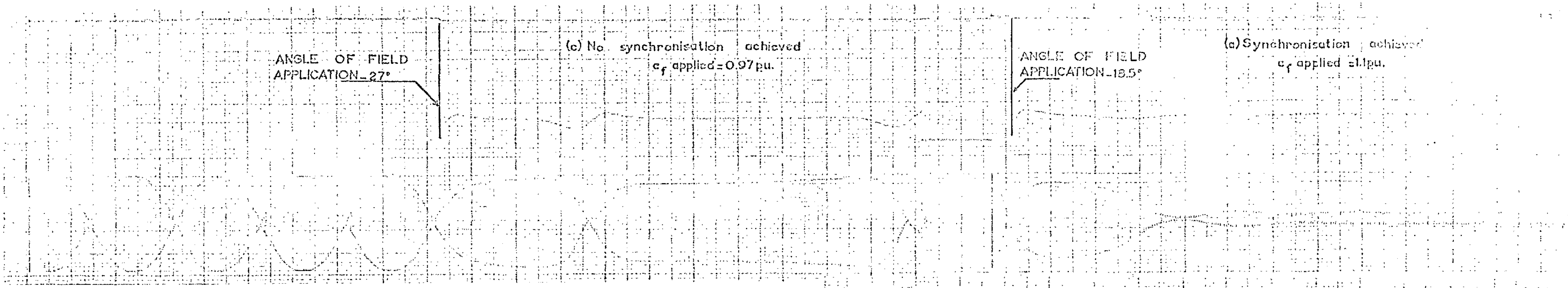
(b) No synchronisation in one slip cycle, e_f applied = 0.84 p.u.



(c) No synchronisation achieved, e_f applied = 0.82 p.u.

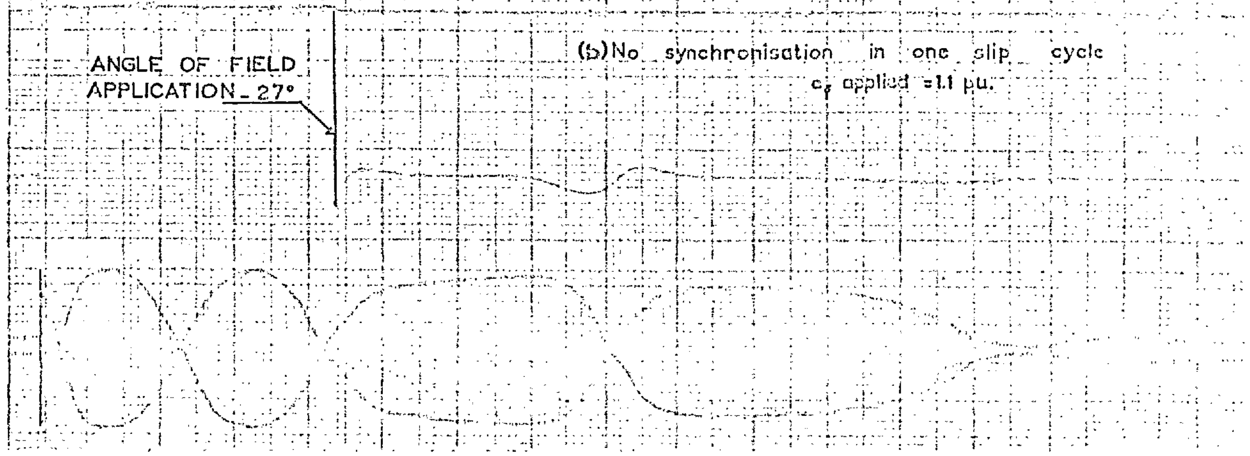
Fig. 8.8 Resynchronisation on micro_machine

Field excited, T_m = 0.913 p.u., x_e = 0, e_{bus} = 1.0 p.u., Laminated rotor



(c) No synchronisation achieved
e_f applied = 0.97 p.u.

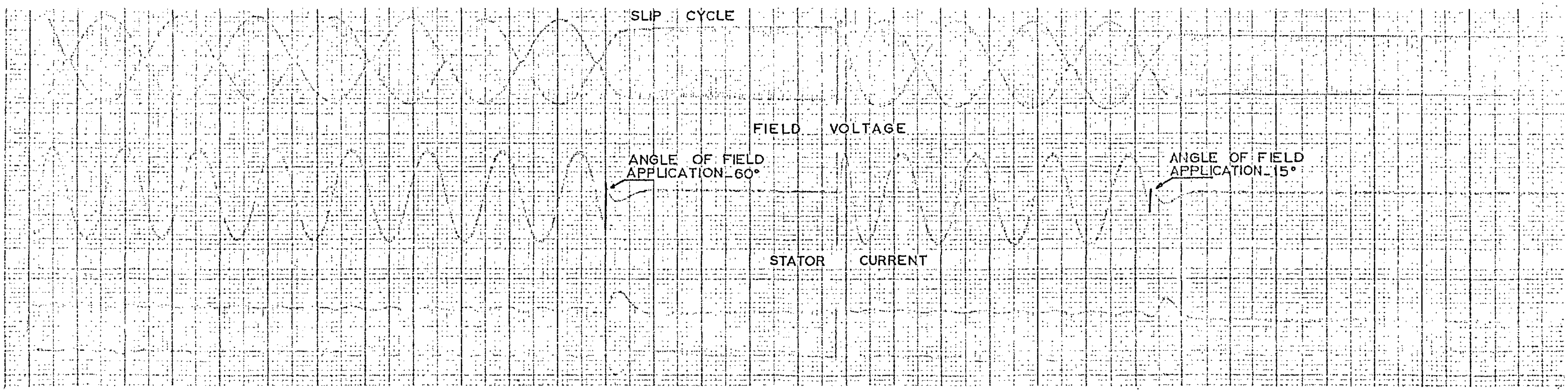
(a) Synchronisation achieved
e_f applied =1.1 p.u.



(b) No synchronisation in one slip cycle
e_f applied =1.1 p.u.

Fig 8.9 Resynchronisation on micro_machine

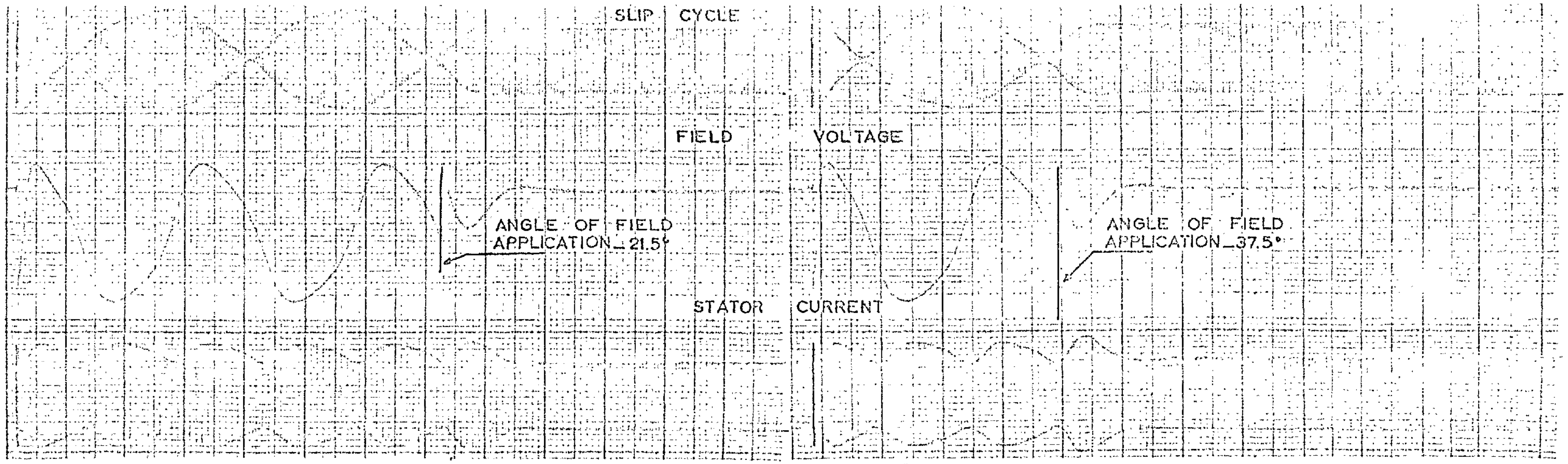
Slip cycle for field open
T_m = 0.6 p.u., x_e = 0.2 p.u., e_{bus} = 1.0 p.u.
Laminated rotor



(b) No synchronisation in one slip cycle

(a) Synchronisation achieved

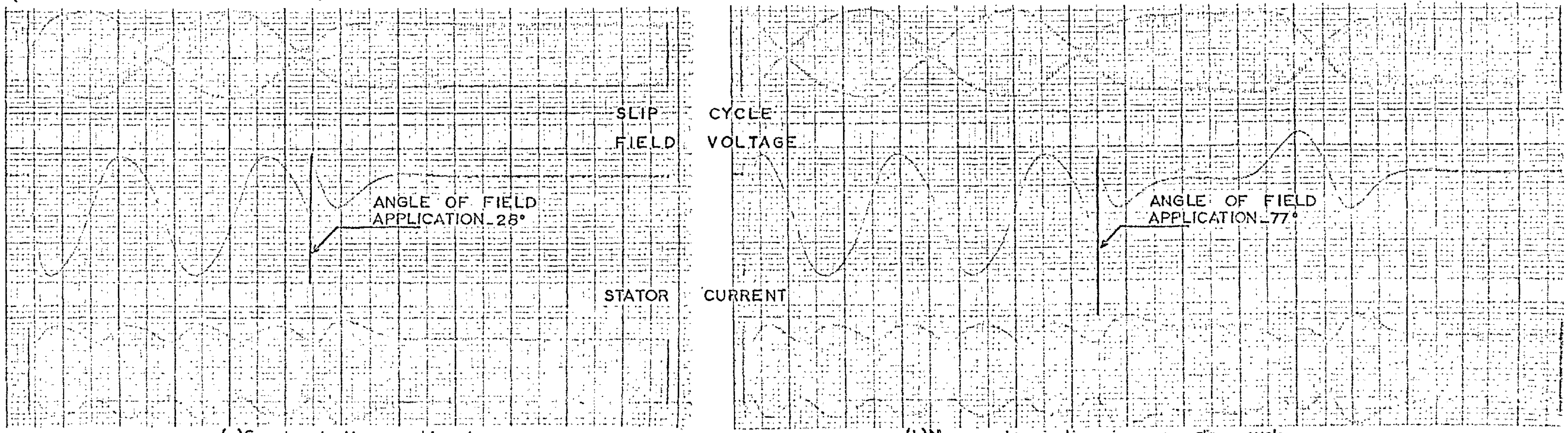
Fig 8.10 Resynchronisation on micro _ machine
Solid rotor, Field open, T_m = 0.522 p.u., X_e = 0, e_f applied = 0.58 p.u.



(a) Synchronisation achieved

(b) No synchronisation in one slip cycle

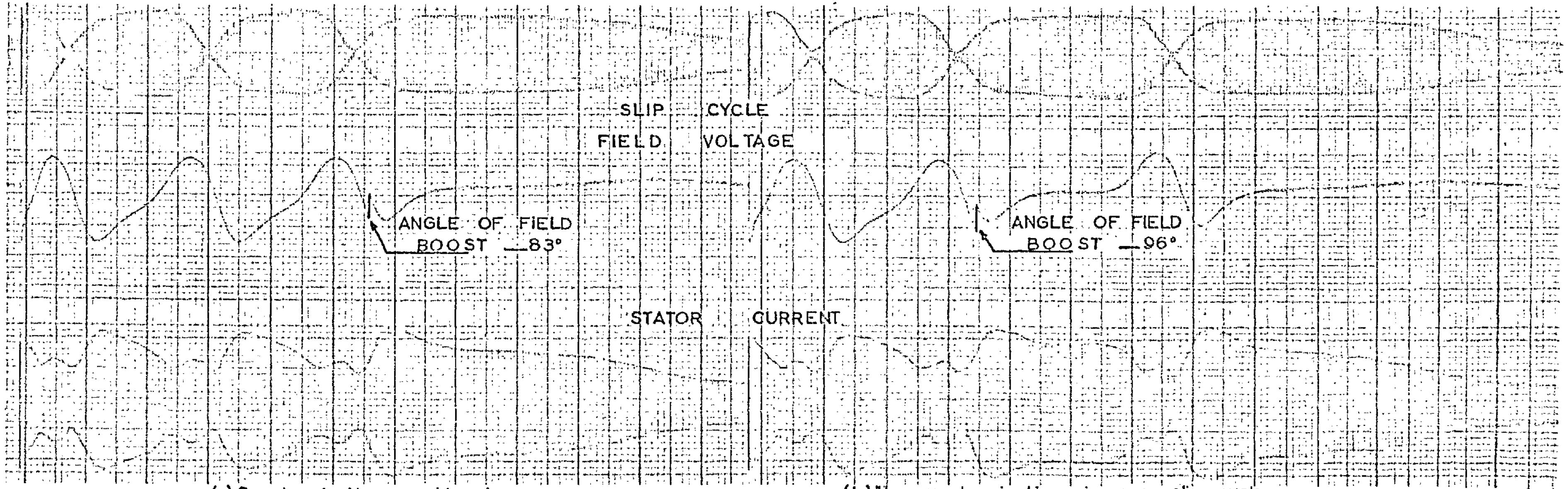
Fig. 8.11 Resynchronisation on micro_machine
Solid rotor
Field shorted through discharge resistor
$T_m = 0.509$ p.u., $X_e = 0.142$ p.u.
e_f applied = 0.573 p.u.



(a) Synchronisation achieved

(b) No synchronisation in one slip cycle

Fig. 8.12 Resynchronisation on micro_machine
Solid rotor
Field shorted through discharge resistor
$T_m = 0.442$ p.u., $X_e = 0.284$ p.u.
e_f applied = 0.58 p.u.



(a) Synchronisation achieved

(b) No synchronisation in one slip cycle

Fig. 8.13 Resynchronisation on micro_machine
Solid rotor
Field excited
$T_m = 0.471$ p.u., $X_e = 0.284$ p.u.
e_f initial = 0.6 p.u., e_f boost = 0.315

torque, until the slip cycle is completed and the machine can resynchronise in the first half of the ensuing slip cycle [Figs. 6.1, 6.2, 6.10, 6.20 and 6.21].

A larger time-constant field would thus require the excitation to be switched-in much earlier than the field with a smaller time-constant, as is shown by a comparison of points marked 1, 12 & 13 (unity T_m) or of points 7, 12(a) & 16 (0.75 T_m) in Fig. 8.14 for different values of time-constants.

This can also be put in an alternative form, that for the same magnitude of field excitation, the machine with a small field time-constant can be resynchronised from a larger slip than the machine with a field circuit having a large time-constant.

ii) Field circuit connection during asynchronous operation. The effect of this factor is shown in Figs. 8.1, 8.2, 8.14 and 8.15, and is discussed in greater detail in Section 8.7 below.

If the field is switched-in just before the limiting value of load-angle, the machine will pull into step with a minimum swing in current, power and VArs. The swing will be bigger if the field is switched-in earlier, although there is a fairly wide range over which the swing will increase only slightly as shown in Figs. 6.10 and 6.11.

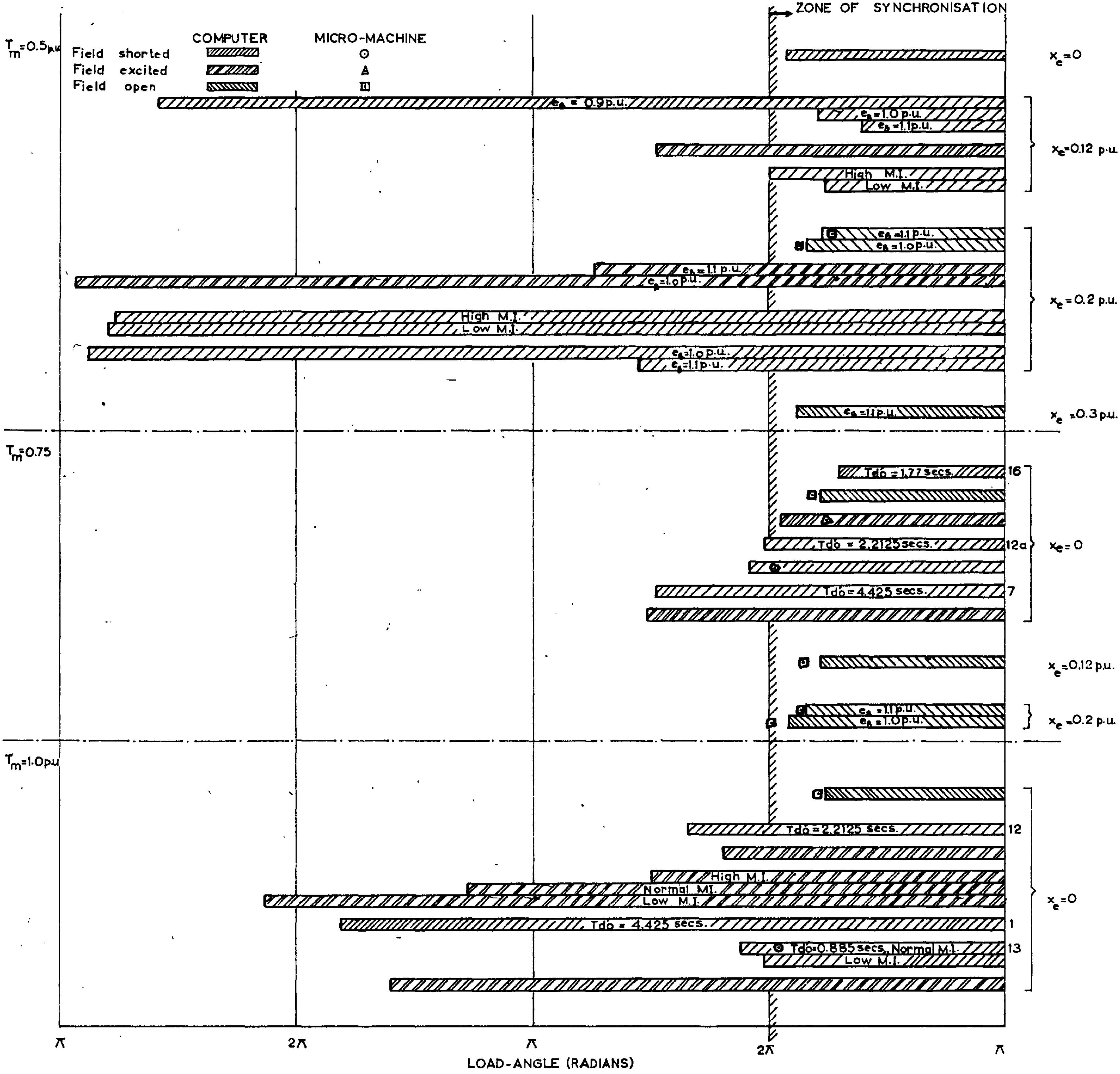


Fig 8.14 Limiting angle of field application for resynchronisation

Start of the shaded area corresponds to the limiting angle before which field must be applied for the machine to resynchronise in the zone indicated (Laminated rotor)

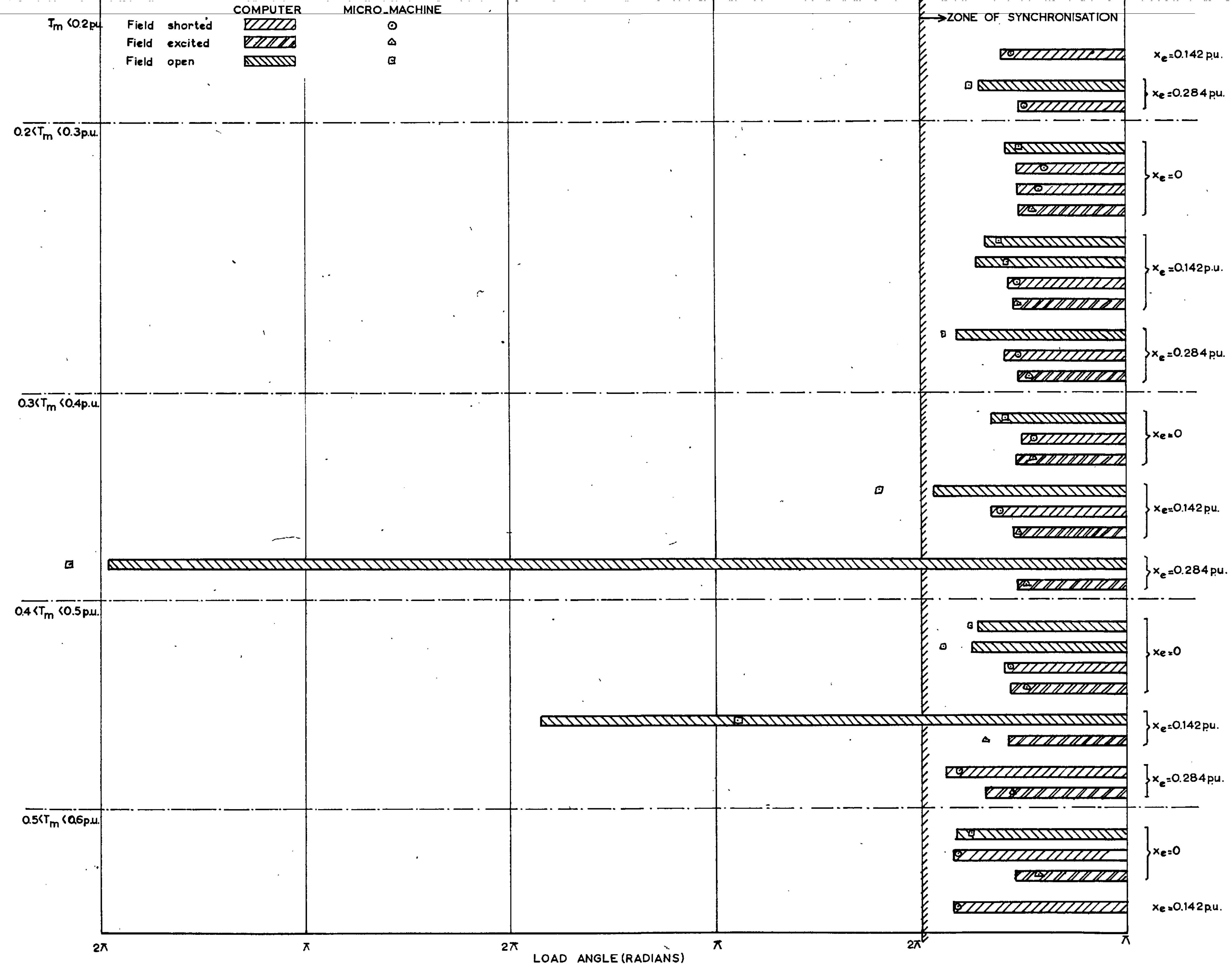


Fig. 8.15 Limiting angle of field application for resynchronisation

Start of the shaded area corresponds to the limiting angle before which field must be applied for the machine to resynchronise in the zone indicated (Solid rotor)

Figs. 6.1, 6.3, 6.5 and 6.14 also show the effect of applying the field excitation beyond the limiting angle. In these cases, the machine does not synchronise within the required period but goes through another slip cycle before pulling into step. Thus there will be one more system fluctuation. In some cases it may even be of bigger amplitude. To avoid this, it is desirable that the field be switched-in before the limiting angle so as to ensure resynchronisation in the shortest possible time.

8.5 Magnitude of excitation

Theoretically, the minimum excitation required to achieve resynchronisation may be very small if the slip is small. However, the excitation applied must be more than the minimum required to keep the machine in synchronism subsequently. In most cases this minimum value is large enough to effect resynchronisation if applied at the correct instant.

It has been previously mentioned that it is possible to pull the machine into synchronism from any slip likely to be encountered in practice, provided that a sufficiently large magnitude of excitation is applied. However, there is a maximum value of the excitation that can be obtained from any excitation system. The maximum value of slip admissible will, therefore, be limited by the maximum excitation available from the excitation system.

8.6 Swing in output

During the time the resynchronisation process lasts, in addition to its normal output (equal to the mechanical input minus losses) the machine must also discharge, in the form of electrical output to the system, the additional stored kinetic energy of its rotor. In general, therefore, the output of the machine would be expected to rise momentarily before settling down to synchronous running. In the case of a motor, a similar swing will be caused by the power required by the machine to meet the increase in kinetic energy of the rotor when it attains synchronous speed. The swing in power and VArs is shown in Figs. 6.1 to 6.6, 6.8 to 6.11, 6.13 and 6.20 to 6.24, and in current in Figs. 6.14 to 6.19 and 6.25 to 6.32. The magnitude of swing in the various quantities is dependent upon a number of factors and their mutual interaction, as briefly discussed below.

8.6.1 Magnitude of slip

The energy to be dissipated depends directly on the magnitude of slip [Eqn. (7.9)], and thus, the smaller the slip, the smaller the swing in power and current.

8.6.2 Nature of asynchronous torque-slip characteristics

As the machine approaches synchronous speed, the asynchronous torque decreases. Depending upon the gradient of the torque-slip characteristics, some of the excess energy would be absorbed by this reduction in the generated electrical power, thereby limiting the jump in output.

8.6.3 Angle of application of excitation

The angle at which the field is applied has a profound effect on the swing in various quantities. After the application of the field, if the machine pulls into step without passing through another slip cycle, there will be a single jump, generally of a comparatively small magnitude, in the power output. If, however, the machine passes through another slip cycle, there is a violent fluctuation in all the quantities because the synchronous torque component becomes negative in the second half of the slip cycle. These two conditions are clearly marked out by a random plot made in Fig. 8.16 for a large number of studies with successful resynchronisation.

8.6.4 External reactance

The value of the external reactance has a relatively small effect on the swing in power, but it significantly reduces the jump in VArs. Even with reasonably small values of external reactance (of the order of 0.15 p.u.), the swing in VArs is practically eliminated.

8.6.5 Magnitude of field excitation

In general, higher the value of field excitation required to pull the machine into step, larger the swing in watts and VArs.

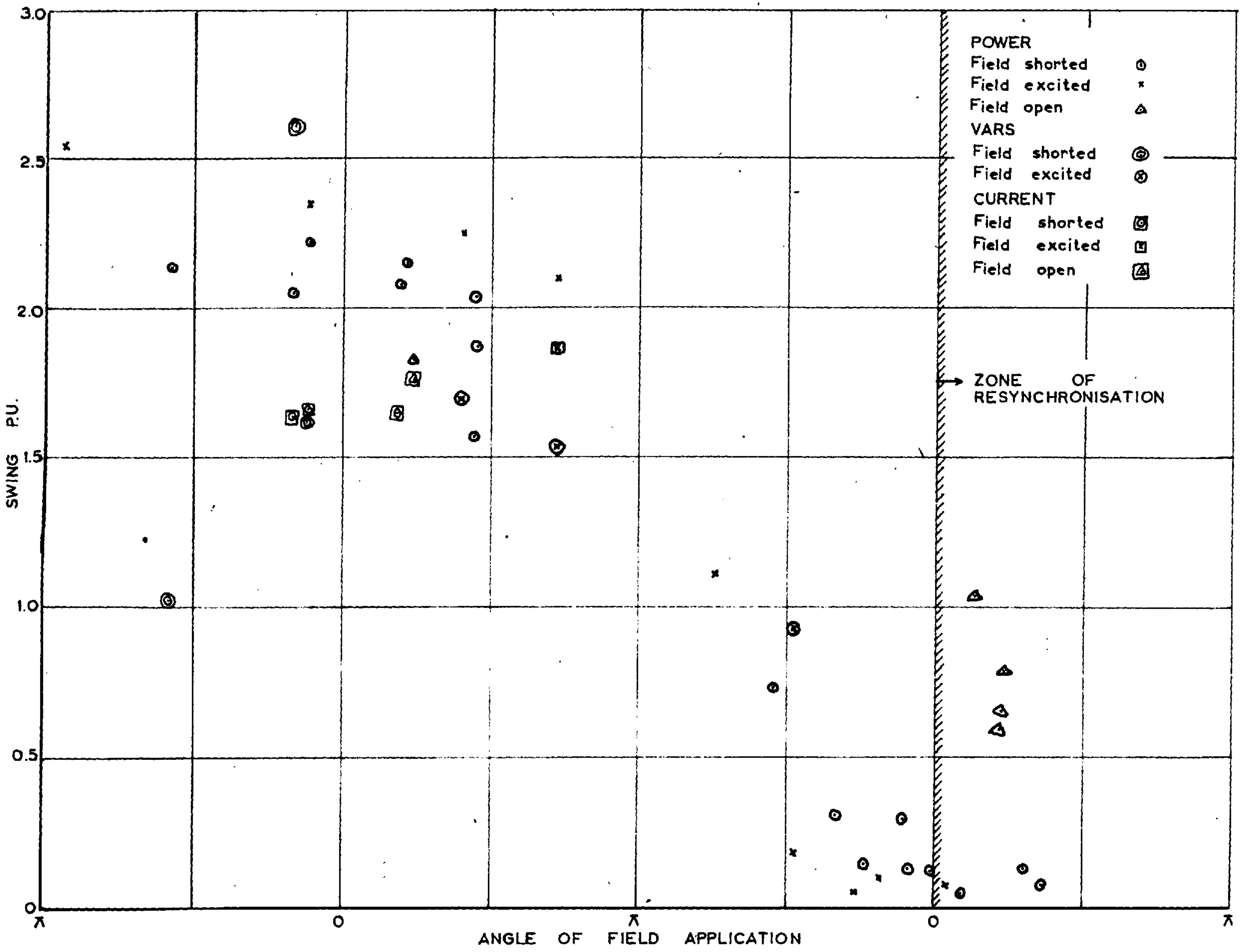


Fig.8.16 Swing in watts, vars and current at the instant of resynchronisation related to the angle of field application

Micro-machine with laminated rotor

8.7 Mode of field connection

The effect on asynchronous operation if the field is connected in one of the three states (i) shorted, (ii) excited or (iii) open, has been discussed in Section 6.8. Effect of these modes of operation on resynchronisation is shown in Figs. 8.1, 8.2, 8.14 and 8.15, and is discussed below.

8.7.1 Field shorted

Asynchronous operation with a shorted field would generally be obtained in practice with the field shorted through a discharge resistor. While applying excitation to resynchronise the machine, the discharge resistor is switched out, thereby increasing the effective field time-constant considerably and simultaneously trapping the flux linking the field circuit at that instant. By virtue of the property of 'constant flux linkages' in a closed circuit, the applied excitation does not become fully effective in producing sufficient synchronous torque until the trapped negative linkages have decayed and finally reversed by the joint action of armature reaction and applied excitation. It therefore requires a comparatively large excitation and long time to resynchronise the machine in this mode.

Also, because of the longer time required for the decay of trapped flux linkages in a machine with a large field time-constant, the magnitude of excitation required to resynchronise will be larger than for a machine with a field circuit of smaller time-constant. This was clearly proved to be so by the various studies performed on the analogue computer and is shown in Fig. 8.14.

8.7.2 Field excited

As in the previous case, the flux linkages in the field circuit at the instant of boosting the excitation have a considerable influence on the magnitude of field required to resynchronise the machine. Because the field excitation is already present, the time required for the field to be fully effective is shorter than in the previous case, but the total magnitude of excitation, i.e. the initial excitation present plus the boost required, is no less than in the case of field shorted through a discharge resistor. This is shown by Figs. 8.1, 8.2, 8.14 and 8.15.

8.7.3 Field open

On exciting the field from the field open condition, the flux starts building up immediately. Because of the absence of any trapped linkages in the field circuit, the rise in the synchronous torque is controlled by the field time-constant only. The applied excitation is thus more effective in this mode of operation than either of the other two cases discussed above. It requires the least time and the minimum magnitude of excitation to resynchronise a machine operating asynchronously with the field open as shown clearly in Figs. 8.1 to 8.3, 8.14 and 8.15. Because of this, it would also entail disturbance to the system for the shortest time.

8.8 Moment of inertia

The total moment of inertia of the machine affects the magnitude of the slip pulsations. A small value increases the pulsations about the mean value, while a large amount of inertia has the opposite effect. As discussed in Section 8.3 and shown in Figs. 6.7 and 8.3, the larger pulsations need smaller field excitation. Thus a lower moment of inertia generally helps in resynchronisation.

8.9 Turbine speed-governor

The turbine speed-governor affects the mean slip and power output of the machine by controlling the input to the turbine. As it has no direct effect on the electrical side of the system, it can simply be used as a useful tool to control the speed of the machine during asynchronous running and to keep it below the optimum slip value so as to render resynchronisation possible. The governor can thus play an important part in the ultimate scheme for automatic resynchronisation. For this purpose, some device will need to be incorporated in the turbine control system to initiate a change in the governing set point during operation in the asynchronous regime.

8.10 Voltage regulator

Automatic voltage regulators affect resynchronisation in two ways; firstly, by the direct effect of the regulator on the machine which has fallen out-of-step, and secondly, by the effect of regulators on other machines in the system.

8.10.1 Effect of the regulator on the out-of-step machine

It has been shown in Section 8.2 that for a particular mean slip value, a minimum value of excitation is required to successfully pull the machine into step. Conversely, for a given per-unit ceiling voltage of a particular voltage regulator, there is a maximum value of mean slip beyond which it would not be possible to resynchronise the machine. The ceiling voltage of modern automatic voltage regulators is generally between 5 and 7 times[95] the value required for no-load excitation to produce rated voltage. Keeping in view the limitations on output during asynchronous operation as discussed in Section 6.6, Figs. 8.1 and 8.2 show that this ceiling is sufficiently high and does not impose any unreasonable limitations.

8.10.2 Effect of regulators on the system

During asynchronous operation, a machine demands heavy lagging reactive voltamps from the system. Under these conditions, if the excitation on the rest of the machines on the system is boosted, it will raise the voltage on the system, which is analogous to the studies made on the computer with high bus-bar voltages. Higher voltage keeps the slip of the out-of-step machine low and thus helps in resynchronisation as shown by a few cases in Fig. 8.14.

8.11 Simulation of full-scale tests

Rarely has a series of tests been conducted with the primary object of studying resynchronisation of synchronous machines under controlled conditions. The literature is, therefore, devoid of any information on this topic. In one test in the Staythorpe series (mentioned in Section 5.5.3) resynchronisation was attempted by applying the field at a random angle. At the instant of switching-in the field, the load-angle was 135° and the machine did not pull-into-step immediately. Instead it started to operate out-of-step at a higher mean slip. It passed through several slip cycles and synchronism was restored by reducing the load setting with the help of the turbine speeder gear mechanism.

This test has been simulated on the analogue computer for further study and the results obtained are given in Fig. 8.17. In Fig. 8.17(a) is shown the attempted resynchronisation as in the test and, as expected, the machine did not synchronise immediately. Fig. 8.17(b) shows the optimum result of a resynchronisation study. With field excitation of 1.0 p.u. [same value as for the case of Fig. 8.17(a)] applied at an angle of 68° instead of 135°, the machine pulled in very smoothly.

Resynchronisation studies have also been performed in a few of the asynchronous operation tests mentioned in Sections 5.5.1 and 5.5.2. The results obtained are summarised in Table 8.1 below. All these studies show that it is possible to resynchronise the machine by applying a reasonable magnitude of field excitation at the correct instant in the slip cycle.

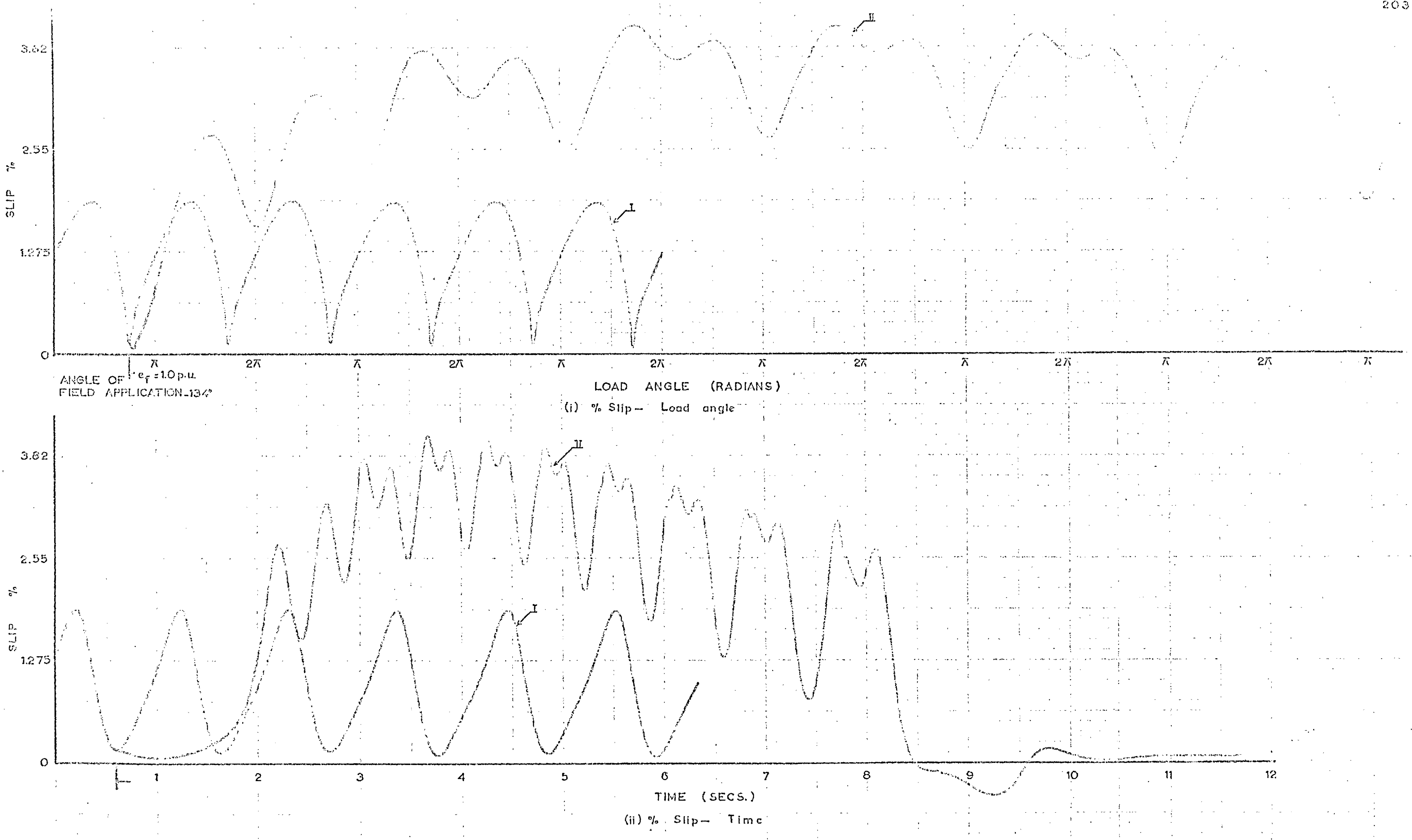
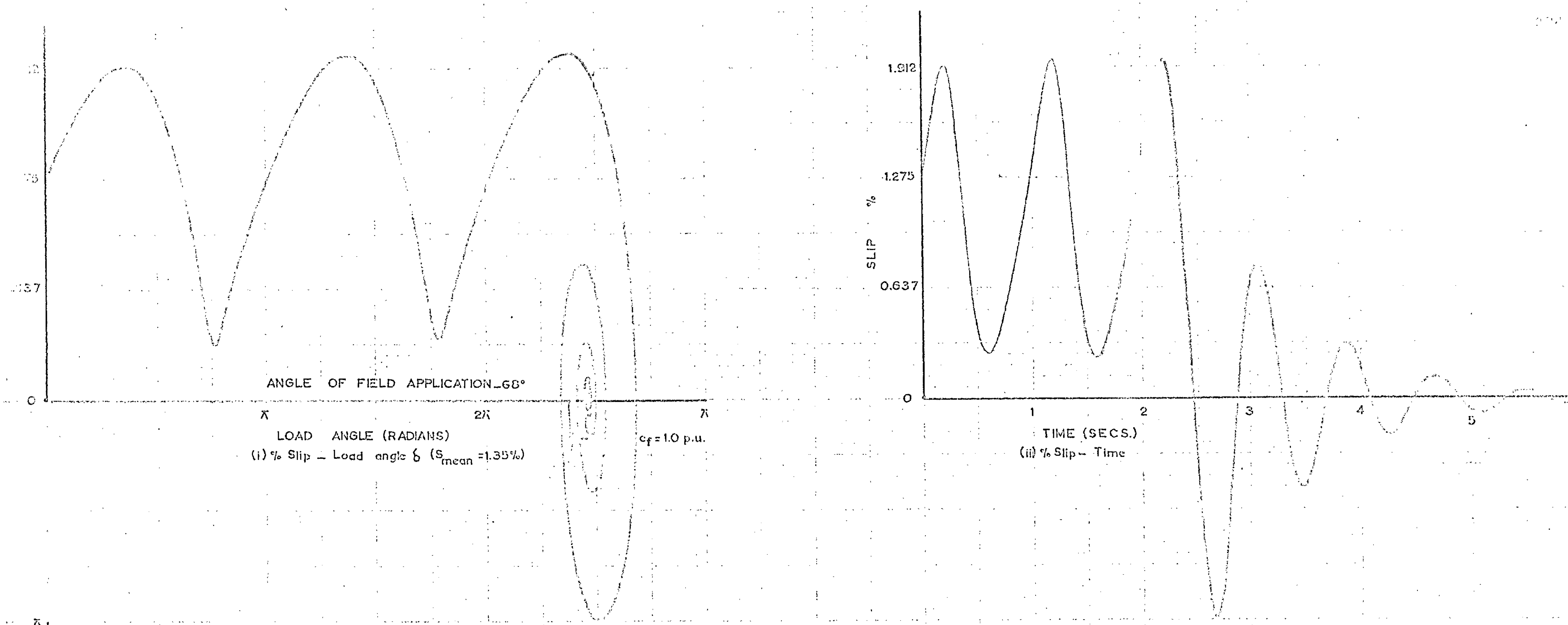


Fig.8.17(a) Attempted resynchronisation of a 120 M.W. Turbo-alternator

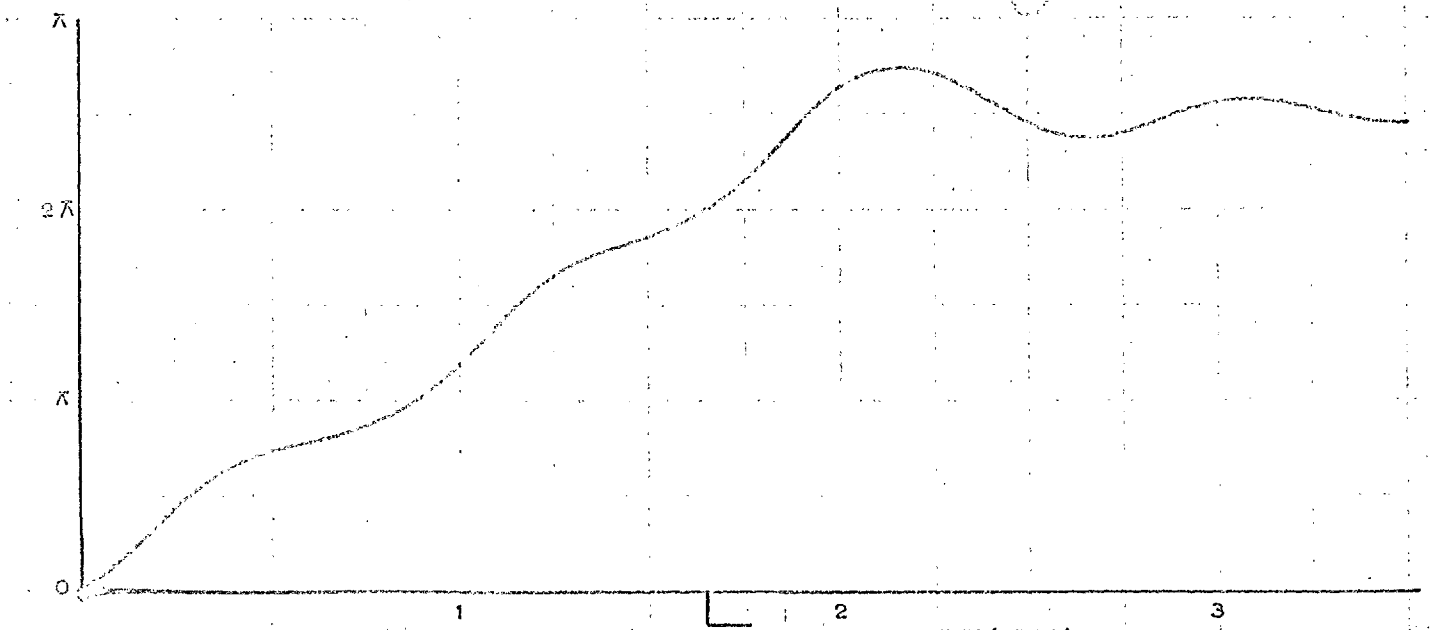
I. Steady asynchronous operation with field shorted through discharge resistor

II. Behaviour after application of field at an angle of 134°



(i) % Slip – Load angle δ (S_{mean} = 1.35%)

(ii) % Slip – Time



(iii) Load angle – Time

Fig.8.17(b) Study of resynchronisation of a 120 M.W. Turbo-alternator

Table 8.1

	Field	Output during asynchronous operation, p.u.	Magnitude of excitation applied, p.u.	Angle of field application, degrees
Marchwood 60 MW machine	Open	1.036	1.190	82.0
	Open	0.790	0.923	87.0
	Shorted	0.953	1.117	85.0
Goldington 30 MW machine	Open	0.560	0.884	85.5
	Shorted	0.560	1.000	85.5

CHAPTER 9

AUTOMATIC RESYNCHRONISING RELAY

9.1 General

Although the suggestion for providing a relay to detect out of synchronism conditions was mooted as far back as 1930[96], no attention has been devoted to its development, except in the USSR where the only known scheme for automatically resynchronising generators has been developed[97]. In this scheme, electromagnetic relays have been used to monitor various conditions and to initiate necessary corrective action. The USSR relay is designed to apply excitation after the slip has been reduced to a predetermined magnitude, but has very little control on the angle δ at which field is actually switched-in.

It has been shown, by the studies described in the previous chapter, that the angle of field application plays a very important part in achieving successful resynchronisation. Based on the results of these studies, an entirely new scheme has been proposed to bring the machine automatically back into synchronism, and an electronic relay employing static relaying principles developed. This relay uses transistors as individual switches and component parts of trigger circuits to monitor various variables, so that the necessary signals to resynchronise the machine can be provided after the required criteria have been satisfied. The relay described is capable of adjustments within wide limits to suit the requirements of individual machines with respect to their location in the system.

9.2 Criteria for resynchronisation

Chapter 8 shows that for a particular machine in operation, there are three factors which have to be controlled to establish resynchronisation. The requirements in respect of these three factors are specified below.

9.2.1 Magnitude of mean slip

There is a maximum value of mean slip beyond which it is practically impossible to resynchronise a machine. In practice, this maximum value is determined by the ceiling voltage of the excitation system. It is desirable that at the instant of initiating necessary action to resynchronise, the mean slip should be within prescribed limits. A check is, therefore, required on the slip magnitude.

9.2.2 Angle of field application

The second most important requirement is that the excitation should be applied at a definite instant in the slip cycle. The exact angle depends upon the system conditions at the instant of the disturbance, but the zone in which the field can be applied is usually fairly wide. So long as the field is switched in before the limiting angle is reached, the machine will pull in smoothly.

Without the aid of some 'on line' computing equipment, a simple resynchronising scheme will need to be pre-adjusted for a definite angle. Based on the limiting slip specified above, it is possible to fix an average value of the angle δ at which the field must be applied or boosted. The actual angle at which action must be initiated will be advanced depending on the time-constant of the field circuit and the operating time of the field circuit-breaker.

9.2.3 Magnitude of excitation

Depending upon the system conditions and the slip, there is a certain minimum magnitude of field excitation which must be applied to pull the machine into step. Depending upon the maximum slip mentioned in Section 9.2.1, the maximum value of excitation that will be required for positive resynchronisation can be determined. By a comparatively simple control loop it is possible to arrange that in the event of a machine losing synchronism, the output of the excitation system would be raised to the predetermined level, thus ensuring that the required value of excitation is switched in at the proper instant.

9.2.4 Accomplishment of the criteria

Depending upon the system conditions, every individual case of resynchronisation will require a different excitation magnitude and angle of application. Any practical scheme using a relay composed of preadjusted single valued components would perforce be a compromise. However, with schemes of automatic control of power stations using 'on-line' digital computers[98,99,100] now being envisaged, it would be very easy to realise the optimum values of all variables as required by the above criteria. By storing a mathematical model of the machine in the computer, it would be possible to recall it in the event of loss of synchronism. By computing the optimum requirements depending upon the actual system conditions, successful resynchronisation can be effected with minimum disturbance. This scheme could be integrated into any scheme for power station control.

9.3 Resynchronisation scheme

9.3.1 General functional arrangement

Any scheme for automatic resynchronisation must perform the following functions in their respective order:

a) detect loss of synchronism,
b) switch the field connection to the desired mode of operation during the disturbance,
c) monitor various quantities to initiate resynchronisation under proper conditions,
d) control the speed-governor, if demanded by (c) above,
e) switch the field circuit back to normal operation.

Fig. 9.1 shows a block schematic representing the performance of the above functions. Functions (a) to (e) and the criteria outlined in Section 9.2 can all be fulfilled quite easily by the use of static relaying techniques. The necessary equipment consists essentially

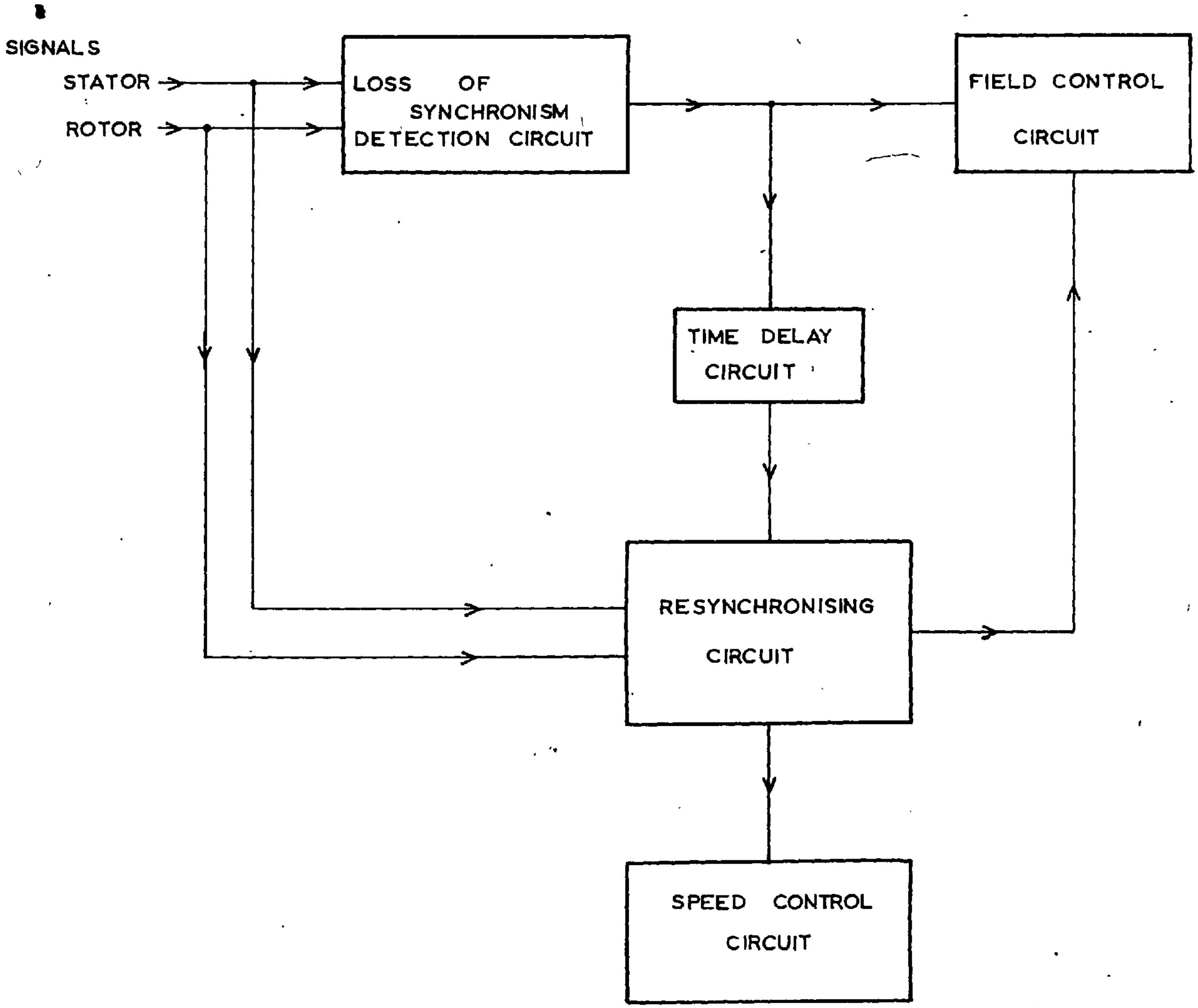


Fig. 9.1 Automatic resynchronising scheme block schematic diagram

of four parts - all transistorised - each with a distinct function, as follows:

i) angle measurement,
ii) maximum slip magnitude control,
iii) phase indicators,
iv) sequential control circuits.

The sequential arrangement of individual transistor circuits for the fulfilment of the required functions is shown in block schematic form by Fig. 9.2.

9.3.2 Loss of synchronism

Loss of synchronism can be detected by continuously monitoring the load-angle of the machine. As soon as the load-angle goes beyond a certain value (δ_5), it can be considered as an indication that the machine has lost synchronism. In the present case two voltage signals - one from the machine stator terminals and the other derived from a tachogenerator on the rotor - are compared in a phase comparator (V). The tacho is initially aligned such that the phase difference between the two voltages is always equal to the instantaneous load-angle.

The phase comparator V has been arranged to generate an output pulse each time the phase difference between the two signals is 180°. This output is fed to the field control circuit and a time delay circuit as shown in the figure.

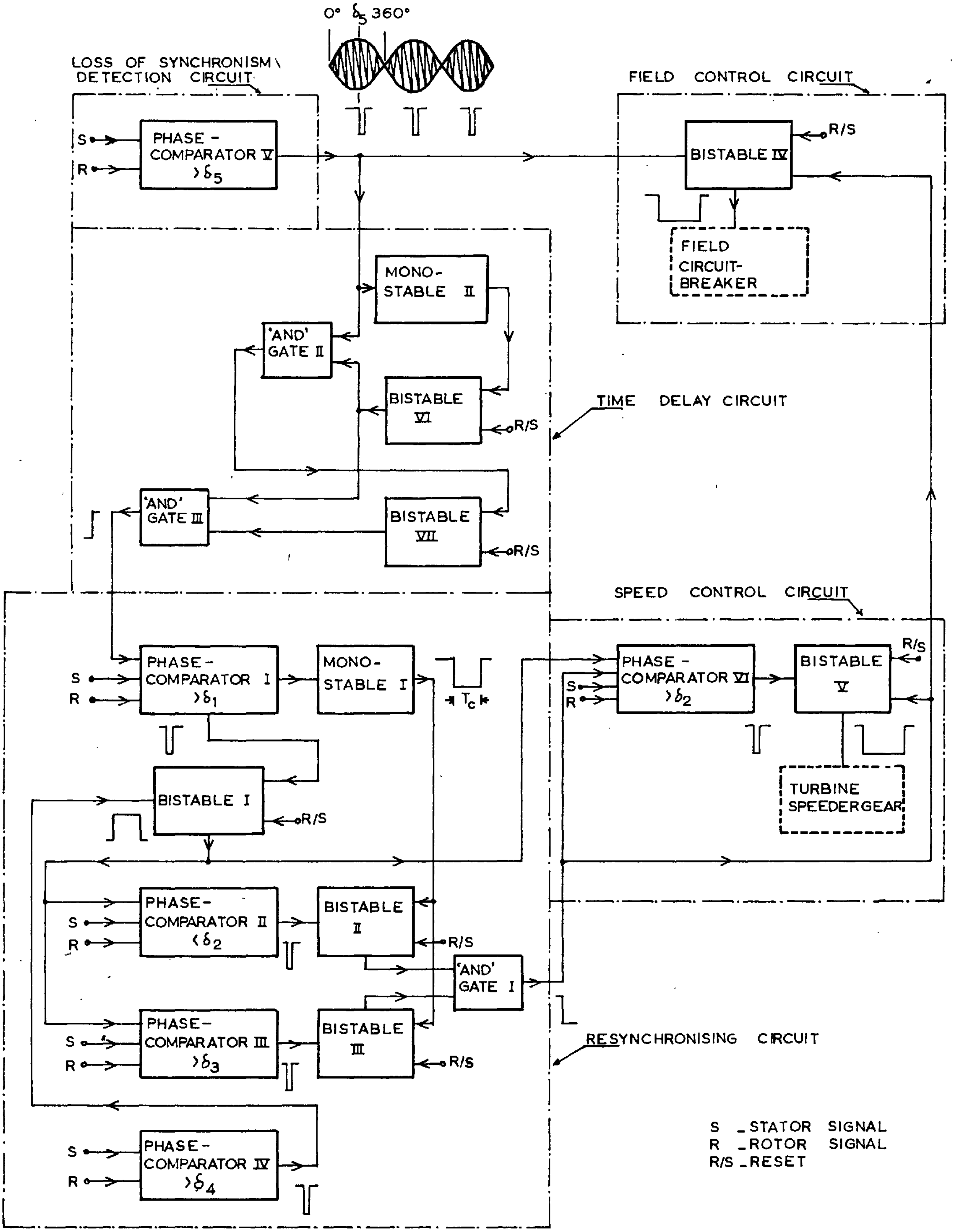


Fig. 9.2 Automatic Resynchronising Relay

Sequential arrangement of transistor circuits

$(\delta_1 < \delta_3 < \delta_2 < \delta_4)$

9.3.3 Field control

During out-of-step operation, the field can be in one of three different modes as described in Chapter 6. Of these, the field excited condition is considered to be the least desirable from an operational point of view. Therefore, provision is required to be made to operate the field circuit-breaker and simultaneously to open the field or short it through a discharge resistor. This has been arranged by means of a simple bistable circuit and a power transistor used as a switch. The signal from the output of synchronism detector opens the switch and shorts the field through a discharge resistor. It can also be arranged to leave the field open. A further signal from the resynchronising circuit will switch in the field at the desired moment.

The micro-machine on which the relay was tested has no voltage regulator. Therefore, no provision was made in the relay, as built, to control the excitation as required in Section 9.2.3. However, in a practical scheme, a signal to the field control circuit, in addition to operating the field switches in the desired manner, can also be made to adjust the excitation to a predetermined level.

9.3.4 Time delay circuit

After losing synchronism, it takes a short time for the machine to settle down to steady asynchronous operation. The resynchronising circuit is, therefore, arranged to come into operation only after this time delay.

In absolute terms, the required time delay would depend upon the mean slip and would thus vary in each case. Some arrangement that would provide a variable time delay proportional to the slip, is therefore, required.

It has been shown in Section 7.3.3 that the machine attains the state of steady asynchronous operation in about two slip cycles. In the present case, a counting circuit has been used to count the number of slip cycles and to provide an output to the resynchronising circuit after the machine has passed the required number. An out-of-synchronism circuit provides an output pulse once every slip cycle. The counting circuit gives an output after the pre-arranged number of slip cycles, thereby providing a variable time delay proportional to the mean slip.

To safeguard against any spurious operation of the counting element, a monostable delay timer has been introduced between the inputs of the bistable VI and the 'And' gate II as shown in Fig. 9.2. This was essential in case the output pulse from the phase comparator V was of sufficient length so that the output pulse from the counting circuit would be given in one slip cycle instead of after the desired number of cycles.

In practice, the counting circuit could be arranged to give a count of two or three. The circuit shown in Fig. 9.2 is designed to provide an output after two slip cycles.

9.3.5 Resynchronising circuit

The resynchronising circuit is the heart of the relay. Its function is to check that all the conditions for successful resynchronisation outlined in Section 9.2 are fulfilled and to give an output signal to apply the excitation at the desired instant. This circuit will be described in detail in Section 9.4.

9.3.6 Speed-governor control circuit

A signal to resynchronise will be given only if the slip is within a certain range. Slip measurement in the resynchronising circuit is achieved by measurement of the angle advanced by the rotor relative to the stator mmf in a fixed time. If the slip is less than the predetermined value, bistables II and III (Fig. 9.2) can operate and send a signal to operate the field circuit, simultaneously blocking the operation of the speed control circuit.

In the case of the slip being high, the phase comparator VI (Fig. 9.2) will produce an output pulse. This pulse will set bistable V which controls the turbine speeder gear mechanism, and reduce the speed. As soon as the speed comes within the required range, the output from the resynchronising circuit will block the operation of phase comparator VI and reset bistable V, thereby returning the governor to normal operation.

9.4 Resynchronising circuit

Operation of the equipment is essentially based on measuring the phase angle between two voltage signals, as already mentioned above. Fig. 9.3 shows the sequential operation of the entire circuit.

9.4.1 Initiation of operation

After receiving an " operate" signal from the time-delay circuit (Section 9.3.4), the actual sequence of operations starts when the load-angle reaches δ_1. Phase comparator I is arranged to produce an output signal [Fig. 9.3(a)] only when both the signals have a phase difference of δ_1. Thus this circuit acts as the operation initiation circuit and also as a reference for the time and phase measurements.

Initial setting of the bistable circuit I is such that it blocks the operation of phase comparators II and III so as to guard against their operation before the desired time. A pulse from phase comparator I sets the bistable circuit I [Fig. 9.3(b)] so that the phase comparators II and III are ready to operate.

9.4.2 Slip measurement

The signal from the phase comparator I is fed to a monostable timing circuit. This is designed to give a negative going square-wave output [Fig. 9.3(b)] of duration T_c proportional to the setting of maximum

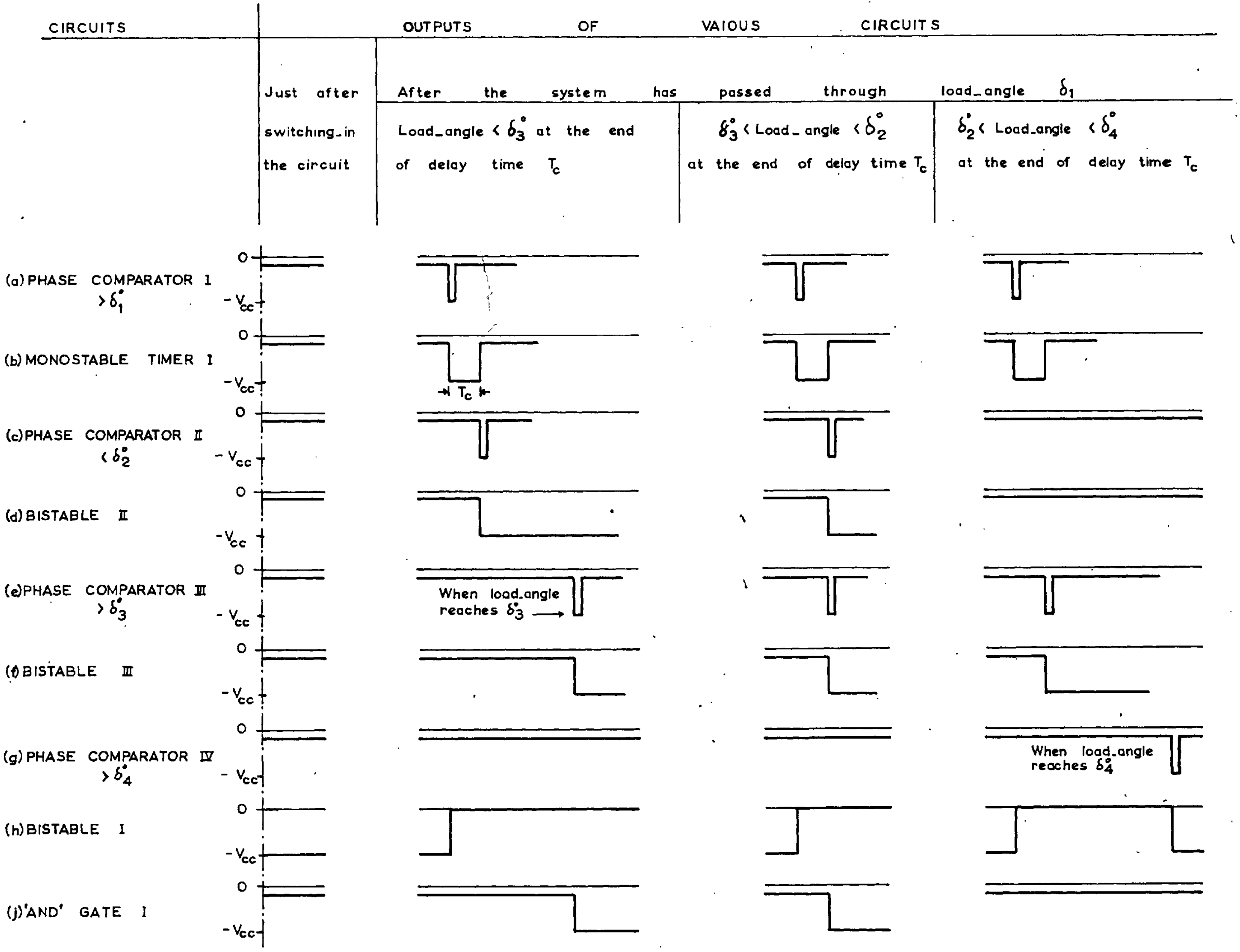


Fig. 9.3 Sequential operation of resynchronising circuit
$(\delta_1 < \delta_3 < \delta_2 < \delta_4)$

slip below which the relay is required to operate. The pulse duration is variable to suit the required maximum values of slip.

A load angle of 360° is traversed in one slip cycle, and this gives the load angle-time relationship. By suitable co-ordination of the delay time of the monostable circuit and the angle of operation fixed for phase comparator II, it can be ensured that the equipment will not operate at a slip higher than a predetermined value. Phase comparator II is so arranged that it will operate only upto a certain load-angle δ_2 [Fig. 9.3(c)]. This is to ensure that the output signal is generated at the correct instant in the slip cycle taking into account the field time-constant and the field circuit-breaker operating time.

At the end of the predetermined delay, fixed by the monostable timing circuit, phase comparator II will measure the load-angle. If the load-angle is more than the preset value (δ_2), the slip is more than the prescribed value and bistable II will not give an output. The operation of the relay will thus be blocked for the rest of the slip cycle and instead the governor control circuit will operate. On the other hand, if the slip is less than the prescribed value, bistable II will give a negative-going output [Fig. 9.3(d)].

9.4.3 Ensuring proper relay operation at low slip values

In case the slip is very small, it is the function of phase comparator III to ensure that the output signal is sent only after the load-angle has reached an appropriate value and not before. It is so arranged that phase comparator III does not produce an output signal till the angle has reached δ_3 [Fig. 9.3(e)]. This ensures that in the case of slips lower than the prescribed maximum value, the relay still operates such that full field excitation is established at the desired angle.

As shown in Fig. 9.3, which depicts the sequential operation of the various elements, it is evident that no output signal can be produced until the slip is below a certain maximum and the load-angle has reached a predetermined value.

9.4.4 General

Phase comparator IV will ensure that the equipment is reset to start its operation again after the load-angle passes through δ_1 and that a faulty sequence of operations does not take place at 360° minus the preset values of angles obtained from the phase comparators II and III. Like phase comparator III, phase comparator IV has also been arranged to operate for load-angles greater than a certain value and not below [Fig. 9.3(g)].

The phase difference for the operation of various phase comparators and the delay time of the monostable timing circuit can be adjusted to any desired value using suitable components. This ensures that the equipment can be calibrated to suit machines with different field time-constants and field circuit-breaker operating times.

9.5 Transistor circuits

9.5.1 Squaring circuit

To obtain a better consistency in the operation of the relay, it is imperative that undesirable effects due to variations in stator terminal voltage and tacho generated voltage during asynchronous operating conditions be eliminated. This can easily be achieved by converting the two sinusoidally varying a.c. signals into square waves in two independent squaring circuits.

The squaring circuit used (Fig. 9.4) is a simple common-emitter circuit, consisting of one transistor to convert the a.c. sine wave signal into a square wave and the second transistor as a phase invertor, so that two negative-going constant magnitude square-waves of equal mark-space ratio but exactly opposite in phase are obtained at the collectors of the two transistors.

During the positive half of the input signal, the first transistor is cut-off and the second transistor is so biased as to be in the fully conducting state. During the negative half of the wave, the first transistor will be fully conducting. Thus the voltage at its collector will be very nearly equal to zero and the second transistor is biased to cut-off, thereby giving an output of $-V_{cc}$ volts.

To restrict the maximum voltage at the base of the first transistor and also to minimise the effects of voltage variation, two diodes have been connected in its base circuit. These diodes restrict the maximum voltage at the base to the voltage drop accross the diodes, both during the positive half and negative half of the a.c. input waves.

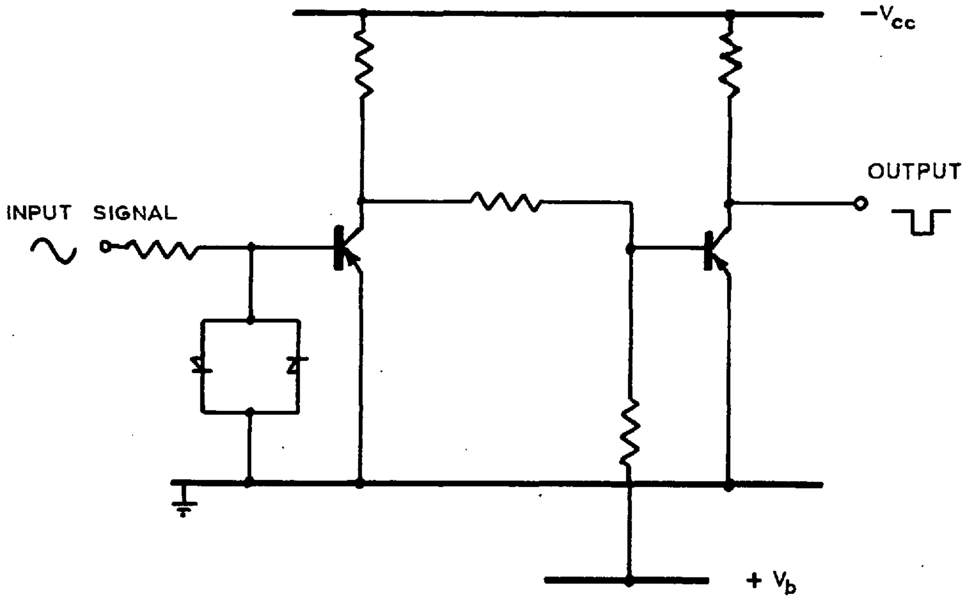


Fig. 9.4 Squaring circuit

9.5.2 Phase comparator

The phase comparator (Fig. 9.5)[101] used in this equipment has been described in detail in references 101 and 102. It consists of a coincidence stage controlled by the two voltage signals which are compared in phase and the starting input (eg., from the time-delay circuit in the case of phase comparator I or from bistable circuit I in the case of phase comparators II and III (Fig. 9.2)). It is followed by an integrating circuit and a level detector output stage as shown in Fig. 9.5(a).

The coincidence circuit will allow operation only if all its input signals are zero or positive at the same time. Should any of the input signals be negative, no operation takes place, since the collector voltage of the circuit will be zero, i.e. the transistor will be conducting.

Phase comparators IV and V are similar with the only difference that they have been set to produce output signals at different angles. Phase comparators I, II and III are normally blocked, as input 1 from the preceding bistable circuits is normally negative, thus maintaining the transistors 'on' irrespective of inputs 2 and 3. When the bistables are set by a pulse from their corresponding circuits, input 1 assumes zero potential, thereby allowing operation of the phase comparators at the appropriate angles. To safeguard against mal-operation, phase comparator IV resets bistable circuit I thereby blocking operation of the relay for the rest of the slip cycle.

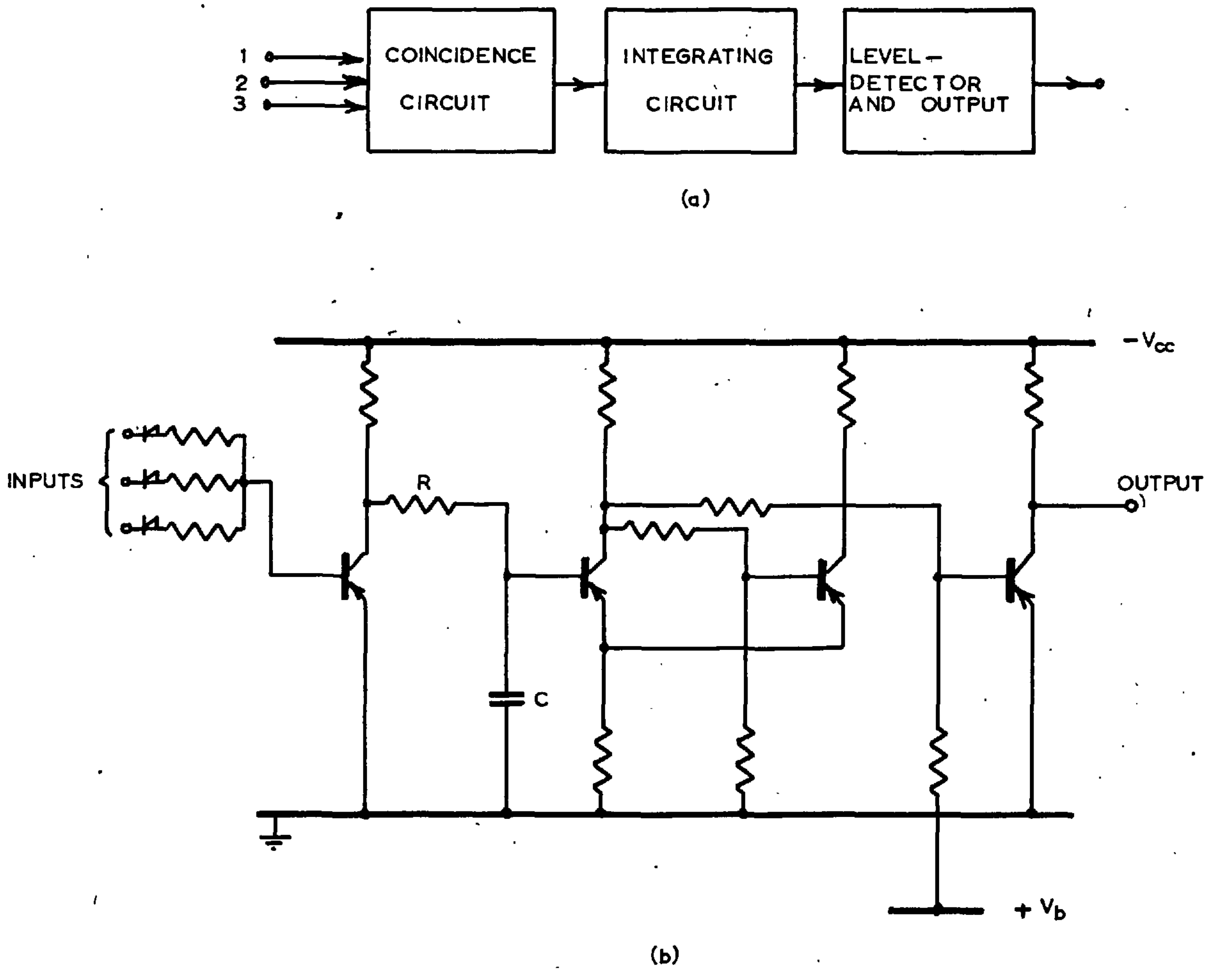


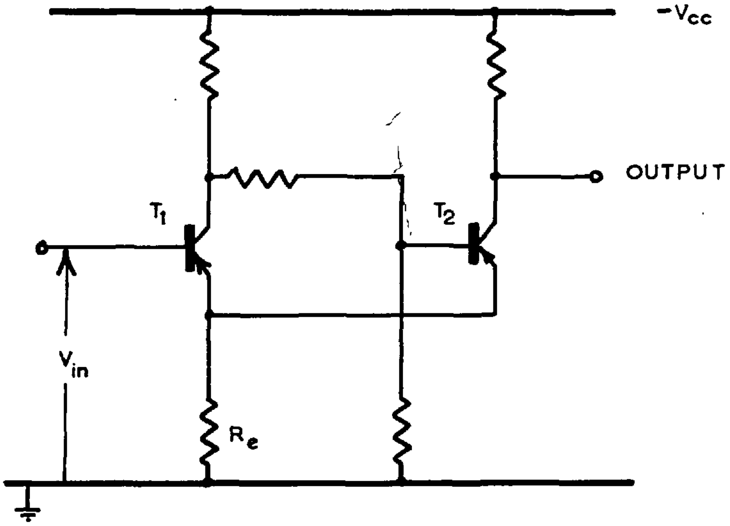
Fig. 9.5 Multiple-input phase comparator

In addition to the normal blocking input 1 from the bistable circuit I, phase comparator VI has an additional input 4 from the 'And' gate I. When the resynchronisation signal is given, phase comparator VI is blocked, thereby preventing any further unloading of the machine.

The integrating circuit is a straight forward series R-C arrangement which operates during intervals when the transistor is not conducting.

The level detector, Fig. 9.6, is an emitter coupled trigger circuit[103]. It remains in one stable state i.e. T_1 cut-off and T_2 fully conducting, so long as its input voltage is lower than the 'pick up' voltage V_p. If the base potential of T_1 is gradually lowered, the collector current of T_2 remains constant until V_{in} reaches the pick up value, when T_1 starts to conduct and its collector voltage starts to rise. This increase in the collector potential is applied to the base of T_2 by the potential divider. The collector current of T_2 thus begins to decrease as the base potential of T_1 continues to fall. When the current of T_1 has become large enough to provide sufficient gain for this action to be cumulative, the circuit snaps over into the state in which T_1 is 'on' and T_2 is 'off'. Transistor T_1 is now fully bottomed and the potential divider biases T_2 beyond cut off.

If the base potential of T_1 is now brought back towards earth potential, T_2 will remain cut-off for as long as the base of T_1 is sufficiently negative to keep its collector bottomed. However, the circuit does not return to its initial state at the same voltage V_p, but will do



Fig· 9.6 Emitter-coupled trigger circuit
(Level detector)

so at a lower drop out voltage V_d, as it is necessary not only to reduce the current passing through T_1 but also for T_2 to start conducting.

9.5.3 Monostable timing circuit

The monostable timing circuit[101] used in the equipment is a common emitter configuration as shown in Fig. 9.7. In the stable state, transistor T_2 is conducting, transistor T_1 being biased to cut off. When the trigger signal at the base of T_1 causes transition from the stable to the quasi-stable state, T_2 cuts off and T_1 starts conducting. After the initial abrupt transition, the base voltage of T_2 starts to fall exponentially towards V_{cc}, all other voltages remaining constant, until the base voltage of T_2 reaches the pick up voltage. At this point the quasi-stable state is terminated, and the voltage finally stabilises to its quiescent level given by I_2R_e.

The circuit thus produces a negative pulse at the collector of T_2 with a duration determined by the time-constant of the RC coupling and the voltage V_s.

9.5.4 Bistable trigger circuit

This circuit has two stable states, in either of which one transistor is fully conducting and the other is cut off. It can remain in one of these states indefinitely unless it is forced to the other state by some means. The circuit can be triggered by a negative pulse

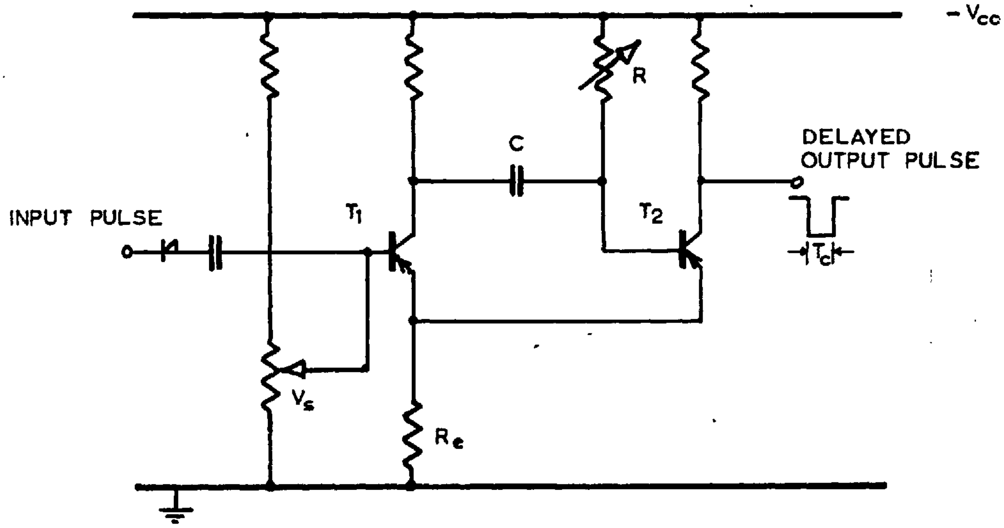


Fig. 9.7 Monostable timing circuit

applied to the base of either of the transistors through a diode depending upon the state to which it is required to be driven.

The bistable trigger circuits[101,104] are all similar consisting of two transistors T_1 and T_2 (Fig. 9.8) with their emitters connected to the zero voltage line through a common emitter resistance R_e shunted by a capacitance C_e. The signal at the collector of each transistor is fed to the base of the other transistor through coupling attenuators R_{11}, R_{21} and R_{12}, R_{22}. Resistors R_{11} and R_{12} are shunted by small capacitors to speed up the triggering. Bistables I, IV and V have, however, been provided with an additional stage, so as to provide an output varying between zero and $-V_{cc}$.

9.5.5 Output signal from resynchronising circuit

The output signal from the resynchronising circuit is provided through an 'And' gate followed by a single output stage. Signals from the bistable circuits II and III are fed into a simple 'And' gate consisting of diodes and resistors. When both the bistable circuits have been operated by the phase comparators II and III, it will produce a negative-going output signal [Fig. 9.3(j)]. In the event of neither or only one of the two bistable circuits having operated, no output signal will be produced.

9.6 Power supplies

The power supply requirements for the relay built in the laboratory are a negative direct voltage of 9 Volts,

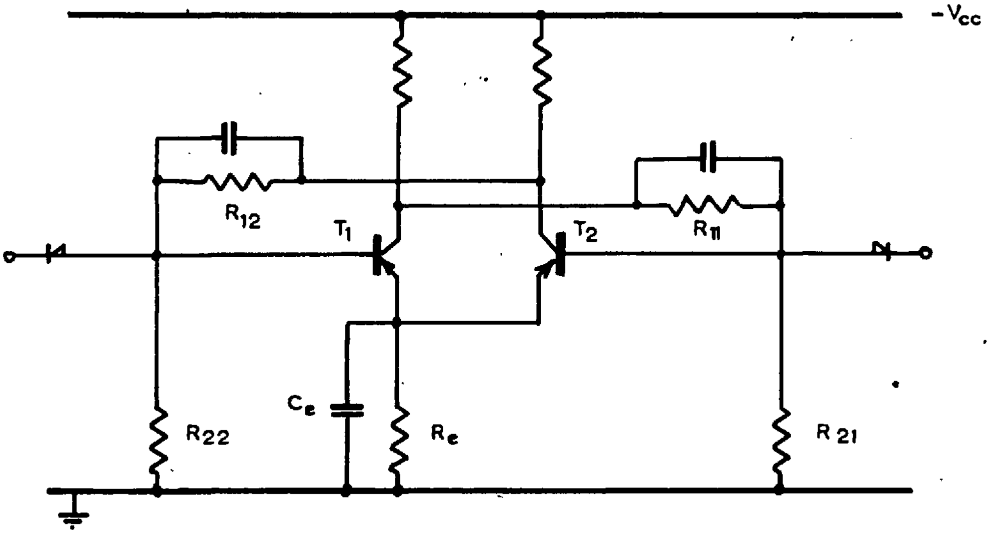


Fig. 9.8 Bistable trigger circuit

capable of delivering upto 100 m.a., and a 4 volts positive bias of 250 μA current drain.

In the laboratory a twin transistor power unit was used. For this unit, the change in output voltage caused by a change in supply of ± 7 % is always less than 5 mV.

9.7 Operation and performance of the automatic resynchronising relay

9.7.1 Complete circuit and construction

The complete circuit arrangement is shown in Fig. 9.9, which also shows the coupling connections between the various individual component circuits and the provision of an initial setting pulse for the bistable circuits. Arrangements made in the relay for field control and governor control for testing on the micro-machine are also shown in this figure. For the field control, a power transistor controlled by bistable IV is used as shown in Fig. 9.9. As no governor was available at the time of conducting the tests, indication of the operation of that circuit was obtained by the illumination of a small 4 volt bulb.

To simplify the wiring of the electronic circuits, various circuits have been constructed on veroboard sheets made as plug-in units to suit standard plugs. The complete relay has been built into one unit of size 17 in. x 10 in. x 5 in.

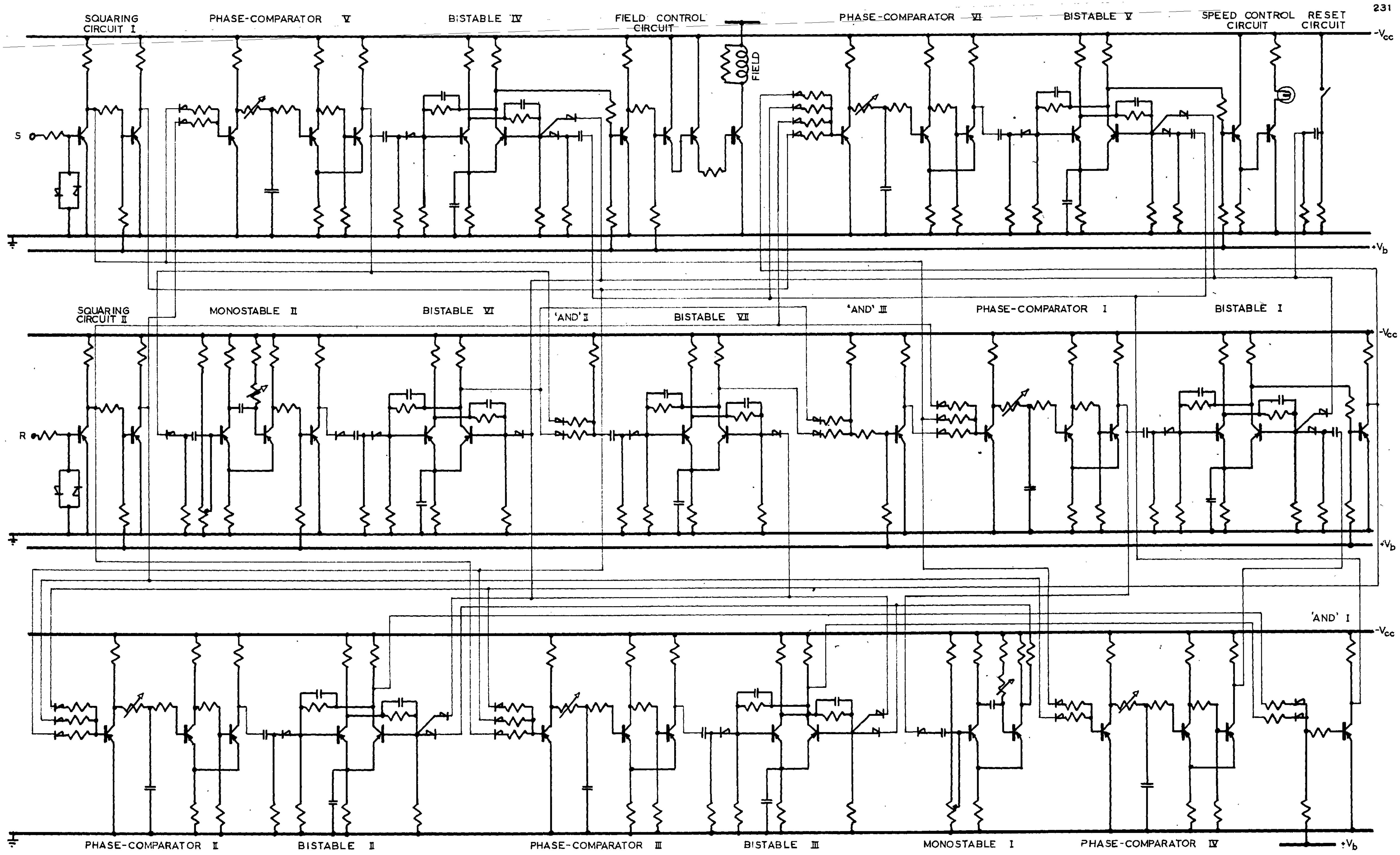


Fig. 9.9 Complete circuit for Automatic Resynchronising Relay

S - Signal from stator
R - Signal from rotor

9.7.2 Slip limitations

The combination of monostable I and phase comparator II circuits ensures that the relay does not operate until the slip magnitude has been reduced below a prescribed value. The relay as constructed has been calibrated to start operation for a slip frequency less than one cycle per second i.e. 2 % of the normal supply frequency of 50 c/s, although it can be adjusted to any value above or below 2 % as desired. The relay, as calibrated, will operate for any slip between ± 1 c/s.

9.7.3 Advance time setting

The relay can be adjusted such that for a range of mean slip values, full field excitation is established within a desired range of load-angle. However, if at the instant that the relay comes into operation, the magnitude of slip is very low, excitation is likely to be established fully at an angle somewhat less than the desired range. Although the machine will still synchronise, this operation will be accompanied by a comparatively large jump of power and VArs.

This difficulty can be overcome by carrying out a few studies on a mathematical model of the machine on which the relay is to be fitted and determining the values for the setting of the various phase comparators and the monostable timer I which are best suited to the actual conditions.

9.7.4 General test arrangements

In the initial stages of construction and calibration, the two voltage signals were obtained from the laboratory main supply - one direct and one through a phase shifter. After the relay had been fully assembled, it was initially tested by these two signals. Finally the relay was tested under actual working conditions on a micro-machine.

A two phase a.c. tacho is available on the micro-machine. The voltage wave form of one of these two phases was compared with the wave form of one phase of the machine stator at no load. The tacho was adjusted so that the two wave forms were aligned. These two signals - the phase difference between which would always be equal to the load-angle - were applied to the relay for all studies.

The two input signals were stepped down to 6.3 volts r.m.s. before being applied to the squaring circuits.

9.7.5 Records of operation

A few resynchronisation studies with the help of the relay described were made on a micro-machine using a salient-pole laminated rotor. Based on the studies of the mathematical model of this machine, phase comparators I, II, III and IV were calibrated to operate for phase angles of 0°, 30°, 25° and 50° respectively. Phase comparator V was adjusted for 180°, that is, if the load-angle reached 180°, the machine was considered to have lost synchronism. The maximum slip for attempting resynchronisation was adjusted to 2 percent. The resynchronisation circuit was adjusted to come into action with a time delay of two slip cycles after losing synchronism.

With the micro-machine connected to the laboratory mains either direct or through an external reactance, the relay was switched in. By reducing the field excitation, the machine was brought out of synchronism. The test arrangements were, that on losing synchronism, the relay would remove the excitation and leave the field shorted through a discharge resistor. After monitoring the necessary conditions, the excitation was switched on automatically at the required instant and the subsequent resynchronisation observed. The full process was also recorded on a pen recorder.

Figs. 9.10 and 9.11 show the actual records obtained during the resynchronisation study on the micro-machine. Fig. 9.10 shows the operation when the slip, after loss of synchronism, was less than the prescribed maximum value. In Fig. 9.11 is shown the case where on losing synchronism, the machine attained a slip higher than the prescribed maximum. In this case, the slip was reduced by reducing the output manually by adjustment of the driving motor. These figures clearly show that the relay functioned correctly as specified and the machine pulled into synchronism very smoothly in the minimum time without any manual intervention.

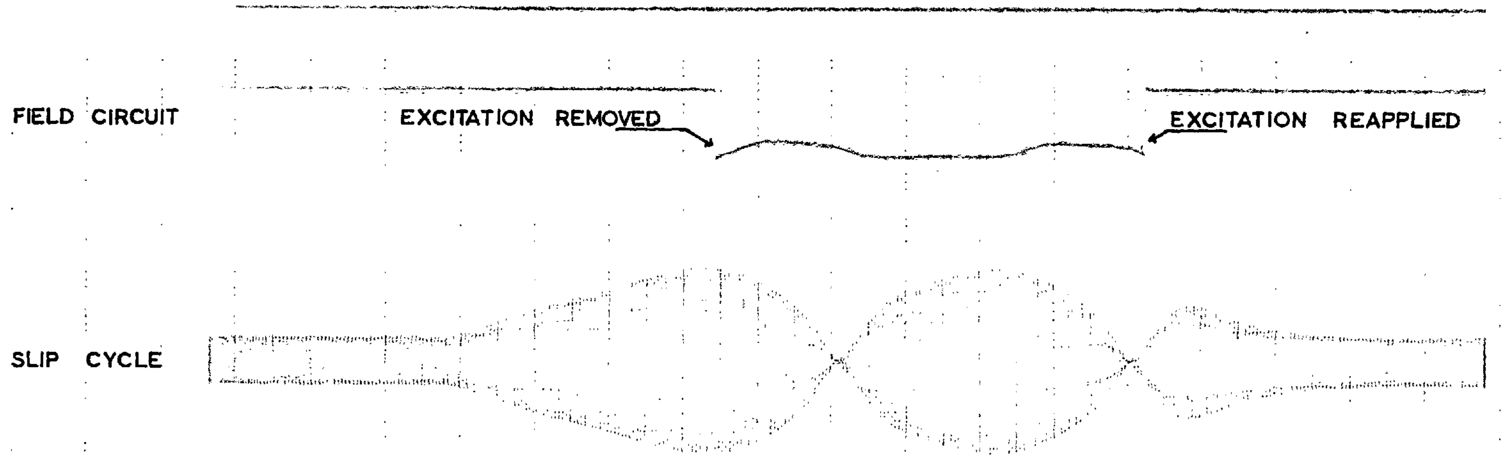


Fig. 9.10 Relay operation for slip magnitude less than the prescribed maximum (2%) after loss of synchronism

$(T_{as})_m = 0.643$ p.u. , $X_e = 0$, Paper speed – 25 mm/sec

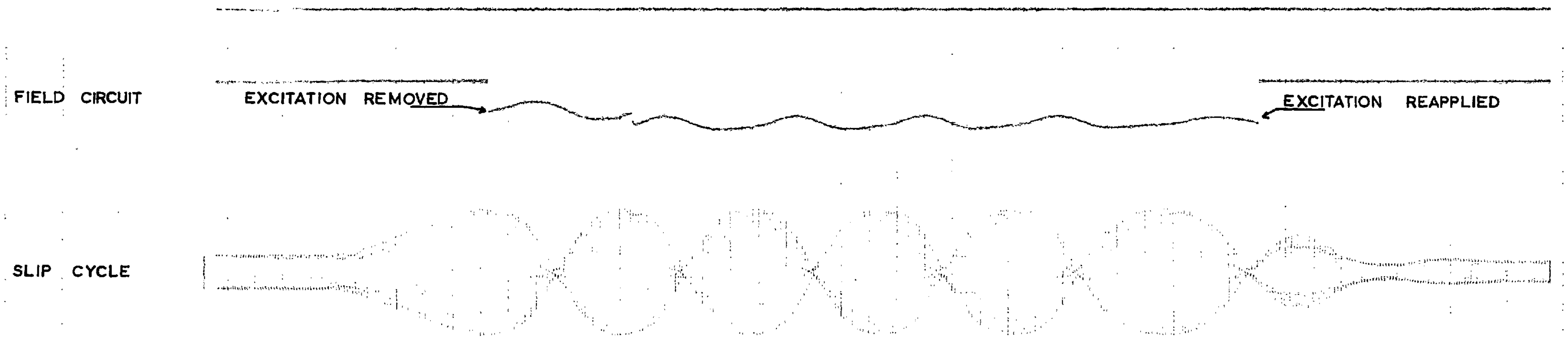


Fig. 9.11 Relay operation for slip magnitude greater than the prescribed maximum (2%) after loss of synchronism

$(T_{as})_m = 0.85$ p.u. , $X_e = 0.115$ p.u. , Paper speed – 25mm/sec

CHAPTER 10

CONCLUSIONS

10.1 A review of results

Asynchronous operation and resynchronisation of synchronous machines has been studied by a number of investigators in the past. Most of this previous work is based on assumptions that are not strictly valid for the particular conditions of operation under study. In the present thesis, asynchronous operation and the process of resynchronisation has been studied using an elaborate representation of the synchronous machine. Most of the work presented in the preceding chapters is based on no additional assumptions than those inherent in the 'General Theory of Machines'[45].

Two mathematical models, one for laminated rotor and one for solid rotor machines, have been developed for the study of asynchronous operation and resynchronisation on a general purpose analogue computer. Salient-pole or cylindrical rotor construction can easily be simulated by either of these two models. Also, the effect of various system or machine parameters and auxiliary equipment can be studied. The equations, on which the two mathematical models are based, are in the general form. The entire work is thus equally valid for both generators and motors.

Every previous attempt to study resynchronisation resulted in studying conditions for what is now called 'spontaneous resynchronisation'. In simple words, spontaneous resynchronisation may be termed as resynchronisation by chance with practically no control over the actual process of resynchronisation. In this thesis, resynchronisation has been studied by an original approach and the process explained in detail. It has been shown feasible to control fully the entire process. Criteria for resynchronisation have been laid down and a scheme for automatic resynchronisation proposed. This scheme can easily be integrated into any overall scheme for automatic control of power stations using 'on line' computers.

The behaviour of an individual machine is of considerable theoretical interest, but of even greater importance is its behaviour when forming part of a power system. In a practical case, a machine's behaviour, though influenced to a certain extent by its parameters, is dictated by its location with respect to other machines and the interconnection of the system. By the very nature of a synchronous machine, there are certain conclusions that can be drawn regarding its behaviour during out of step operation and during resynchronisation. Inferences based on the studies of Chapters 6 and 8 are summarised below.

10.1.1 Asynchronous operation

1. At reasonably low slips, it is possible to obtain a considerable amount of output from a normal machine running asynchronously.

2. Under the operating conditions obtaining in practice, asynchronous operation with open field gives the

best results since this condition produces the minimum of disturbance to the system. This mode of operation is subject to the over-riding proviso that for the slips at which machine operates, the induced voltage in the field winding is not allowed to exceed its designed insulation level.

3. High bus-bar voltage is an aid in the reduction of disturbances on the system and in obtaining higher power output from the machine.

10.1.2 Resynchronisation

1. There is a maximum value of slip beyond which it is almost impossible to resynchronise a machine.

2. Because of the ceiling voltage of any excitation system, there is, in practice, an upper limit on the slip magnitude - generally lower than the maximum value - beyond which it is not practicable to resynchronise a machine.

3. To effect easy resynchronisation with the minimum of disturbance to the system, the angle of field application should be well controlled. In the majority of practical cases, the most favourable angle of switching lies between zero and 45 degrees in a slip cycle.

4. Resynchronisation is, in most cases, accompanied by a swing in power and current, which is only of short duration when resynchronisation is effected under properly controlled conditions.

5. Resynchronisation from the field open mode of asynchronous operation is generally the easiest, requiring minimum time and least magnitude of field excitation.

6. Lower moment of inertia generally helps in resynchronisation.

7. Control of turbine speed-governor and automatic voltage regulators is essential in achieving automatic resynchronisation.

10.1.3 Automatic resynchronisation scheme

On the basis of the above conclusions, it is possible to specify a practical scheme for achieving automatic resynchronisation without human intervention. The proposed scheme has been described in Chapter 9. This scheme can be incorporated in any scheme for the automatic control of power stations by computer as is being now developed.

10.2 Further work

10.2.1 Mode of field connection

With the usual d.c. excitation systems, the field can be in one of the three modes as considered in the present studies. A.C. exciters and rectifiers are now being introduced to replace the d.c. exciter. Because of different forward and backward resistances of the rectifiers, asymmetry is introduced into the field circuit during out of step operation, and may considerably affect the operational characteristics of the machine. This is likely to have a significant effect on asynchronous operation, but the process of resynchronisation should not be affected to any great extent.

Depending upon the actual configuration of the scheme adopted, its effect on asynchronous operation needs to be studied as a special operational problem. Although the simulation techniques described in Chapters 4 and 5, in general, still hold good, the simulation of the field circuit would need to be modified to take account of the changed circuit parameters.

10.2.2 Effect of speed governor and voltage regulator

Because of the lack of sufficient elements on the TR48 analogue computer used in the present studies, the effect of a simple velocity governor with a single time-constant only has been studied. This is reasonable for the case of hydraulic turbines. To study the operation of alternators driven by modern reheat, compound steam turbines, a more elaborate representation of governor and turbine is essential. Also the effect of a more sensitive governor compounded of velocity and acceleration feedback signals needs to be studied.

Throughout the present studies, no voltage regulator action has been considered. It has been proposed that excitation should be removed as soon as machine loses synchronism. Thus the voltage regulator would be out of action during out-of-step operation and will come into play only during the process of resynchronisation. To study resynchronisation, constant excitation was applied. If, however, sufficient additional elements are available on the computer, it would be worthwhile to simulate a voltage regulator and study its influence, if any, on this process.

10.2.3 Digital techniques

Availability of a sufficient number of elements is one of the main limitations in the use of the analogue computer. For the study of larger problems, it is becoming possible to develop suitable digital techniques, particularly as larger digital computers are available. Most of the programmes so far developed for the study of power system problems on digital computers are based on a step-by-step method using a fixed step length. This necessitates introduction of many simplifying assumptions which are not always valid, thereby introducing many errors in the solution particularly if the computation is carried out for a reasonable length of time.

A programme called 'MIDAS'[105], employing variable step length, has been developed recently for use on the IBM 7090 digital computer. This programme can be written directly from the analogue computer flow chart, without any further simplifying assumptions. It would be interesting to carry out studies on the two computers simultaneously and to compare results. In the event of reasonable results being obtained by the 'MIDAS' programme, it would be possible to study the problem in much greater detail.

10.3 Concept of stability

In general terms, the stability of synchronous machines may be defined as their ability to remain in synchronism with the power system to which they are connected[67]. Traditionally, the stability limit is determined on the basis of first swing and does not provide for any pole slipping. This concept was adopted because of the lack of proper control devices. With the development of the modern fast-acting automatic voltage regulators and electro-hydraulic speed-governors[106,107,108], transient stability boundaries are being considerably modified.

It has been shown in the present studies that it is quite practicable to control the process of resynchronisation of synchronous machines with proper control devices. By allowing the synchronous machine to lose synchronism and to resynchronise, substantial gains in transient stability are possible[109]. Schemes for fully automatic control using 'on line' digital computers are being planned for the power stations of the future. These schemes envisage control on the basis of a single integrated unit, with every operation during normal functioning or during disturbed conditions being controlled by a master controller. In schemes like this, asynchronous operation and resynchronisation could be handled as a routine function.

In view of these modern developments, the entire concept of system stability needs revising. It is suggested that the definition of stability based on the first swing hypothesis be changed and a new definition which allows for pole slipping, under certain conditions, be worked out. This will allow for much higher stability limits than at present and could result in quite considerable economies, in addition to increasing the reliability of operation of power systems.

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APPENDIX 'A'

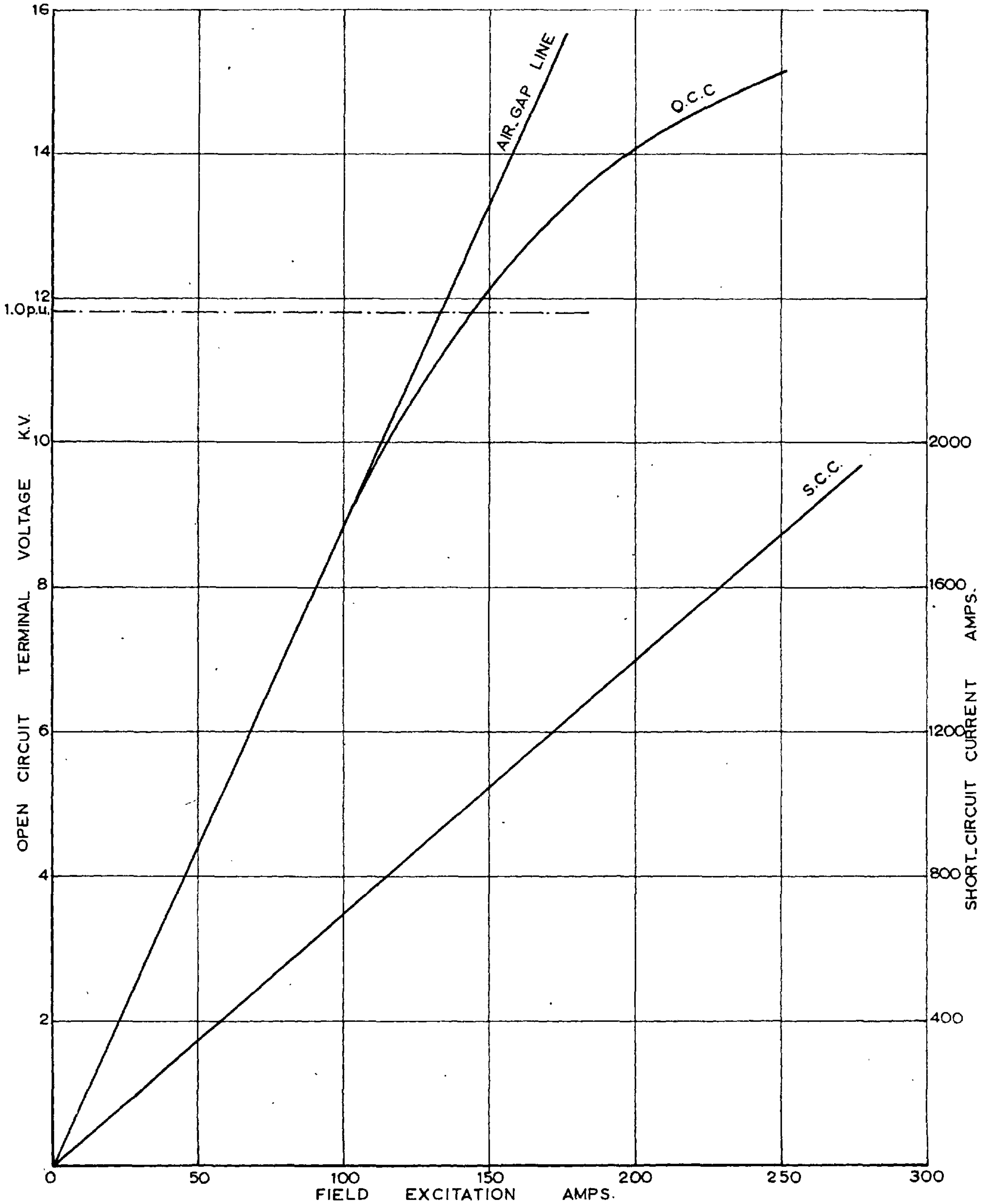
MACHINE DATA

A.1 Solid rotor machines

Quantity	Goldington 30 MW machine	Marchwood 60 MW machine	Staythorpe 120 MW machine	Micro-machine Stator no.334818 Rotor no.334828
Base quantities				
Voltamps KVA	37.5×10^3	75×10^3	150×10^3	2.286
Voltage (phase) KV	6.8	6.8	7.96	0.127
Current (phase) amps	1,835	3,675	6,260	6
Impedance ohms	3.7	1.85	1.27	21.15
Field current amps	266.5	239.6	984	1.06

Quantity	Goldington 30 MW machine	Marchwood 60 MW machine	Staythorpe 120 MW machine	Micro-machine Stator no.334818 Rotor no.334828
Parameters p.u.				
x_d (saturated)	1.68	1.52	1.75	1.59
x_q	1.5	1.52	1.37	1.49
x'_d	0.175	0.17	0.30	0.191
x''_d	0.125	0.11	0.19	0.138
x_a	0.10	0.096	0.08	0.1
x_f	0.14	0.13	0.253	0.1276
r_a	0.00166	0.0017	0.00121	0.0109
r_f	1.195×10^{-3}	4.79×10^{-4}	1.14×10^{-3}	1.135×10^{-2}
r_f discharge	3.61×10^{-3}	5.61×10^{-4}	4.52×10^{-3}	1.48×10^{-2}
x_e	0.133	0.145	0.24	Various values

Quantity	Goldington 30 MW machine	Marchwood 60 MW machine	Staythorpe 120 MW machine	Micro-machine Stator no.334818 Rotor no.334828
Physical data				
$T_{effective} = (T_{ph} x k_w)$	15.8	21.1	22.2	118.5
width w metre	2.66	3.68	3.71	0.114
length ℓ metre	1.0	1.1	0.864	0.2
pole pairs - p	1	1	1	2
B_s Wb./m^2	1.75	1.75	2.236	1.6
Frequency f c/s	50	50	50	50
Resistivity ρ ohm-m	27×10^{-8}	21.5×10^{-8}	27.94×10^{-8}	14×10^{-8}
Inertia constant H KW sec/KVA	4.6	3.98	3.1	4.15
Field current at open-circuit rated voltage amps	142.5	168	589	0.71
Magnetisation characteristics	Fig. A.1	Fig. A.2	Fig. A.3	Fig. A.4



Fig·A.1 Open-circuit and short-circuit characteristics

30 M.W. Goldington Turbo-alternator

O.C.C. - Open-circuit characteristic

S.C.C. - Short-circuit characteristic

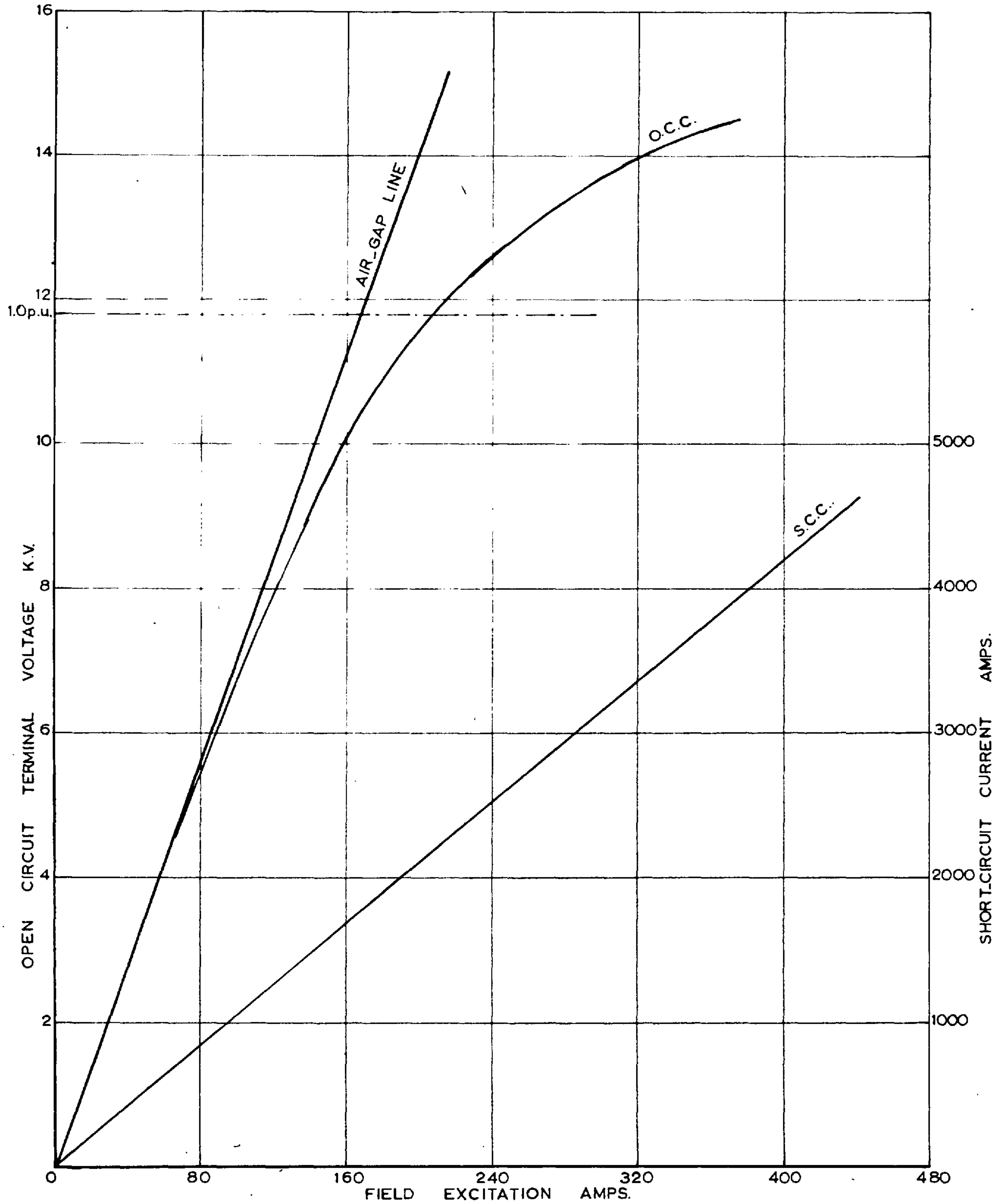


Fig. A.2 Open_circuit and short_circuit characteristics

60 M.W. Marchwood Turbo_alternator

O.C.C. _ Open _circuit characteristic

S.C.C. _ Short _circuit characteristic

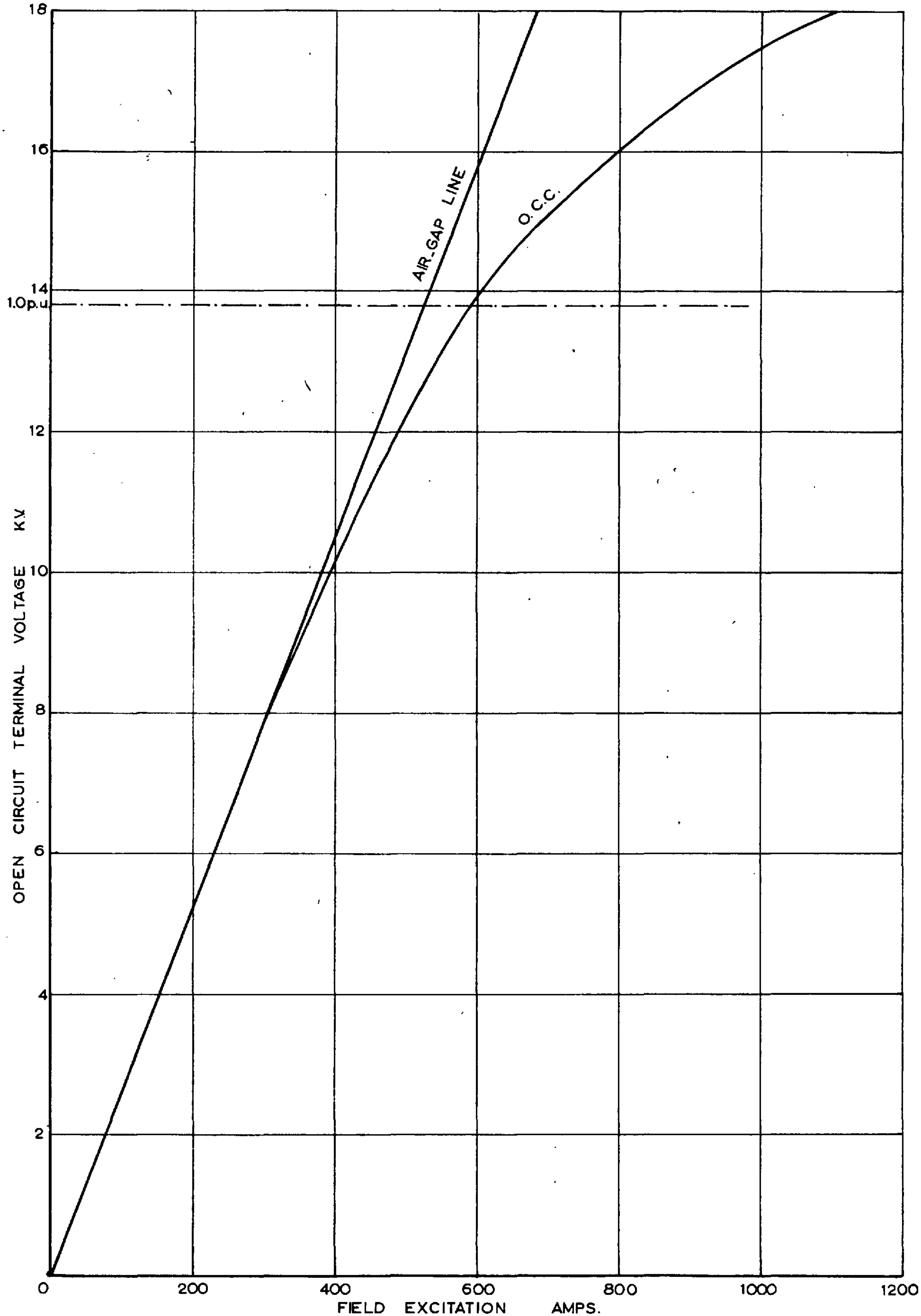


Fig. A.3 Open-circuit characteristic

120 M.W. Staythorpe 'B' Turbo-alternator

O.C.C. - Open-circuit characteristic

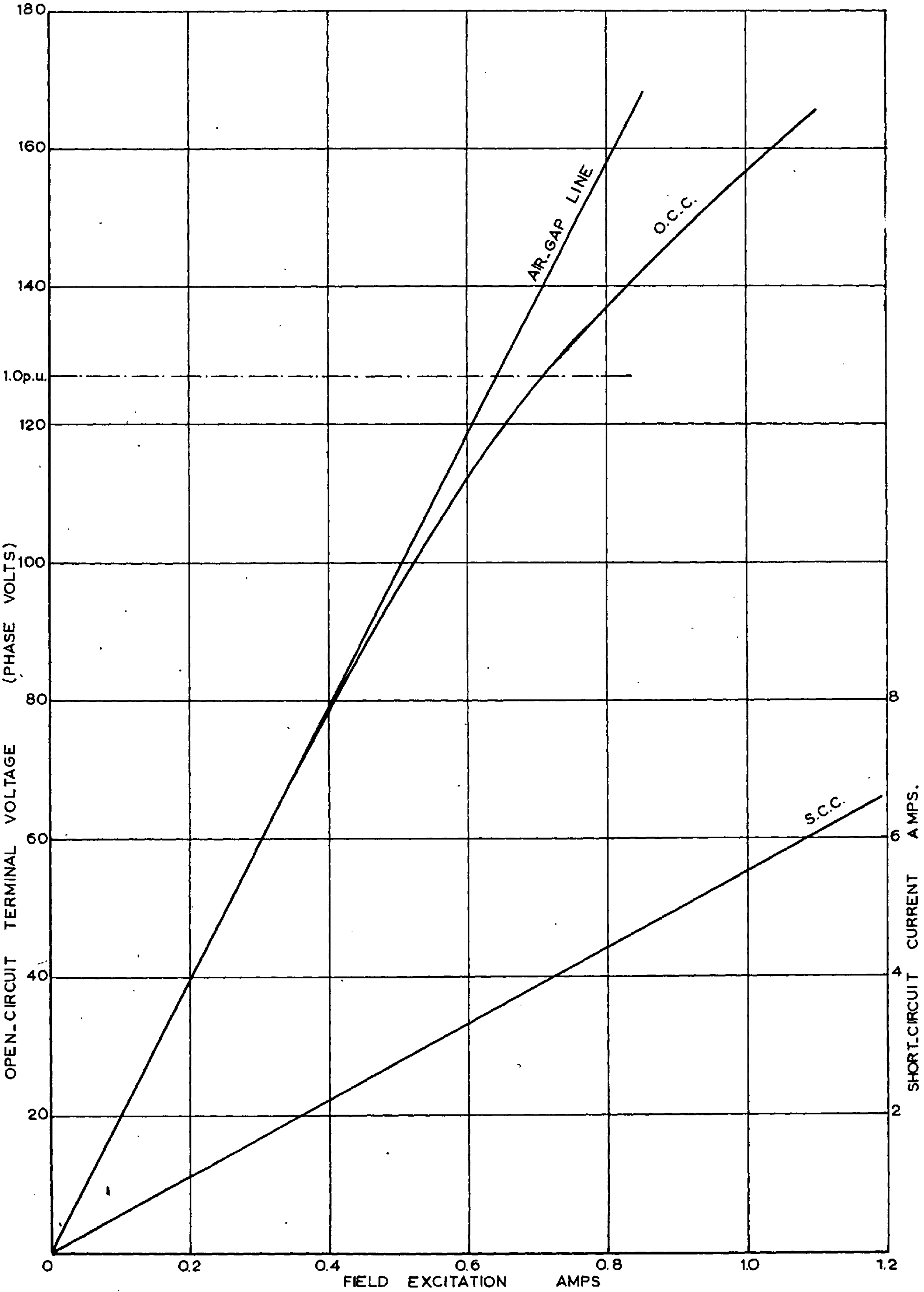


Fig. A.4 _ Open_circuit and short_circuit characteristics

Micro_machine with solid rotor

O.C.C. _ Open_circuit characteristic

S.C.C. _ Short_circuit characteristic

A.2 Laminated rotor micro-machine

Stator no. 334819
Rotor no. 334818

Base quantities

Voltamps	-	1,525 VA
Voltage (phase)	-	127 volts
Current (phase)	-	4 amps
Impedance	-	31.75 ohms
Field current	-	0.519 amps

Parameters p.u.

x_d (saturated)	-	0.9403
x_q	-	0.568
x_d'	-	0.237
x_d''	-	0.1495
x_q''	-	0.1425
x_a	-	0.0976
x_f	-	0.2124
x_{kd}	-	0.0383
r_a	-	0.007
r_f	-	0.00446
T_{do}'	-	0.885 secs.
T_d'	-	0.188 secs.
T_{do}''	-	0.046 secs.
T_d''	-	0.017 secs.

T''_{qo} – 0.094 secs.

T''_{q} – 0.0218 secs.

T_{a} – 0.0672 secs.

T_{kd} – 0.00832 secs.

H – 3.64 KW sec/KVA

Magnetisation characteristics – Fig. A.5

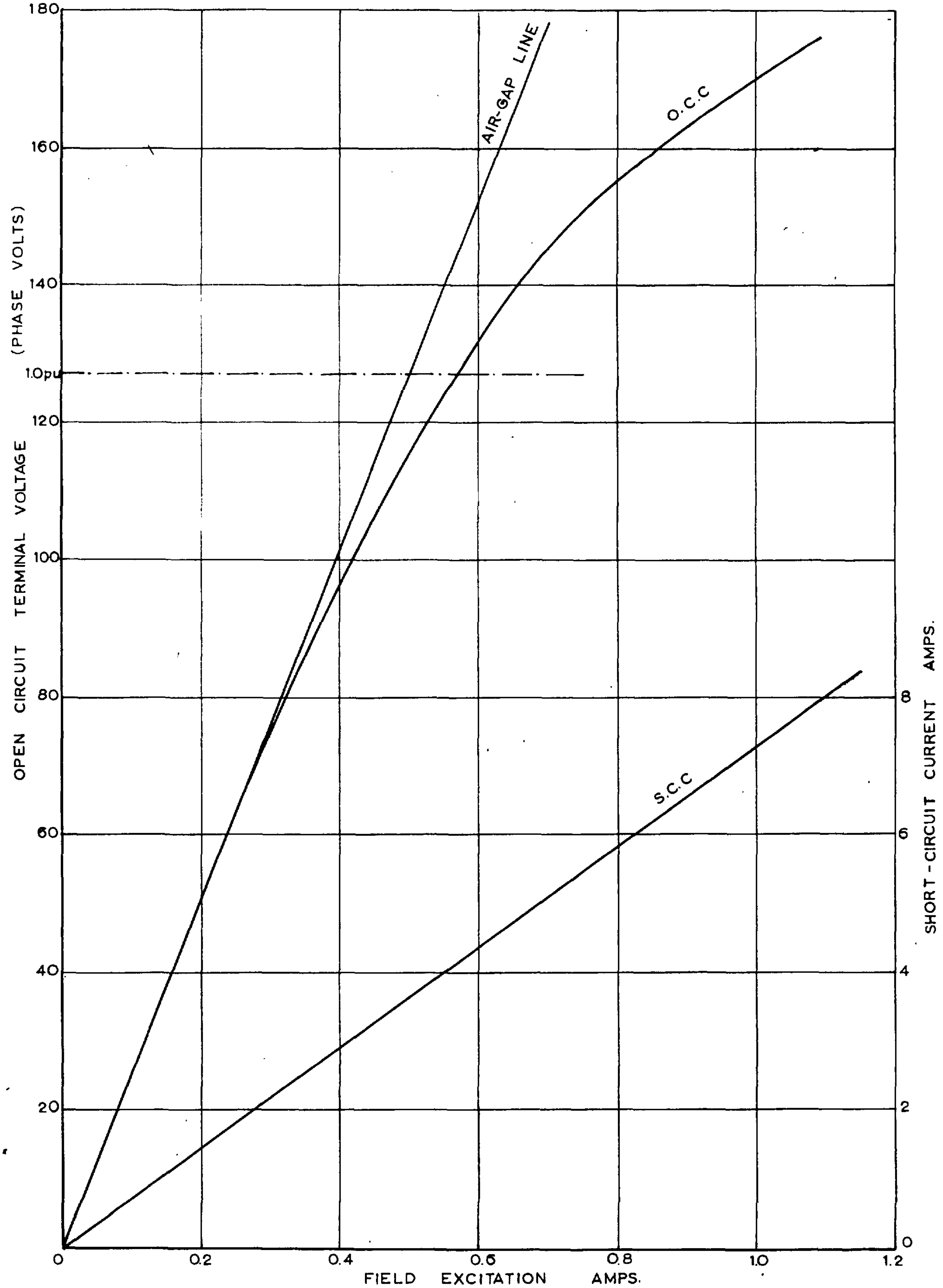


Fig. A.5 Open-circuit and short-circuit characteristics

Micro-machine with laminated rotor

O.C.C - Open-circuit characteristic
S.C.C. - Short-circuit characteristic

APPENDIX 'B'

ANALYTICAL SOLUTION FOR LAMINATED ROTOR MACHINE

Based on the assumptions described in Section 4.3, pulsations in torque and slip can be calculated as described below.

B.1 Torque pulsations based on constant slip

With a constant slip s, load-angle increases uniformly with time, i.e. $\delta = s\omega_o t$. Eqns. (3.12) and (3.13), neglecting r_a, then become

$$E_m \cdot \operatorname{Sin} s\omega_o t = p\Psi_d + (1-s)\omega_o\Psi_q \qquad \ldots(B.1)$$

$$E_m \cdot \operatorname{Cos} s\omega_o t = -(1-s)\omega_o\Psi_d + p\Psi_q \qquad \ldots(B.2)$$

Since the equations are linear, the solution may be obtained by superimposing two separate parts for which additional suffixes are used: suffix 1, solution with applied terminal voltage but no field voltage; suffix 2, solution with applied field voltage but no terminal voltage. This superimposition is valid on the assumption that the two components are independent of each other. This assumption is not strictly true, and the result obtained is only a first order approximation.

B.1.1 Calculation of torque with no field voltage

During steady asynchronous operation with $e_f = 0$, axis currents and flux linkages obtained by the simultaneous solution of Eqns. (3.20), (3.22), (B.1) and (B.2) are sinusoidal quantities at slip frequency. These equations can be converted into vector equations[45] by substituting $p = js\omega_o$ and replacing the variables by the corresponding vectors.

$$\omega_o\bar{\Psi}_{d1} = x_d(js\omega_o) \cdot \bar{I}_{d1} \qquad \ldots (B.3)$$

$$\omega_o\bar{\Psi}_{q1} = x_q(js\omega_o) \cdot \bar{I}_{q1} \qquad \ldots (B.4)$$

$$-jE = js\omega_o\bar{\Psi}_{d1} + (1-s)\omega_o\bar{\Psi}_{q1} \qquad \ldots (B.5)$$

$$E = -(1-s)\,\omega_o\bar{\Psi}_{d1} + js\omega_o\bar{\Psi}_{q1} \qquad \ldots (B.6)$$

With assumption (ii) of Section 4.3, Eqns. (B.5) and (B.6) simplify to

$$\omega_o\bar{\Psi}_{d1} = -E \qquad \ldots (B.7)$$

$$\omega_o\bar{\Psi}_{q1} = -jE \qquad \ldots (B.8)$$

$$\bar{I}_{d1} = \frac{-E}{x_d(js\omega_o)} = -E(Y_a + jY_b) \qquad \ldots (B.9)$$

$$\bar{I}_{q1} = \frac{-jE}{x_q(js\omega_o)} = -jE(Y_c + jY_d)$$

$$= E(Y_d - jY_c) \qquad \ldots (B.10)$$

where Y_a and Y_c are the real and Y_b and Y_d are the imaginary components of

$$\frac{1}{x_d(js\omega_o)} \text{ and } \frac{1}{x_q(js\omega_o)} \text{ respectively.}$$

Values of $x_d(js\omega_o)$ and $x_q(js\omega_o)$ are obtained from Eqns. (3.19) and (3.21) respectively by substituting p with $(js\omega_o)$ in these equations. However, as it is difficult to obtain with reasonable accuracy the values of all the time-constants T_1 to T_6 in Eqn. (3.19), this expression is further simplified[45] into the form given below, on the assumption that the per-unit resistance of the damper winding is generally much larger than that of the field winding.

$$x_d(p) = \frac{(1+T_d'p)(1+T_d''p)}{(1+T_{do}'p)(1+T_{do}''p)} \cdot x_d \qquad \ldots (B.11)$$

where T_d', T_d'', T_{do}' and T_{do}'' are the four well-known principal time-constants of the synchronous machine.

The instantaneous values of the flux linkages and currents are given by

$$\omega_o \cdot \Psi_{d1} = - E_m \cdot \text{Cos}\, s\omega_o t \qquad \ldots (B.12)$$

$$\omega_o \cdot \Psi_{q1} = E_m \cdot \text{Sin}\, s\omega_o t \qquad \ldots (B.13)$$

$$i_{d1} = - E_m(Y_a \cdot \text{Cos}\, s\omega_o t - Y_b \cdot \text{Sin}\, s\omega_o t) \qquad \ldots (B.14)$$

$$i_{q1} = E_m(Y_d \cdot \text{Cos}\, s\omega_o t + Y_c \cdot \text{Sin}\, s\omega_o t) \qquad \ldots (B.15)$$

Substituting Eqns. (B.12) to (B.15) in Eqn. (3.24),

$$T_{e1} = -\frac{E^2}{2}\left[(Y_b + Y_d) + (Y_c - Y_a)\text{Sin } 2s\omega_o t + (Y_d - Y_b)\text{Cos } 2s\omega_o t\right] \qquad \ldots(B.16)$$

From Eqn. (B.16), mean torque is

$$T_{e(mean)} = -\frac{E^2}{2}(Y_b + Y_d) \qquad \ldots(B.17)$$

B.1.2 Calculation of torque with a field voltage

Torque component T_{e2} resulting from the application of a field voltage is calculated by putting $E_m = 0$ in Eqns. (B.1) and (B.2). In this case, axis currents and flux linkages are constant quantities and solution is obtained by putting $p = 0$.

$$\Psi_{d2} = \Psi_{q2} = 0 \qquad \ldots(B.18)$$

$$i_{d2} = -\frac{x_{md}}{r_f \cdot x_d} \cdot e_f \qquad \ldots(B.19)$$

$$i_{q2} = 0 \qquad \ldots(B.20)$$

Although the components of Eqns. (B.18) to (B.20) by themselves would produce no torque, there is, however, a torque due to the interaction of i_{d2} and Ψ_{q1}.

Total torque of a machine running asynchronously with supply voltage E and field voltage e_f is, therefore,

$$T = T_{e1} + T_{e2}$$

$$= -\frac{E^2}{2}\left[(Y_b + Y_d) + (Y_c - Y_a)\cdot\text{Sin}\,2s\omega_o t + (Y_d - Y_b)\text{Cos}\,2s\omega_o t\right]$$

$$- \frac{E\cdot E_o}{x_d}\cdot\text{Sin}\,s\omega_o t \qquad \ldots(B.21)$$

where $E_o = -\frac{1}{\sqrt{2}}\cdot\frac{x_{md}}{r_f}\cdot e_f$ . . .(B.22)

= open circuit voltage induced by the excitation at synchronous speed

B.2 Calculation of slip pulsations

For calculating the slip pulsations, it is assumed that the prime-mover torque has the constant value given by Eqn. (B.17) and that the electrical torque is still given by Eqn. (B.21) with $s\omega_o t$ replaced by δ.

The equation of motion is then

$$\frac{2H}{\omega_o}\cdot\frac{d^2\delta}{dt^2} = -\frac{E\cdot E_o}{x_d}\cdot\text{Sin}\,\delta - \frac{E^2}{2}(Y_c - Y_a)\text{Sin}\,2\delta - \frac{E^2}{2}(Y_d - Y_b)\text{Cos}\,2\delta \qquad \ldots(B.23)$$

Multiplying by $\frac{d\delta}{dt}$ and integrating, using $\omega_o s = \frac{d\delta}{dt}$,

$$\omega_o H s^2 = \frac{E\cdot E_o}{x_d}\cdot\text{Cos}\,\delta + \frac{E^2}{4}(Y_c - Y_a)\text{Cos}\,2\delta - \frac{E^2}{4}(Y_d - Y_b)\text{Sin}\,2\delta + X \qquad \ldots(B.24)$$

X, a constant of integration is equal to the mean value, taken with respect to δ, of the function on the right-hand side and is given by $X = \omega_o \cdot H \cdot s_m^2$. Consequently,

$$s^2 = s_m^2 + \frac{1}{\omega_o H}\left[\frac{E \cdot E_o}{x_d} \cdot \operatorname{Cos}\delta + \frac{E^2}{4}(Y_c - Y_a)\operatorname{Cos} 2\delta - \frac{E^2}{4}(Y_d - Y_b)\operatorname{Sin} 2\delta\right] \quad \ldots (B.25)$$

APPENDIX 'C'

ALTERNATIVE FORMS OF EXPRESSIONS FOR OPERATIONAL IMPEDANCES

From Eqns. (3.19) and (3.20),

$$\frac{x_d(p)}{\omega_o} = \left[\frac{1 + (T_4 + T_5)p + T_4 \cdot T_6 p^2}{1 + (T_1 + T_2)p + T_1 \cdot T_3 p^2}\right] \cdot L_d \qquad \ldots (C.1)$$

Substituting the expressions for various time-constants, as defined in Reference 45, in an expanded form Eqn. (C.1) becomes

$$\frac{x_d(p)}{\omega_o} = \frac{r_f \cdot r_{kd} \cdot L_d + \left[r_f \cdot \ell_a \cdot L_{kd} + r_{kd} \cdot \ell_a \cdot L_f + L_{md}(r_f \cdot \ell_{kd} + r_{kd} \cdot \ell_f)\right] p}{r_f \cdot r_{kd} + (r_{kd} \cdot L_f + r_f \cdot L_{kd})p + (\ell_f \cdot L_{kd} + \ell_{kd} \cdot L_{md})p^2}$$

$$+ \frac{\left[\ell_f \cdot \ell_{kd} \cdot L_d + L_{md} \cdot \ell_a(\ell_f + \ell_{kd})\right] p^2}{r_f \cdot r_{kd} + (r_{kd} \cdot L_f + r_f \cdot L_{kd})p + (\ell_f \cdot L_{kd} + \ell_{kd} \cdot L_{md})p^2}$$

which by some re-arrangement can be written in the following alternative form:

$$\frac{x_d(p)}{\omega_o} = L_d - \frac{(r_f + r_{kd})p + (\ell_f + \ell_{kd})p^2}{r_f \cdot r_{kd} + (r_{kd} \cdot L_f + r_f \cdot L_{kd})p + (\ell_f \cdot L_{kd} + \ell_{kd} \cdot L_{md})p^2} \cdot L_{md}^2 \qquad \ldots (C.2)$$

From the same two Eqns. (3.19) and (3.20)

$$\frac{G(p)}{\omega_o} = \frac{1 + T_{kd} \cdot p}{1 + (T_1 + T_2)p + T_1 \cdot T_3 \cdot p^2} \cdot \frac{L_{md}}{r_f}$$

and in an expanded form,

$$= \frac{r_{kd} + \ell_{kd} \cdot p}{r_f \cdot r_{kd} + (r_{kd} \cdot L_f + r_f \cdot L_{kd})p + (\ell_f \cdot L_{kd} + \ell_{kd} \cdot L_{md})p^2} \cdot L_{md} \qquad \ldots (C.3)$$

Similarly, from Eqns. (3.21) and (3.22)

$$\frac{x_q(p)}{\omega_o} = \frac{1 + T_q'' p}{1 + T_{qo}'' p} \cdot L_q \qquad \ldots (C.4)$$

By substituting the expressions for various time-constants and rearrangement, Eqn. (C.4) can be put in the following alternative form:

$$\frac{x_q(p)}{\omega_o} = L_q - \frac{L_{mq}^2 \cdot p}{r_{kq} + (\ell_{kq} + L_{mq})p} \qquad \ldots (C.5)$$

APPENDIX 'D'

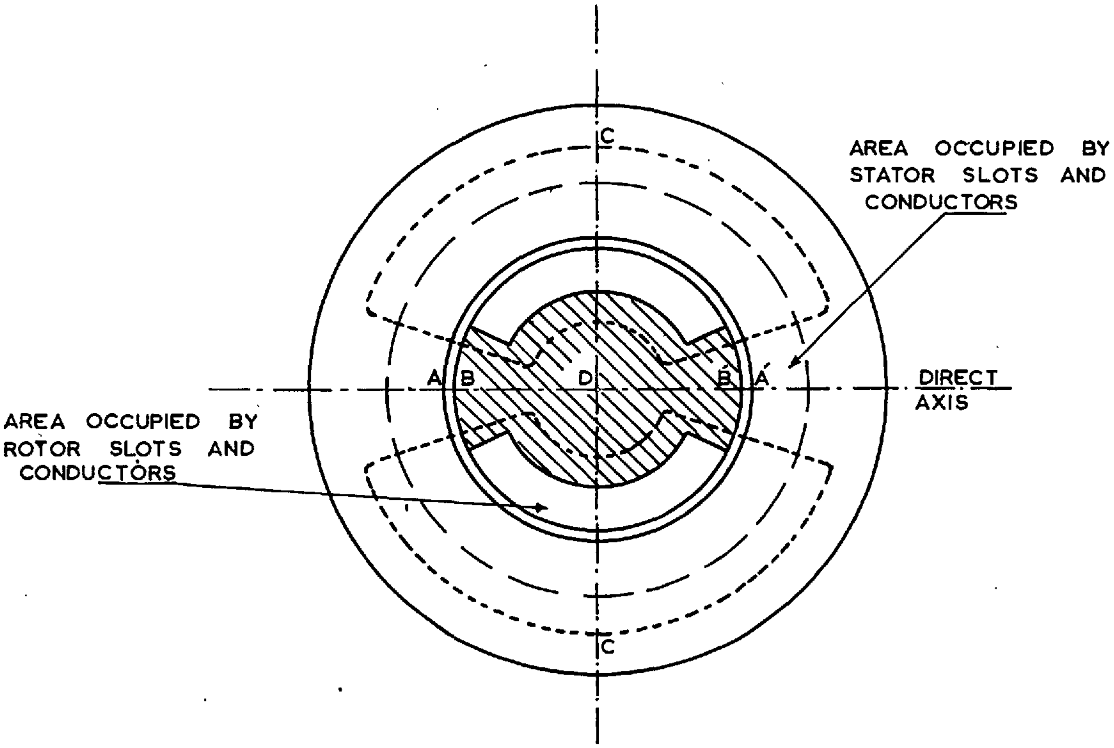
EXPRESSION FOR SOLID - ROTOR IMPEDANCE

D.1 General

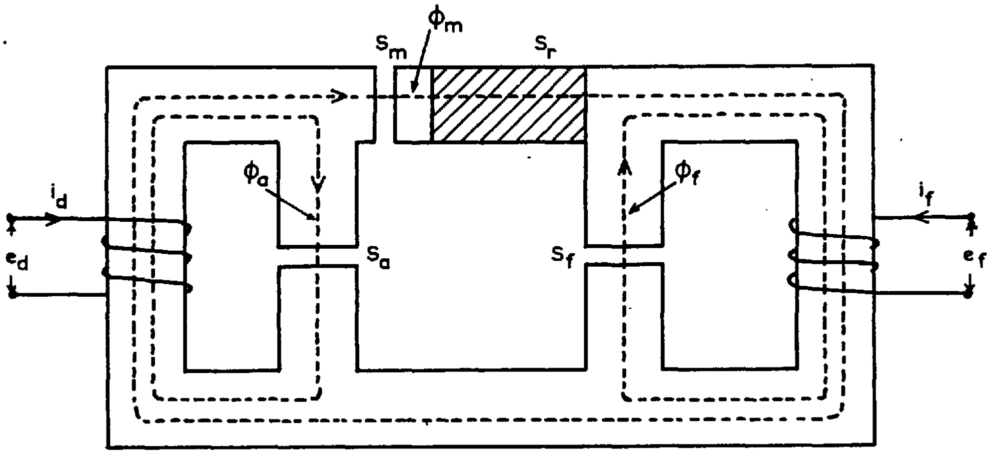
Adequate representation of eddy-current effects in the solid rotor body during asynchronous operation of a synchronous machine will require an infinite number of coils on each axis. The complexity involved will, for most practical problems, render a reliable solution unfeasible. Considering the rotor as a semi-infinite slab of iron, eddy currents in the rotor body can be calculated. Based on this method, an expression for the effective impedance of the solid rotor body has been derived[40]. Brief outline of the derivation is given below.

D.2 Direct-axis electric and magnetic circuits

During asynchronous operation, the synchronous machine can be considered as a transformer, of which the stator winding is the primary, while the rotor circuits form the secondary. The configuration of the magnetic circuit of the transformer is that of the machine, a simplified section of which is shown in Fig. D.1. The main direct axis flux passes round the stator core and through the main body of the rotor inside the slots, as indicated by the dotted lines. Because of the skin-effect caused by the eddy currents in the iron, the flux is thrown outwards and is concentrated in a band of iron material at each side of the rotor body.



Fig·D.1 Direct_axis flux path of a turbo_alternator.



Fig· D.2 Idealised electromagnetic model of the direct_axis flux paths

Fig. D.2 is a diagrammatic representation of the magnetic system. The part corresponding to the solid-rotor body is shaded in the two figures D.1 and D.2. The unshaded parts in the diagram indicate laminated iron portions, which are assumed to have infinite permeability. The laminated iron portions, shown on the rotor side, are fictitious and are used to indicate various leakage flux paths. The main flux ϕ_m links both the armature and field windings and passes across the main air-gap of reluctance S_m and the rotor body of reluctance S_r. S_m is a real constant calculated from the dimensions of the air-gap, but including an allowance for the stator core and teeth. On the other hand, S_r is a complex number varying both with the frequency and the flux.

The electromagnetic model of Fig. D.2 can be represented by an equivalent circuit given in Fig. D.3. In this equivalent circuit, all the components have the usual values except for the rotor impedance Z_{kd}, which is a complex number depending on the reluctance of the rotor body. For practical purposes, it is more convenient to calculate the reluctance of the rotor body S_r in actual units. The relation between Z_{kd} in ohms and S_r in ampere turns per weber is given by

$$Z_{kd} = j\, k_v \cdot k_i / S_r \qquad \ldots (D.1)$$

where the constants k_v and k_i are functions of the effective number of turns in series per phase of the stator winding and the number of phases.

If there is no applied field voltage e_f, the stator induced voltage depends on the operational impedance

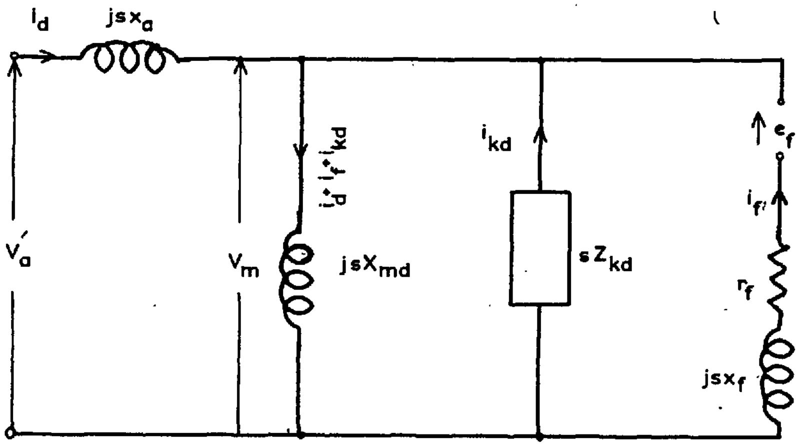


Fig. D.3 Direct-axis equivalent circuit

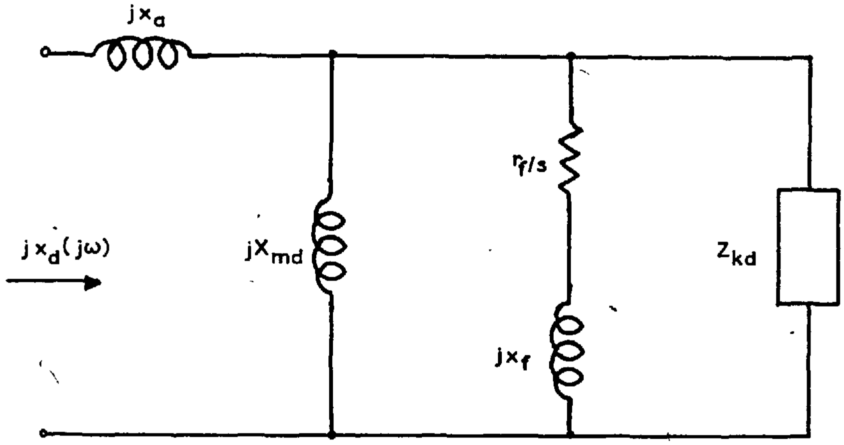


Fig. D.4 Equivalent circuit giving $x_d(j\omega)$

$$V_a' = j\,s\,x_d(j\omega) \cdot I_d \qquad \text{. . .(D.2)}$$

Hence $x_d(j\omega)$ is given by the equivalent circuit of Fig. D.4.

D.3 Quadrature-axis circuits

The quadrature-axis operational impedance $x_q(j\omega)$ can be calculated by a similar method. The dotted lines in Fig. D.5 indicate the mean path of the quadrature-axis flux if the frequency was high enough to cause a pronounced skin effect. For this case, it is however more difficult to determine an equivalent simplified system. Tests taken on the 30 MW machine at Marchwood showed that the quadrature-axis impedance locus agrees quite closely with that for the direct axis with the field circuit open. Working of the theory is, therefore, based on the assumption that the impedances with the field circuit open are the same for the two axes.

Application of the operational impedances to the study of operational problems in synchronous machines assumes that the flux paths on the two axes are independent and that the principle of superposition can be used. Figs. D.1 and D.5 show that the flux paths in the rotor body are to some extent independent although there must certainly be some interaction when saturation occurs.

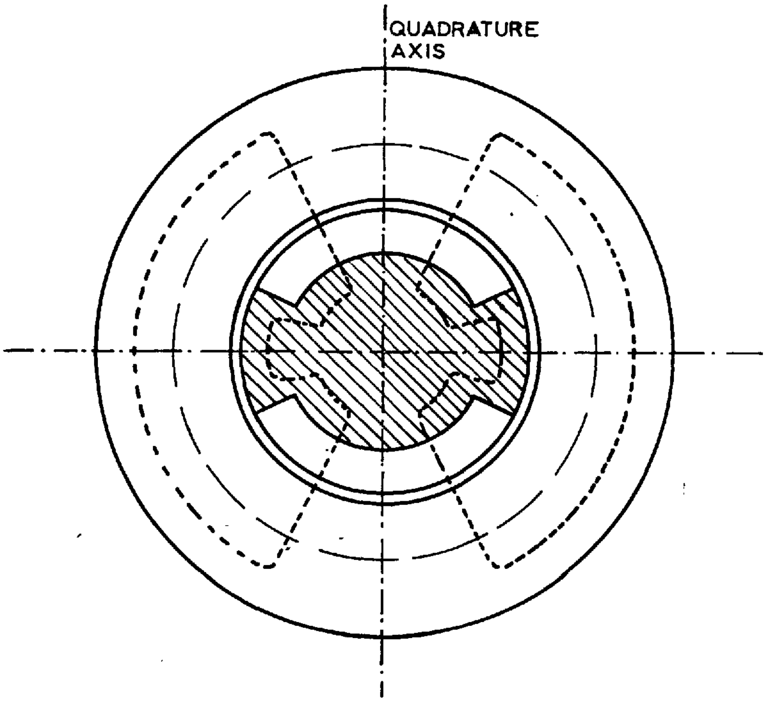


Fig. D.5 Quadrature-axis flux path of a turbo-alternator

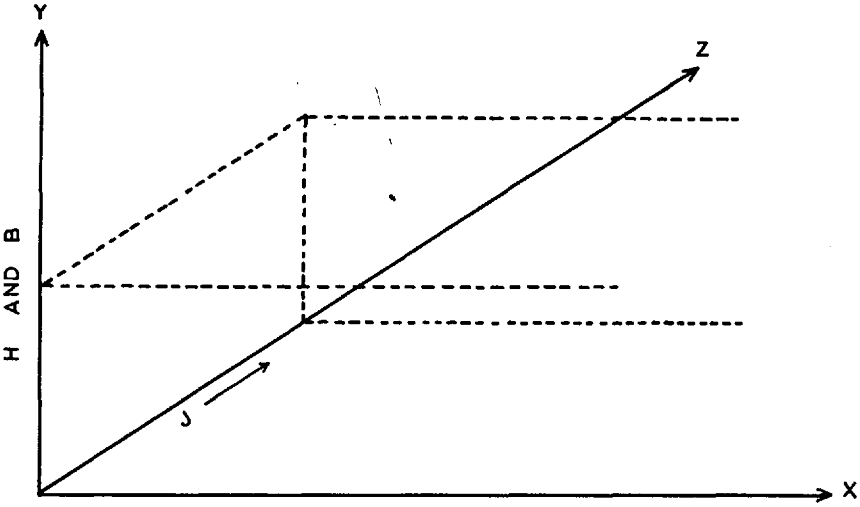


Fig. D.6 Semi-infinite slab with co-ordinate axes

The dotted lines indicate an element of unit area

D.4 Calculation of impedance of the rotor body

D.4.1 Basic equations

The method depends on a mathematical solution for a slab of iron of uniform thickness 2d and extending to infinity in the x-direction, as shown in Fig. D.6. The differential equation for this one-dimensional problem is

$$\frac{\partial^2 H}{\partial x^2} = \frac{1}{\rho} \cdot \frac{\partial B}{\partial t} \qquad \ldots(D.3)$$

where H and B are the magnetic force and the flux density in the y-direction. The boundary condition of the problem is that the surface value of H, when $x = 0$, is given by

$$H_o = H_{mo} \cdot \sin \omega t \qquad \ldots(D.4)$$

The problem is to determine the flux per unit width in the z-direction at a given frequency ω. The solution for the condition of asynchronous operation has been made on the basis of a rectangular approximation to the B/H curve.

D.4.2 Explanation of the approximation

The working of the theory is based on the rectangular magnetisation curve shown in Fig. 5.1. The flux density is assumed to have a constant saturated value B_s whenever H has a value greater that zero in either direction. The application of this method depends on estimating an appropriate value of B_s for any particular condition.

The saturated flux density B_s must necessarily be greater than that due to the maximum flux ϕ_m if uniformly distributed. Consequently, at the instant of maximum flux, the distribution of B in the iron is that shown in Fig. D.7(a), where

$$\delta = \phi_m / B_s \cdot w$$

D.4.3 Calculation of impedance

Eddy currents flow in the iron as a result of the electric force induced by the changing flux. The current density J which flows in the z-direction at a distance x from the surface is given by

$$\left.\begin{aligned} J &= \frac{1}{\rho} \cdot \frac{d}{dt}\left[B_s(\xi - x) - B_s(\delta - \xi)\right] & & \\ &= \frac{2}{\rho} \cdot B_s \cdot \frac{d\xi}{dt} & x &< \xi \\ &= 0 & x &> \xi \end{aligned}\right\} \quad \ldots (D.5)$$

The current distribution at time 't' is, therefore, that shown in Fig. D.7(c). Since $H = 0$ when $x > \delta$, the surface value of H is equal to the total current flowing in the region $x < \delta$. Taking zero time at the instant when $\xi = 0$ and $H_o = 0$,

$$H_o = H_{mo} \cdot \mathrm{Sin}\, \omega t = \frac{2}{\rho} \cdot \xi \cdot \frac{d\xi}{dt} \cdot B_s = \frac{B_s}{\rho} \cdot \frac{d}{dt}(\xi^2) \quad \ldots (D.6)$$

Integrating Eqn. (D.6) and taking the square root,

$$\xi = \sqrt{\left(\frac{2\rho H_{mo}}{\omega B_s}\right)} \cdot \mathrm{Sin}\frac{\omega t}{2} \quad \text{over the period } 0 < t < \frac{\pi}{\omega} \quad \ldots (D.7)$$

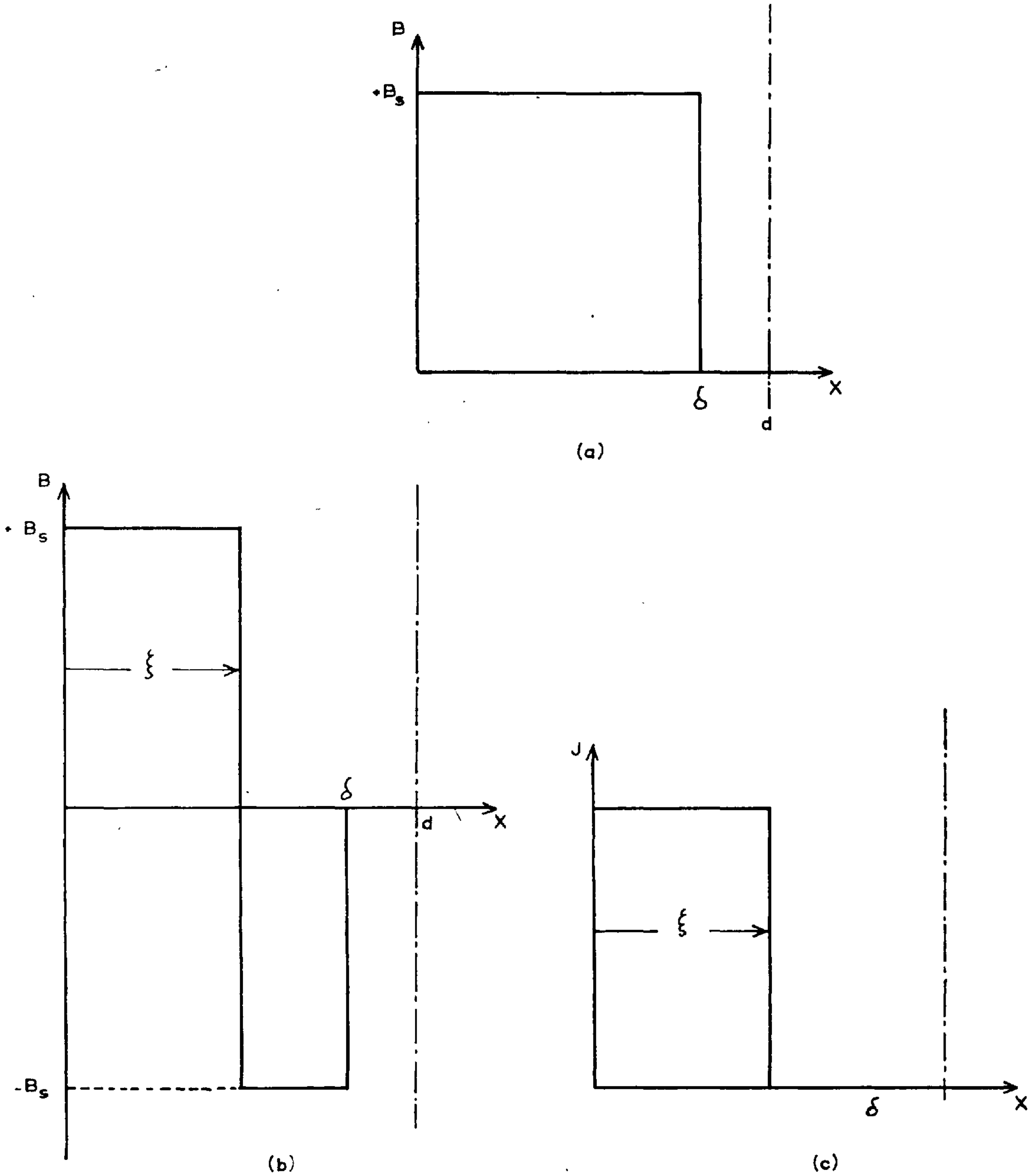


Fig. D.7 Flux density and current distribution for non-linear theory

(a) Flux density at instant of maximum flux

(b) Flux density at any instant

(c) Current density at any instant

The maximum value of ξ is δ, i.e.

$$\delta = \sqrt{\left(\frac{2\rho H_{mo}}{\omega B_s}\right)} \qquad . \; . \; .(D.8)$$

Flux in the rotor body at any instant is given by

$$\emptyset = 2w \cdot B_s \cdot \delta \left(2 \mathrm{Sin} \frac{\omega t}{2} - 1\right) \qquad . \; . \; .(D.9)$$

By Fourier analysis, fundamental component of the flux is given by

$$\emptyset_1 = \emptyset_m \cdot \mathrm{Sin}(\omega t - \lambda) \qquad . \; . \; .(D.10)$$

where

$$\emptyset_m = \frac{4 \cdot \sqrt{5}}{3\pi} \cdot 2w \cdot B_s \cdot \delta \qquad . \; . \; .(D.11)$$

$$\lambda = \arctan 2 = 63.4^{\circ} \qquad . \; . \; .(D.12)$$

From Eqns. (D.8) and (D.11),

$$H_{mo} = \frac{9\pi^2}{640} \cdot \frac{\omega}{w^2 \rho} \cdot \frac{\emptyset_m^2}{B_s} \qquad . \; . \; .(D.13)$$

Hence the effective **reluctance** is

$$S_r = \frac{H_{mo} \cdot \ell}{\emptyset_m} = \frac{9\pi^2}{640} \cdot \frac{\omega \ell}{w^2 \rho} \cdot \frac{\emptyset_m}{B_s} \cdot \mathcal{E}^{\,j63.4} \qquad . \; . \; .(D.14)$$

and the effective impedance of the rotor body is

$$Z_{kd} = k_v \cdot k_i \cdot \frac{640}{9\pi^2} \cdot \frac{w^2 \rho \, \omega_o}{\omega \ell} \cdot \frac{B_s}{\emptyset_m} \cdot \mathcal{E}^{\,j26.6^{\circ}}$$

$$= \frac{640}{9\pi^2} \cdot k_v \cdot k_i \cdot \frac{w^2}{\ell} \cdot \frac{\rho \cdot B_s}{\emptyset_m} \cdot \frac{1}{s} \cdot \mathcal{E}^{\,j26.6^{\circ}} \qquad . \; . \; .(D.15)$$

because $\omega = s\,\omega_o$.

Using rationalised MKS system of units, value of Z_{kd} will be given in ohms.

It is significant to observe that the phase angle (26.6^o) for the rotor impedance obtained by this method works out to be exactly the same as that suggested by Chalmers[20] and Sudan[28].