CHOPPER CONTROLLED KRAMER DRIVE

A DISSERTATION

Submitted in partial fulfilment
of the requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Power Apparatus and Electric drives)

By

SUNIL KUMAR JAIN

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE, (INDIA)
Nov, 1978

CERTIFICATE

Certified that the dissertation entitled 'CHOPPER CONTROLLED KRAMER DRIVE', which is being submitted by SUNIL KUMAR JAIN in partial fulfilment of the requirements for the award of degree of MASTER OF ENGINEERING (Power Apparatus and Electric Drives) in Electrical Engineering Department of the University of Roorkee, Roorkee is a record of students' own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is further to certified that he has worked for a period of about 8 months from March to October, 1978 for preparing this dissertation at this University.

K. Venkatesan
(K. VENKATESAN)
READER
ELECTRICAL ENGINEERING DEPTT.
UNIVERSITY OF ROORKEE
ROORKEE

ROORKEE
15
DATED 11 NOVEMBER ,1978

ACKNOWLEDGEMENTS

The author wishes to express his deep sense of gratitude to Dr. K.Venkatesan, Reader, Department of Electrical Engineering, University of Roorkee, his supervisor for this work for initiating this topic and the liberal guidance and persistent encouragement he has given so lavishly throughout the period of this dissertation.

Thanks are due to Shri S.P. Gupta, Lecturer in Electrical Engineering Department, for his valuable suggestions and timely help without which this work would have been very much impoverished.

Last, but not the least, the author also expresses his thanks to the staff of Drives Laboratory and particularly to Shri Ganguli for their assistance throughout the tenure of this work.

Sunil Kumar Jain

ABSTRACT

In the present work a scheme has been proposed for controlling the speed of Kramer Drive. The scheme employs a solid state chopper for the purpose. The performance equations of the system have been derived. Experimental results are compared with theoretical results and the discrepancies explained.

CONTENTS

.....

LIST OF SYMBOLS

C_1 = Commutating capacitor (uF)

E_2 = rotor phase voltage (V)

i = instantaneous value of current (A)

I_1 = Primary phase current (A)

I_f = field current of d.c.motor (A)

I_a = d.c. motor armature current (A)

I_L = load current (A)

I_{CL} = Locked rotor current (A)

K_f = rotational voltage coefficient of d.c.motor

L_{11}, L_{22} = stator and rotor self inductance (H)

L_{12} = mutual inductance (H)

L_a = d.c. motor armature self inductance (H)

L_1 = inductance in chopper circuit (H)

L_2 = external inductance in series with load (H)

N = speed (r.p.m.)

N_2/N_1 = rotor to stator turn ratio

P_1 = number of poles on induction motor

P_{osy} = output of synchronous generator (W)

r_1, r_2 = stator and rotor resistance (Ω)

r_a = d.c. motor armature resistance (Ω)

R_{sg} = synchronous generator resistance (Ω)

S = per unit slip

S_o = Slip at steady state

δ_n = no load slip

T_{el} = electromagnetic torque of induction motor (Nw-m)

T_e = steady state torque developed by the drive (Nw-m)

$T_{n.l}$ = no load torque

v = instantaneous value of voltage (V)

V_1 = applied r.m.s.phase voltage to stator (V)

V_2 = applied r.m.s.phase voltage to rotor (V)

V_d = rectified d.c.voltage (V)

V_c = Voltage across capacitor

V_L = Load voltage (V)

W = Input power to induction motor (W)

W_{syn} = Cu.losses of synchronous generator (W)

ϕ = Power factor angle (degree)

δ = duty cycle

ω = supply frequency (rad/sec.)

<u>Subscript</u>

d = direct axis quantity

q = quadrature axis quantity

o = steady state quantity

s = stator quantity

r = rotor quantity

CHAPTER - I

INTRODUCTION

Many industrial processes require variable speed drive. But essentially induction motor is a constant speed drive. If by some means the speed control of Induction motor can be achieved then induction motor is the most economical in comparison to D.C.motor and thus avoid the expense of a.c./d.c. conversion.

The wound rotor induction motor is not as rugged as the squirrel-cage motor and cannot operate at very high speeds. But the outstanding feature of the slip ring type of induction motor is that the starting and operating characteristics can be determined by suitably controlling the rotor circuit, as for example, by connecting resistances in series with the slip rings for the improvement of the starting torque as well as for the control of speed and power factor. The reduced speed operation with an ordinary wound rotor induction motor supplied at constant frequency source, as is well known, is possible only by the wasteful expedient of 'bleeding off' slip frequency energy from the rotor and dissipating it in a set of external rotor resistances. During reduced speed operation at any given torque, the power difference between the fixed stator input power determined by the torque and the actual output power at the shaft is wasted in the rotor external resistances. Such an inefficient arrangement is clearly quite unsuitable.

1.1 Speed Control Through Slip Power Recovery Schemes

An attempt to replace the additional resistances from the rotor circuit of the wound rotor induction motor by means of auxiliary machines was made by Scherbius and Kramer in order to obtain the desired speed control at higher efficiency with the help of recovered rotor slip power. All slip power recovery schemes enable the motor to operate at continuously variable speeds. These schemes can be divided into two groups -

(a) Electrical Recovery

(b) Mechanical Recovery

1.1.1 Electrical Recovery Scheme

In Electrical Recovery shown in Fig. 1.1, the slip power converter converts motor electrical power at slip frequency into an electrical power at the line frequency. In this scheme mechanical torque remains constant. For subsynchronous operation, the additional rotor slip power converted into that at line frequency is returned to the supply whereas for super synchronous operation, the additional power required is taken from the supply at the line frequency, which is converted into that at the slip frequency of the rotor, and is fed to the rotor winding.

1.1.2 Mechanical Recovery Scheme

In the scheme shown in Fig. 1.2 the rotor slip power is converted into mechanical power by an auxiliary machine which is then, for subsynchronous operation, added to the

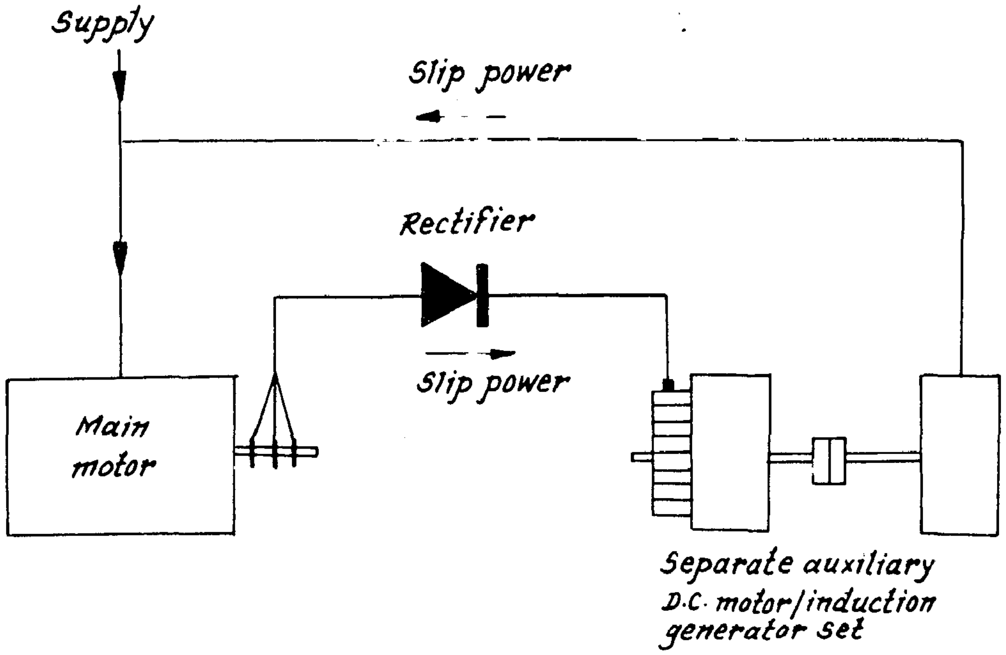


Fig1.2B

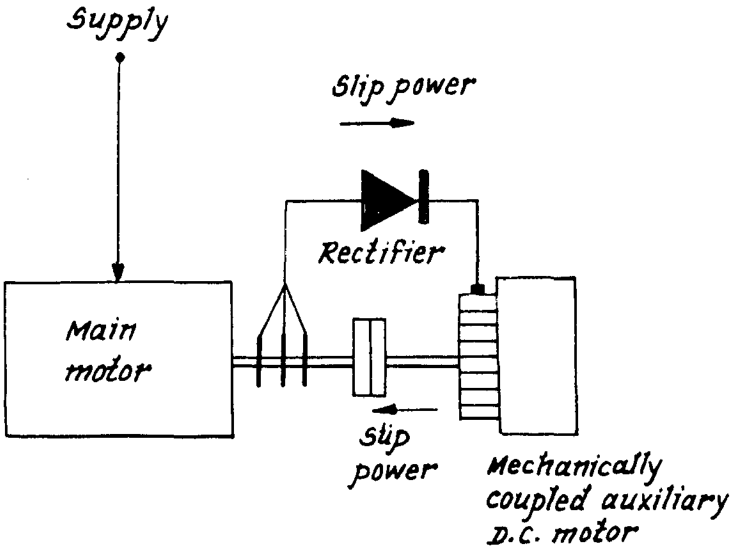


Fig1.2A

rotor shaft. For super synchronous operation, the additional power required is taken from the rotor shaft (in the form of mechanical power) which is converted into an electrical power at the slip frequency and is fed to the rotor winding. This scheme maintains mechanical power constant throughout.

1.2 Literature Review

The basic kramer combination(1,2) developed some sixty years ago, used a rotary converter to provide the necessary slip frequency a.c./d.c. conversion, but the cost of providing and maintaining the multiplicity of machines and brush gear naturally told rather heavily against this type of drive. It was however often successfully employed, especially for limited speed ranges and at very large outputs, where no very practicable alternative was available. The actual speed control is effected by varying the field current of d.c. motor.

In the original kramer system the speed of the main motor must be less than about 80 percent or greater than 120 percent of its synchronous speed as the rotary converter becomes unstable with less than about 10 Hz at its slip rings. A continuous range of speed control both above and below synchronous is thus not practicable.

The recent developments in the field of solid state devices which can handle large quantum of power e.g., silicon didoes and SCRS, have diverted the attention towards the use of these static devices. By using these static devices the rotary machines can be replaced to achieve high efficiency and greater reliability besides low maintenance, smaller size and reduced cost.

In one of the papers by M.Ramamoorty(4), a scheme has been proposed for the speed control of slip ring induction motor using thyristor controlled chopper. It has been shown that a wide range of speed variation is obtained and it can be used for any type of drive. Inspite of the simple and cheap control the scheme has a disadvantage. Simple chopper circuit produces discontinuous rotor currents and causes excessive rotor heating which results in derating of the motor. The speed range obtainable by the simple chopper is also limited.

Another scheme has been investigated by Sen and Ma(7) for speed control of induction motor using a chopper circuit in the rotor side. The control scheme provides continuous and contactless variation of rotor resistance by electronic means and thereby eliminates the undesirable features of the conventional rotor resistance, control method. Further a d.c. and a.c. circuit models have been developed and a thorough analysis of steady state performance of the system is presented. The feasibility of the system and verification of theoretical results are demonstrated by experimental results and it is anticipated that such simple and elegant control scheme will find applications in many industrial drives.

Bland and Hancock(5) presented a paper on 'considerations concerning a modified kramer system'. In view of the above paper a variable speed drive can be obtained by means of a modified kramer system consisting of a polyphase induction motor, the rotor circuit of which is connected through a 3-phase bridge rectifier to the armature of a d.c. motor directly coupled to the induction motor. Control is obtained by varying the field excitation of the d.c.motor. The operation of such a system is considered in respect of the commutating reactance, the speeds at which locking torques due to current harmonics could occur and, the possible magnitudes of the current harmonics and the losses.

1.3 Present State of Art

The modified Kramer variable-speed cascaded motor combination consists essentially of a wound rotor motor and a rectifier feed auxiliary d.c. motor, the two machines being mechanically coupled and connected electrically in cascade i.e. with the d.c. motor energised via the rectifier from the slip-rings of the induction motor. With this scheme speed control in the subsynchronous region from synchronous to 50 percent of synchronous speed is only possible.

1.4 Work Presented

In the present work a chopper has been introduced between the rectifier and the d.c. motor and the speed control range is increased from zero to synch. speed.

Experimental results have been compared with the theoretical ones and the discrepencies explained.

CHAPTER - II

PERFORMANCE EQUATIONS OF THE SYSTEM

This chapter deals with the performance equations of the Kramer Drive. These equations have been derived in reference (11).

The basic diagram showing voltages and currents of Kramer Drive is shown in Fig. 2.1. In deriving the performance equations two basic assumptions have been made.

(1) The commutation time of the thyristors is negligible.

(2) Chopper input is a steady d.c. voltage

2.1 Dynamic Equations of the System

The induction motor equations expressed in the synchronously rotating reference frame are(9)

$$V_{ds} = (r_1 + L_{11}p)\, i_{ds} - wL_{11} i_{qs} + L_{12}p\, i_{dr} - wL_{12} i_{qr} \qquad (2.1)$$

$$V_{qs} = wL_{11}\, i_{ds} + (r_1 + L_{11}p) i_{qs} + wL_{12}\, i_{dr} + L_{12}p\, i_{qr} \qquad (2.2)$$

$$V_{dr} = L_{12}p\, i_{ds} - SwL_{12}\, i_{qs} + (r_2 + L_{22}p)\, i_{dr} - SwL_{22}\, i_{qr} \qquad (2.3)$$

$$V_{qr} = SwL_{12}\, i_{ds} + L_{12}p\, i_{qs} + SwL_{22}\, i_{dr} + (r_2 + L_{22}p)\, i_{qr} \qquad (2.4)$$

and the electromagnetic torque developed in Newton meters is given by

$$T_{ei} = \frac{3}{2}\,\frac{P_1}{2}\, L_{12}\,(i_{qs}\, i_{dr} - i_{ds}\, i_{qr}) \qquad (2.5)$$

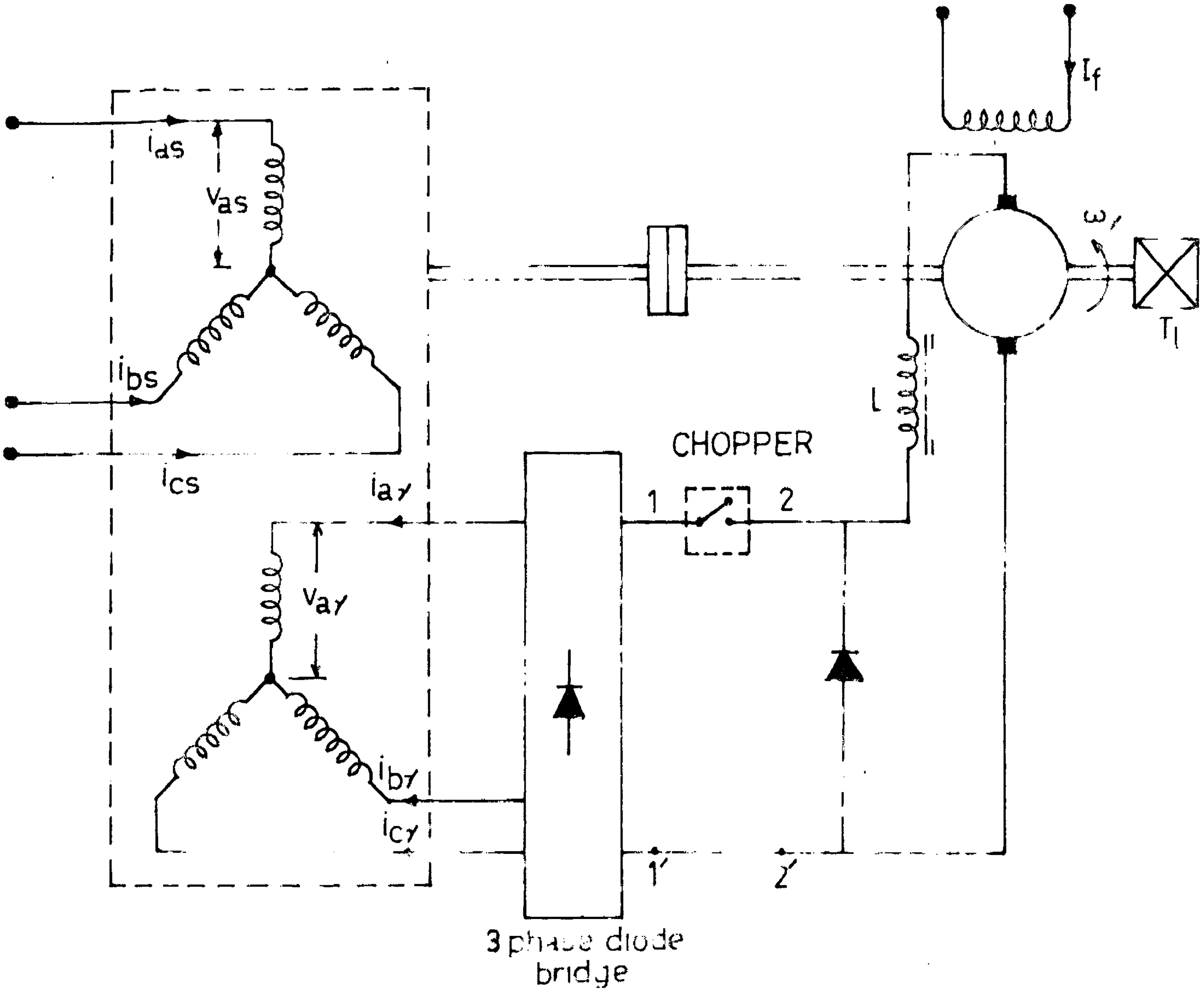


FIG. 2.1 VOLTAGES AND CURRENTS IN THE DRIVE.

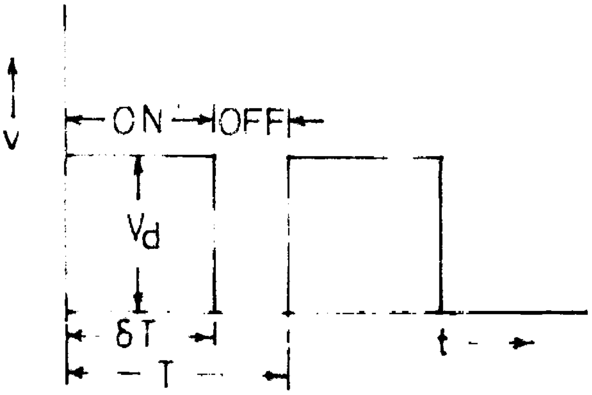


FIG. 2.2 CHOPPER OPERATING CONDITION.

Let the voltages applied to the stator phase be

$V_A = \sqrt{2}\ V_1 \cos \omega t, \qquad V_B = \sqrt{2}\ V_1 \cos (\omega t - \frac{2\pi}{3})$ and

$$V_c = \sqrt{2}\ V_1 \cos (\omega t + \frac{2\pi}{3}) \tag{2.6}$$

and to the rotor phases be

$$V_a = \sqrt{2}\ V_2 \cos s\omega t, \quad V_b = \sqrt{2}\ V_2 \cos (s\omega t - \frac{2\pi}{3})$$

$$\text{and } V_c = \sqrt{2}\ V_2 \cos (s\omega t + \frac{2\pi}{3}) \tag{2.7}$$

Selecting the angular relationship between the d-axis of the reference frame and the magnetic axes of the stator and rotor phases such that these axes coincide at time zero, the dq component voltages obtained using equations (2.6) and (2.7) are

$$V_{ds} = \sqrt{2}\ V_1 \qquad V_{qs} = 0 \tag{2.8}$$

$$V_{dr} = \sqrt{2}\ V_2 \qquad V_{qr} = 0 \tag{2.9}$$

For the uncontrolled bridge rectifier in Fig.(2.1) the voltage relationship is given by$^{(8)}$

$$V_d = 1.35\sqrt{3}\ V_2 \tag{2.10}$$

From eqs. (2.8) and (2.10)

$$V_{dr} = \frac{1}{1.35\sqrt{1.5}}\ V_d \tag{2.11}$$

Slip power $= \delta\ V_d \cdot I_a$

and the power balance equation is given by

$$\delta\ V_d\ I_a = -\frac{3}{2}\ V_{dr}\ I_{dr} \qquad (2.12)$$

Where the negative sign is due to considering an input power to the rotor and the factor 3/2 due to actual units is different terms.

or, $$\delta\ V_d I_a = -\frac{3}{2}\ \frac{1}{1.35\sqrt{1.5}}\ V_d\ I_{dr}$$

or $$I_a = -\frac{3}{2}\ \frac{1}{1.35\sqrt{1.5}}\ \frac{1}{\delta}\ I_{dr} \qquad (2.13)$$

Voltage balance e.g. for the d.c. motor armature circuit is given by

$$\delta\ V_d = r_a + (L_a + L_2)\ p\quad I_a + K_f\ I_f\ \frac{2(1-s)\ \omega}{P_1}$$

In steady state

$$V_d = -r_a \frac{3}{2}\ \frac{1}{1.35\sqrt{1.5}}\ \frac{1}{\delta^2}\ I_{dr}$$
$$+ K_f\ I_f\ \frac{2(1-s)\ \omega}{\delta\ P_1} \qquad (2.14)$$

From (2.10) and (2.14)

$$V_{dr} = -\ r_a \frac{1}{\delta^2 (1.35)^2}\ I_{dr} + \frac{K_f I_f\ 2(1-s)\ \omega}{\delta\ 1.35\ \sqrt{1.5}\ P_1} \qquad (2.15)$$

Under steady state (p = 0)

$$\begin{bmatrix} \sqrt{2}\, V_1 \\ 0 \\ \dfrac{K_f I_f\, 2\omega(1-s_o)}{\sqrt{1.5}\, P_1 1.35\delta} \\ 0 \end{bmatrix} = \begin{bmatrix} r_1 & -\omega L_{11} & 0 & -\omega L_{12} \\ \omega L_{11} & r_1 & \omega L_{12} & 0 \\ 0 & -s_o \omega L_{12} & r_2 + \dfrac{r_a}{(1.35)^2 \delta^2} & -s_o \omega L_{22} \\ s_o \omega L_{12} & 0 & s_o \omega L_{22} & r_2 \end{bmatrix} \begin{bmatrix} i_{dso} \\ i_{qso} \\ i_{dro} \\ i_{qro} \end{bmatrix}$$

(2.16)

Steady state torque developed by the drive

$$T_e = \frac{3}{2} \frac{P_1}{2} L_{12} (i_{qso}\, i_{dro} - i_{dso}\, i_{qro}) - K_f I_f \frac{\sqrt{1.5}}{1.35} \cdot \frac{1}{\delta} \cdot I_{dro}$$

(2.17)

2.2 NO Load Slip

Since the current in the secondary circuit is zero under ideal no load condition, the rectified rotor induced voltage should be equal to the induced voltage in the d.c. machine. Hence

$$\delta \cdot 1.35 \sqrt{3} \frac{N_2}{N_1} V_1 S_n = \frac{K_f I_f (1-S_n) 2 \omega}{P_1} \qquad (2.18)$$

Where S_n is the ideal no load slip. From (2.18)

$$S_n = \frac{A I_f}{B + A I_f}$$

Where $$A = \frac{2 K_f \omega}{P_1}$$

and $$B = \delta \; 1.35 \sqrt{3} \, \frac{N_2}{N_1} \, V_1$$

2.3 Expressions for Primary Phase Current and Power Factor

Primary phase current is given by

$$I_1 = \frac{\sqrt{I_{dso}^2 + I_{qro}^2}}{\sqrt{2}}$$

Power factor is given by

$$\cos \phi_1 = \frac{i_{dso}}{\sqrt{i_{dso}^2 + i_{qso}^2}}$$

CHAPTER - III

EXPERIMENTAL SETUP AND WORKING PROCEDURE

3.1 Experimental Setup

The complete experimental setup of 'chopper controlled Kramer Drive' system has been shown in Fig. 3.1. In the present setup an induction motor, having two stators and two rotors of 6 pole and 2 pole, is directly coupled to a separately excited d.c. motor. The 6-pole induction motor is run as the main motor which provides input supply through its slip rings to the 3-phase bridge rectifier. The 2-pole induction motor of the set is made to run as a synchronous generator which is used to load the main motor. The rectified output of the bridge circuit is given to the armature of the d.c. motor through a chopper circuit. Consequently by adjusting the ON time of the chopper unit with the help of a suitable controlling circuit, the average d.c. voltage applied to the armature of the d.c. motor can be controlled. The field control of D.C.motor gives a certain range of speed control so by controlling the armature voltage we can have the speeds ranging from stand still to just below the synchronous speed of the Kramer drive.

3.2 Working of Chopper

Chopper is a power switch electronically monitored by a control module which can be turned ON and OFF very fast. For the purpose the chopper circuit used here is known as

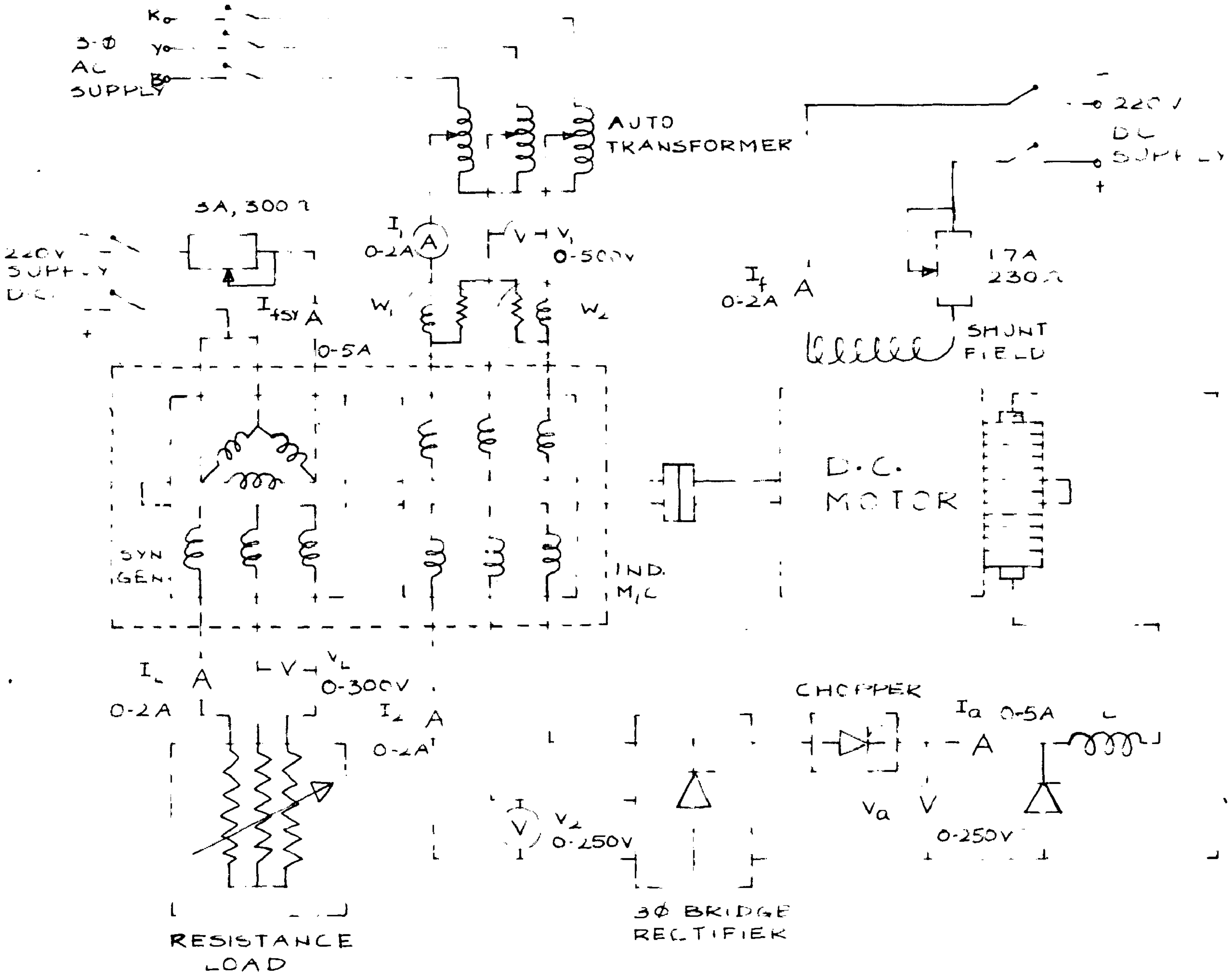
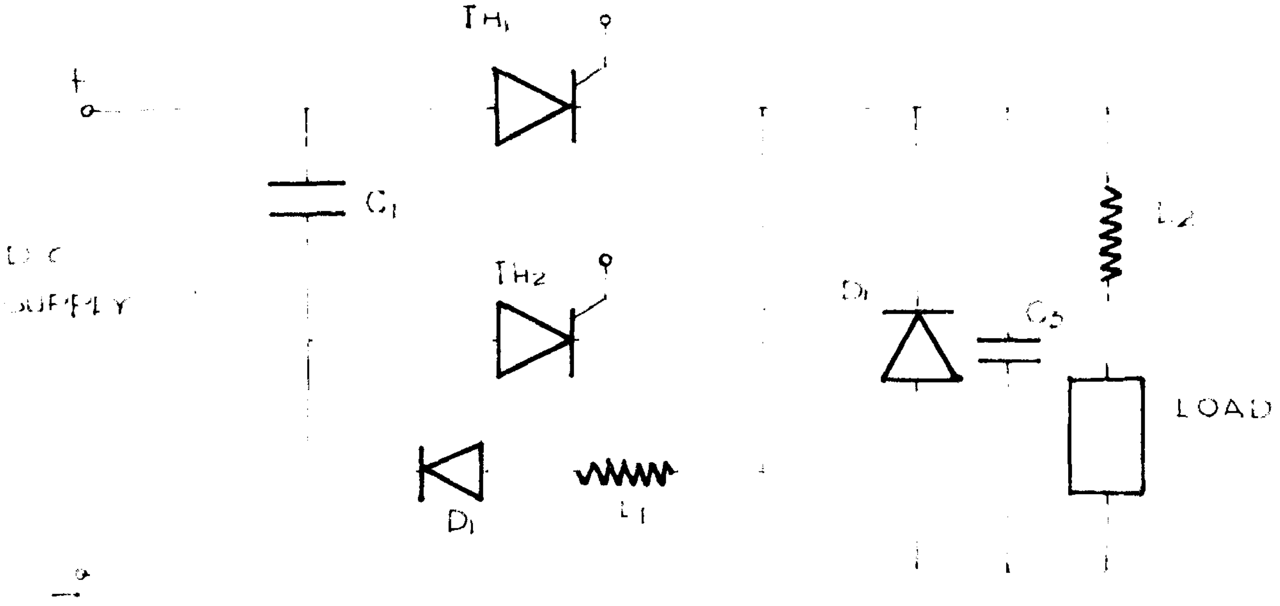
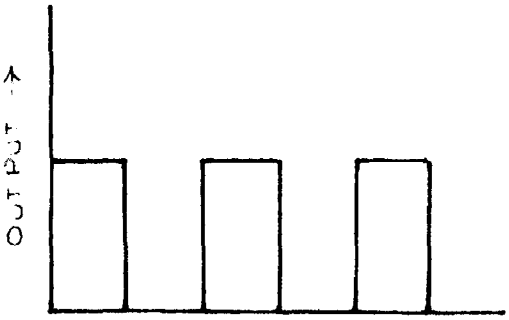


FIG EXPERIMENTAL SET UP FOR CHOPPER CONTROLLED KRAMER DRIVE



OSCILLATING CHOPPER

fig.



IDEAL OUTPUT OF CHOPPER

fig

oscillating chopper shown in Fig. 3.2. The advantage of this type of circuit is that it has a higher characteristic frequency of switching. The operation is started by applying a firing pulse to SCR_2. The switching capacitor C_1 then charges through the load, so that the lower plate in the diagram is negative with respect to the upper plate. Upon SCR_1 being fired, the supply is connected directly to the load, and in addition, C_1 is discharged into the choke L_1. C_1 and L_1 form a lightly damped resonant circuit. Current continues to flow in it, therefore, until the charge on C_1 is reversed and builds up almost to the original voltage, i.e. the supply voltage. The current can not reverse because of the diode D_1 and hence C_1 remains charged with its lower plate now positive. When SCR_2 is subsequently fired again, the charge on C_1 is applied in reverse across SCR_1 and turns it off. The load current free wheels through the free wheeling diode D_2 during periods when SCR_1 is non-conducting. A high inductance L_2 in series with the armature of the D.C.motor is also included for stabilization of current.

It is observed that chopping the current in this manner does not involve chopping the current supplied to the motor. In fact, if the chopping frequency is high in relation to the time constant of the load circuit, the load current is virtually smooth. Under these conditions the mean input current is equal to the load current divided by the voltage reduction ratio.

The ideal output of the chopper is a rectangular pulse shown in Fig. 3.3.

3.3 Working of the System

The whole operation takes place as follows -

(1) The gate signal to the main thyristor SCR_1 is disconnected and commutating capacitor C is charged via auxiliary thyristor SCR_2 by giving voltage to the 6-pole stator of Induction motor with autotransformer.

(2) The gate signal is given to the main thyristor SCR_1 consequently motor starts up.

(3) The field excitation to the D.C.motor is applied and kept at a fixed value for a set of readings for different values of δ, the ON time of chopper.

(4) The speed control can be achieved just by a potentiometer in the firing circuit which changes the d.c. level in the comparator. By applying full field d.c. excitation and further by potentiometer control a very low values of speed can be obtained.

(5) The excitation of the synchronous generator is given to the rotor of 2-pole motor from external d.c.source. The output voltage of the synchronous generator is connected to a 3-phase resistance load.

(6) At different loads the speeds, currents and voltages etc. are measured.

CHAPTER - IV

DESIGN CONSIDERATIONS AND DESIGN PROCEDURE

4.1 Design of Chopper

Design Trade Offs.

The following information is required for the design of components in the oscillation chopper.

V_d = d.c. supply voltage

I_{CL} = The rotor current required to provide load breakaway torque.

Both maximum motor current and d.c. supply voltage are key variables assuming a fixed motor H.P. required. Other important and interrelated variables are commutating capacitor size and SCR current and voltage requirements. All of the above mentioned parameters and circuit component requirements are interrelated.

The thumb rule equation generally used for circuit turn off time in a chopper is

$$t_{off} = \frac{C_1 \; V_d}{I_{CL}} \qquad (4.1)$$

The voltage V_C across capacitor, which is also equal to the supply voltage V_d, can be determined as follows -

The energy stored in the inductor L is

$$\frac{1}{2} I_{CL}^2 \quad L,$$

This energy must be transferred to the capacitance C_1. Then

$$\frac{1}{2} I_{CL}^2 L_1 = \frac{1}{2} C_1 V_C^2$$

$$L_1/C_1 = V_C^2 / I_{CL}^2$$

$$V_C = I_{CL} \sqrt{L_1/C_1} \qquad (4.2)$$

Substituting (4.2) in (4.1), gives

$$t_{off} = \sqrt{L_1 C_1}$$

Defining $r_a = V_d/I_{CL}$ (4.3)

It is seen that major design revolves around the selection of r_a, L_1 and C_1 where L_1 and C_1 determines both circuit turn off time for SCR_1 and the circuit voltages.

The chopper is designed to control a d.c. motor directly coupled to the shaft of an induction motor. Specifications of d.c. motor are as follows -

0-220 V, 20 Amp, 750-1000 RPM

3.75 KW output

It has an armature resistance of 2.5 ohms.

r_a = 2.5 ohms.

The relation between rectified d.c. voltage and slip ring voltage is given by

$$V_d = 2.34 E_2$$

When stator is given 400 volts in star maximum slip ring voltage = 182 V.

$$V_d = 2.34 \times \frac{182}{\sqrt{3}}$$

$$= 246 \text{ Volts}$$

$$I_{CL} = 246/2.5 \quad 10 \text{ Amp.}$$

Taking $T_{off} = 2\ T_q = 2 \times$ Thyristor turn off time

$= 2 \times 15 \times 10^{-6}$ sec.

Capacitor

Assuming a turn off time of the SCR_1 to be 15 micro-sec. value of capacitor can be determined from equation

$$t_{off} = \frac{C_1\ V_C}{I_{CL}}$$

Taking a safety factor of 2 to ensure commutation

$$2 \times 15 \times 10^{-6} = \frac{C \times 246}{100}$$

$$C_1 = 12 \text{ micro Farad.}$$

Inductance

Inductance value is determined from equations (4.2) and (4.3).

$$r_a = \sqrt{L_1/C}$$

$$L_1/C_1 = (2.5)^2$$

$$L_1/C_1 = 6.25$$

$$L_1 = 6.25 \times 12 \times 10^{-6} = 75 \times 10^{-6} \text{ Henry}$$

Thyristors

The maximum current rating of the d.c. motor armature winding is 20 amp. and maximum voltage appearing at standstill is 246 volts. Taking into account for safety factor the thyristors chosen are 28 TB6. They can withstand 600 V and 28 Amp. current.

4.2 Freewheeling Diodes

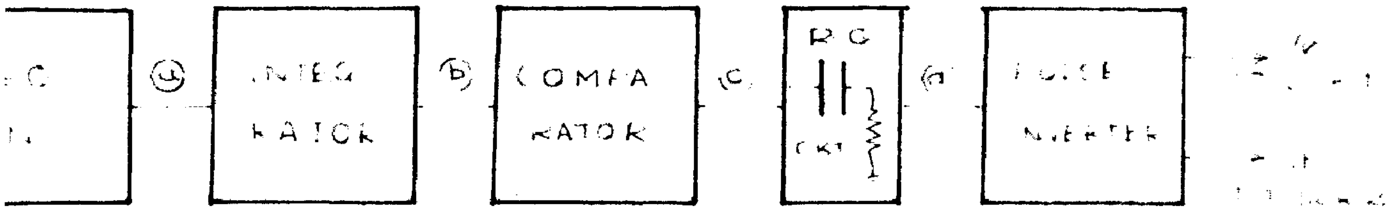
Free wheeling diode handles with 1/4 of the average load current so under normal operating conditions it should be able to withstand about 5 amp. But it is chosen as per starting current of 100 amp., hence, a diode with current rating of 25 amp. will suffice. A capacitor is also included across it for surge protection.

4.3 Design of Rectifier

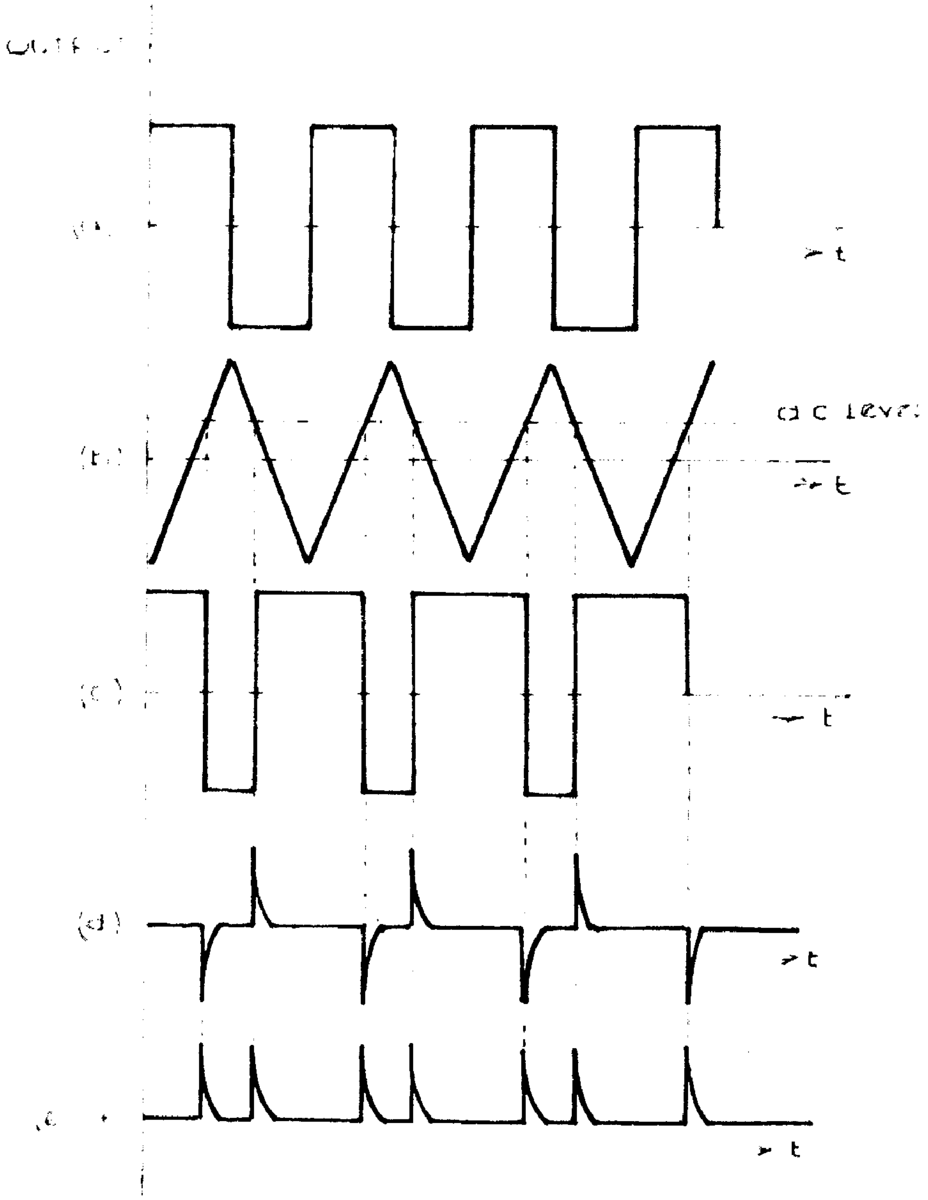
There is no complexity involved in the design of three phase bridge rectifier. Selection is based on the current it has to carry and the maximum voltage it has to withstand. For the purpose power diodes of 40 amp. and 600 volts rating have been used.

4.4 Details and Design of Firing Circuit

In the present chopper circuit the thyristors used are 28TB6. The aim is to have the gate pulses of sufficient magnitude to turn ON the thyristor. For the present thyristors the pulses of 3 V are needed for effective firing.

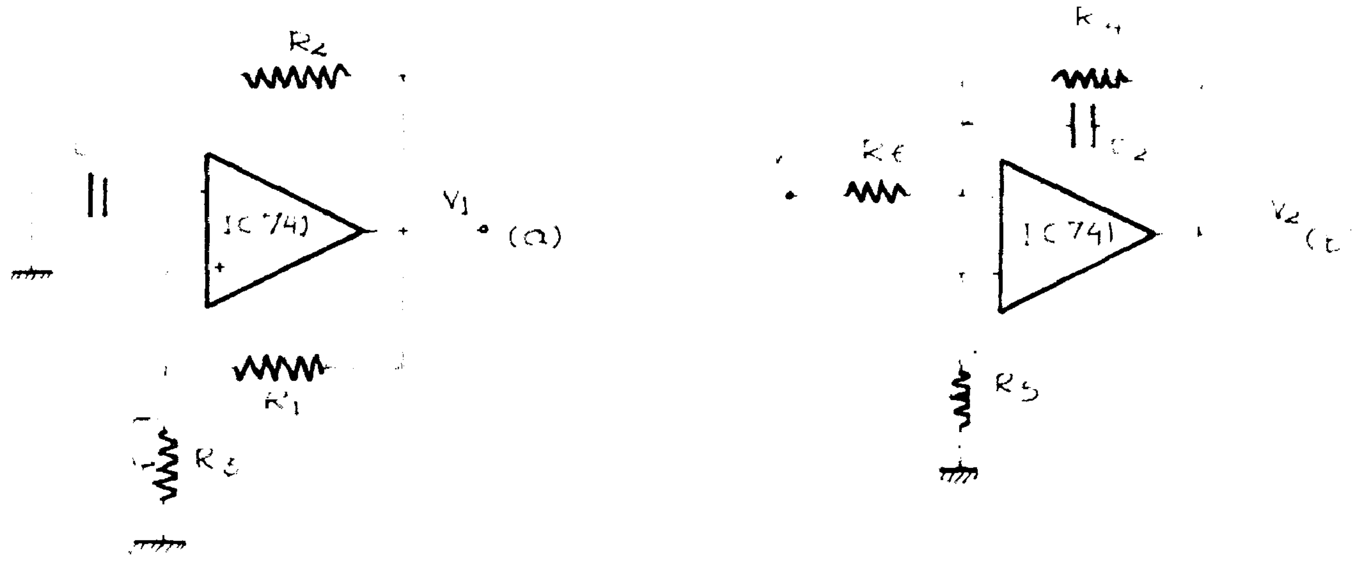


BLOCK DIAGRAM OF CONTROL CKT.



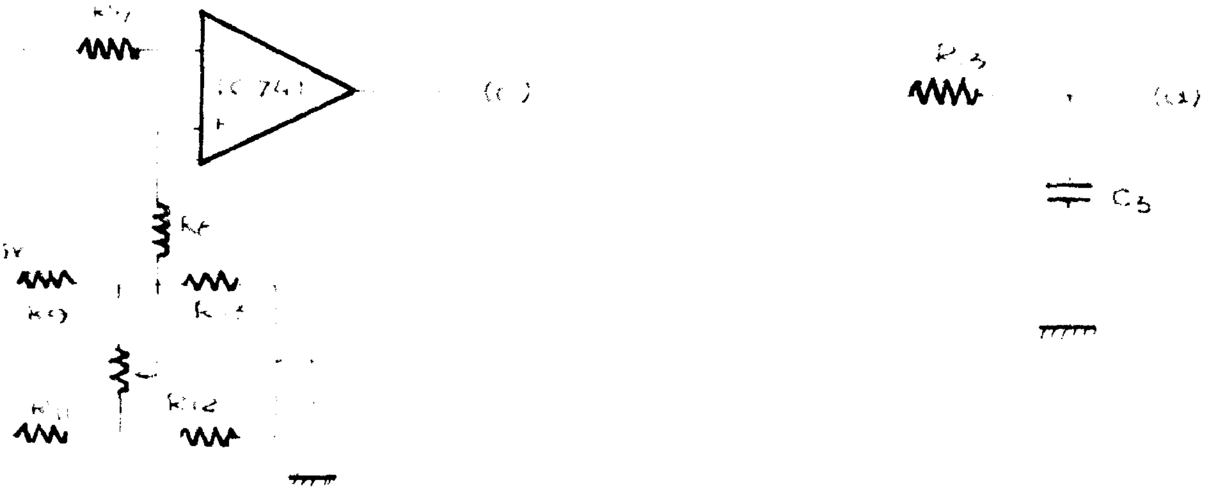
OUTPUT WAVE FORMS & FIRING PULSES

Fig



FREQ GENERATOR

(b) INTEGRATOR



COMPARATOR

(d) R-C DIFFERETIATOR

OF

DIFFERENT BLOCKS FOR FIRING CIRCUIT

As is well known chopper is nothing but an electric switch which can be made ON and OFF for a certain period depending upon the duty cycle. Now the main aim is to vary the duty cycle to change the average value of chopper output which inturn will change the speed of the drive. If the relative position of two pulses in a particular frequency cycle can be changed our aim is fulfilled. To achieve this a scheme has been developed which is as follows -

The block diagram of such scheme has been shown in Fig. 4.1. The whole circuitary can be divided into five parts.

(1) Frequency Generator - The first block determines the chopping frequency. For the purpose square waves are required for which IC 741 can be used readily. In fact, square waves can also be obtained using transistor circuit but due to the versatility and cheapness of IC741 it is being preferred. It has got an additional advantage that frequency can be varied only with the help of one potentiometer. Here it has been used as an astable multivibrator, shown in Fig. 4.3a. The normal recommended values for feedback resistances R_2 and R_3 are 10 K for good stability. Now the frequency of this astable is given by

$$f = \frac{R_1 + 2\,R_3}{2\,R_2\,R_3\,C}$$

Choosing a value of 0.1 /micro farad for C the upper and lower limit of variable resistor R_3 are determined for two extremum of operating frequencies. By changing the value of the potentiometer R_3 the frequency can be varied. The output wave shape of astable multivibrator is shown in Fig. 4.2a. The output of astable is fed to the next block integrator.

(2) Integrator - The second block integrates the square output of the astable. The configuration of integrator is shown in Fig. 4.3b. Here again IC 741 is used due to its versatility. While calculating the changing time resistance R_4 is omitted. The slope of integration depends upon resistance R_6 and capacitance C_2 whereas the two limits of time are decided by input V_1 and output V_2. Now taking the normal recommended value of R_6 as 10K we can calculate the value of capacitor C_2 using $i\ t = CV$. Here i is V_1/R_6, t is reciprocal of frequency and V equals V_2 which is the desired output voltage level. Non-inverting input is grounded through a resistance of 10K. So the inverting and non-inverting inputs are at the same level. The output of integrator is a triangular wave which is shown in Fig.4.2b.

(3) Comparator - The third block is one of the important blocks of the complete firing circuit which also employs IC 741. The configuration of comparator is shown in Fig. 4.3c. It compares the triangular output of integrator with a

variable d.c. voltage. The maximum d.c. level depends upon the upper limit of the triangular output. When it is compared with maximum d.c. level we get no output and maximum output is obtained when compared with minimum level. The output width of comparator which is shown in Fig. 4.2c. is the desired output or ON time which inturn varies the average d.c. voltage to the armature of d.c. motor. The values of resistances in the comparator circuit are chosen so as to obtain the d.c. level for comparison in the required range only.

(4) Differentiator - The fourth block of the firing circuit differentiates the rectangular, output from the comparator. For the purpose a R-C differentiator has been used. The turn ON time of thyristors are taken as about 10 microsecond. The differentiator time constant must be more than the thyristor turn ON time. To ensure reliable turn ON 0.1 micro farade and 10K values are chosen for ~~turn~~ differentiator. The R-C network is shown in Fig. 4.3d and the output waveform is shown in Fig. 4.2d.

(5) Pulse Inverter Circuit - Output of the comparator is fed to the part which utilises two complementary circuits of S K 100 and SL 100. The function of this part is to invert the outgoing pulse from the output of the capacitor and produce the firing pulses for main and auxiliary circuit through diodes. The output wave shapes are shown in Fig. 4.2 e and f.

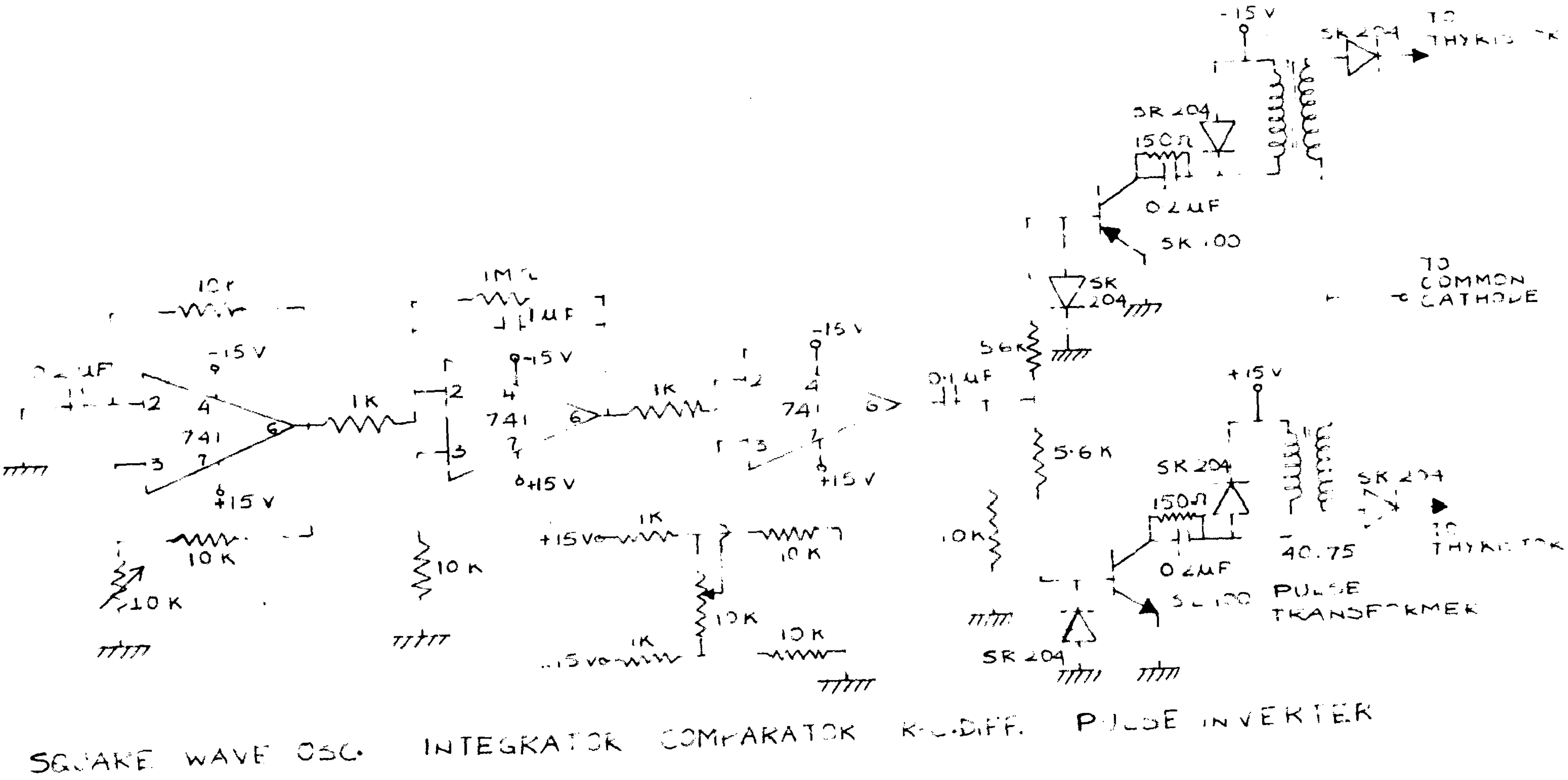
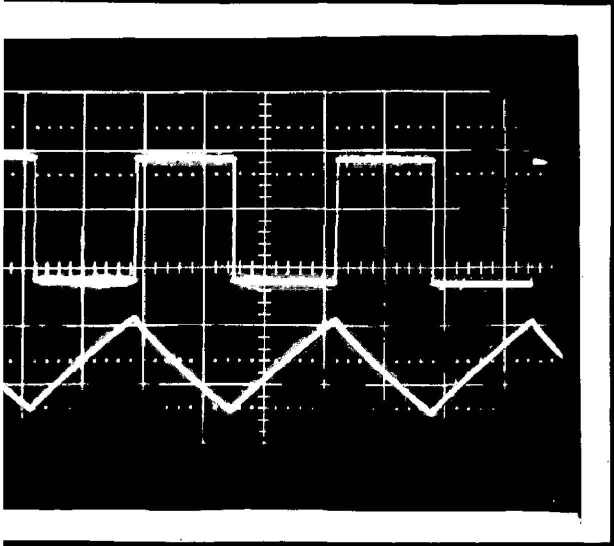
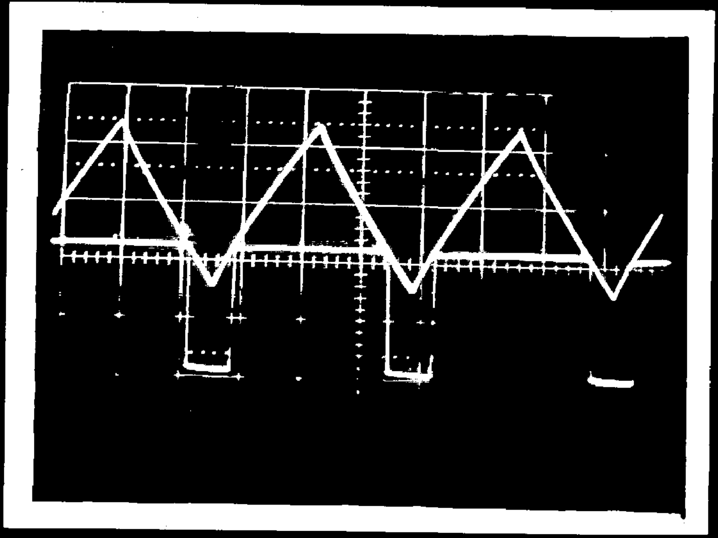


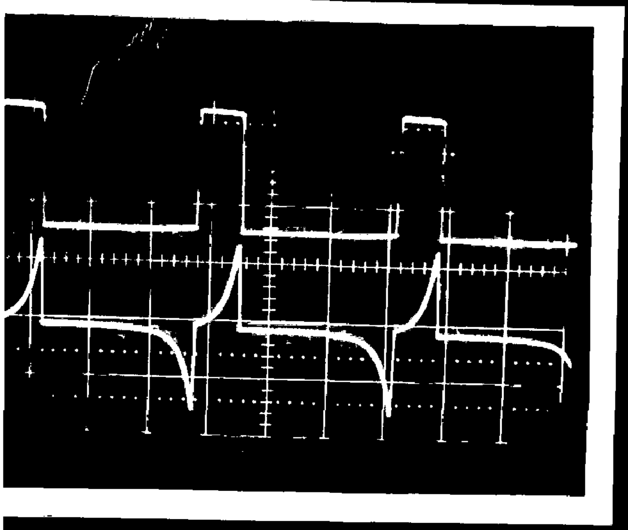
FIG. THYRISTOR FIRING CIRCUIT FOR THE CHOPPER



Output Waveforms of Frequency Generator and Integrater.

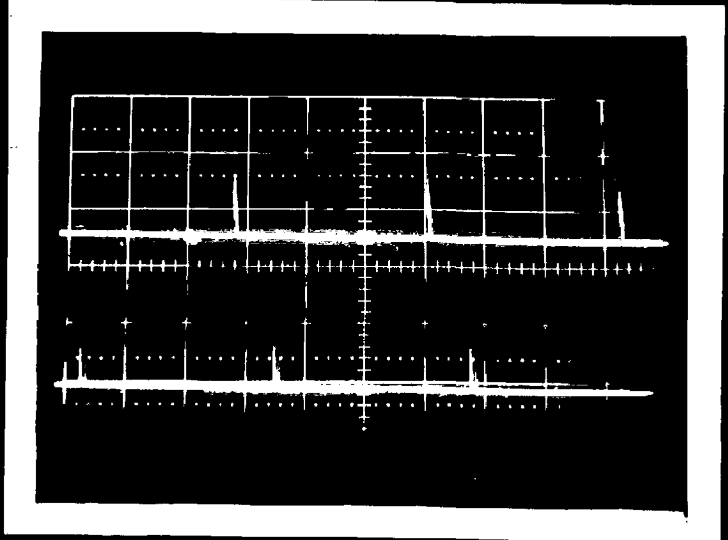
utput Waveform of Comparator howing d.c. level.





Output Waveform of Differentiator

Firing Pules for SCR$_1$ and SCR$_2$



The pulses thus obtained are weak in magnitude to fire the thyristor so the magnitude is increased through a pulse transformer which also provides the electrical isolation between the firing and the main power circuitary. A free wheeling diode is also included across the primary of pulse transformer. Due to the oscillations set up in primary a high voltage can be induced which can damage the driving transistor. Further when the transistor is turned ON, current can not build up suddenly due to the inductance of primary of pulse transformer but it shoots up to a very high value as there is no resistance in the circuit. To limit that current ~~but~~ a resistance is included in the circuit but to by pass the pulse to the pulse transformer a capacitor is added in parallel with this resistance otherwise the pulses also reduce in magnitude.

All the experimental output waveforms of each block are shown in Fig. 4.4. Complete circuit with relevant values is shown in Fig. 4.5.

CHAPTER - V

EXPERIMENTAL RESULTS

This chapter deals with the verification of theoretical results with the experimental results. Various experiments were performed on the machines whose specifications are as follows -

Induction Motor
2-pole and 6-pole
Volt 400/440 Delta primary
400 star secondary
5.5 Amp. primary, 3.5 Amp secondary
50 Hz, 3-phase
D.C. Machine
0.220V, 20 Amp., 750-1000 RPM
3.75 KW output.

Armature resistance of D.C.Machine

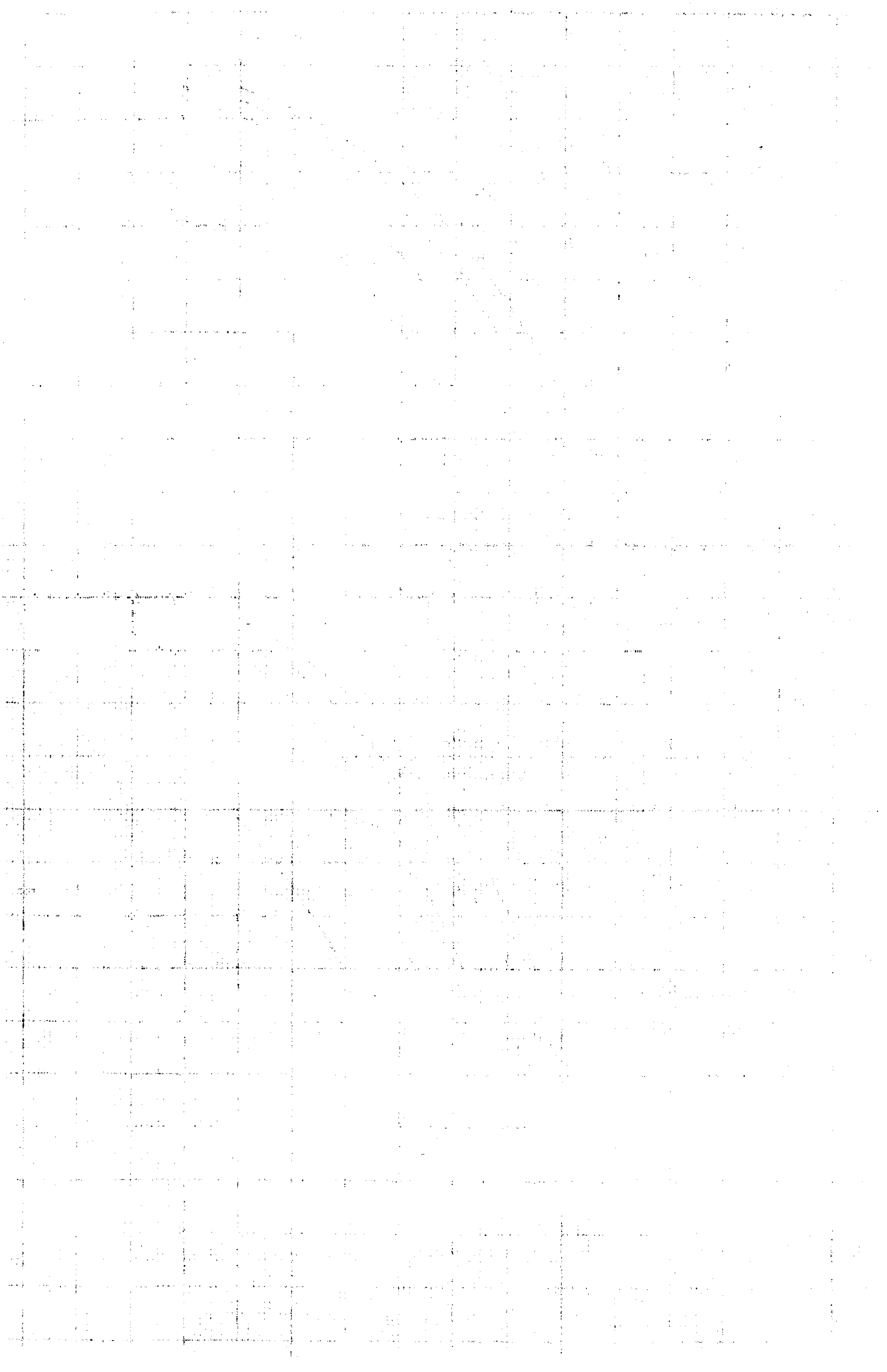
$r_a = 2.5$ ohms

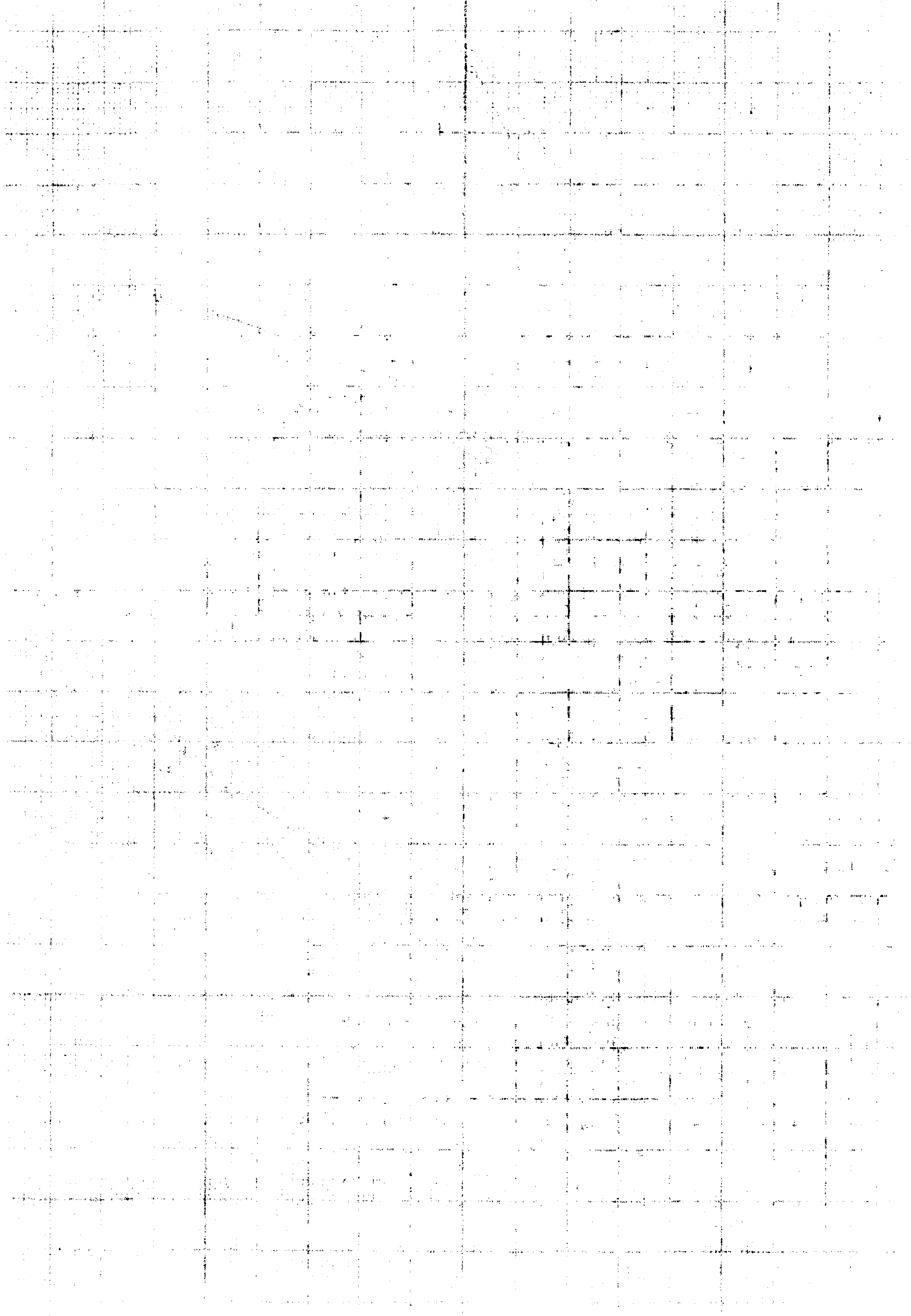
Synchronous Generator Resistance

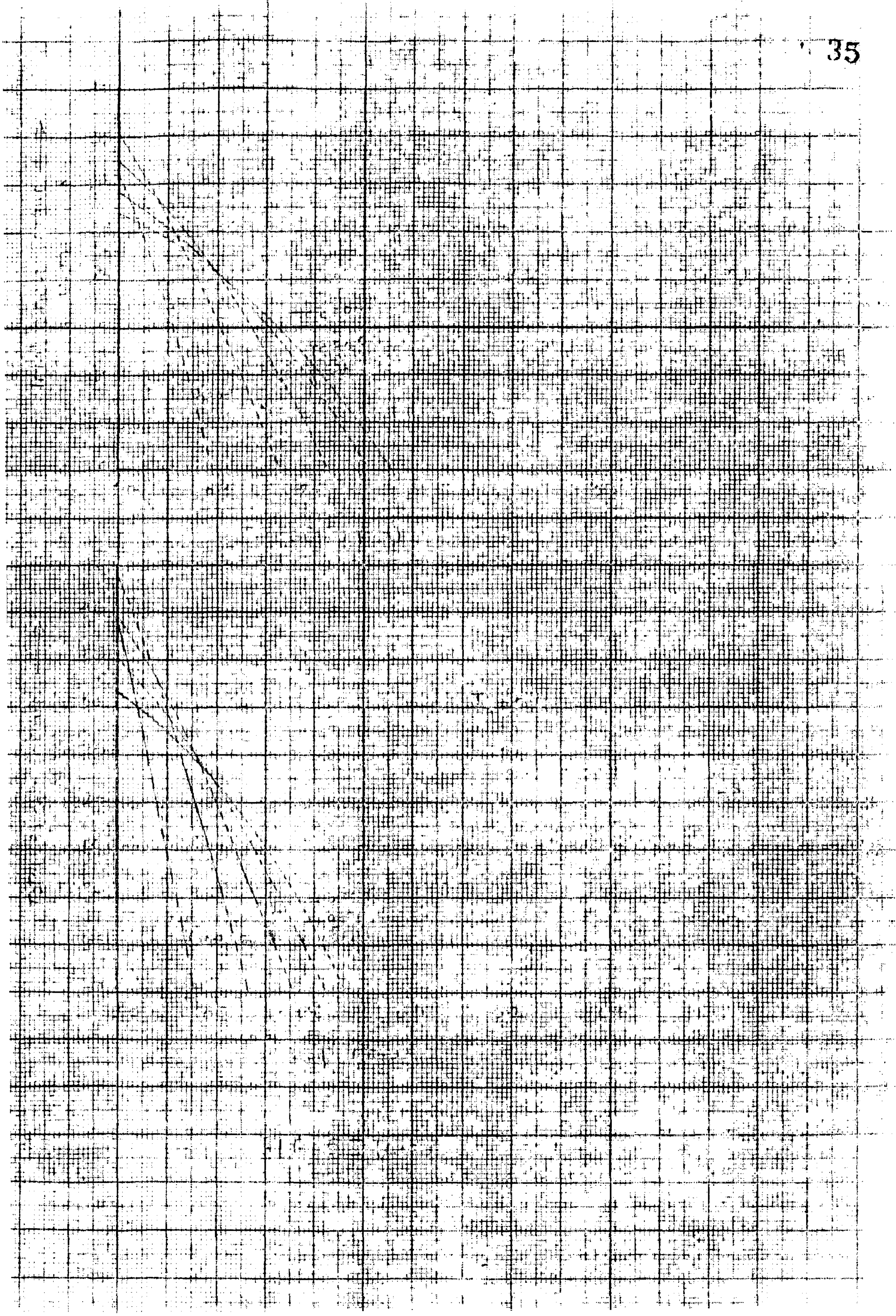
$R_{sg} = 7.5$ ohms

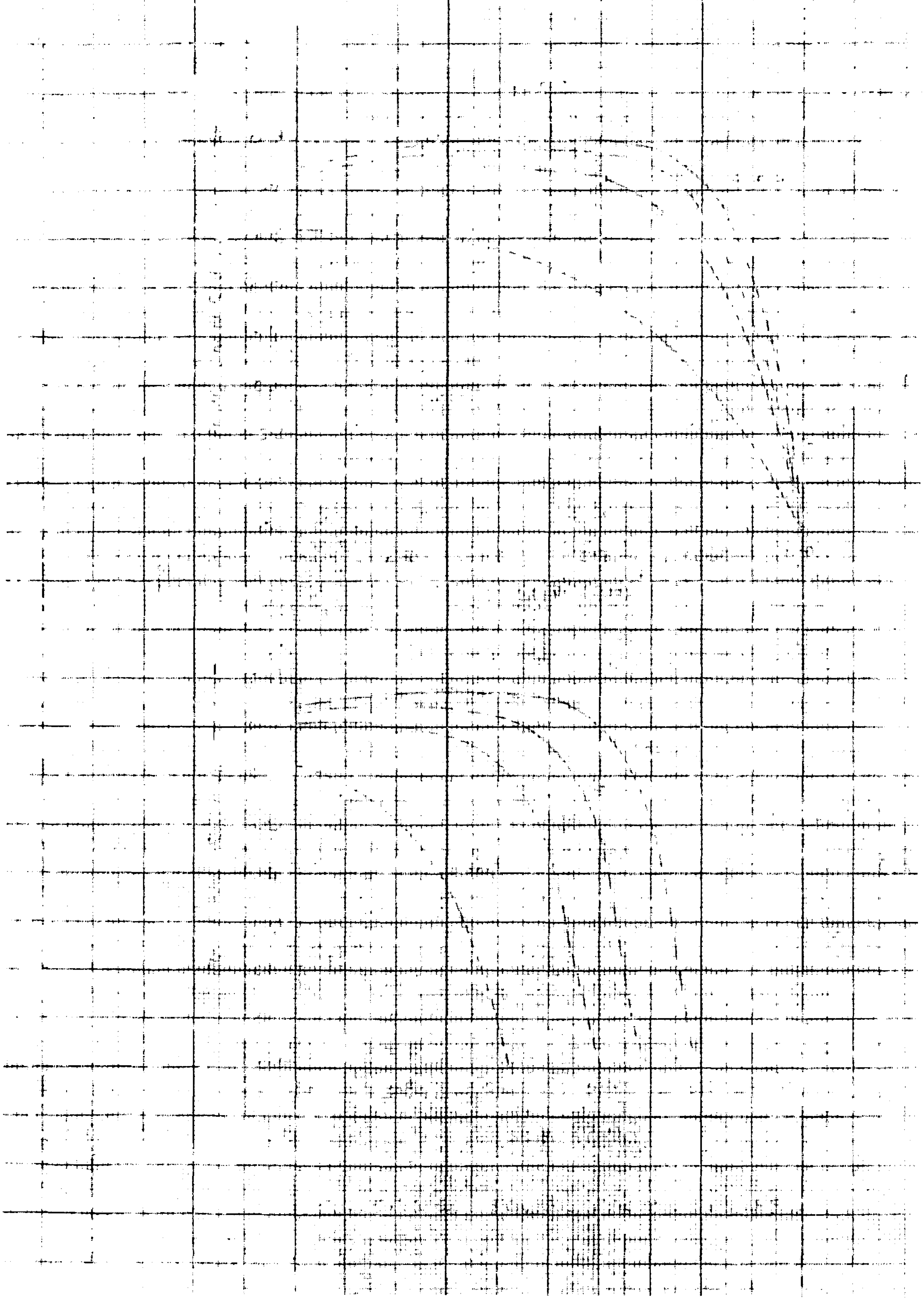
5.1 Theoretical Curves

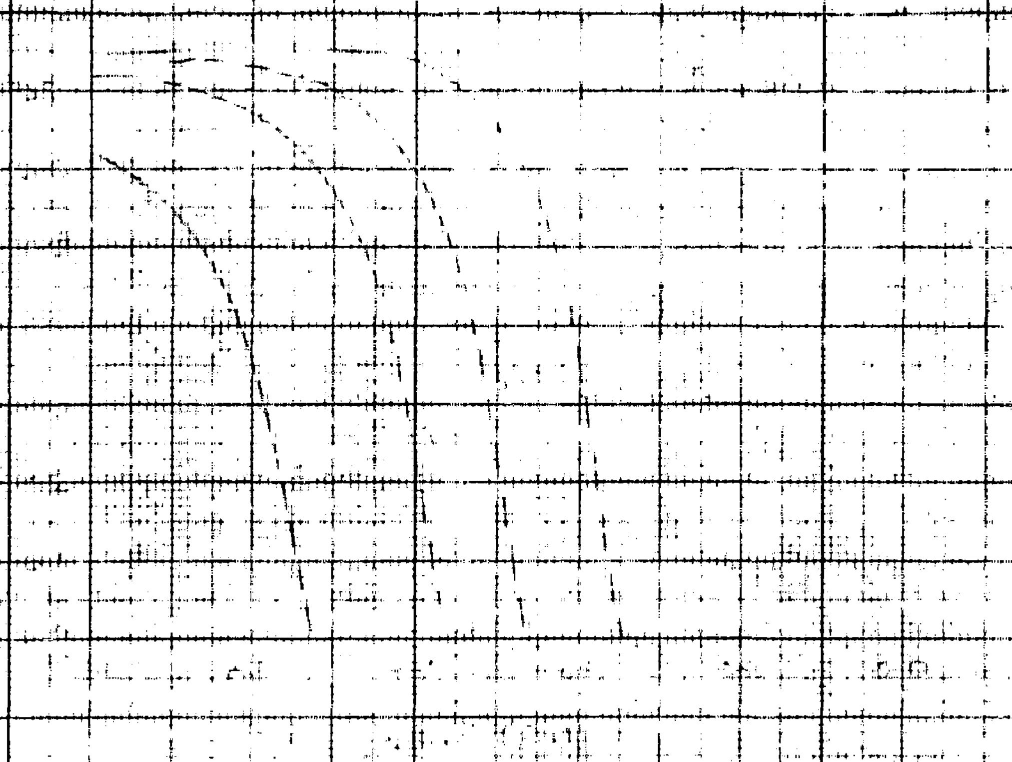
Following ideal curves are obtained in reference (11). No frictional and windage losses have been considered for ideal case. These curves are obtained for different values of field current and duty cycle.

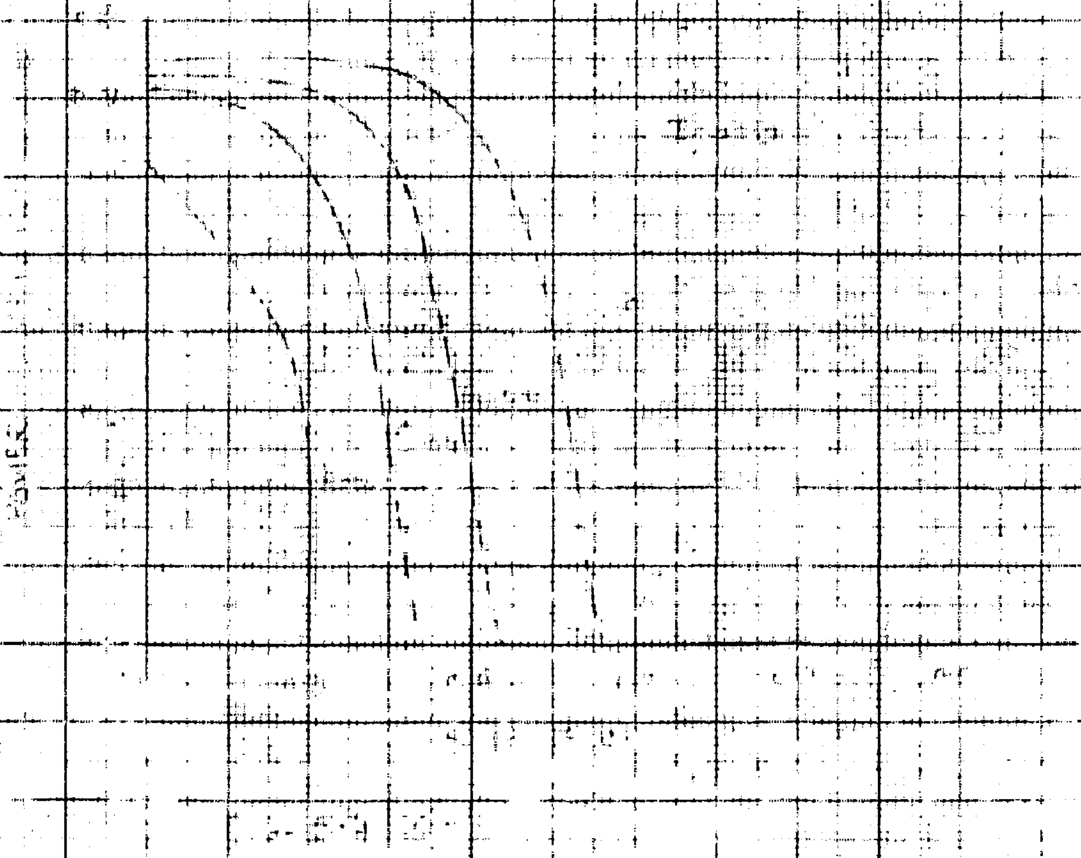


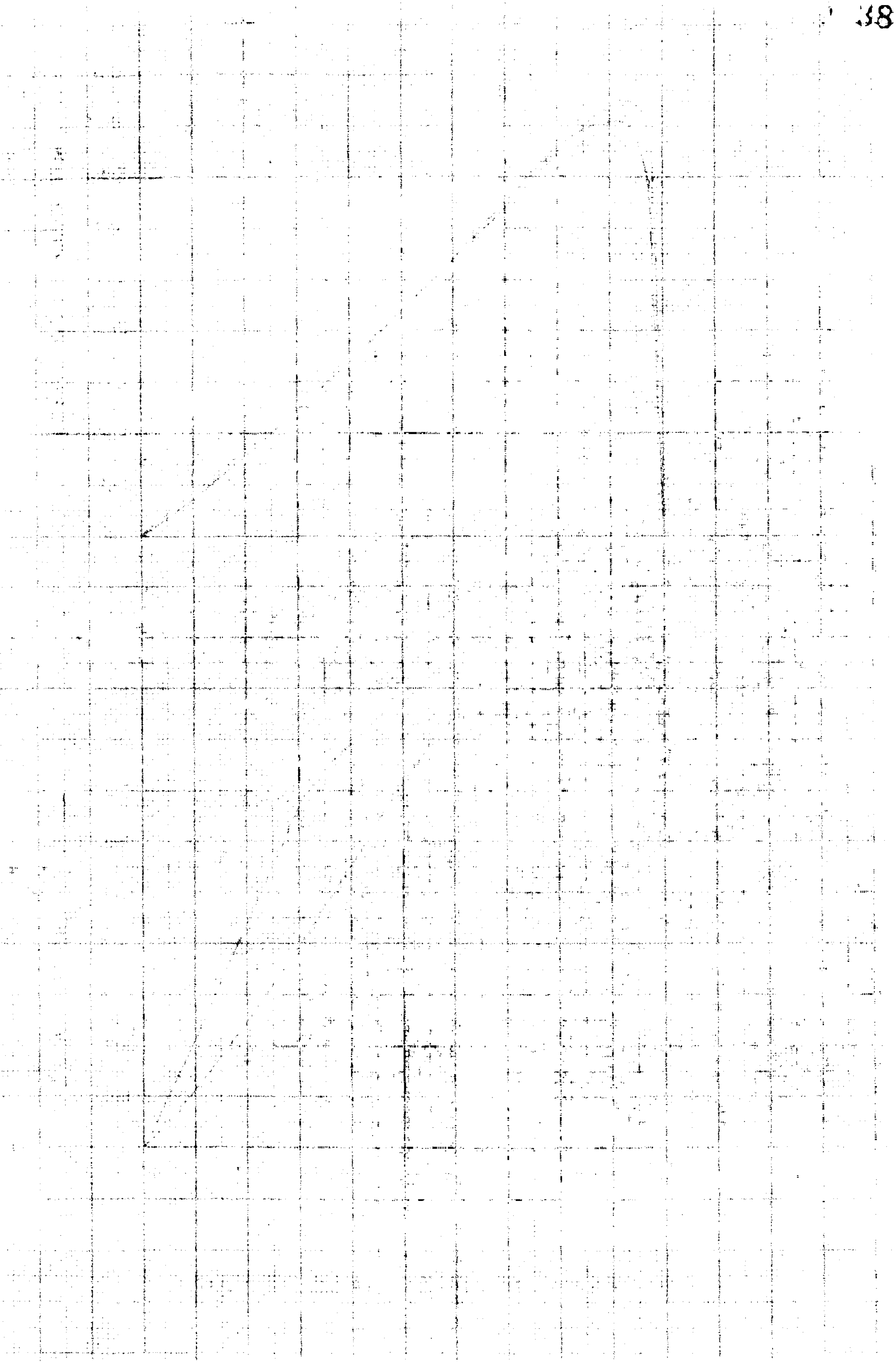


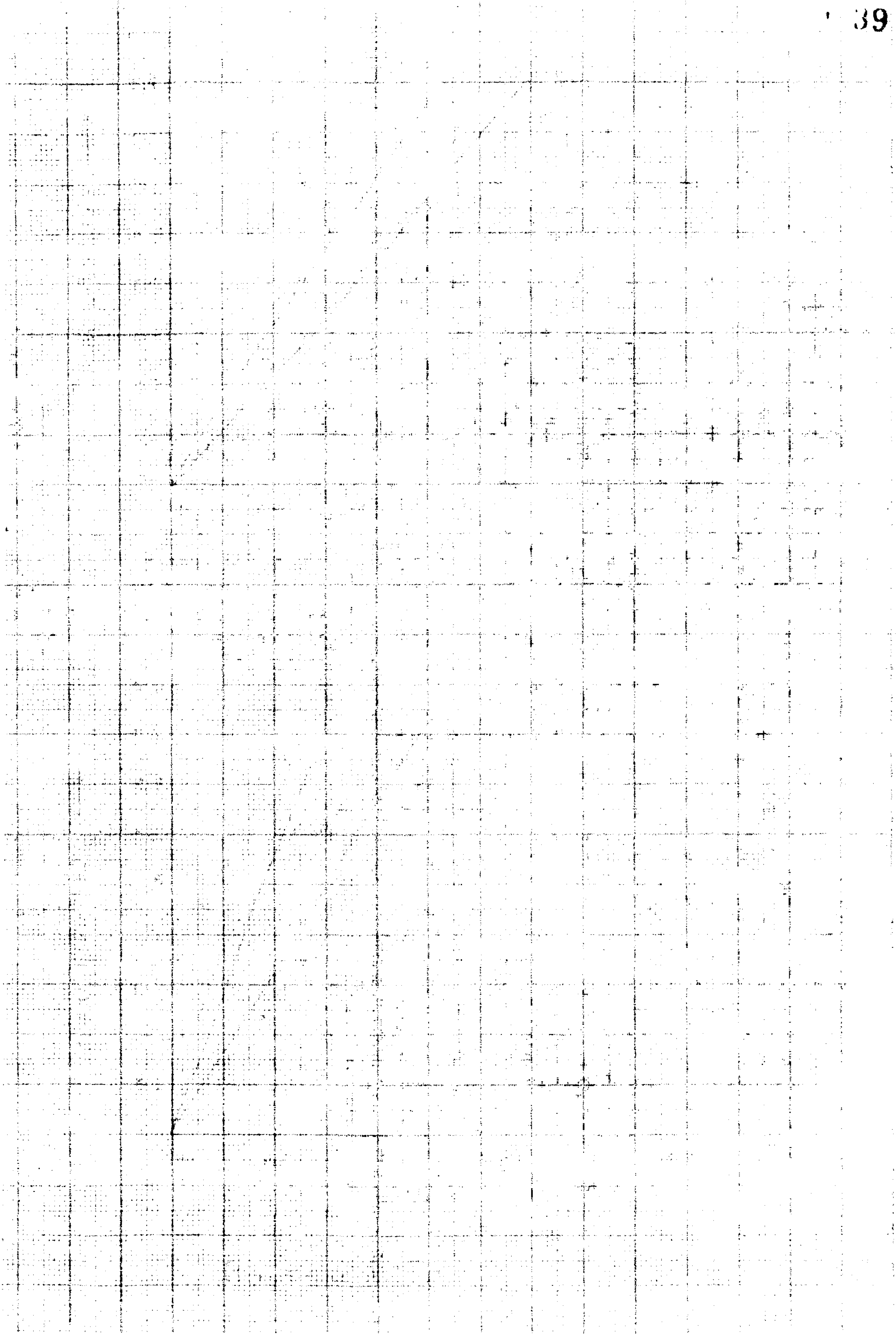


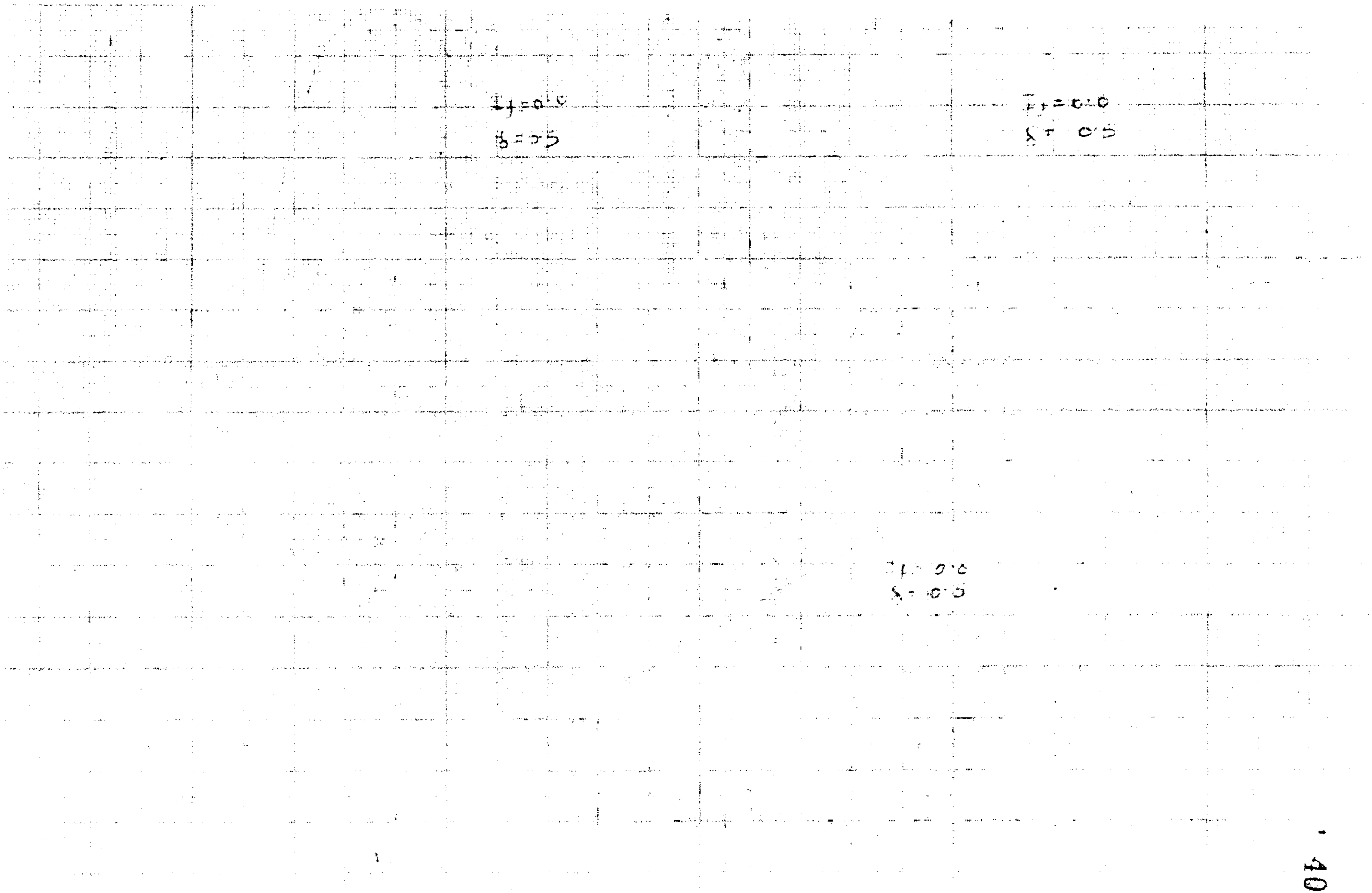


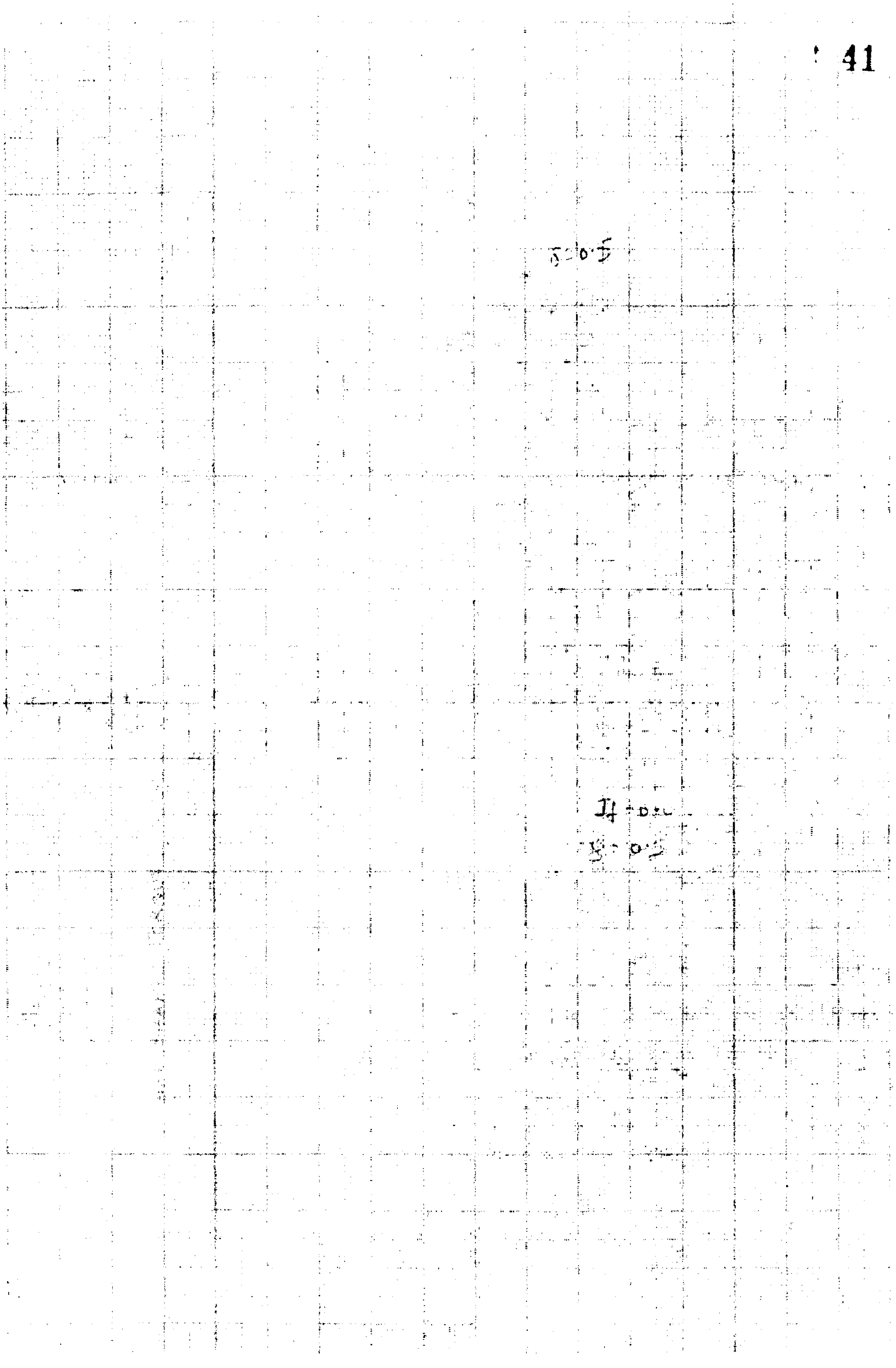


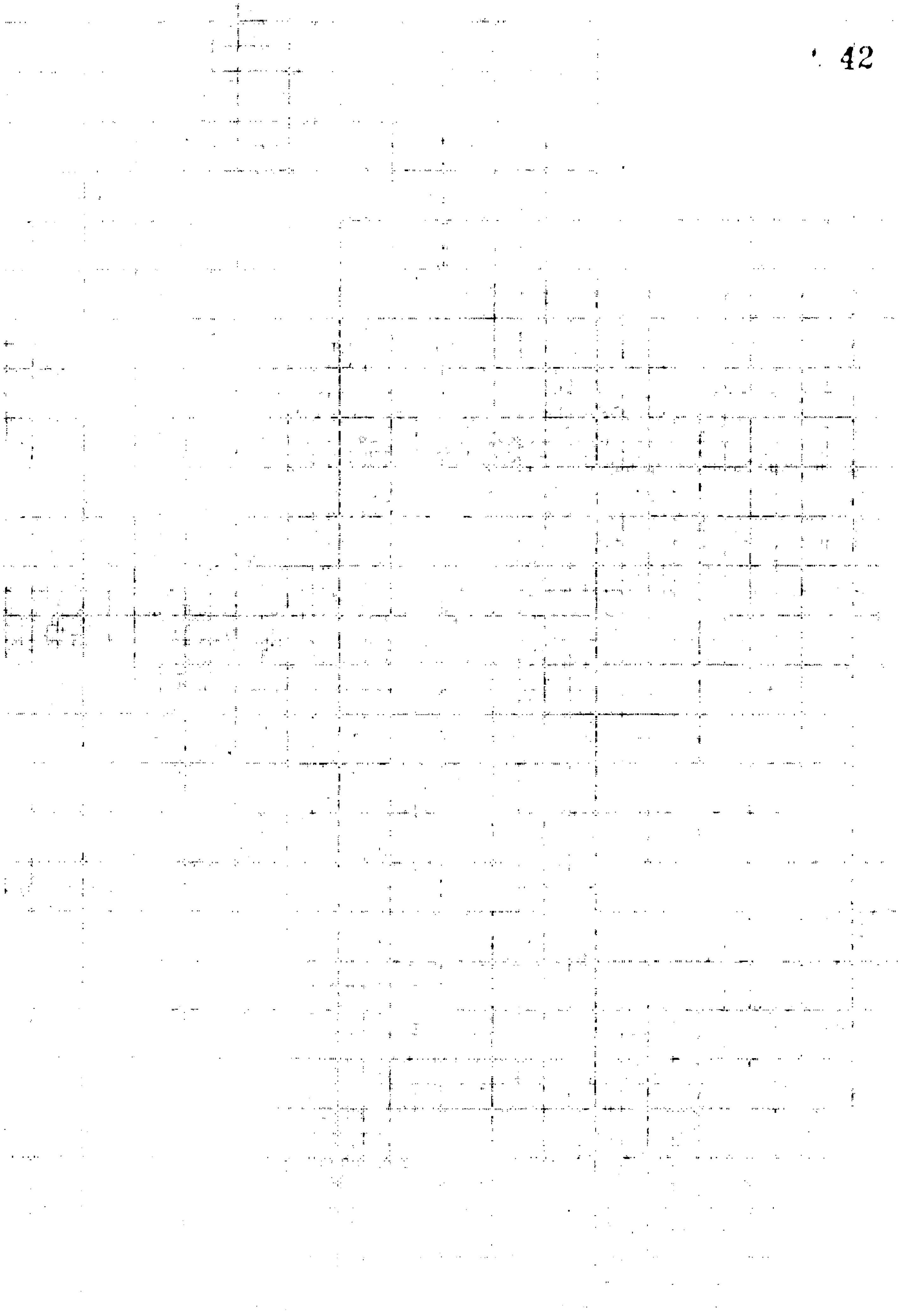

POWER






$T_f = 0.0$
$\delta = 0.5$
$T_f = 0.0$
$\lambda = 0.5$
$T_f = 0.0$
$\lambda = 0.5$


ξ = 0.5
Tf = 0.2
ξ = 0.5



(1) No load speed(Fig. 5.1)
(2) Torque developed by induction motor (Fig. 5.2a-d)
(3) Total torque developed at the Shaft -(Fig. 5.3a-d)
(4) Power factor curve (Fig. 5.4a-d)
(5) Efficiency curve (Fig. 5.5a-d).

5.2 Experimental Results

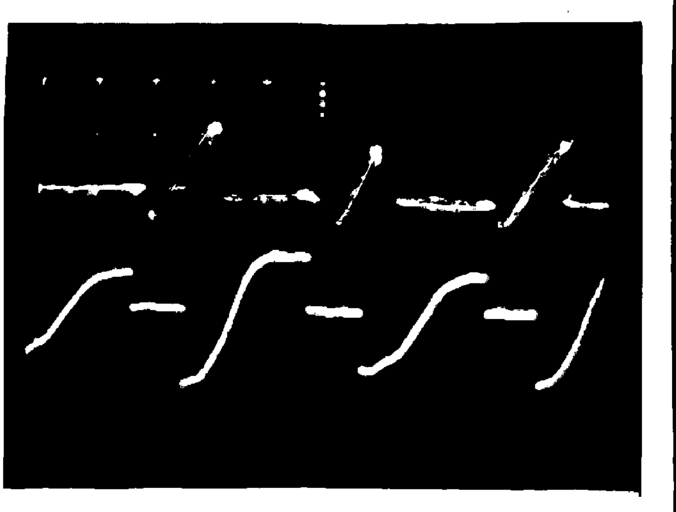
All the experimental data are tabulated in Appendix-A.

In actual practice there are certain friction and windage losses which causes no load torque, hence, to be accounted in calculating the net shaft torque.

Fig. 5.11 shows the NO load torque vs speed characteristic. For verification of theoretical results only one set of curves is shown. Taking d.c. field excitation $I_f = 0$ and duty cycle $\delta = 0.5$, actual theoretical curves are drawn in Fig. (5.6 - 5.10) and the experimental points are marked on the same curves.

5.3 Discussion

The induction motor used in the Kramer Drive system has a high starting torque characteristic. In the conventional Kramer system the speed is controlled by varying d.c.spee field excitation of the motor by which the speeds upto about half the synchronous speed can be obtained. But using chopper in between the rectifier and d.c.motor, armature voltage can be controlled which brings down the speed of the drive to practically zero. The aim was to verify the performance

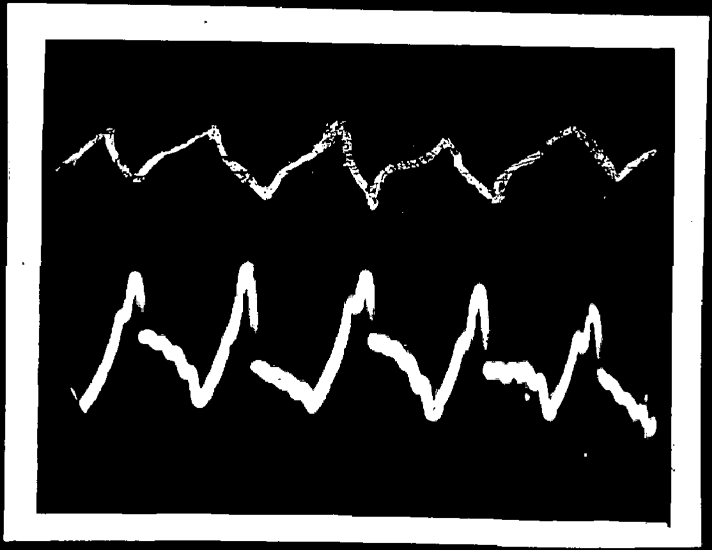


Voltage Waveform across Auxiliary Thyristor.

Voltage Waveform across main Thyristor.

Rotor Current Waveform

Voltage Waveform at Armature of d.c. Motor.



equations derived using chopper with the experimental results. The experimental points marked on the theoretical curves show a close agreement.

CHAPTER - VI

CONCLUSION

The speed of the Kramer Drive can be controlled upto zero by controlling the d.c.armature voltage besides the field control. The armature voltage control is obtained incorporating a chopper unit between the rectifier and d.c. motor. The slip energy property of the Kramer combination makes it inherently a high-efficiency system which naturally compares very favourably with alternatives such as rotor resistance control. As the additional secondary circuit losses tend to become decreasingly significant the modified Kramer system offers a competitive proposition at larger outputs.

The presence in the rotor circuit of the three-phase bridge rectifier produces harmonics in the rotor current and these inevitably affect both the performance of the combination as a motor and the commutation of the d.c.machine.

The close agreement between actual theoretical and experimental curves shows that the derived performance equations are correct and can be used to predetermine the performance characteristic of the chopper Controlled Kramer Drive.

APPENDIX

TABLE 4.1 - NO LOAD SPEED TEST

δ = 0.5, Stator Suppby Voltage 400 V, Star - Star

I_f	0	0.1	0.2	0.3	0.4
N	850	570	440	365	335

TABLE A-2 DATA OF LOAD TEST ON KRAMER DRIVE

Stator Supply Voltage V_1 = 400 V, Star-Star Connection, R_{sg} = 7.50 Ohms

I_f = 0.0 A, I_{fsy} = 2.0 A, δ = 0.5

I_1 Amp.	W Watts	V_d Volts	I_a Amp.	I_L Amp.	V_L Volts	N r.p.m.	P_{osy} Watts	W_{SYN} Watts	T_{sh} Nw-m	Cos ϕ	η
0.9	260	8.0	0.9	0.00	197	840	0	0	0	0.416	0
1.2	538	11.0	1.9	0.55	160	750	157.5	6.8	2.1	0.67	0.305
1.25	564	11.2	2.05	0.70	150	740	181.5	11.0	2.49	0.65	0.342
1.3	606	12.0	2.20	0.85	135	720	199.0	16.2	2.86	0.674	0.354

REFERENCES

1. 'Modified Kramer Combination', Clapham and J.Griffin, Electrical Times, Vol.151, No.9, March 2,1967,pp.335.
2. 'Modified Kramer Combination', Clapham and J.Griffin, Electrical Times, Vol.151,No.10,March 9,1967,pp.386.
3. 'A Static Scherbius Drive with Chopper', Pillai and Desai, Tr. IEEE (IECI),Feb.1977, Vol.IECI-24, pp.24.
4. 'Chopper Controlled Slip Ring Induction Motor', Ramamoorthy, M., Journal of Inst.of Engrs., Vol.56, April 1976, pp.206.
5. 'Considerations concerning a modified Kramer System', Bland and Hancock and Whitehead, Proc. IEE (London), Vol. 110, pp.2228, Dec. 1963.
6. 'The Application of SCR's to the Control of Electrical Machines', K.G.King, IEE Proc. (Lon.), Vol.110, Jan. 1963, pp.197.
7. 'Rotor Chopper Control for Induction Motor Drive', Sen and Ma, Tr. IEEE on Industry Application, Jan./Feb. 1975, pp.43.
8. 'Thyristor Control of A.C. Motors', J.M.D. Murphy, ((Pergamon Press, 1973).
9. 'Electric Machinery', A.E.Fitzgerald and Jr.Charles' Kingsley, (McGraw-Hill Book Company, INC. 1952).
10. SCR Manual (V Edition), General Electric.

11. Paper Communicated to Journal of Institution of Engineers by K.Venkatesan and S.P. Gupta, Electrical Engineering Department, University of Roorkee.

12. 'Slip Power Recovery in an Induction Motor by the use of a Thyristor invertor' Shephard and Stanway, IEEE Tr. on Ind. and General Application IGA-5, 74 (1969).

13. 'Speed Control of Large Induction Motor' by Thyristor Convertor', Paice, D.A., IEEE Tr. on IGA-5, 234 (1969).

14. 'The Performance and Design of A.C. Commutator Motor', E.Openshaw Taylor, (Wheeler 1972).