ON CERTAIN ASPECTS OF ANALYSIS OF A CONSTANT H. P. DRIVE SYSTEM

A DISSERTATION
Submitted in partial fulfilment of
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MASTER OF ENGINEERING
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(Power Apparatus and Electric Drives)

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CERTIFICATE

Certified that the dissertation entitled, 'ON [illegible] D.C. DRIVE [illegible]', which is being submitted by Shri M. [illegible] in partial fulfilment of the requirements for the degree of MASTER OF ENGINEERING in ELECTRICAL ENGINEERING (Power Apparatus and Electric Drives) of the University of Roorkee, Roorkee is a record of student's 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 certified that he has worked for a period of about eight months from January to August 1977 for preparing this dissertation at this University.

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ABSTRACT.

In the present work the steady state performance of a static Kramer drive system has been investigated neglecting the effect of rotor current harmonics. Equivalent circuit for the system has been developed using which the performance equations have been derived. These equations are to be used to predetermine the performance of a static Kramer drive. The calculated performance is compared with that of the experimental ones. Stability performance of the system has also been investigated.

CONTENTS

[illegible]

a	Turn ratio (N_1/N_2) of induction motor windings
E	E.M.F. per phase
E_a	E.M.F. of synchronous generator
E_b	Induced back e.m.f. by d.c. motor
E_j	E.M.F. injected in the rotor circuit
I_1	Stator or primary current of induction motor
I_2	Rotor or secondary current of induction motor
I_2'	Rotor current referred to primary side
I_c	Current in the d.c. motor
I_f	D.C. motor field current
I_L	Load current
I_m	Magnetizing current
I_0	No load current of induction motor
I_w	Iron loss component of current
I_{sg}	Synchronous generator excitation current
K_a	Synchronous generator constant
K_d	D.C. motor constant
N_r	Rotational speed of rotor, r.p.m.
N_s	Synchronous speed, r.p.m.
n	Turns ratio
P_1	Stator input power
P_d	D.C. motor input power
P_g	Air gap power
R	[illegible] resistance in the rotor circuit element
s	Rectifier output
T_{sg}	Synchronous generator input or total shaft load

P_{osg}	Synchronous generator output
R	Equivalent resist. of the rectifier and d.c. motor
R_1	Stator resistance per phase (ohms)
R'_{1o}	Equivalent stator resistance per phase during braking
R_2	Rotor resistance per phase
R'_2	Rotor resistance per phase referred to primary side
R_a	Equivalent rectifier circuit resistance during braking
R_d	D.C. motor armature resistance
R_m	Magnetising branch resistance (parallel circuit)
R_{se}	External starting resistance per phase
R_{sg}	Synchronous generator resistance per phase
R_{ss}	Single starting resistance
R'	Equivalent resistance $= a^2 \frac{K_v}{K_1} R_d$
s	Fractional slip $= \frac{n_s - n_r}{n_s}$
T_1, T_2	Number of primary and secondary turns
T	Torque developed in N-m
t_b	Braking time in sec.
T_b	Total braking torque
T_m	Torque developed per phase by main induction motor
T_M	Total torque developed by main induction motor
T_{DC}	Total torque developed by d.c. motor
T_{sh}	Total torque developed at the shaft
V_o	Open circuit voltage of d.c. motor
V_1	Stator input voltage
V_s	Synchronous generator terminal voltage
V_{sr}	Voltage between rotor slip rings

V_d	Rectifier output or voltage across d.c. motor
X_1	Stator or primary leakage reactance
X_2'	Rotor or secondary leakage reactance (referred)
X_m	Magnetising reactance (parallel circuit)
Z_1	Leakage impedance of primary winding
Z_2	Leakage impedance of secondary winding
Z_m	= Magnetising branch impedance (parallel circuit)
Z'_{2s}	Referred impedance of secondary
α	Firing angle
[illegible]	Ratio of maximum to minimum speed
θ	Phase angle between voltage and current
θ_j	Phase angle between secondary current and E_j (injected voltage)
ω	Angular speed $2\pi f$ radians/sec.
ω_r	Rotor angular speed
ω_s	Synchronous angular speed

CHAPTER - I

INTRODUCTION

The induction motor is essentially a constant speed machine and much thought has been and is being exercised on the problem of overcoming this limitation, so that it can compete with the d.c. machine and thus avoid the expense of a.c./d.c. conversion. Although the majority of industrial drives are of substantially constant speed, there are many applications in which variable speed is a necessity.

1.1 SPEED CONTROL WITHOUT SLIP POWER RECOVERY SYSTEM

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 introduction of external resistances in the rotor circuits for speed control are inherently inefficient, for instance, operating the motor at half the synchronous speed more than half the power crossing the air gap is dissipated in the rotor winding and external resistances. The speed regulation with change of load is also poor at reduced speeds. The drive is suitable for crane and hoist applications where sustained speed control is not required.

If the rotating field in induction motor , given power

'P_G' to the rotor then the quantity (1-s) P_G is converted into mechanical power at the shaft and the balance, sP_G is in the form of electrical power in the rotor. When the rotor is closed on itself or closed through external resistance this power is dissipated as heat. An interesting means of speed control of wound rotor induction motor is based on the economic use of slip power, and uses a slip ring power converter for this purpose. All slip power recovery schemes enable the motor to operate at continuously variable speeds efficiently and economically. They can be divided into two main groups

(a) Electrical Recovery
(b) Mechanical Recovery

1.1.1 Electrical Recovery Scheme

In Electrical Recovery the slip power converter converts rotor electrical power at slip frequency into an electrical power at the line frequency. Such a scheme maintains the mechanical torque approximately constant. For sub-synchronous 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 of the slip frequency of the rotor, and is fed to the rotor winding.

1.1.2 Mechanical Recovery Scheme

Mechanical Recovery on the other hand [illegible] constant mechanical power, where, for sub-synchronous operation the rotor slip power is converted into mechanical power by an auxiliary machine, which is then added to the 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. Obviously, for proper function, the frequency of the e.m.f. injected by the slip power converter must always be the same as the frequency of the induced e.m.f. in the rotor winding, and must automatically adjust itself with the change of rotor speed. Thus in Electrical Recovery (also called constant torque drive) the slip power is either returned to or taken from the supply whereas in Mechanical Recovery (also called constant h.p. drive) the slip power is either added to or taken from the main motor shaft for sub-synchronous and super-synchronous operations respectively.

2.2 [illegible]

The conventional Kramer System (const.h.p.) which consists of three machines namely, main induction motor, rotary converter and d.c. motor is shown in Fig. 2.2. The slip frequency a.c. being converted to d.c. by rotary converter is fed to the d.c. motor mechanically coupled with the main induction motor. Speed control is effected by variation of d.c. field excitation.

In the electrical counterpart or electrical recovery

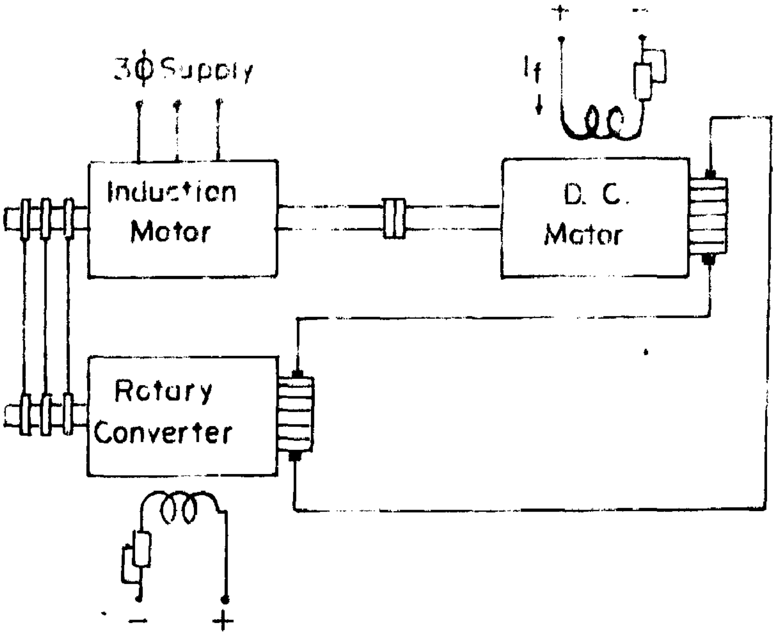
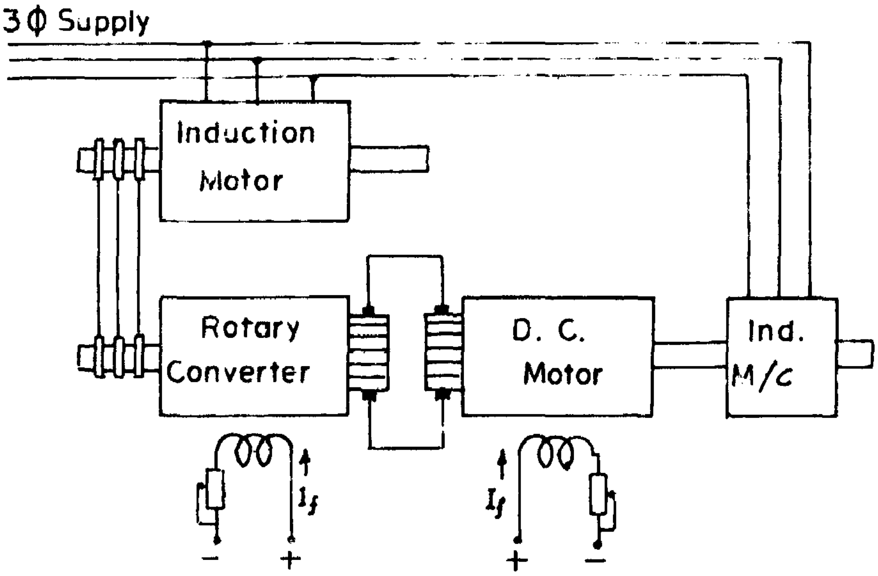


FIG.1.1 MECH. SLIP POWER RECOVERY SCHEME.



1.2
FIG. ELECT. SLIP POWER RECOVERY SCHEME.

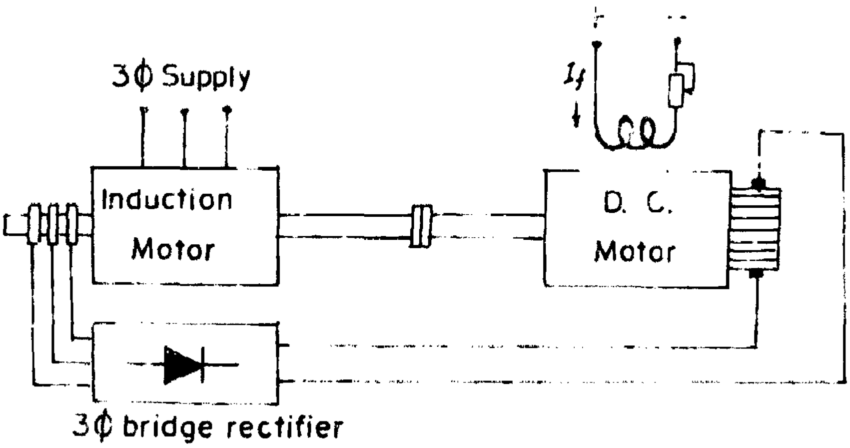


FIG.1.3 CONSTANT H.P STATIC KRAMER DRIVE SCHEME.

scheme shown in Fig. 1.2 the d.c. output from the rotary converter is fed to the d.c. motor mechanically coupled with an induction generator which returns power back to the supply system. If the rotary converter in this scheme is replaced by a synchronous motor and generator set the Ilgner [4] system is formed which has been used for several large wind tunnel drives.

In the slip power recovery schemes mentioned above if rotary converter is substituted by silicon power rectifiers the modified versions are obtained. The static Kramer constant h.p. drive system shown in Fig. 1.3 still requires a d.c. motor to convert the rectified slip power to mechanical power. In the original Kramer system the speed of the main motor must be less than about 90 per cent or greater than 110 per cent 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 synchronism is thus not practicable.

Nowadays, the problems of commutation and stability associated with the use of rotary converter in a cascade scheme are eliminated by the use of semi-conductor rectifiers [8] which offer high efficiency, greater reliability, low maintenance, smaller size and reduced cost.

The following are the disadvantages of the cascade scheme using semi-conductor rectifiers.

(a) Extra cost and considerations for rectifiers protection.

(b) Greater losses, hunting tendency and poor power factor due to harmonics.

(c) Only sub-synchronous range of speed is possible as power flow takes place from main motor to D.C. motor.

1.2 CONTRIBUTION BY AUTHOR

Although the operation of a static Kramer (rectifier) drive system has been studied by various authors [3,4,5,6,7,8,9] none of them have given performance equations for predetermining the performance of such a system. In this work the steady state performance of a static Kramer drive has been investigated neglecting the effect of rotor current harmonics. Equivalent circuit for the system has been developed using which the performance equations have been derived. These equations can be used to predetermine the performance of a static Kramer drive. The calculated performance is compared with that of the experimental one. Braking performance of the system has also been investigated.

CHAPTER - II

EQUIVALENT CIRCUIT [illegible]

In this chapter the equivalent circuit for the static [illegible] system has been developed. The expressions for torque, primary current etc. are obtained using the equivalent circuit.

2.2 [illegible] NO LOAD [illegible]

In the static Kramer System shown in Fig. 1.3 the rectified output of the bridge rectifier is given by

$$V_d = 1.35\, s\, V_{2L} \qquad \ldots (2.1a)$$

or

$$V_d = 2.34\, s\, E_2 \qquad \ldots (2.1b)$$

where

$$s = \frac{\omega_s - \omega_r}{\omega_s} \qquad \ldots (2.2)$$

The e.m.f. induced in the d.c. motor is given by

$$E_b = K_d\, I_f\, \omega_r \qquad \ldots (2.3a)$$

$$= K_d\, I_f\, (1-s)\, \omega_s \qquad \ldots (2.3b)$$

where

$$\omega_s = 2\pi n_s. \qquad \ldots (2.4)$$

On finding an ideal no load case in which the secondary circuit current will be zero, one has to obtain no load

on equating eqns.(2.1a) and (2.3b), the value of slip
N
as

[No I_o V_d]

$$S = \frac{1}{1 + \frac{1.35\,V_{L}}{K_1 I_f \omega_0}} \qquad \ldots \quad (2.5a)$$

If phase value is used the slip is given by

$$S = \frac{1}{1 + \frac{2.34\,E_2}{K_1 I_f \omega_0}} \qquad \ldots \quad (2.5b)$$

If the rectifiers used in this scheme are substituted by silicon controlled rectifiers (SCR) the slip thus obtained is given by [10]

$$S = \frac{1}{1 + \frac{2.34\,E_2 \cos\alpha}{K_1 I_f \omega_0}} \qquad \ldots \quad (2.6)$$

where α is the firing angle.

From eqn. (2.6) it is clear that the slip and hence the speed may be varied by varying (a) the firing angle 'α' and (b) the d.c. motor field current, I_f. By adjustment of both I_f and 'α' a wide range of speed control is possible.

2.2 DEVELOPMENT OF EQUIVALENT CIRCUIT

In Fig. 2.1 the electrical circuit representation of the scheme (Fig. 1.9) is given. Accurately enough, we may represent the rectifier and d.c. machine by a sinusoidal

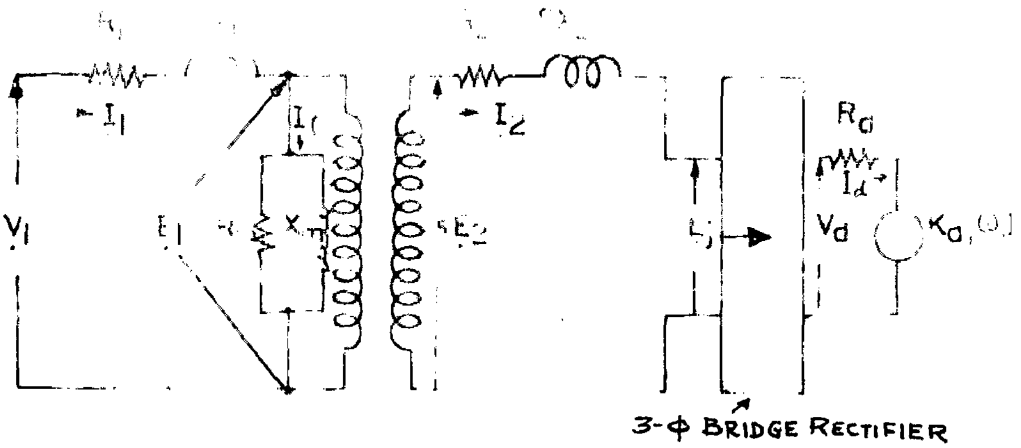


FIG.2.1 ELECT. CIRCUIT REPRESENTATION OF KRAMER DRIVE SYSTEM.

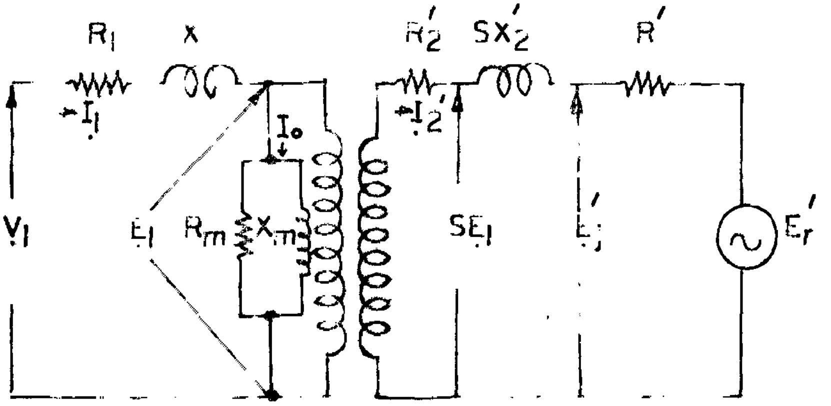


FIG.2.2 EQUIVALENT CIRCUIT OF CONSTANT H.P. KRAMER DRIVE SYSTEM.

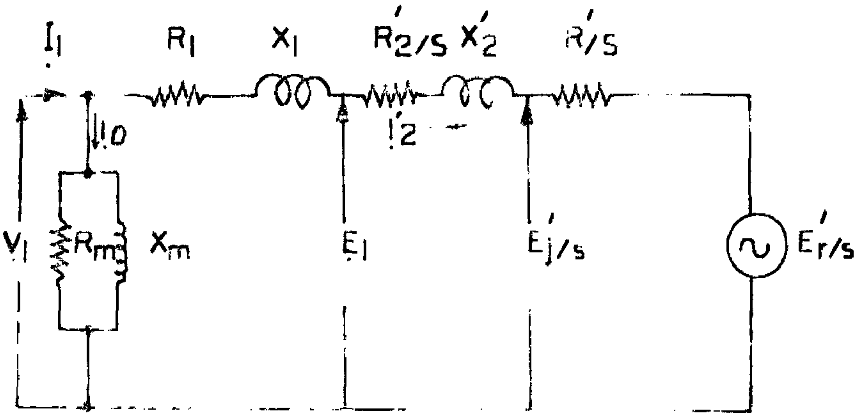


FIG.2.3 APPROXIMATE EQUIVALENT CIRCUIT OF CONSTANT H.P. KRAMER DRIVE SYSTEM.

[illegible] E_r in series with a resistance R. Thus we have,

$$\dot{E}_g = \dot{E}_r + \dot{I}_a R \qquad \ldots \quad (2.17)$$

Moreover, the phase angle of I_a can practically be assumed to be in phase with the voltage $\dot{E}_g$ [11]

Thus we may write

$$|\dot{E}_g| = |\dot{E}_r| + |\dot{I}_a| R \qquad \ldots \quad (2.18)$$

Now

$$\frac{|\dot{E}_g|}{V_d} = K_v \qquad \ldots \quad (2.19)$$

and

$$\frac{I_a}{I_d} = K_i \qquad \ldots \quad (2.20)$$

where K_v and K_i are constants for a given rectifier configuration.

From eqn. (2.19)

$$|\dot{E}_g| = K_v V_d \qquad \ldots \quad (2.21)$$

The voltage applied to the d.c. motor is given as

$$V_d = K_d \omega_r I_f + I_d R_d \qquad \ldots \quad (2.22)$$

From eqns. (2.21) and (2.22)

$$\dot{E}_g = K_v (K_d \omega_r I_f + I_d R_d) \ldots \quad (2.23)$$

Multiplying both sides of eqn. (2.18) by I_a/[illegible] and substituting the value of I_d from eqn. (2.20), we have

$$V_j = K_a \left(K_v \omega_r I_2 \frac{s_1}{s_2} \right) + \frac{K_v}{K_1} \left(I_2 \frac{s_2}{s_1} \right) K_a \left(\frac{s_1}{s_2} \right)^2$$

$$= K_a \left(K_v \omega_r I_2 \frac{s_1}{s_2} \right) + K_a \frac{K_v}{K_1} \left(\frac{s_1}{s_2} \right)^2 \left(I_2 \frac{s_2}{s_1} \right)$$

$$= K_a K_v \omega_o (1-s) I_2 \frac{s_1}{s_2} + K \left(\frac{s_1}{s_2} \right)^2 \left(I_2 \frac{s_2}{s_1} \right)$$

Thus

$$= E_r \left(\frac{s_1}{s_2} \right) + K \left(\frac{s_1}{s_2} \right)^2 \left(I_2 \frac{s_2}{s_1} \right)$$

$$\dot{V}_j' = \dot{E}_r' + K' \dot{I}_2' \qquad \ldots (2.34)$$

where

$$E_r' = a K_a K_v \omega_o (1-s) I_a \qquad .. (a)$$

and

$$K' = a^2 \frac{K_v}{K_1} K_a \qquad .. (b) \qquad \ldots (2.35)$$

Considering the equivalent circuit [11] of induction motor with injected voltage V_j shown in Fig. 2.2, the secondary quantities in the diagram have been referred to the primary in the usual way so that by inspection the following equations can be written down

$$\dot{V}_1 = \dot{I}_1 \dot{Z}_1 + \dot{E}_1 \qquad .. (a)$$

$$Y_o \dot{E}_1 = \dot{I}_o \qquad .. (b)$$

$$\dot{I}_1 = \dot{I}_o + \dot{I}_2' \qquad .. (c) \qquad \ldots (2.36)$$

$$\dot{Z}_2' \dot{I}_2' = s \dot{E}_1 - \dot{V}_j' \qquad .. (d)$$

where

$$\left.\begin{aligned} Z_1 &= R_1 + j\,X_1 & \ldots (a) \\ Z'_{2s} &= R'_2 + j\,s\,X'_2 & \ldots (b) \\ Z_m &= R_m + j\,X_m & \ldots (c) \end{aligned}\right\} \quad \ldots (2.17)$$

From eqns. (2.16a), (2.16b) and (2.16c)

$$V_1 = I_1\left(\frac{Z_1}{Z_m} + 1\right) + Z'_2\,Z_1$$

$$= I_1\,c + Z'_2\,Z_1 \qquad \ldots (2.18)$$

Now Z_1 is small compared with Z_m, but both are inductive and hence impedance angle of the same order. It is convenient to write

$$c = \left(1 + \frac{Z_1}{Z_m}\right) = c\ \gamma \qquad \ldots (2.19)$$

A complex number slightly greater than unity (i.e. 1.1 with a small angle 'γ' usually negligible)

From eqn. (2.18) $$I_1 = \frac{1}{c}\left(V_1 - Z'_2\,I_2\right) \qquad \ldots (2.20)$$

and from eqns. (2.16d), (2.18) and (2.20)

$$I'_2 = \frac{(c\,V_1 - c\,E'_1)}{(c\,Z'_{2s} + c\,Z_1)} \qquad \ldots (2.21)$$

so that from eqn. (2.21c)

$$\dot{I}_1 = \frac{1}{\dot{c}}\left[\frac{\dot{V}_1}{\dot{Z}_m} + \frac{c\,\dot{V}_1 - c\,\dot{E}_3'}{\dot{c}\,\dot{Z}_{20} + c\,\dot{Z}_1}\right] \qquad \ldots (2.22a)$$

As $\frac{\dot{Z}_1}{\dot{Z}_m}$ is normally very small in induction motor with respect to unity, to a first approximation c may be regarded as unity; the primary current thus becomes

$$\dot{I}_1 = \frac{\dot{V}_1}{\dot{Z}_m} + \frac{c\,\dot{V}_1 - \dot{E}_3'}{\dot{Z}_{20} + c\,\dot{Z}_1} \qquad \ldots (2.22b)$$

If $\dot{E}_3 = 0$ this reduces to the expression resulting from the equivalent circuit for an induction motor with the magnetising branch moved to the supply terminals.

The approximate equivalent circuit for the scheme undertaken is now given in Fig. 2.9.

2.9 [illegible] DEVELOPED

The electrical power supplied to the rotor circuit from the primary is $c\,E_1\,I_2'\cos\theta_2$ and this is balanced by electrical power absorbed in rotor cu-loss and in the external element [19]

$$P_3 = E_3'\,I_2'\cos\theta_3 \qquad \ldots (2.23)$$

Hence

$$c\,E_2\,I_2'\cos\theta_2 = I_2'^2\,R_2' + P_3 \qquad \ldots (2.24)$$

Mechanical power developed is

$$(1-s)\, E_1 I_2' \cos\theta_2$$

Therefore, the torque developed by the induction motor is

$$T_d = \frac{(1-s)\, E_1 I_2' \cos\theta_2}{\omega_r} = \frac{E_1 I_2' \cos\theta_2}{\omega_s} \quad \ldots (2.29a)$$

From eqns. (2.23), (2.24) and (2.29a)

$$T_d = \frac{I_2'^2 R_2'}{s\,\omega_s} + \frac{1}{s\,\omega_s} E_3' I_2' \cos\theta_3 \quad \ldots (2.29b)$$

As E_3' and I_2' are in the same phase, $\cos\theta_3$ will be unity. On substituting the value of E_3' from eqn. (2.14) the eqn. (2.29b) yields

$$T_d = \frac{I_2'^2 R_2'}{s\,\omega_s} + \frac{1}{s\,\omega_s} R' I_2'^2 + \frac{R_3' I_2'}{s\,\omega_s} \quad \ldots (2.29c)$$

Hence the total torque developed by the induction motor is given

$$T_d = 3\left[\frac{I_2'^2 R_2'}{s\,\omega_s} + \frac{1}{s\,\omega_s} R' I_2'^2 + \frac{R_3' I_2'}{s\,\omega_s}\right] \text{N-m.} \quad \ldots (2.30)$$

Alternatively, this can also be obtained as follows:

The air gap power, P_g is given by

$$P_g = I_2'^2 \frac{R_2'}{s} + I_2'^2 \frac{R'}{s} + \frac{E_r' I_2'}{s} \qquad \ldots (2.27)$$

where losses or powers absorbed in the system are

$$P_{cu} = I_2'^2 R_2' + I_2'^2 R' + I_2' E_r' \qquad \ldots (2.28)$$

Hence the mechanical power developed is

$$P_g - P_{cu} = I_2'^2 \frac{R_2'}{s} (1-s) + I_2'^2 \frac{R'}{s} (1-s) + \frac{E_r'}{s} I_2' (1-s) \qquad \ldots (2.29)$$

The eqn. (2.29) when divided by the angular speed of the rotor, yields the torque developed per phase the same value as that given by eqn. (2.25c)

Hence the expression for total torque developed by the induction motor is the same as eqn. (2.26)

Now the total power developed by the d.c. motor is given by

$$P_{dc} = 3 E_r' I_2' \qquad \ldots (2.30)$$

Therefore, the torque developed by d.c. motor is

$$T_{dc} = \frac{P_{dc}}{\omega_r} = \frac{3 E_r' I_2'}{\omega_r} = \frac{3 E_r' I_2'}{\omega_s (1-s)} \qquad \ldots (2.31)$$

The total electro-magnetic torque developed by the cascade will be the sum of induction motor and d.c. motor torques developed.

Hence

$$T_{sh} = T_s + T_{sg} \qquad \ldots (2.32)$$

On substituting the values of T_s and T_{sg} from eqns. (2.26) and (2.31) respectively the eqn. (2.32) yields

$$T_{sh} = 3\left[\frac{I_2'^2 R_2'}{s\,\omega_s} + \frac{I_2'^2 R'}{s\,\omega_s} + \frac{E_r' I_2'}{s\,\omega_s}\right] + 3\left[\frac{E_r' I_2'}{\omega_s(1-s)}\right] \text{N-m}$$

$$\ldots (2.33a)$$

After substituting the values of E_r' and R' from eqns. (2.15a) and (2.15b) respectively the total shaft torque becomes

$$T_{sh} = 3\left[\frac{I_2'^2 R_2'}{s\,\omega_s} + \frac{I_2'^2 a^2 K_v R_d}{s\,\omega_s K_1} + \frac{a K_d K_v (1-s) I_2 I_2'}{s}\right] + 3\left[a K_d K_v I_2 I_2'\right]$$

$$\ldots (2.33b)$$

2.4 [illegible] FOR STEADY STATE

For sub-synchronous speed alone which is true in this drive system, the voltage E_d must be in phase with the rotor current, I_2' [19]

In the circuit shown in Fig. 2.3 for the steady state analysis

Let $\frac{E_2'}{s} = \frac{E_2}{s}\angle 0^\circ$ as reference

Then $I_2' = I_2' \angle 0^\circ$

Hence the applied voltage to the stator, V_1 is given as

$$V_1 = \left[R_1 + \frac{R'_2}{s} + \frac{R'}{s}\right] I'_2 \angle 0^\circ + \frac{E'_r \angle 0^\circ}{s} + j\,(X_1 + X'_2)\, I'_2 \angle 0^\circ \quad \ldots (2.34)$$

The absolute value of the stator voltage from eqn. (2.34) is given as

$$|V_1| = \left\{\left[\left(R_1 + \frac{R'_2}{s} + \frac{R'}{s}\right) I'_2 + \frac{E'_r}{s}\right]^2 + \left[(X_1 + X'_2)\, I'_2\right]^2\right\}^{1/2}$$

$$= \left\{(A\, I'_2 + B)^2 + (C\, I'_2)^2\right\}^{1/2}$$

Hence

$$V_1^2 = (A\, I'_2 + B)^2 + (C\, I'_2)^2 \quad \ldots (2.35)$$

where

$$A = R_1 + \frac{R'_2}{s} + \frac{R'}{s} \quad \ldots (a)$$

$$B = \frac{E'_r}{s} \quad \ldots (b) \qquad \ldots (2.36)$$

$$C = X_1 + X'_2 \quad \ldots (c)$$

Rearranging eqn. (2.35), gives the quadratic form as

$$I'^2_2 (A^2 + C^2) + 2\,AB\, I'_2 + B^2 - V_1^2 = 0 \quad \ldots (2.37)$$

Solving eqn. (2.37) for the rotor current

$$I_2' = \frac{-AB \pm \sqrt{A^2 B^2 - (A^2 + C^2)(B^2 - V_1^2)}}{A^2 + C^2} \qquad \ldots (2.38)$$

Substituting from eqns. (2.36) and (2.38) into eqn.(2.34) we obtain the stator input voltage in vector form, from which the magnetising branch current is obtained as

$$I_0 = \frac{\underset{\cdot}{V}_1}{R_m \| j X_m} \qquad \ldots (2.39)$$

Adding eqns. (2.38) and (2.39), the primary current is obtained as

$$\underset{\cdot}{I}_1 = \frac{\underset{\cdot}{V}_1}{R_m \| j X_m} + \frac{-AB \pm \sqrt{A^2 B^2 - (A^2 + C^2)(B^2 - V_1^2)}}{A^2 + C^2}$$

$$\ldots (2.40)$$

2.9 DETERMINATION OF INPUT POWER FACTOR

The cosine of the angle between the stator input voltage, $\underset{\cdot}{V}_1$ from eqn. (2.34) and stator input current, $\underset{\cdot}{I}_1$ from eqn. (2.40) gives the input power factor.

CHAPTER - III

[illegible]

This chapter deals with the experimental set up of the ct h.p. Kramer drive system. The design considerations of the controller are also given.

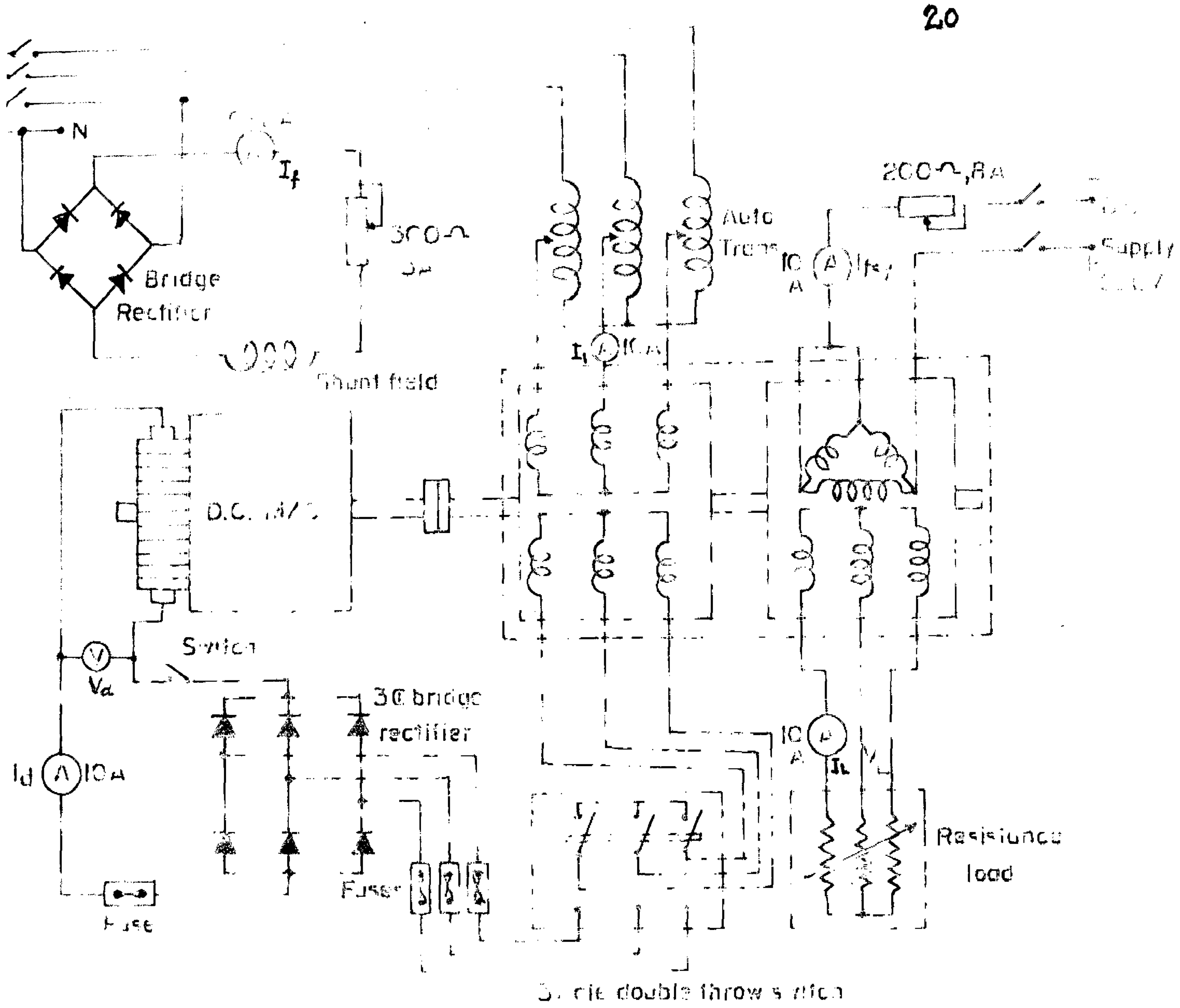
3.1 EXPERIMENTAL SETUP

Fig. 3.1 shows the complete experimental set up of the constant h.p. Kramer drive system. In this scheme 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 feed the main motor. The rectified output of the bridge circuit is given to the armature of the d.c. motor coupled to the main motor shaft. The operation takes place as follows:

(i) The rotor terminals of the main motor are first short circuited with triple pole double throw switch (T.P.D.T) and, with auto-transformer the main motor is started.

(ii) The voltage rise of the d.c. motor for a given shunt field current is observed.

(iii) At suitable running speed the change over switch is operated to introduce the excited d.c. motor into the rotor circuit. To ensure that the d.c. motor power is added to the shaft of main motor



IG.3.1 EXPERIMENTAL SET UP FOR CONSTANT H.P. DRIVE SYSTEM.

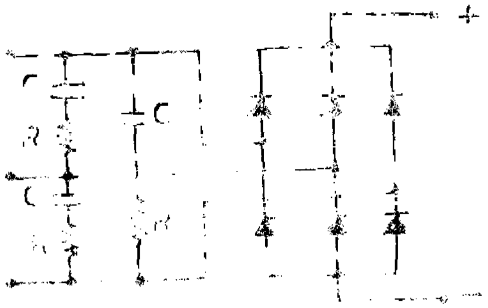


FIG.3.2 SNUBBER CIRCUIT.

it is essential that the rectified output and d.c. machine voltages must oppose each other.

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

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

3.2 DESIGN CONSIDERATIONS

The 3-phase bridge rectifier has a voltage rating which is determined by the maximum working slip of the motor, since rotor e.m.f. and slip are proportional. The current rating of the bridge rectifier is determined by the maximum rotor current corresponding to maximum output torque. With fan type load the torque varies as the square of the speed hence rotor current is maximum at full speed. The rectifier bridge must be rated for the maximum alternating voltage and current, even though they do not occur simultaneously [3]. The silicon rectifier must be designed for the ideal d.c. power [6].

$$P_r = S_{max} P_{gmax} \qquad \ldots (3.1)$$

in which S_{max} is the slip at the lower limit of speed range. P_{gmax} is the maximum air gap power occurring in the motor which, except for the rotor losses, is equal to the maximum power output. The maximum power must be assumed because the silicon cells have only a small thermal capacity.

The size of the d.c. motor will be determined by the speed variation required. In case the d.c. motor is connected to the same shaft as the a.c. motor the approximate rating of the d.c. motor may be obtained from the relation

$$N = \beta - 1 \qquad \ldots (3.8)$$

where β represents the ratio of the maximum to the minimum speed required and N, the ratio of the rating of the d.c. and a.c. motors. For a two-to-one speed ratio the d.c. motor must equal the a.c. motor in capacity [6]. The d.c. motor is, however, used less effectively at the lower speeds. If the speed range is greater than two-to-one it will be more economical to absorb the output of the rectifier in a constant speed d.c. motor, connected to an a-c generator, to form an auxiliary motor generator set. In this case

$$N = \frac{\beta - 1}{\beta} \qquad \ldots (3.9)$$

For a two-to-one speed control the d.c. motor must be half the rating of the main a.c. motor. In a static Kramer operation, the inclusion of rectifying elements in the induction motor rotor circuit results in harmonic current of appreciable magnitude. Associated components of current are induced in the stator winding and in the supply system. These currents introduce [illegible] of additional harmonic torques and loss which necessitates some derating of the induction motor. The harmonic currents in stator and rotor cause harmonic copper losses to a given percentage of the machine losses which slightly reduces the motor efficiency [14].

As the Kramer drive is usually of limited speed range the converter rating will only be a fraction of that of the main motor, hence the magnitude of the harmonics will in general, be lower than those occurring in d.c. solid state drive where the machine and converter ratings are matched.

3.2.1 Practical Voltage Ratings[15]

The availability of silicon diodes of high peak transient voltage (p.t.v.) ratings varies with the size and type of device. Higher voltage rating of diodes is obtained at some increase in forward losses and sacrifice of over current capability. In some cases it is possible for voltage doubling to occur at transformer switch on due to ringing, a margin of about 2.2 is usual. This corresponds to an input voltage of about 32 V r.m.s. for every 100 V of diode (p.t.v.) capability. In practice the solid state rectifiers are chosen with a peak voltage rating of 2.5 times the normal peak voltage working.

3.2.2 Practical Current Ratings

For a particular diode a range of current rating is derived by considering the maximum permissible working junction temperature, the internal thermal resistance between junction and base, and the losses at the chosen forward voltage limit. Practical current ratings are usually somewhat below maximum ratings. Diodes operate at only about 60% of the test current or less. The losses are roughly 1.2 W per ampere d.c.

3.2.3 Diode Connection

For large voltage requirement series combination of diodes are used. As the reverse voltage characteristic of the cells are not the same, for proper voltage division of reverse voltage it is necessary to have resistance in parallel. In some cases voltage balancing circuits are used.

When more current is required, the diodes are connected in parallel. Since the voltage drop in forward direction is not the same for all the diodes, the current sharing is not proper. Saturable reactors are used for this purpose [16].

3.2.4 Rectifier Arrangements

Single phase bridge rectifier arrangement is most common. Each arm must be rated for a mean current of one half of the d.c. output and for the full r.m.s. line voltage. The fundamental output ripple is 48%.

Three phase bridge rectifier is also very common arrangement, capable of handling relatively high voltages and giving only 4% fundamental ripple. Each arm must be rated for a mean current of one-third of the d.c. output for the full r.m.s. line voltage.

3.2.9 Diode Protection [17]

Silicon diodes are very sensitive to voltage rise and over current. If the junction temperature goes high due to high current the capacity to withstand (PIV) reduces appreciably and thus the diodes are damaged.

To protect diodes against over voltages it is necessary to have a capacitor and resistor or even capacitor across it. If the over voltage is of high magnitude a non-linear resistor (silicon carbide) can be connected in parallel to the diode.

R-C networks may be designed to limit the transient voltage surges which occur in transformer fed circuits. The capacitor will limit the switching-off surge to a safe value and the resistor will restrict the surge at switching-on to a value which will not cause destruction of semi-conductor junctions. This R-C network is called snubber. Fig. 3.2 shows the R-C snubber for 3-phase bridge rectifier. The size of the capacitor is not especially critical, but it is related to the junction area of the diode, and a rule-of thumb guide is to use a value of 0·0007 µF for each ampere. Thus a suitable capacitance for a diode rated at 15A would be approximately 0·01 µF.

To protect over-current, high speed d.c. circuit breaker and fuse are used. Circuit breaker is used for over load on the d.c. side and fuse for short circuit either on d.c. side or on the individual cell. Where only a single bridge is used, the fuses may be inserted into the supply leads only. If parallel combination diodes are to be used, it is customary to fuse the individual rectifier legs.

The basic requirements for selecting fuses are that the fuse current rating must be equal or larger than the r.m.s. arm current to be carried and the fuse voltage rating must be equal and greater than the circuit voltage [20].

3.3 DESIGN EXAMPLE : [19, 20]

(i) Single Phase Bridge Rectifier

For D.C. motor field excitation a 1-phase bridge rectifier is designed from the relation given below

$$\frac{E_2}{V_d} = 1\cdot 11 \text{ or } V_d = \cdot 9E_2 \quad \ldots (3.4)$$

$$\frac{PIV}{V_d} = 1\cdot 57 \text{ or } PIV = E_m = 1\cdot 41\, E_2 \quad \ldots (3.5)$$

$$\text{Average current} = \cdot 5\, I_d \quad \ldots (3.6)$$

$$\text{R.M.S. Input current} = 1\cdot 11\, I_d \quad \ldots (3.7)$$

$$\text{Transformer Rating} = 1\cdot 11 \text{ time d.c. out put } (V_d\, I_d) \ldots (3.8)$$

(ii) Three Phase Bridge Rectifier

$$\frac{E_2}{V_d} = .428 \text{ or } V_d = 2\cdot 34\, E_2 \quad \ldots (3.9)$$

$$\frac{PIV}{V_d} = 1{\cdot}047 \text{ or } PIV = \sqrt{3}\, E_m = \sqrt{6}\, E_p \quad \ldots \quad (3.10)$$

$$\text{Average current} = \frac{1}{3}\, I_d \quad \ldots \quad (3.11)$$

$$\text{R.M.S. Input current} = \sqrt{2/3}\, I_d = {\cdot}816\, I_d \quad .. \quad (3.12)$$

[illegible]
Type Cascaded A.C./D.C. M/C
No. E4479

A.C.

Volt 400/440 Delta primary

400 Star secondary

3.5 Amp. primary, 3·5 Amp. secondary

50 HZ. 3-phase

D.C.

G- 220 volt, 20 Amp. 750-1000 r.p.m.

3·75 KW output

For 220 V output the input to the rectifier bridge will be obtained from eqn. (3.9)

$$E_p = \frac{220}{2{\cdot}34} = 94 \text{ V}$$

Hence

$$V_{ML} = 163 \text{ V}$$

It at [illegible] will the rectifier output voltage when stator is given full supply voltage is obtained from eqn. (3.9)

$$V_d = 2\cdot34\ V_2$$

or

$$V_d = 2\cdot34 \times \frac{182}{\sqrt{3}} = 246\ \text{V}$$

For full load current of d.c. motor (i.e., $I_d = 20$ Amp.) the rotor current will be using eqn. (3.12)

$$I_r = \cdot816 \times 20 = 16\cdot32\ \text{Amp.}$$

For I_d = 20 Amp. Average current of each diode is

$20/3 = 6\cdot66$ Amp.

For full load rotor current i.e., 3·5 Amp. the current in the d.c. motor is obtained from eqn. (3.12) as

$$I_d = \frac{3\cdot5}{\cdot816} = 4\cdot3\ \text{Amp.}$$

Hence current per diode in the bridge rectifier is

$4\cdot3/3 = 1\cdot43$ Amp.

For 50% speed reduction the rotor slip ring voltage is 182/2 = 91V (between slip rings)

As the voltage between slip rings at stand still is V_{2L} = 182 or V_2 = 105 volts the PIV rating of the diode used should be greater than $\sqrt{6}\ V_2$ = 253 volts.

Silicon diodes which may be used for bridge rectifier silicon CR 20 - 0 [illegible] 25 [illegible] 640

Diodes used in the scheme for 3-phase bridge rectifier circuit are

6 Nos. [illegible] 6 Amp. [illegible]

Design of 1-phase bridge rectifier for the d.c. motor.

The voltage rating of a diode is taken as the product of its average current and its peak inverse voltage (PIV) and the rating of the transformer winding is the product of its r.m.s. voltage and r.m.s. current.

For 230 volts input to the 1-phase bridge rectifier the corresponding output voltage is obtained from eqn. (9.4) which is

$$V_d = .9 \times 230 = 207 \text{ volts.}$$

For maximum field current of 2 amp the average current through each diode is given by eqn. (9.5), that is 1 Amp. In the scheme the d.c. motor field excitation can also be provided by step-down transformer and 1-phase bridge rectifier. Input to the transformer in this case is given from any two terminals of 3-phase supply. The design of transformer will be based on eqns. (9.7) and (9.8). Diodes for 1-phase bridge rectifier may be

IN 126 1 Amp [illegible] (PIV)

IN 127 1 Amp 1200 (PIV)

But the diodes used are 4 nos. of 3 Amp. 920 (PIV).

R_b = 1040 Ohms

X_b = 292 Ohms

R_1 = 12 Ohms

Armature Resistance of D.C. Machine

R_d = 2 Ohms

Synchronous Generator Resistance

R_{sg} = 5·4 Ohms

The constant 'K_d' for the d.c. motor is obtained as follows:

From the open circuit characteristic of d.c. machine shown in Fig.44 a point on the linear portion is taken which for a field current (I_f = 0·1 Amp.) gives corresponding open circuit voltage (V_o = 63 Volt.)

The value of K_d is obtained from the eqn. (2.9a)

$$K_d = \frac{63}{97\cdot4 \times \cdot1} = 6\cdot47, (\omega_r = 97\cdot4)$$

Effective Turn Ratio of Induction Motor, a = 2

4.2 THEORETICAL RESULTS

Using the parameters of the systems the following have been determined from the performance equations.

1. No Load Speed
2. Rotor Current Referred to Primary side
3. Torque Developed by Induction Motor
4. Torque Developed by D.C. Motor

CHAPTER - IV

EXPERIMENTAL [illegible] OF A [illegible]

This chapter deals with the verification of theoretical results. All the constants of the system used in the performance equations have been measured experimentally. The performance of the system determined experimentally is compared with the theoretical results.

4.1 DETERMINATION OF PARAMETERS OF THE SYSTEM[21,22,23]

The specifications of the different machines are as follows:

[illegible]

2-pole and 6-pole

Volt 400/440 Delta primary

400 Star secondary

5·5 Amp. primary, 5·5 Amp. secondary

50 c/s, 3-phase

D.C. MACHINE

0-220 Volt, 20 Amp., 750-1000 R.P.M

3·75 kW output

The various parameters of the system, determined from light running at variable voltage, and blocked rotor tests are as follows:

$$R_2' = 98 \text{ Ohms}$$

$$R_1 + R_2' = 50 \text{ ohms}$$

5. Total Torque Developed at the Shaft
6. Stator Input Current
7. Stator Input Power Factor

A sample calculation is as follows:

No Load Speed

Using eqn. (2.5a) the no load slip and hence the speed of the system is determined

(i) Delta - Star Connection

$$V_1 = 400 \text{ Volts}, \; V_{2L} = 315 \text{ Volts}$$

For $I_f = 0{\cdot}1$ Amp., the slip is given as

$$s = \frac{1}{1 + \dfrac{1{\cdot}95 \times 315}{6{\cdot}47 \times 105 \times {\cdot}1}} = {\cdot}130$$

Hence

$$n_r = 362 \text{ r.p.m.}$$

Similarly the no load speed from the above equation is obtained at different values of field current.

(ii) Star-Star Connection

$$V_1 = 400 \text{ Volts} \quad V_{2L} = 182 \text{ Volts}$$

Using the same equation the slip and hence the speed is determined.

For $I_f = 0{\cdot}1$ Amp., the slip in this case is given as

$$s = \frac{1}{1 + \frac{1\cdot25 \times 122}{6\cdot47 \times 105 \times \cdot1}} = \cdot226$$

Hence

$$N_r = 704 \text{ r.p.m.}$$

8. Rotor Current, I_2'

Using eqn. (2.30) the values of I_2' is calculated at different values of 'I_g' and 's'

For $I_g = 0\cdot1$ Amp. and $s = \cdot45$

$$I_2' = \frac{92\cdot4 \times 71 \pm \sqrt{(92\cdot4\times71)^2 - \{(92\cdot4)^2 + (30)^2\}\{(71)^2 - (231)^2\}}}{(92\cdot4)^2 + (30)^2}$$

$$= \frac{6560 \pm 22280}{9944} = 1\cdot645, - 2\cdot97$$

Hence

$$I_2' = 1\cdot645 \text{ Amp.}$$

Similarly I_2' for other values of 'I_g' and 's' is determined.

9. Torque Developed by Main Induction Motor

Using eqn. (2.26) the torque, T_m is calculated for a given value of I_g, s, and corresponding I_2'

For

$$I_g = 0\cdot1 \text{ Amp.}, s = \cdot45, I_2' = 1\cdot645$$

$$T_i = 9\left[\frac{(1\cdot649)^2 \times 18}{\cdot45 \times 109} + \frac{(1\cdot649)^2 \times 4\cdot10}{\cdot45 \times 109} + 2\times6\cdot47\times\cdot420\,\frac{(1-\cdot45)}{\cdot45} \times\cdot1 \times 1\cdot649\right]$$

$$= 9\left[1\cdot01 + \cdot230 + 1\cdot11\right] = 9\cdot474 \text{ N-m.}$$

4. Torque Developed by D.C. Motor

Using eqn. (2.31), T_{DC} is given as

$$T_{DC} = 9 \times 2 \times 6\cdot47 \times\cdot420 \times\cdot1 \times 1\cdot649$$

$$= 2\cdot79 \text{ N-m}$$

5. Total Torque Developed at the Shaft

$$T_{SH} = 9\cdot474 + 2\cdot79 = 12\cdot264 \text{ N-m.}$$

Similarly the T_i, T_{DC} and T_{SH} for different values of s, I_2 and I_2' (calculated) is evaluated.

6. Stator Input Current, I_1

First V_1 is calculated from eqn. (2.34) with the given values of s, I_2 and corresponding I_2'.

For I_2 = 0·1 Amp. and s = ·45 and I_2' = 1·649 Amp.

$$V_1 = \left(11 + \frac{18}{\cdot45} + \frac{4\cdot10}{\cdot45}\right) \times 1\cdot649 + 2 \times 6\cdot47 \times\cdot420 \times 109\,\frac{(1-\cdot45)}{\cdot45} \times\cdot1$$

$$= 222 + j\,62\cdot5 = 221\,|15\cdot0^\circ$$

Calculation of No Load Current, I_o.

From eqn. (3.39)

$$I_o = \frac{231 \angle 15.3^\circ \times 1060 \angle 9^\circ}{597 \times 10^4 \angle 90^\circ}$$

$$= \cdot 8 \angle -65.2^\circ = \cdot 335 - j \cdot 725 \text{ Amp.}$$

The Stator Input Current, I_1 is given as

$$I_1 = I_0 + I_2'$$

$$= \cdot 335 - j \cdot 725 + 1 \cdot 645$$

$$= 1 \cdot 98 - j \cdot 725 = 2 \cdot 1 \angle -20.2^\circ$$

7. Stator Input Power Factor

It is the cosine of the angle between V_1 and I_1

Hence

$$\text{P.F.} = \text{Cos} (20 \cdot 2 + 15 \cdot 3)$$

$$= \text{Cos } 35 \cdot 5^\circ = \cdot 8$$

In a similar way the P.F. is computed for different values of I_2 and s.

From the above results obtained theoretically the following characteristics have been plotted

(i) Torque developed by main induction motor versus slip as shown in Fig. 4.1

(ii) Torque developed by D.C. motor versus slip as shown in Fig. 4.2

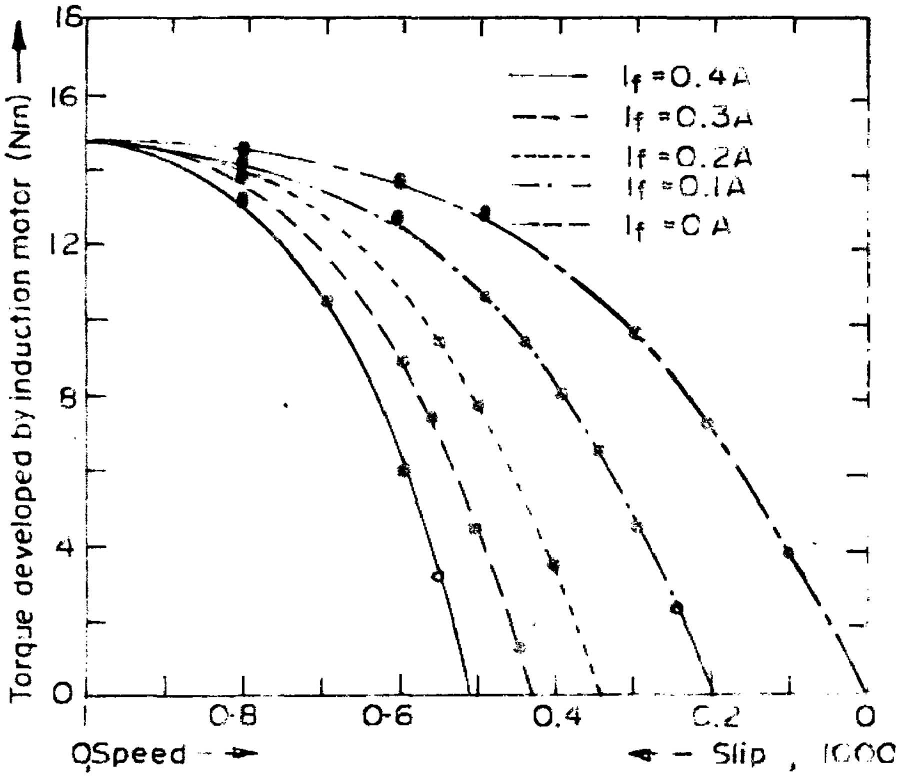


FIG.4.1 TORQUE DEVELOPED BY INDUCTION MOTOR Vs SLIP CHARACTERISTICS IN COMPLETE SPEED RANGE.

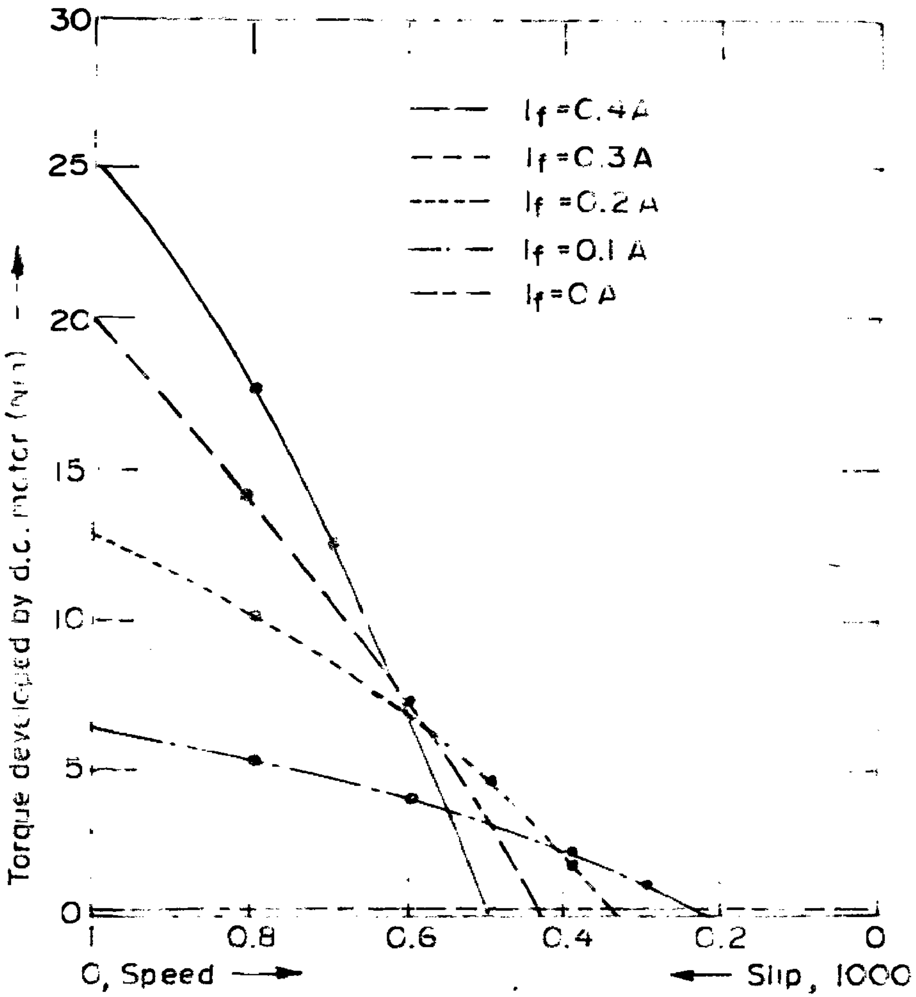


FIG.4.2 TORQUE DEVELOPED BY D.C. MOTOR Vs SLIP CHARACTERISTICS IN COMPLETE SPEED RANGE.

(iii) Total torque developed at the shaft versus slip as shown in Fig. 4.3

4.3 EXPERIMENTAL RESULTS

All the experimental data are tabulated in Appendix, A.

1. Fig. 4.4 shows the open circuit characteristic of the d.c. motor from the data in Table A-1
2. Fig. 4.5 shows the relation between constant losses ($P_d = I_d^2 R_d$) and speed of the set from the data in Table A-2
3. Fig. 4.6 illustrates the curve drawn from the data of Table A-3 for obtaining core loss of induction motor.
4. Table A-4 gives the data of load test on the set.
5. Fig. 4.7 gives the relation between speed and total load on the shaft.
6. Fig. 4.8 illustrates the relation between no load speed and field current of the d.c. motor for (a) delta-star and, (b) star-star connections, data being taken from Tables A-5a and A-5b respectively
7. Fig. 4.9 gives the variation of speed with total shaft (load) torque in the working range of speed both for experimental and theoretical results.
8. Fig. 4.10 indicates the relation between stator input current and shaft output obtained both theoretically and experimentally.

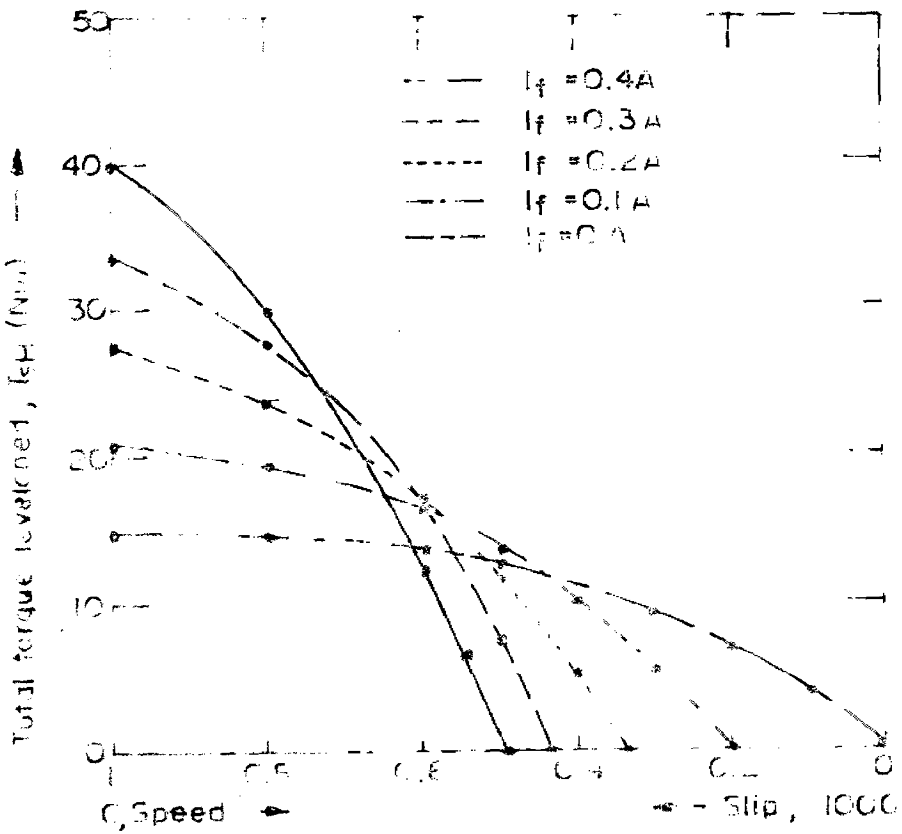


FIG.4.3 TOTAL TORQUE DEVELOPED Vs SLIP CHARACTERISTICS IN COMPLETE SPEED RANGE.

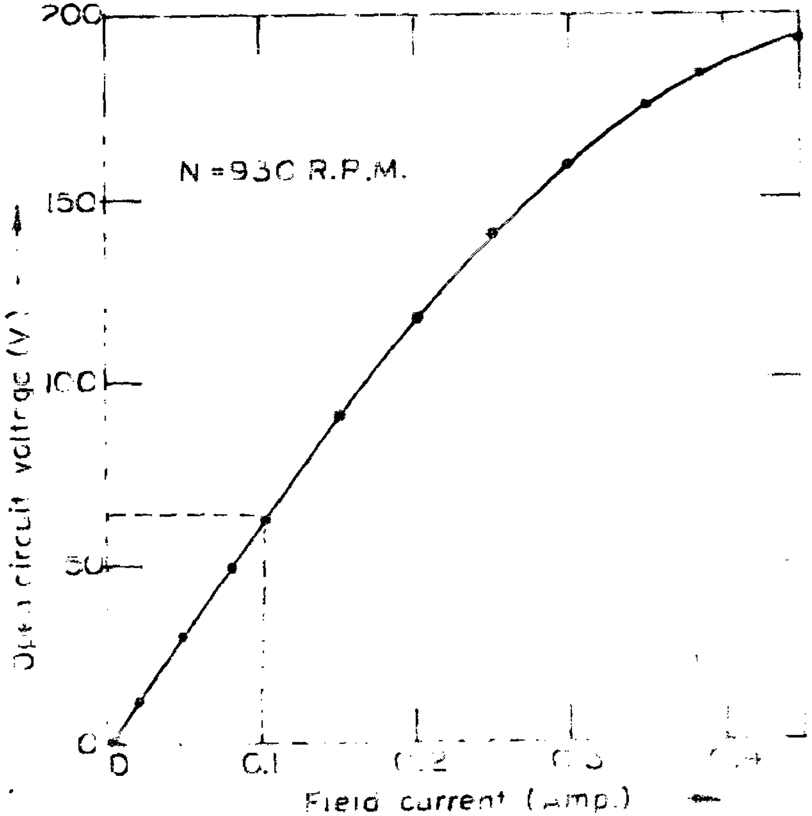


FIG.4.4 OPEN CIRCUIT CHARACTERISTIC OF D.C. MOTOR.

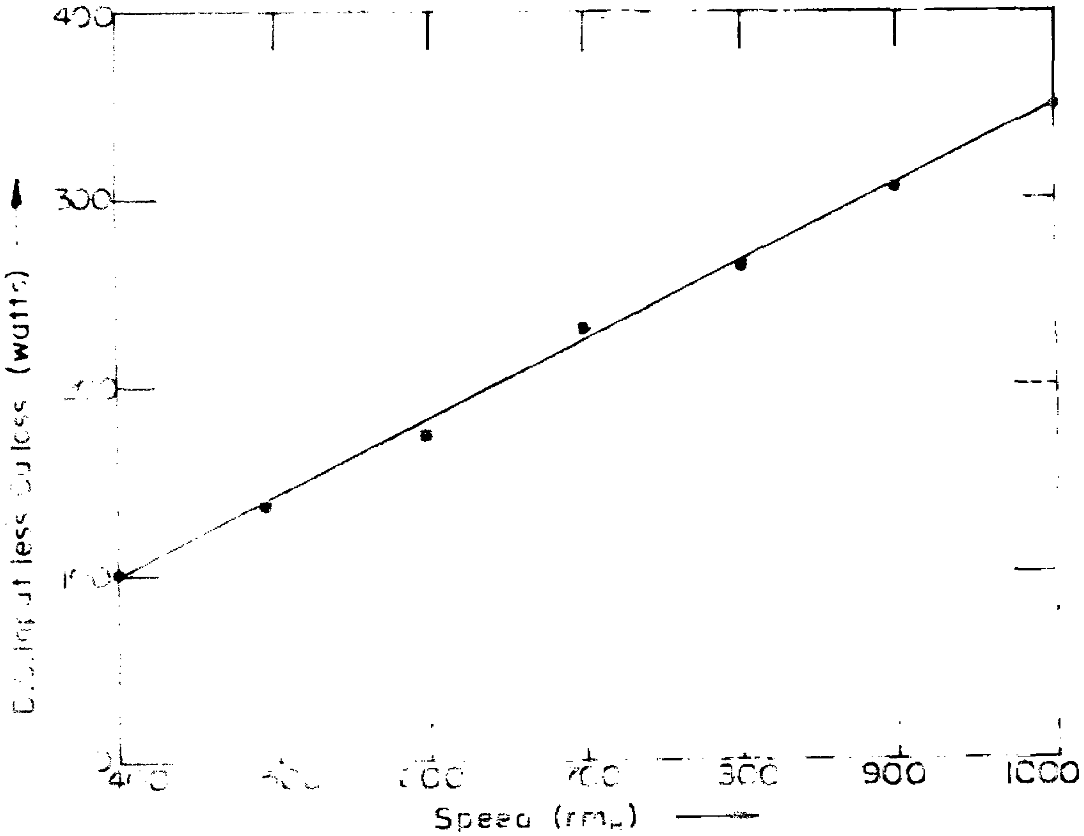


FIG.4.5 CONSTANT LOSSES Vs SPEED CHARACTERISTICS.

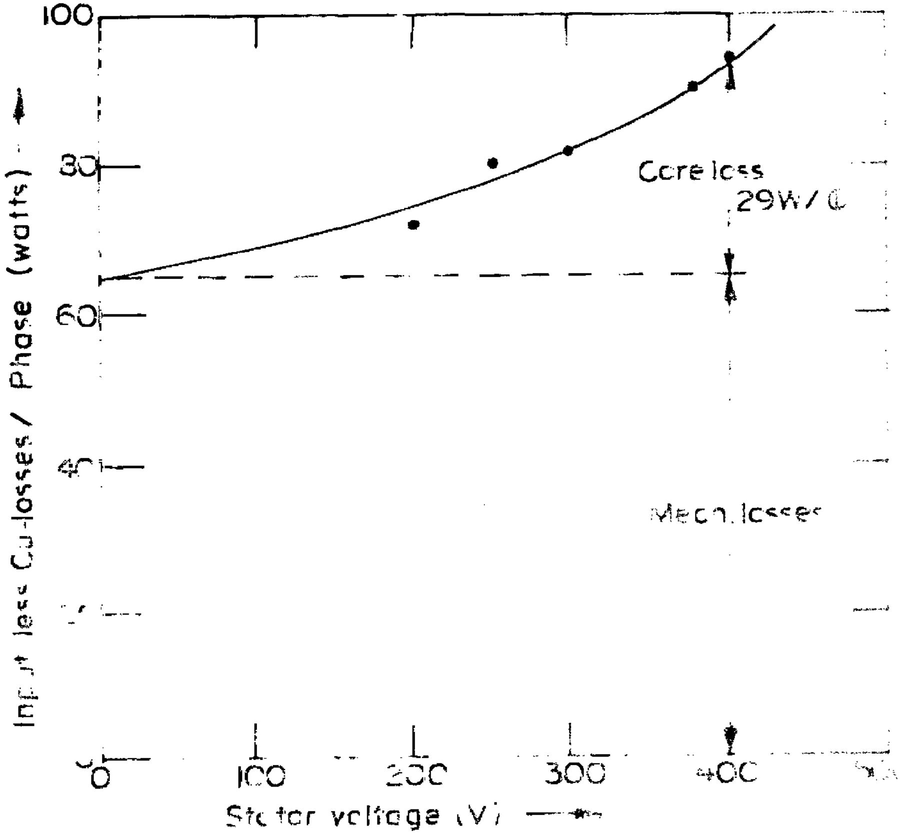


FIG.4.6 DETERMINATION OF CORE LOSSES IN INDUCTION MOTOR.

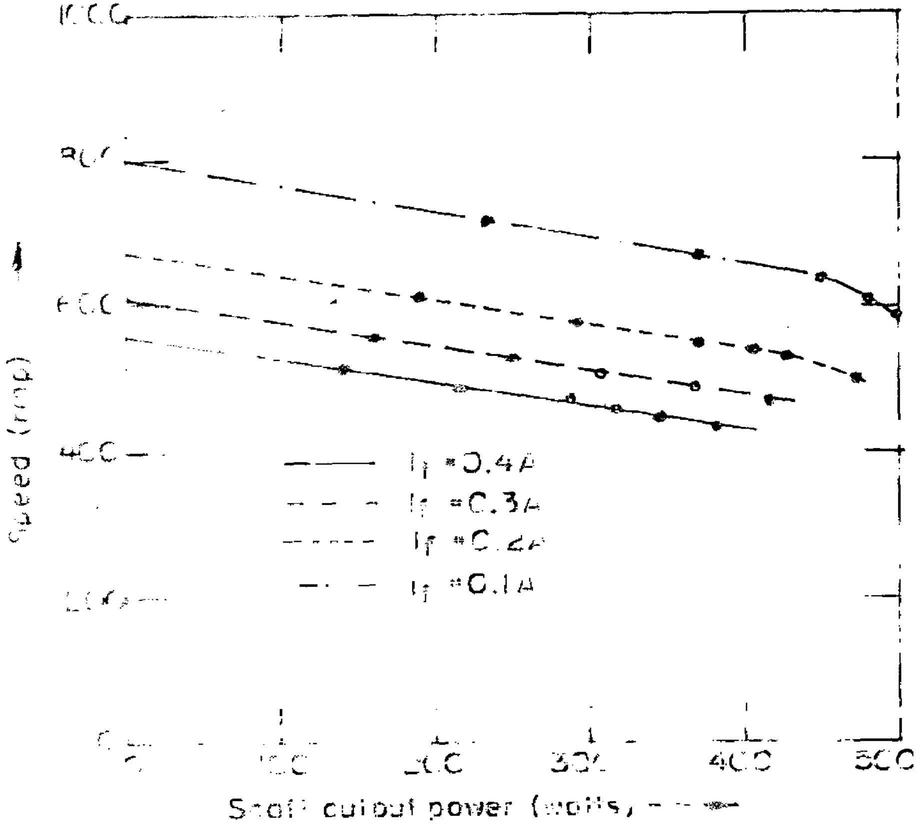


FIG. 4.7A RELATION BETWEEN SPEED & SHAFT OUTPUT POWER IN WORKING SPEED RANGE

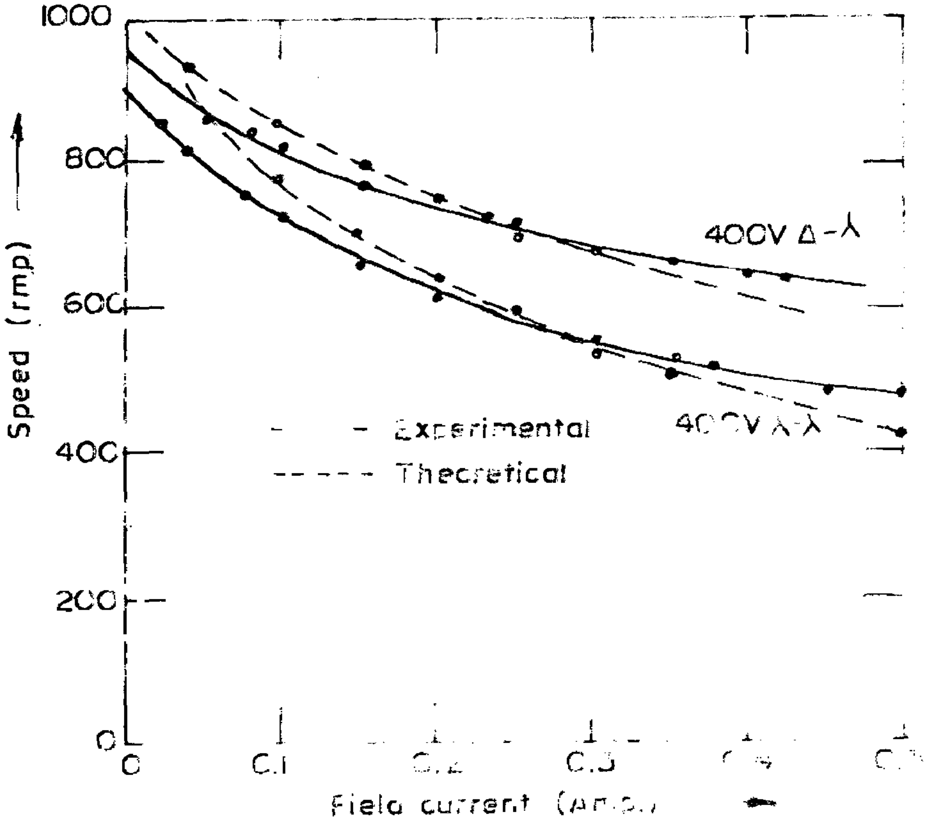


FIG. 4.8 NO LOAD SPEED CHARACTERISTIC OF KRAMER DRIVE SYSTEM.

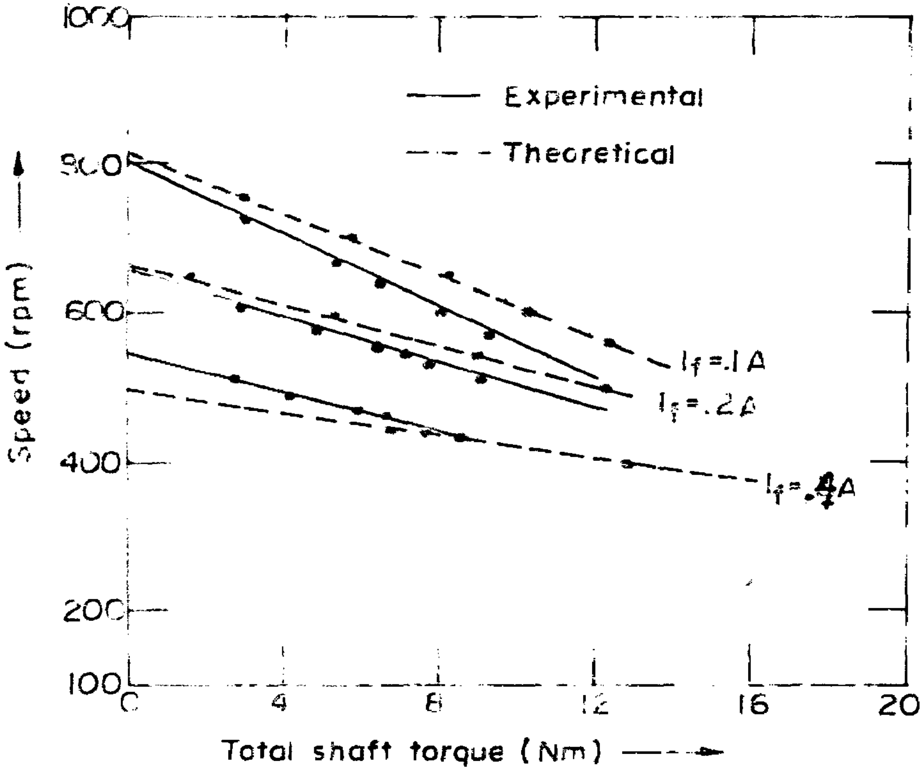


FIG.4.9 RELATION BETWEEN SPEED & TOTAL LOAD TORQUE.

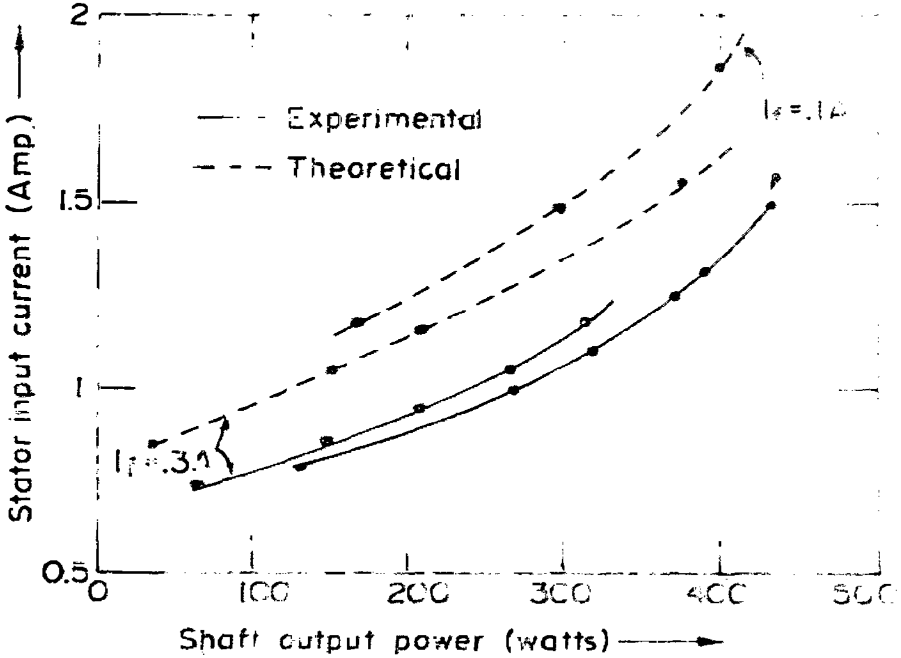


FIG.4.10 STATOR CURRENT Vs SHAFT OUTPUT POWER CHARACTERISTICS.

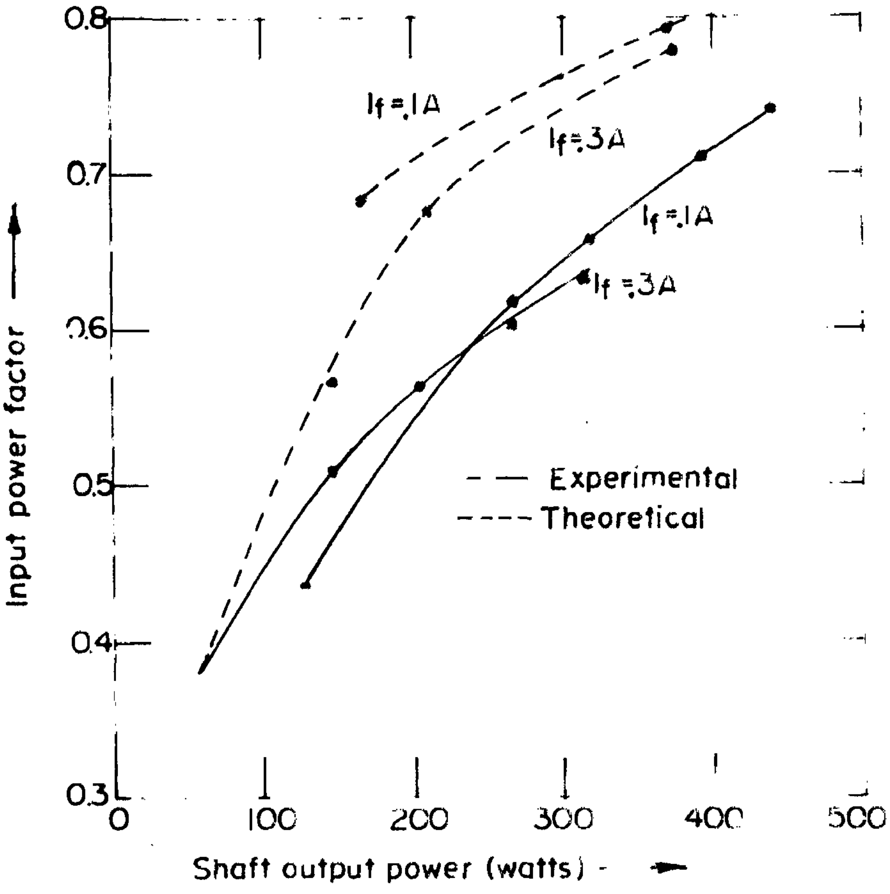


FIG.4.11 RELATION BETWEEN INPUT POWER FACTOR & SHAFT OUTPUT POWER.

9. Fig. 4.11 gives power factor versus shaft output characteristics both for experimental and theoretical data.

4.4 DISCUSSION

In the no load speed characteristics theoretical results have been determined for ideal case i.e., neglecting voltage drops in the rotor and rotor circuit elements. The additional voltage drops in the rotor circuit elements, that is, the rectifier and the d.c. motor, result in the more drooping characteristic than the short circuited slip ring **induction** motor.

As there is no provision for loading the system by external means, the input to the synchronous generator is taken as the load. The input is obtained by adding cu-losses and a constant losses to the output of the synchronous generator. The input to the d.c. motor less its armature cu-losses gives the constant losses (i.e., core loss in d.c. motor + mechanical losses + core loss in synchronous generator) at a given speed when field excitations of the d.c. motor and the synchronous generator are kept at their mean values. This method has been adopted to obtain total load and load torque at a given working speed.

There has been discrepancy between theoretical and experimental results indicated on different plots of the solutions. This discrepancy may be attributed to the following reasons:

1. Parameters have been used constant.
2. Inaccuracy in the determination of parameters by tests.
3. Use of approximate equivalent circuit in the calculation of performance equations.

CHAPTER 5

STARTING AND BRAKING OF KRAMER DRIVE SYSTEM

This chapter deals with the study of starting and braking of the Kramer drive system. An expression for braking torque has been derived. The effect of braking resistance and d.c. motor field current on braking time has been investigated experimentally.

5.1 STARTING OF INDUCTION MOTOR

For wound rotor motors, the simplest and cheapest method of starting is by means of external resistance. As the motor starts and accelerates, the additional resistance is decreased in steps so that the available electromagnetic torque is always maximum. Under operating condition, additional resistance is completely cut off and the slip rings are short circuited so that the motor operates on its normal characteristic giving a large pull out torque at a low value of slip. The resistors and accelerating contactors for very large wound rotor motors are very bulky and expensive. This fact indicates a need for a different way of accomplishing the functions of inserting resistance into the rotor circuit. One such equipment is liquid rheostat. It is a variable resistor using an electrolytic solution as the resistive element. By changing the distance between a set of fixed and movable electrodes, immersed in the electrolyte, with a small motor, smooth, stepless control of the resistance of the liquid rheostat may be achieved.

Saturable reactors have also been used in the rotor circuit for starting. Now-a-days the semi-conductor rectifiers are fast becoming popular and very attractive for such applications.

9.2 STARTING OF THE KRAMER DRIVE SYSTEM

The customary means of starting the modified Kramer cascade is shown in Fig. 9.1. The set is started first similar to that of wound rotor motor starting by means of external resistors. In these circumstances the choice of the starting resistance R_{ss} is influenced by the maximum permissible current or by the required starting torque. The induction motor could also be started by means of a single resistor, provided rotor current, I_2 is first rectified with the help of 3-phase bridge rectifier as given in Fig. 9.2.

To limit the current in the secondary to the value as obtained with three resistors a single resistor value can be calculated with the help of eqns. (9.9) and (9.12). The equivalent resistor is thus

$$R_{ss} = 1.92\,R_{as} \qquad \ldots (9.2)$$

The advantages of single-resistor starting are:

1. The starting resistor is simple (two terminal) and therefore much cheaper.

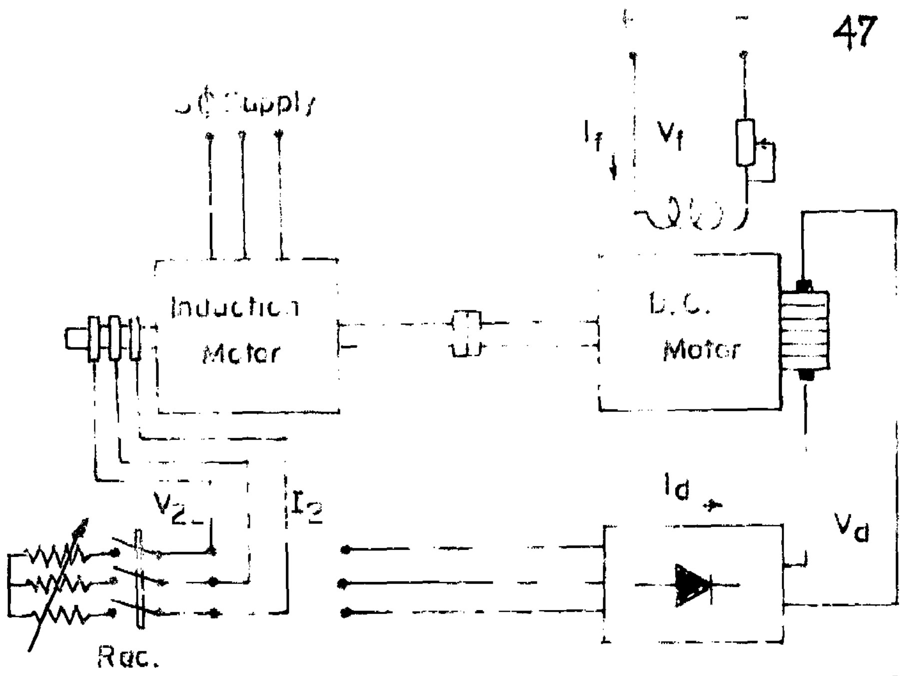


FIG.5.1 RESISTANCE STARTING OF KRAMER DRIVE SYSTEM.

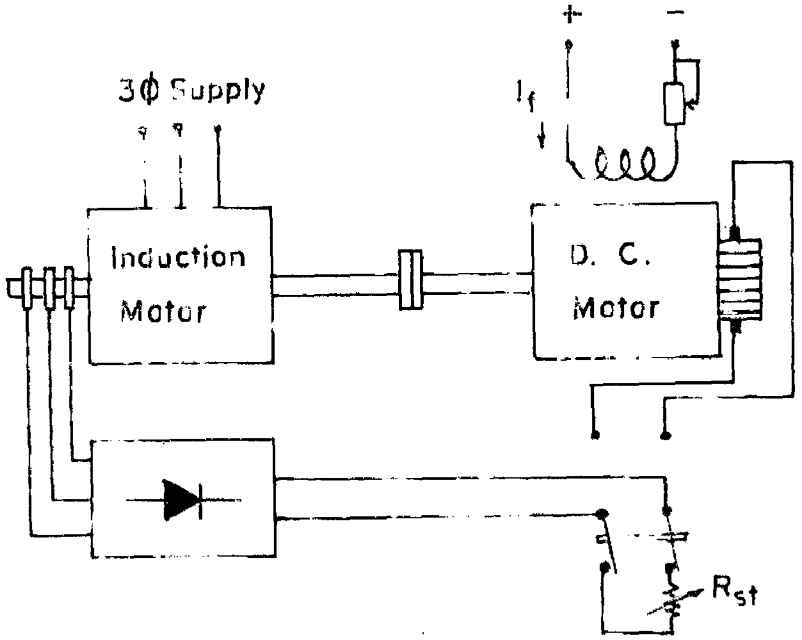


FIG.5.2 SINGLE RESISTANCE STARTING SCHEME.

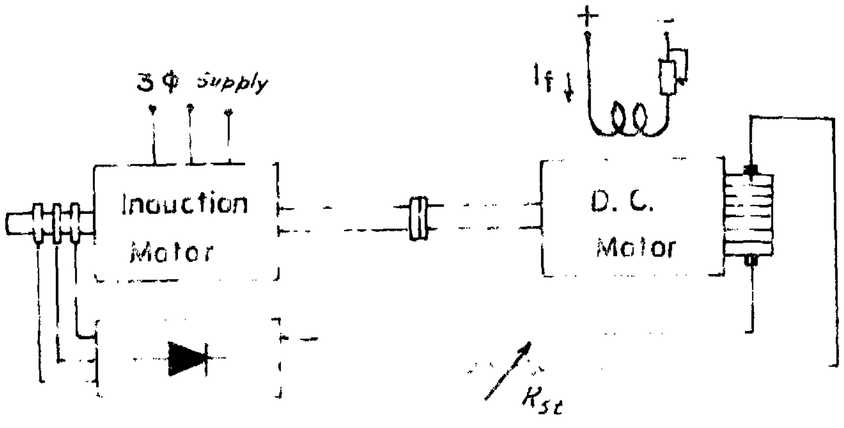


FIG.5.3 COMMON RESISTANCE STARTING SCHEME.

2. Slight difference of resistors gives rise to asymmetric rotor current which is obviated in the case of single resistor.

3. Provision of diodes in the rotating shaft results in the rotor having only two slip rings instead of customary three.

But the disadvantage is that this scheme requires six diodes.

The bridge rectifier used in former cascade system can also be used for starting purpose. The starting performance can be improved if the scheme according to Fig.5.9 is used as in this case the d.c. motor contributes part of the starting torque. The choice of R_{st} in this case is made on the basis of the maximum permissible current in the d.c. motor. In this scheme no change over switch is necessary and the transition to normal running condition is both smooth and automatic. This also provides improved torque/starting current ratio and considerable reduction in energy losses to be absorbed by the starting resistance[90]. It is found that starting is effected at the same field current but with different starting resistance. Increasing the resistance limits the starting current and increases starting time. A similar result can be obtained by increasing the field current of the d.c. motor.

9.3 BRAKING OF INDUCTION MOTOR[24]

It is sometimes necessary to stop an induction motor quickly, or decelerate it under controlled conditions as when lowering a load in a crane or hoist. Such retardation is effected to by providing a braking torque.

The most natural means of braking the drive is that of interrupting the stator or rotor current of the induction motor. But braking time would be too long if the drive system has high inertia.

The various methods of electrical braking for induction motors are:-

(a) D.C. Braking or Dynamic Braking
(b) Plugging
(c) Regenerative braking
(d) Braking with excitation by capacitors
(e) Braking by unbalanced operations.

9.3.1 D.C. Braking

In this case the stator is switched off from the a.c. supply and connected across a source of direct current. The d.c. excitation can be obtained from a separate source or from the a.c. supply to the induction motor through a transformer-rectifier unit. The interaction of the resultant field and rotor emf will develop a torque in opposite to the motoring torque and braking will result. The magnitude of the braking torque will depend on the d.c. excitation, the rotor speed and the rotor circuit resistance.

To determine the electro-magnetic torque developed at any speed for a given d.c. exciting current under this braking condition, the equivalent alternating current is first calculated knowing the stator winding connections. For star connected stator windings the magnitude of the d.c. excitation between any two terminals (third terminal open) is 1·225 times the a.c. full load current but the practical values generally taken are 1·7 to 1·9 times full load a.c. current [25].

5.3.2 Plugging

This is simply achieved by interchanging any two of the supply leads. Though a fast braking performance is achieved by a simple arrangement and installation, this method of braking results in high energy consumption (3-times the K.E. of the rotor) and consequent heating of the motor [26]. Also a zero speed switch or consistent timing relay is required if reversing is to be prevented.

5.3.3 Regenerative Braking

This is the method of retarding the motor by making it function as a generator, pumping the generated power back to the supply line. This occurs when the load over-hauls the motor. The braking torque will be exerted by this action. The machine actually acts as an induction generator and no extra equipment or change in connection is needed.

3.3.4 Braking with Excitation by Capacitor

In this method of braking suitably rated capacitors are connected across the stator terminals when the machine is disconnected from the supply, excites the winding and thus induction generator action is achieved . This method of braking is less popular than the d.c. braking owing to relatively high cost of capacitors. Moreover no braking torque is produced below about one-third of the synchronous speed.

3.3.5 Braking by Unbalanced Operation

Unbalanced operation of an induction motor can be performed by applying an unbalanced voltage to the stator winding or by asymmetrical connection of the stator winding or introducing unbalanced external impedance in the rotor circuit. By adjusting the extent of unbalance the driving and retarding torques can be varied for getting different torque/speed characteristics. This type of control has been widely used in a number of industrial applications.

3.4 BRAKING OF SERIES TANDEM SYSTEM [27]

Due to high inertia of the two rotors the braking time would be too long for some applications and a more rapid method would be desirable which has been suggested as in Fig. 3.4. In this case, both machines participate in braking the drive, the a.c. machine because the d.c. current I_{dc} flows through its stator (dynamic braking) and the d.c.

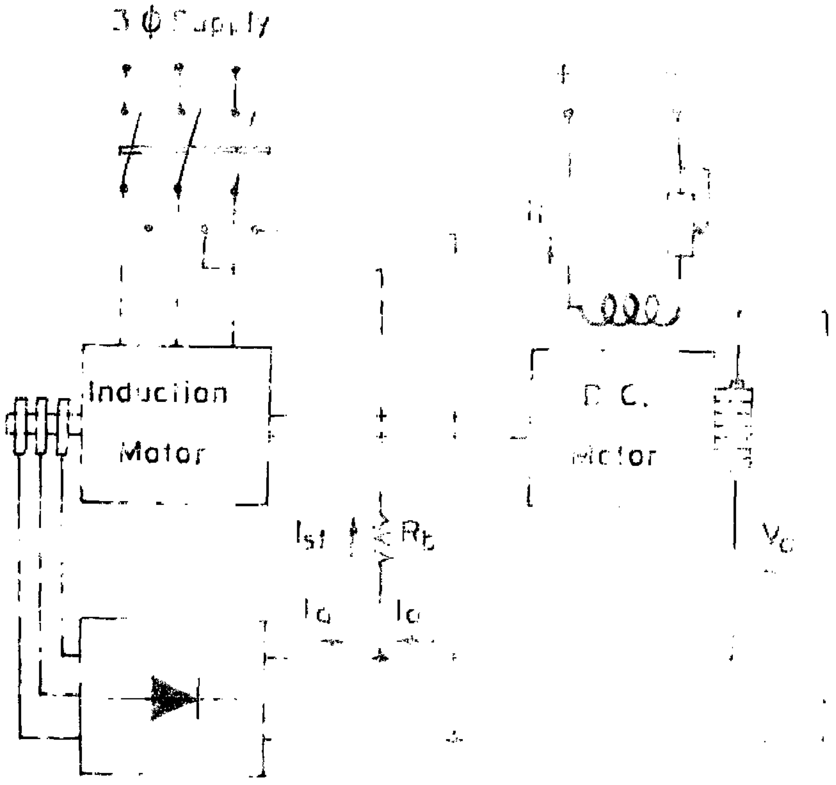


FIG.5.4 BRAKING OF KRAMER DRIVE SYSTEM.

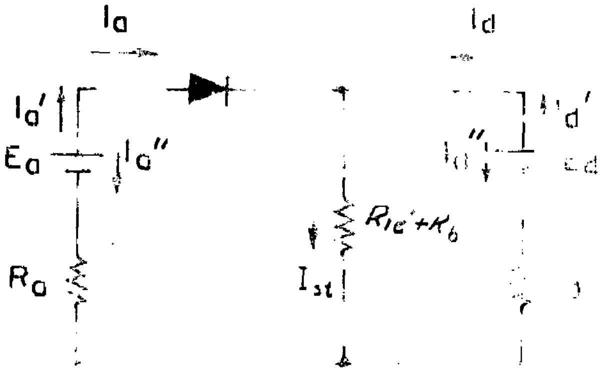


FIG.5.5 EQUIVALENT CIRCUIT OF BRAKING SYSTEM.

machine because it contributes part of this current (and thereby acts as a generator). Combined this has the effect of reducing braking time to a fraction of the time required when disconnected the a.c. motor. The equivalent circuit of the system braking is given in Fig. 9.9

The e.m.f. induced in the d.c. motor is given by

$$V_d = K_d \omega I_f \quad \ldots \quad (9.1)$$

The stator resistance through which the current flows is

$$R'_{1e} = K_{eq} R_1 \quad \ldots \quad (9.2)$$

where $K_{eq} = 2$ for star connected stator.
The induction motor acts as a synchronous generator being excited through the stator windings. Its e.m.f. may be approximated by

$$E_a = K_a \omega I_{at} \quad \ldots \quad (9.3)$$

where K_a depends on the data, connection of stator winding and on the slope of the magnetization characteristic.

Applying super position theorem the values of I_a, I_d and I_{at} can be easily calculated from the equivalent circuit.

$$I_a = I'_a - I''_a \quad \ldots \quad (9.4)$$

$$I_d = I'_d - I''_d \quad \ldots \quad (9.5)$$

$$I_{at} = I_a + I_d \quad \ldots \quad (9.6)$$

where

$$I'_a = \frac{R_n}{R_a + \frac{(R_b + R'_{1n})\,R_n}{(R_b + R'_{1c} + R_d)}}$$

$$I'_d = \frac{R_d}{R_d + \frac{(R_b + R'_{10})\,R_n}{(R_a + R'_{10} + R_b)}}$$

and

$$I''_a = \frac{(R_b + R'_{10})\,I'_a}{(R_a + R_b + R'_{10})}$$

$$I''_d = \frac{(R_b + R'_{10})\,I'_n}{(R_b + R_d + R'_{10})} \qquad \ldots \quad (5.7)$$

Substituting the values of I'_a and I''_a from eqn. (5.7) in (5.4)

$$I_a = \frac{1}{r}\,E_d\,\omega\,I_f\,(L_a\,\omega - R'_{10} - R_b) \quad \ldots \quad (5.8)$$

where

$$r = R_a R_b + R_a R'_{10} + R_a R_d + R_b R_d + R_d R'_{10} - L_a\,\omega\,R_d \quad \ldots \quad (5.9)$$

Similarly

$$I_d = \frac{1}{r}\,E_d\,\omega\,I_f\,(-L_a\,\omega + R'_{10} + R_a + R_b) \quad \ldots \quad (5.10)$$

The value of I_{ot} can be obtained from eqns. (5.8),(5.7) and (5.10)

Hence

$$I_{ot} = \frac{E_n\,\omega\,I_f\,R_n}{r} \quad \ldots \quad (5.11)$$

Now the braking torque produced by d.c. motor is given as

$$T_{cb} = C_c I_f I_a \qquad \ldots (5.22)$$

and braking torque due to main motor is given as

$$T_{ab} = C_a I_{ot} I_a \qquad \ldots (5.23)$$

where C_a and C_c are machine constants.

The total braking torque applied to the cascade set is

$$T_b = T_{cb} + T_{ab} \qquad \ldots (5.24)$$

Substituting the values of T_{cb} and T_{ab} in eqn. (5.24) the total braking torque obtained is

$$T_b = C_c I_f I_a + C_a I_{ot} I_a \qquad \ldots (5.25)$$

Substituting the values of I_a, I_c and I_{ot} from eqns.(5.9) (5.20) and (5.21) in eqn. (5.25) the total braking torque in terms of the parameters is obtained as

$$T_b = \frac{1}{D} C_c I_f K_a \omega I_f (X'_{lo} + X_a + X_b - K_c \omega) + \frac{1}{D}$$
$$C_a K_a \omega K_a I_f \frac{1}{r} K_c \omega I_f (X_a \omega - X'_{lo} - [illegible])$$
$$= \frac{1}{D} K_a \omega I_f^2 \left[\omega^2 \left(\frac{1}{r} C_a K_c K_a R_a\right) - \omega \left(C_a K_a^2 + \frac{1}{r} C_c K_a X'_{lo} R_a + \frac{1}{r} C_a K_a K_b R_a\right) + C_c (X'^2_{lo} + X_a + X_b)\right] \qquad \ldots (5.26)$$

I_b is the d.c. current supplied to the stator and may have to be chosen on the latter basis instead of the maximum torque.

Eqn. (5.26) shows that the resulting braking torque varies as the square of the field current. If non-linearities

are taken this proportion is smaller. An increase in the field current reduces braking time.
With the circuit connections shown in Fig. 5.4 the braking experiment was performed. For a given value of R_b the time taken in braking the set was recorded at different values of field excitation of the d.c. motor. Different sets of readings at different values of R_b were taken and tabulated in Table B-1

Time taken/field current curves for different values of braking resistance 'R_b' are shown in Fig. 5.6.

Braking of the same drive by disconnecting the a.c. supply took 15 seconds compared with 2 seconds at R_b = 5 ohms.

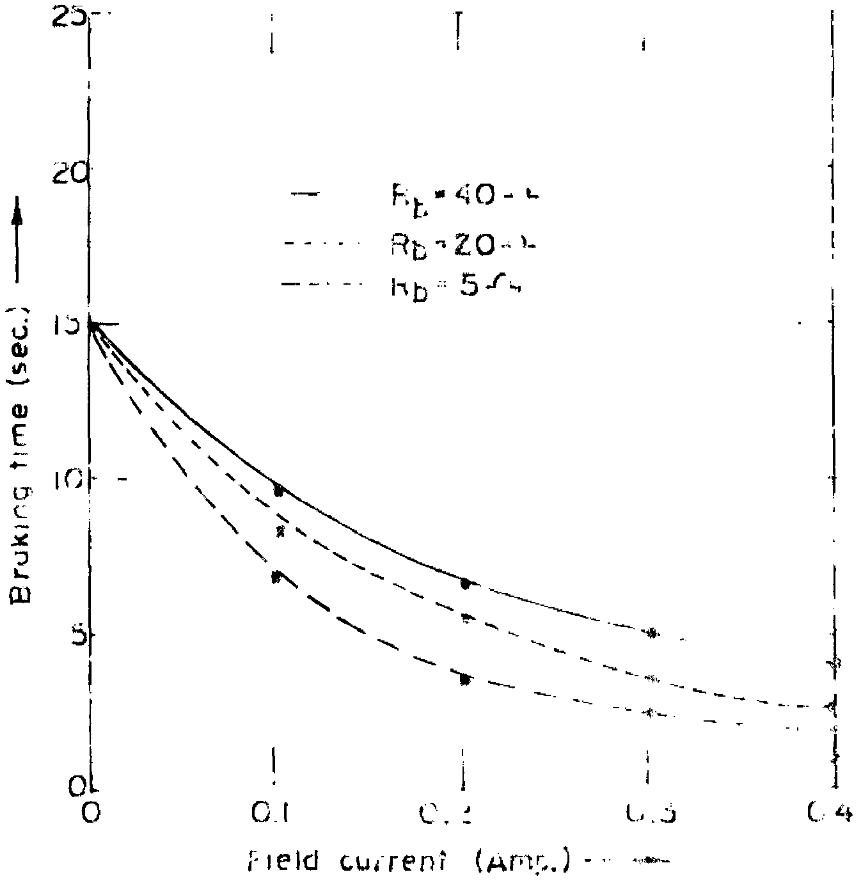


FIG.5.6 BRAKING OF CONSTANT H.P. KRAMER DRIVE SYSTEM.

CHAPTER - VI

CONCLUSION

An equivalent circuit has been developed for static Kramer drive system. The close comparison between theoretical results based on the equivalent circuit and experimental results support that the equivalent circuit can be used for predetermining the performance characteristics of the static Kramer drive system.

The investigations on braking indicate that the braking time is very much reduced with increased field current of the d.c. machine. Hence in order to stop the drive quickly, highest field current permitted in the d.c. motor can be used.

The bridge rectifier in this drive system can also provide a simple and efficient means of starting.

APPENDIX - A

TABLE OF EXPERIMENTAL OBSERVATIONS

Table 5-4 : Data of Load Test on Constant [illegible] Drive System
Stator Supply Volt V_s = 400 V. [illegible] connections; R_{ex} = 5·[illegible] ohms

[illegible]	I_1 Amp.	I_d Amp.	V_d Volt.	[illegible] Amp.	[illegible] Volt.	P_1 Watts.	N r.p.m.	[illegible] Watts.	[illegible] Watts.	Experimental η in %	Experimental Cos ϕ_2
0·1	·9	·67	54	0	122	280	720	0	232	5·00	·434
	1	1·65	51	·32	104	424	650	140	355	5·27	·612
	1·1	1·9	50·7	1·22	96	496	640	203	423	6·3	·65
	1·25	2·33	50·2	1·72	82	532	610	245	479	7·5	·664
	1·38	2·56	50	2·06	70	643	590	253	496	7·9	·72
	1·5	3·12	49	2·45	65	776	560	276	537	9·15	·747
0·2	·72	·6	81·5	0	107	192	610	0	135	2·9	·533
	·77	1·21	77	·7	92	323	575	112	250	4·02	·545
	1	1·66	75	1·32	79	432	550	131	369	6·4	·625
	1·1	1·93	74	1·72	63	496	540	203	406	7·13	·652
	1·15	2·06	72·5	2·02	60	520	525	210	426	7·75	·66
	1·3	2·3	70·5	2·4	53	624	500	242	469	9	·695
0·3	·72	·54	97	0	96	184	550	0	160	2·77	·363
	·84	1	94	·65	83	296	525	90·5	250	4·54	·51
	·95	1·36	92	1·21	72	363	500	151	309	5·9	·55
	1·05	1·7	90	1·76	60	400	490	193	365	7·12	·605
	1·2	2·05	87·5	2·14	53	520	465	215	433	8·5	·636
·4	·7	·5	110	0	90	134	510	0	140	2·62	·370
	·8	·82	105	·6	78	272	490	81	219	4·27	·451
	·9	1·24	102	1·16	63	328	470	137	237	5·0	·527
	·95	1·45	99	1·5	61	392	450	159	317	6·6	·59
	1·05	1·63	95·5	1·82	52	446	435	173	345	7·6	·605
	1·16	2	94	2·00	56	512	430	202	382	8·5	·64

Table-[illegible]-1 : Open Circuit Test on D.C.Motor

I_f Amp.	0	·02	·05	·08	·1	·15	·2	·25	·3	·35	·37	·4
V_o Volt	4	15	32	50	63	92	117	143	161	177	184	193

Table-[illegible]-2 : Constant Losses Test on the System Used, keeping I_f = ·2 Amp. and I_{av} = 3·5 Amp.

V_d Volts.	I_d Amp.	P_d Watts.	$I_d^2 R_d$ Watts	N r.p.m.	$P_d - I_d^2 R_d$ Watts.
67	1·6	107	5	400	102
78	1·8	140	6	500	134
90	2·0	180	8	600	172
112	2·15	240	9	700	231
125	2·2	275	10	800	265
141	2·25	317	10	900	307
162	2·35	380	11	1000	369

Table-[illegible]-3 : Light Running Test on Induction Motor

V_1(Volt)	I_1(Amp.)	W_1(Watts)	$3 I_1^2 R_1$(Watts)	$W_{n1} = \frac{W_1 - 3I_1^2 R_1}{3}$ (Watts)
400	·8	304	23	94
350	·75	293	20	91
300	·7	264	18	82
250	·75	260	20	80
200	·8	240	23	72

Table [illegible]-3: No Load Speed Test on Kramer Drive System
Stator Supply Voltage = 400V

(a) Delta-Star Connection		(b) Star-Star Connection	
I_f (Amp.)	N_r (r.p.m.)	I_f (Amp.)	N_r (r.p.m.)
0	940	0	990
.04	900	.02	955
.08	845	.04	915
.1	825	.06	880
.15	765	.08	790
.2	740	.1	725
.25	700	.15	660
.3	680	.2	620
.35	660	.25	590
.4	645	.3	550
.42	640	.35	530
		.4	515
		.45	490
		.5	480
		.6	465

APPENDIX - B

EXPERIMENTAL DATA OF BATTING

Table B-1 : Braking Test on Kramer Drive System

R_b(ohm)	I_f(Amp.)	t_b(sec.)
40	0	15
	·1	9·8
	·2	6·5
	·3	5
	·4	4
20	0	15
	·1	8·5
	·2	5·5
	·3	3·4
	·4	3
5	0	15
	·1	6·5
	·2	3·5
	·3	2·3
	·4	2

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