ANALYSIS OF A THYRISTOR–CONTROLLED D. C. SERIES MOTOR

A DISSERTATION

submitted in partial fulfilment
of the requirement for the award of the Degree
of
MASTER OF ENGINEERING
in
POWER APPARATUS & ELECTRIC DRIVES

By

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C E R T I F I C A T E

CERTIFIED that the dissertation entitled "Analysis of a thyristor-controlled d.c. series motor", which is being submitted by SRI S.L. NAKKAPAKKI, in partial fulfilment for the award of the degree of MASTER OF ENGINEERING in "POWER APPARATUS AND ELECTRIC DRIVES" of the University of Roorkee is a record of bonafide 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 about 6 months from February to August, 1976 for preparing this dissertation at this University.

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S Y N O P S I S

The operation of a thyristor controlled dc series motor fed from a single phase ac supply has been investigated.

A half controlled convertor with freewheeling diode, and associated control circuit, have been designed, fabricated and tested.

With the pulsed supply voltage to the armature circuit and assuming linear magnetic circuit, expression for armature current has been deduced using Laplace transform method.

From this expression for armature current, expressions for average and rms values of armature current, torque developed, rms value of line current, input power factor, displacement and distortion facotrs have been obtained.

A comparision between experimental and theoretical results has been made.

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LIST OF SYMBOLS

A = torque constant due to rotational less, N-m.

B = viscous torque constant due to rotational loss, N-m per radian per second

I_{av} = armature current, average value

I_{rms} = armature current, r.m.s. value

I_{Lrms} = R.M.S. line current

I_{L1} = R.M.S. fundamental component of line current

K = rotational e.m.f. coefficient, volts per ampere per radian per second.

L = $L_a + L_f$ = total armature circuit inductance in henries

N = motor speed in r.p.m.

R = $R_a + R_f$ = total armature circuit resistance in ohms

T = periodic time of supply frequency in seconds

T_e = electromagnetic torque developed by motor, N-m

T_L = load torque, N-m

V_{av} = armature voltage, average value

V_m = supply voltage, maximum value

Z = $\sqrt{(R + KW)^2 + (WL)^2}$

a_1 and b_1 = Fourier coefficients

i = armature current, instantantaneous value

v = armature voltage, instantaneous value

t_α = thyristor triggering delay time, seconds

α = thyristor triggering delay angle

θ = $\tan^{-1} \frac{WL}{R + KW}$ = armature circuit impedence angle

W = motor speed, radians per second

w = $2 \pi f$ = supply frequency in radians per second.

ϕ_1 = displacement angle between fundamental component of line current and supply voltage.

μ = distortion factor.

to negative maximum by controlling triggering angle α. However the output current is always positive. Hence power can flow from ac side to dc side (when V > 0 and I > 0) or from dc side to ac side (when V<0 and I >0). In other words, a two quadrant convertor can act as a converter as well as an invertor.

The four quadrant convertor shown in figure I-3(C) is the most versatile in as much as both the output voltage and current can be varied from positive maximum to negative maximum. They are obtained by connecting two 2-quadrant convertors in push pull. They find application in regenerative braking of motors used in electric traction, coil winders, rolling mill drives etc.

Another way of classifying convertors is based on the number of output voltage pulses obtained in one full cycle of ac input voltage.

1.3 REVIEW OF PAST WORK

The major problem in the analysis of thyristor controlled dc series motor arises due to the non-linear relation between armature induced voltage and armature current. The armature is connected to the supply terminals only during a part of the cycle. Hence equations are set up for conduction period, free-wheeling period and coasting period (if armature current is discontinuous). Due to large inductance of the armature circuit generally continuous conduction takes place. For a rigourous solution of both steady state and dynamic response numerical solution is simple algebraic equations under steady state conditions, assuming average current is equal to rms current. For any load torque and triggering angle, the two unknown quantities N and I_{av} are evaluated. Expressions for stalling torque when triggering angle is kept constant and for triggering angle at which motor stalls when torque is constant are presented. The results of I_{av} and N_{av} from the expressions developed are compared with the results of numerical analysis. There is good agreement between the two.

In the paper by Doradla and Sen(1) a study of the performance characteristics under phase control scheme and current control scheme has been presented. Voltage balance and torque balance equations for conduction period, freewheeling period and coastingperiod (when current is discontinuous) are set up. Assuming constant speed, voltage balance equations for conduction period and freewheeling period are solved and expressions for current are obtained. The solution of these equations greatly reduces computer time compared to the solutions of basic voltage balance and torque balance differential equations. The difference between the two is claimed to be less than ± 1%. After establishing steady state condition at a particular speed and triggering angle, the information obtained from the last cycle of current is used to determine the performance quantities, viz., r.m.s. armature current, supply rms current, Fourier coefficients, hence torque developed, input power factor etc. are calculated. Phase control scheme and current control scheme are compared. Improved power factor, continuous conduction under all load conditions, limitation on peak current reduced ripple and hence commutating capability of motor are possible with current control scheme.

In another paper by Dorodla and Sen[2] two more methods of control, viz., symmetrical and extinction angle control, are presented. Analysis is same as above. These methods are mainly concerned with the improvement of input power factor. In the extinction angle control scheme power factor tends to be leading.

1.4 SUMMARY OF THE PRESENT WORK

The operation of a thyristor controlled dc series motor fed from a single phase ac supply has been investigated.

A half controlled convertor with freewheeling diode, and associated control circuit, have been designed, fabricated and tested.

With the pulsed supply voltage to the armature circuit and assuming linear magnetic circuit, expression for armature current has been deduced using Laplace transform method.

From this expression for armature current, expressions for average and rms values of armature current, torque developed, rms value of line current, input power factor displacement and distortion factors have been obtained.

A comparision between experimental and theoretical results has been made.

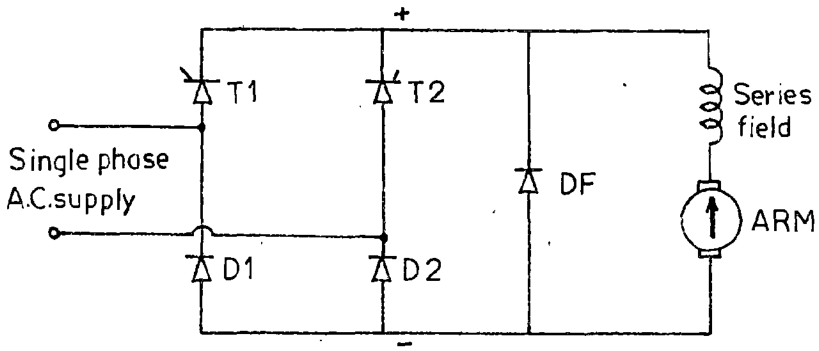


Figure I-1 _ Half controlled convertor for D.C.series motor.

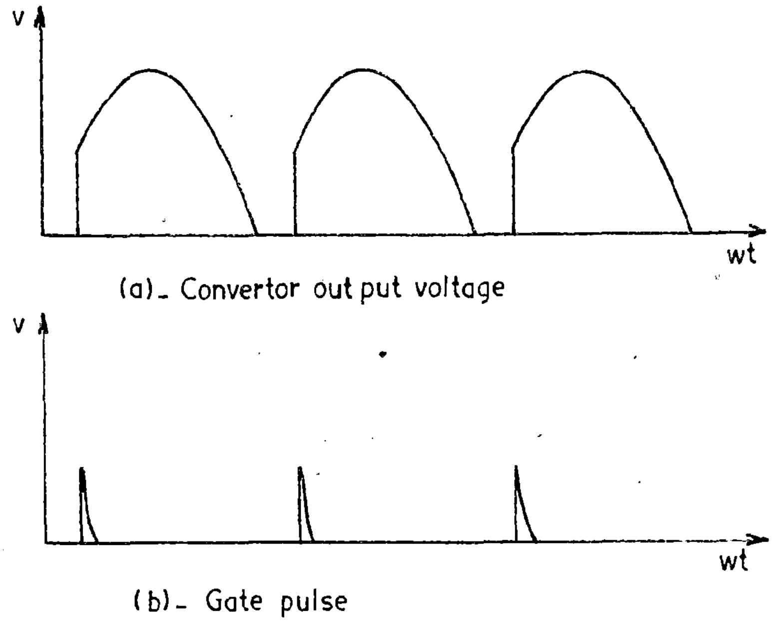


Figure I - 2

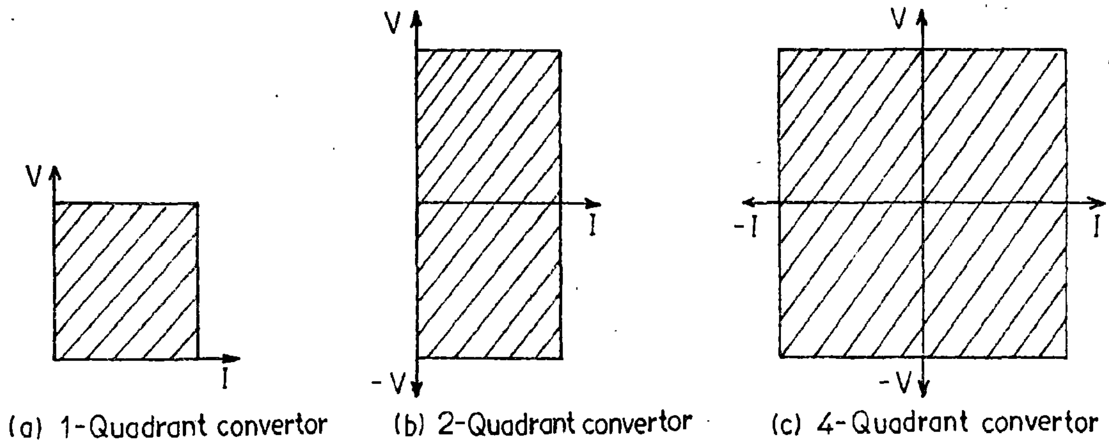


Figure I-3_ Types of convertors.

CHAPTER-II

STEADY STATE ANALYSIS

In this Chapter expressions for armature current, torque, rms value of line current, distortion factor etc. are developed. With the pulsed voltage applied to the armature circuit, expression for armature current is obtained using the Laplace transform method.

2.1 EXPRESSION FOR ARMATURE CURRENT

The following assumptions have been made:-

(1) Resistance and inductance of armature circuit are assumed constant.

(2) Thyristors and diodes are assumed to be ideal switches.

(3) Speed is assumed constant, in other words mechanical time constant is large.

(4) Iron losses are neglected.

(5) Rotational voltage due to residual magnetism is neglected.

(6) Rotational voltage coefficient has been assumed constant.

(7) Since d.c. series motors have large inductance, continuous conduction has been assumed.

Referring to figure 2.1, the voltage balance equation is,

$$iR + L\frac{di}{dt} + K\ i = v \qquad \ldots\ldots (1)$$

Taking Laplace transform and considering i_o to be initial value of current,

$$I(S) = \frac{V(s)}{L(s + \frac{R + K W}{L})} + \frac{i_o}{(s + \frac{R + KW}{L})} \quad \ldots \quad (2)$$

Where V(s) is the Laplace transform of the applied voltage.

Now, for steady state analysis, only response to a single voltage pulse is necessary[6]. This is because of the fact that, the response to subsequent pulses in steady state is same as the response to one pulse considered and the magnitude of response at the beginning of a pulse is same as that at the end of the previous pulse.

The single pulse applied to armature circuit shown in figure 2.2, is expressed by using a gate function, which has a magnitude of unity during pulse period and zero elsewhere.

Hence,

$$V(s) = \mathcal{L}\left[V_m \sin\left(\frac{2\pi}{T} t\right) . \left[u(t-t_\alpha) - u(t-T/2)\right]\right]$$

$$= \mathcal{L}\left[V_m \sin\left(\frac{2\pi}{T} t\right) \; u(t-t_\alpha)\right]$$

$$- \mathcal{L}\left[V_m \sin\left(\frac{2\pi}{T} t\right) \; u\left(t - \frac{T}{2}\right)\right]$$

$$= \frac{V_m e^{-t_\alpha s} \left[\frac{2\pi}{T} \cos\left(\frac{2\pi}{T} t_\alpha\right) + s.\sin\left(\frac{2\pi}{T} t_\alpha\right)\right]}{s^2 + \left(\frac{2\pi}{T}\right)^2}$$

$$+ \frac{V_m e^{-\left(\frac{Ts}{2}\right)} . \frac{2\pi}{T}}{s^2 + \left(\frac{2\pi}{T}\right)^2} \quad \ldots \quad (3)$$

Substituting for V(S) in euqation (2),

$$I(S) = \frac{V_m}{L} e^{-(t\alpha S)} \frac{\frac{2\pi}{T}\cos\left(\frac{2\pi}{T} t\alpha\right)}{\left(S + \frac{R+KW}{L}\right)\left(S^2 + \left(\frac{2\pi}{T}\right)^2\right)}$$

$$+ \frac{V_m}{L} e^{-(t\alpha S)} \frac{S.\sin\left(\frac{2\pi}{T} + \alpha\right)}{\left(S + \frac{R+KW}{L}\right)\left(S^2 + \left(\frac{2\pi}{T}\right)^2\right)}$$

$$+ \frac{V_m}{L} e^{-\left(\frac{T_S}{2}\right)} \frac{2\pi / T}{\left(S + \frac{R+KW}{L}\right)\left(S^2 + \left(\frac{2\pi}{T}\right)^2\right)}$$

$$+ \frac{i_o}{\left(S + \frac{R+KW}{L}\right)} \qquad \ldots\ldots \quad (4)$$

Taking inverse transform,

$$i = \frac{V_m}{L} \cdot \frac{2\pi}{T} \cdot \cos\left(\frac{2\pi}{T} t\alpha\right) \left\{ \frac{1}{\left(\frac{R+KW}{L}\right)^2 + \left(\frac{2\pi}{T}\right)^2} \times \right.$$

$$\left[e^{-\left(\frac{R+KW}{L}\right)(t - t\alpha)} \right.$$

$$\left. \left. + \frac{1}{2\pi/T} \cdot \left(\left(\frac{R+KW}{L}\right)^2 + \left(\frac{2\pi}{T}\right)^2\right)^{1/2} .\sin\left(\frac{2\pi}{T}(t - t_\alpha) - \theta\right) \right] \right\}$$

$$\times u(t - t_\alpha)$$

$$+ \frac{V_m}{L} \sin\left(\frac{2\pi}{T} t_\alpha\right) \left\{ \frac{-\frac{R+KW}{L}}{\left(\frac{R+KW}{L}\right)^2 + \left(\frac{2\pi}{T}\right)^2} \times \right.$$

$$e^{-\left(\frac{R+KW}{L}\right)(t-t_\alpha)}$$

$$-\frac{1}{\left(\frac{R+KW}{L}\right)}\left(\left(\frac{R+KW}{L}\right)^2+\left(\frac{2\pi}{T}\right)^2\right)^{1/2}$$

$$\left.\left.\cdot\cos\left(\frac{2\pi}{T}(t-t_\alpha)-\theta\right)\right]\right\} \quad u(t-t_\alpha)$$

$$+\frac{V_m}{L}\cdot\frac{2\pi}{T}\left\{\frac{1}{\left(\frac{R+KW}{L}\right)^2+\left(\frac{2\pi}{T}\right)^2}\times\right.$$

$$e^{-\left(\frac{R+KW}{L}\right)\left(t-\frac{T}{2}\right)}$$

$$\left.+\left(\frac{\left(\left(\frac{R+KW}{L}\right)^2+\left(\frac{2\pi}{T}\right)^2\right)^{1/2}}{2\pi/T}\right)\sin\left(\frac{2\pi}{T}\left(t-\frac{T}{2}\right)-\theta\right]\right\}$$

$$\times u(t-T/2)+i_o\,e^{-\frac{(R+KW)}{L}t}$$

Where,

$$\theta=\tan^{-1}\left(\frac{\frac{2\pi}{T}L}{R+KW}\right)$$

Putting $\frac{2\pi}{T}=w$, $\omega t_\alpha=\alpha$, $\frac{wL}{R+KW}=\tan\theta$,

$$Z=\left(\left(\frac{R+KW}{L}\right)^2+(wL)^2\right)^{1/2}$$

$\sin\theta=\frac{wL}{Z}$ and $\cos\theta=\frac{R+KW}{Z}$

$$i = \Big[\frac{V_m}{Z} \sin\theta \cos\alpha \; e^{-\left(\frac{wt-\alpha}{\tan\theta}\right)}$$

$$+ \frac{V_m}{Z} \sin(wt - \alpha - \theta)\cos\alpha$$

$$- \frac{V_m}{Z} \cos\theta \sin\alpha \; e^{-\left(\frac{wt-\alpha}{\tan\theta}\right)} + \frac{V_m}{Z} \cos(wt - \alpha - \theta)\sin\alpha \Big]$$

$$\times u(t - t_\alpha)$$

$$+ \left[\frac{V_m}{Z} \sin\theta \; e^{-\left(\frac{wt-\pi}{\tan\theta}\right)} - \frac{V_m}{Z} \sin(wt - \theta) \right]$$

$$\times u(t - T/2) + i_o \, e^{-\left(\frac{wt}{\tan\theta}\right)}$$

Simplifying,

$$i = \frac{V_m}{Z} \sin(wt - \theta) \left[u(t - t_\alpha) - u(t - T/2) \right]$$

$$+ \frac{V_m}{Z} \sin(\theta - \alpha) \; e^{-\left(\frac{wt-\alpha}{\tan\theta}\right)} \; u(t - t_\alpha)$$

$$+ \frac{V_m}{Z} \sin\theta \; e^{-\left(\frac{wt-\pi}{\tan\theta}\right)} \cdot u(t - T/2) + i_o \, e^{-\left(\frac{wt}{\tan\theta}\right)} \quad \ldots\ldots (5)$$

Since $i = i_o$ at $t = T/2$,

$$i_o = \frac{V_m}{Z} \sin\theta + \frac{V_m}{Z} \sin(\theta - \alpha) \; e^{-\left(\frac{\pi-\alpha}{\tan\theta}\right)} + i_o \, e^{-(\pi/\tan\theta)}$$

$$\therefore \; i_o = \frac{1}{(1 - e^{-\pi/\tan\theta})} \frac{V_m}{Z} \left[\sin\theta + \sin(\theta - \alpha) \, e^{-((\pi-\alpha)/\tan\theta)} \right] \quad \ldots\ldots (6)$$

2.2 AVERAGE VALUE OF ARMATURE CURRENT, I_{av}

Average value of armature current is obtained by integrating expression (5) over one pulse and taking average value of the same.

$$I_{av} = \frac{1}{\pi} \int_0^{\pi} i \, dwt$$

$$= \frac{1}{\pi} \left\{ \int_0^{\pi} i_o \, e^{-(wt/\tan\theta)} \, dwt + \int_{\alpha}^{\pi} \left[V_m / Z \; \sin(wt - \theta) + \sin(\theta - \alpha) \, e^{-\left(\frac{wt - \alpha}{\tan\theta}\right)} \right] dwt \right\}$$

$$= \frac{1}{\pi} \left| i_o \tan\theta \, (1 - e^{-\pi/\tan\theta}) + V_m/Z \left[\cos(\alpha - \theta) + \cos\theta \right] + V_m/Z \sin(\theta - \alpha) \tan\theta \left(1 - e^{-\left(\frac{\pi - \alpha}{\tan\theta}\right)}\right) \right|$$

Substituting for $i_o \, (1 - e^{-\pi/\tan\theta})$ from (6),

$$I_{av} = 1/\pi \left\{ V_m/Z \tan\theta \left[\sin\theta + \sin(\theta - \alpha) \, e^{-((\pi - \alpha)/\tan\theta)} \right] + \frac{V_m}{Z} \left[\cos(\alpha - \theta) + \cos\theta \right] + \frac{V_m}{Z} \sin(\theta - \alpha) \tan\theta \left(1 - e^{-((\pi - \alpha)/\tan\theta)}\right) \right\}$$

Simplifying,

$$I_{av} = V_m / \pi Z \cos\theta \left| \sin^2\theta + \cos(\alpha - \theta) . \cos\theta + \cos^2\theta + \sin(\theta - \alpha) \sin\theta \right|$$

$$= \frac{V_m}{\pi Z \cos\theta} (1 + \cos\alpha) \quad \ldots\ldots \quad (7)$$

Now, for half controlled rectifier with freewheeling diode average output voltage,

$$V_{av} = \frac{V_m}{\pi} (1 + \cos \alpha) \quad \ldots\ldots\ldots \quad (8)$$

Substituting (8) into (7) and noting that $Z \cos \theta = R + KW$

$$I_{av} = \frac{V_{av}}{R + KW} \quad \ldots\ldots \quad (9)$$

2.3 RMS VALUE OF ARMATURE CURRENT, I_{rms}

Expression for I^2_{rms} is given by,

$$I^2_{rms} = \frac{1}{\pi} \int_0^{\pi} i^2 \, dwt$$

$$= \frac{1}{\pi} \left\{ \int_0^{\pi} i_o^2 \; e^{-\left(\frac{2wt}{\tan\theta}\right)} dwt + \left(\frac{V_m}{Z}\right)^2 \int_{\alpha}^{\pi} \left[\sin(wt-\theta) + \sin(\theta-\alpha)\, e^{-\left(\frac{wt-\alpha}{\tan\theta}\right)}\right]^2 dwt \right.$$

$$+ \frac{2 i_o V_m}{Z} \int_{\alpha}^{\pi} \left[\sin(wt-\theta) + \sin(\theta-\alpha)\, e^{-\left(\frac{wt-\alpha}{\tan\theta}\right)}\right] e^{-\left(\frac{wt}{\tan\theta}\right)}($$

$$= \frac{1}{\pi} \left[\int_0^{\pi} i_o^2 \quad e^{-\left(\frac{2wt}{\tan\theta}\right)} dwt + \left(\frac{V_m}{Z}\right)^2 \int_{\alpha} \sin^2(wt-\theta)\, dwt \right.$$

$$+ \left(\frac{V_m}{Z}\right)^2 \sin^2(\theta-\alpha)\; e^{2\alpha/\tan\theta} \int_{\alpha}^{\pi} e^{-\left(\frac{2wt}{\tan\theta}\right)} dwt$$

$$+ 2\left(\frac{V_m}{Z}\right)^2 \sin(\theta-\alpha)\; e^{\alpha/\tan\theta} \int_{\alpha}^{\pi} \sin(wt-\theta)\, e^{-\frac{wt}{\tan\theta}}\, dw$$

$$+ \frac{2 i_o V_m}{Z} \int_{\alpha}^{\pi} \sin(wt-\theta)\; e^{-\left(\frac{wt}{\tan\theta}\right)} dwt + \frac{2 i_o V_m}{Z}$$

$$\left. \sin(\theta-\alpha)\; e^{\alpha/\tan\theta} \int_{\alpha}^{\pi} e^{-\left(\frac{2wt}{\tan\theta}\right)} dwt \right\}$$

— — — (10)

Where,

$$\int_0^{\pi} e^{-\left(\frac{2\,wt}{\tan\theta}\right)}\,dwt = \left[\frac{e^{-\left(\frac{2wt}{\tan\theta}\right)}}{-2/\tan\theta}\right]_0^{\pi} = \frac{\tan\theta}{2}$$

$$\left(1 - e^{-\left(\frac{2\pi}{\tan\theta}\right)}\right) \quad \ldots\ldots \quad (11)$$

$$\int_{\alpha}^{\pi} e^{-\left(\frac{2wt}{\tan\theta}\right)}\,dwt = \frac{\tan\theta}{2}\left(e^{-\left(\frac{2\alpha}{\tan\theta}\right)} - e^{-\left(\frac{2\pi}{\tan\theta}\right)}\right) \ldots (\,$$

$$\int_{\alpha}^{\pi} \sin^2(wt-\theta)\,dwt = \frac{1}{2}\int_{\alpha}^{\pi}\left[1 - \cos 2\,(wt-\theta)\,dwt\right]$$

$$= \frac{1}{2}\left[wt - \frac{\sin 2\,(wt-\theta)}{2}\right]_{\alpha}^{\pi}$$

$$= \frac{1}{2}\left[(\pi-\alpha) + \frac{\sin 2\theta - \sin 2\,(\theta-\alpha)}{2}\right]$$

$$= \frac{1}{2}\left[(\pi-\alpha) + \cos\,(2\theta-\alpha)\,\sin\alpha\right] \quad \ldots\ldots \ (13)$$

and

$$\int_0^{\pi} \sin(wt-\theta)\,e^{-\left(\frac{wt}{\tan\theta}\right)}\,dwt = \frac{\tan\theta}{1+\tan^2\theta}$$

$$\left[-\sin(wt-\theta)\,e^{-\left(\frac{wt}{\tan\theta}\right)} - \tan\theta\,\cos(wt-\theta) \times e^{-\left(\frac{wt}{\tan\theta}\right)}\right]_{\alpha}^{\pi}$$

$$= \sin\theta\,\cos\theta\left[\sin(\alpha-\theta)\,e^{-\alpha/\tan\theta} + \tan\theta\,\cos(\alpha-\theta)\,e^{-\alpha/\tan\theta}\right]$$

$$= \sin\theta\,\sin\alpha\,e^{-\alpha/\tan\theta} \quad \ldots\ldots \quad (14)$$

Substituting for i_o from (6) and for other terms from (11) to (14) in (10),

$$I_{rms}^2 = \frac{1}{\pi} \left[\left(\frac{V_m}{Z}\right)^2 \frac{\tan\theta}{2} \left(\frac{1 + e^{-\pi/\tan\theta}}{1 - e^{-\pi/\tan\theta}} \right) \right.$$

$$\left(\sin^2\theta + \sin^2(\theta-\alpha)\, e^{-2\left(\frac{\pi-\alpha}{\tan\theta}\right)} \right.$$

$$\left. + 2 \sin\theta \,.\, \sin(\theta-\alpha)\, e^{-\left(\frac{\pi-\alpha}{\tan\theta}\right)} \right) + \frac{1}{2} \left(\frac{V_m}{Z}\right)^2$$

$$\sin(\theta - \alpha)\sin\theta . \sin\alpha$$

$$+ 2 \left(\frac{V_m}{Z}\right)^2 \left(\frac{1}{1-e^{-\pi/\tan\theta}} \right) \left[\sin\theta + \sin(\theta-\alpha)\, e^{-\left(\frac{\pi-\alpha}{\tan\theta}\right)} \right]$$

$$\sin\theta \sin\alpha \quad e^{-\alpha/\tan\theta}$$

$$+ 2 \left(\frac{V_m}{Z}\right)^2 \left(\frac{1}{1 - e^{-\pi/\tan\theta}} \right)$$

$$\left[\sin\theta + \sin(\theta-\alpha)\, e^{-\left(\frac{\pi-\alpha}{\tan\theta}\right)} \right] \frac{\tan\theta}{2} \,.\, \sin(\theta - \alpha)$$

$$\left. \times \left(e^{-\alpha/\tan\theta} - e^{-\left(\frac{2\pi-\alpha}{\tan\theta}\right)} \right) \right]$$

On simplifying and rearranging the terms,

$$I_{rms}^2 = \frac{V_m^2}{2\pi Z^2} \left[(\pi - \alpha) + \cos(2\theta - \alpha)\sin\alpha + \frac{4 \sin\theta \sin\alpha}{(1-e^{-\pi/\tan\theta})} \right.$$

$$\times \left(\sin(\theta-\alpha) + \sin\theta\, e^{-\alpha/\tan\theta} \right) + \frac{\tan\theta}{(1-e^{-\pi/\tan\theta})} \times$$

$$\left[(\sin^2(\theta - \alpha) + \sin^2\theta)(1 + e^{-\pi/\tan\theta}) \right.$$

$$\left. + 2\sin(\theta-\alpha)\sin\theta \left(e^{-\alpha/\tan\theta} + e^{-\left(\frac{\pi-\alpha}{\tan\theta}\right)} \right) \right]$$

2.4 RMS VALUE OF LINE CURRENT, I_{Lrms}.

Since the motor is connected to supply terminals during the conduction period only ($\alpha \leqslant wt \leqslant \pi$), the expression for line current from expression (5) is given by

$$i_L = \frac{V_m}{Z} \sin (wt - \theta) + \frac{V_m}{Z} \sin (\theta - \alpha)\, e^{-\left(\frac{wt-\alpha}{\tan \theta}\right)} + i_o e^{-\left(\frac{wt}{\tan \theta}\right)} \quad \ldots\ldots \alpha \leqslant wt \leqslant \pi \quad \ldots($$

Hence,

$$I^2_{Lrms} = \frac{1}{\pi} \int_o^{\pi} i_L^2 \, dwt$$

$$= \frac{1}{\pi} \int_{\alpha}^{\pi} \left[\frac{V_m}{Z} \sin (wt - \theta) + \frac{V_m}{Z} \sin (\theta - \alpha)\, e^{-\left(\frac{wt-\alpha}{\tan \theta}\right)} + i_o e^{-\left(\frac{wt}{\tan \theta}\right)} \right]^2 dwt$$

$$= \frac{1}{\pi} \Bigg[\left(\frac{V_m}{Z} \right)^2 \int_{\alpha}^{\pi} \sin^2 (wt - \theta)\, dwt + \left(\frac{V_m}{Z} \right)^2 \sin^2 (\theta - \alpha)\, e^{\frac{2\alpha}{\tan \theta}} \int_{\alpha}^{\pi} e^{-\left(\frac{2wt}{\tan \theta} \right)} dwt + i_o^2 \int_{\alpha}^{\pi} e^{-\left(\frac{2wt}{\tan \theta}\right)} dwt +$$

$$2 \left(\frac{V_m}{Z}\right)^2 \sin (\theta - \alpha)\, e^{\alpha / \tan \theta} \int_{\alpha}^{\pi} \sin (wt - \theta)\, e^{-\left(\frac{wt}{\tan \theta} \right)} dwt + \frac{2 i_o V_m}{Z} \int_{\alpha}^{\pi} \sin (wt - \theta)\, e^{-\left(\frac{wt}{\tan \theta} \right)}$$

$$dwt + \frac{2 i_o V_m}{Z} \sin(\theta - \alpha) \, e^{\alpha / \tan \theta} \int_{\alpha}^{\pi} e^{-\left(\frac{2 wt}{\tan \theta}\right)} dwt \Bigg]$$

Substituting for i_o from (6) and for other terms from (12) to (14).

$$I^2_{Lrms} = \frac{1}{\pi} \Bigg\{ \frac{1}{2} \left(\frac{V_m}{Z}\right)^2 \Big[(\pi - \alpha) + \cos(2\theta - \alpha) \sin \alpha \Big]$$

$$+ \frac{1}{2} \left(\frac{V_m}{Z}\right)^2 x \sin^2(\theta - \alpha) \tan \theta \left(1 - e^{-2\left(\frac{\pi - \alpha}{\tan \theta}\right)}\right.$$

$$+ \left(\frac{V_m}{Z}\right)^2 \frac{1}{(1 - e^{-\pi / \tan \theta})^2}$$

$$x \Big[\sin^2 \theta + \sin^2(\theta - \alpha) \, e^{-2\left(\frac{\pi - \alpha}{\tan \theta}\right)}$$

$$+ 2 \sin \theta . \sin(\theta - \alpha) \, e^{-\left(\frac{\pi - \alpha}{\tan \theta}\right)} \Big]$$

$$x \frac{\tan \theta}{2} \left(e^{-\left(\frac{2 \alpha}{\tan \theta}\right)} - e^{-\left(\frac{2\pi}{\tan \theta}\right)} \right) + 2 \left(\frac{V_m}{Z}\right)^2$$

$$\sin(\theta - \alpha) \sin \theta \sin \alpha + 2 \left(\frac{V_m}{Z}\right)^2 \frac{1}{(1 - e^{-\pi / \tan \theta})}$$

$$\Big[\sin \theta + \sin(\theta - \alpha) \, e^{-\left(\frac{\pi - \alpha}{\tan \theta}\right)} \Big] \sin \theta \sin \alpha \, e^{-\alpha /}$$

$$+ 2 \left(\frac{V_m}{Z}\right)^2 \frac{1}{(1 - e^{-\pi / \tan \theta})} \Big[\sin \theta + \sin(\theta - \alpha)$$

$$-\left(\frac{\pi - \alpha}{\tan \theta}\right) \Big] \sin(\theta - \alpha) \; x \; \frac{\tan \theta}{2}$$

$$\left(e^{-\alpha / \tan \theta} - e^{-\left(\frac{2\pi - \alpha}{\tan \theta}\right)} \right) \Bigg\}$$

Simplifying and rearranging the terms

$$I_{Lrms}^2 = \frac{V_m^2}{2\pi Z^2} \Bigg\{ (\pi - \alpha) + \cos(2\theta - \alpha) \sin\alpha +$$

$$+ \frac{4 \sin\theta \cdot \sin\theta}{(1 - e^{-\pi/\tan\theta})} \times (\sin(\theta - \alpha) + \sin\theta\, e^{-\alpha/\tan\theta})$$

$$+ \frac{\tan\theta}{(1 - e^{-\pi/\tan\theta})^2} \times \Big[(\sin(\theta - \alpha) + \sin\theta\, e^{-\alpha/\tan\theta})^2$$

$$(1 - e^{-2\left(\frac{\pi - \alpha}{\tan\theta}\right)}) \Big] \Bigg\} \quad \ldots\ldots (17)$$

2.5 FOURIER COEFFICIENTS OF LINE CURRENT

To determine the displacement and distortion factors it becomes necessary to know the Fourier coefficients of the line current waveform.

$$a_1 = \frac{2}{\pi} \int_0^{\pi} i_L \cos wt\, dwt$$

Substituting the expression for i_L from (16),

$$a_1 = \frac{2}{\pi} \int_{\alpha}^{\pi} \Big[\frac{V_m}{Z} \sin(wt - \theta) + \frac{V_m}{Z} \sin(\theta - \alpha)$$

$$e^{-\left(\frac{wt - \alpha}{\tan\theta}\right)} + i_o\, e^{-\left(\frac{wt}{\tan\theta}\right)} \Big] \cos wt\, dwt$$

$$\ldots (18)$$

Where,

$$\int_{\alpha}^{\pi} \sin(wt - \theta) \cos wt\, dwt = \frac{1}{2} \int_{\alpha}^{\pi} \Big[-\sin\theta + \sin(2wt - \theta) \Big]$$

where V_{av} and I_{av} are given by (8) and (9), V_L is rms value of applied voltage and I_L is rms value of line current given by expression (17).

(C) Displacement angle is defined as the angle between line voltage and fundamental component of line current. Cosine of displacement angle, ϕ_1, is called displacement factor or fundamental power factor.

Fundamental component of line current is obtained from Fourier coefficients a_1 and b_1 of line current (21) and (22)

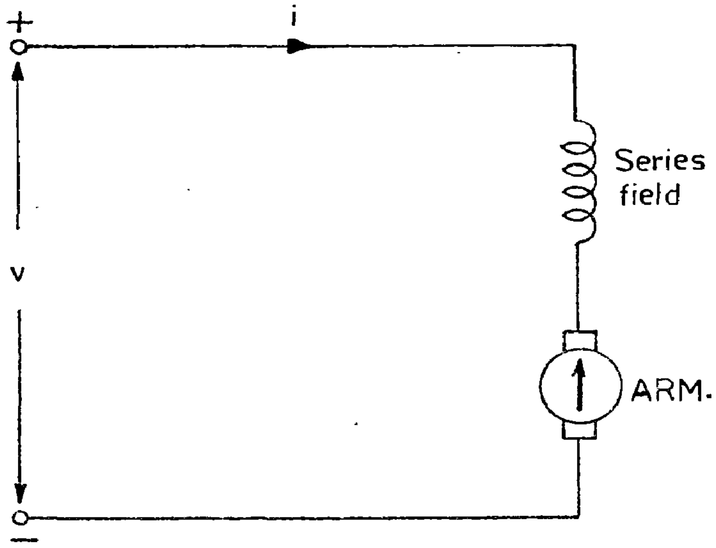
$$I_{L1} = \sqrt{(a_1^2 + b_1^2)/2} \quad \ldots\ldots\ldots \quad (26)$$

$$\phi_1 = \text{displacement angle} = \tan^{-1} a_1/b_1 \quad \ldots. \quad (27)$$

$$\text{displacement factor} = \cos \phi_1 \quad \ldots. \quad (28)$$

(D) Distortion factor is defined as the ratio of fundamental component of line current to rms value of line current.

$$\text{distortion factor } \mu = \frac{I_{L1}}{I_L} \quad \ldots. \quad (29)$$



$$R = R_a + R_f$$

$$L = L_a + L_f$$

Figure-II-1 _ Pulse controlled D.C. series motor.

$$v = V_M \sin(2\pi/t)\,\{u(t-t_\alpha) - u(t-T/2)\}$$

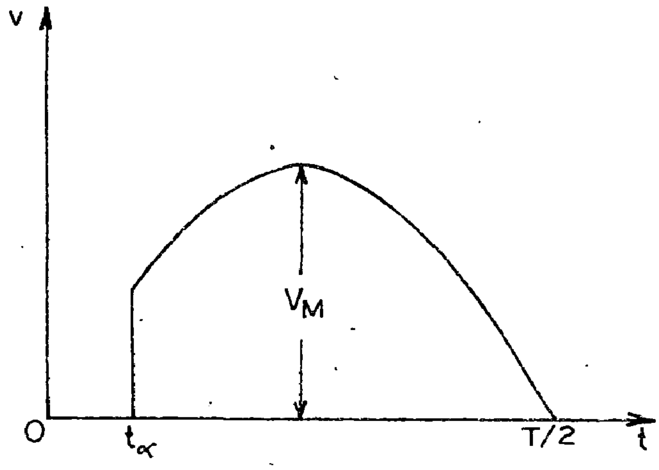


Figure-II-2 _ Single pulse applied to armature circuit.

CHAPTER-III

DESIGN AND FABRICATION OF A HALF CONTROLLED CONVERTOR

A half controlled convertor with freewheeling diode has been used for the control of a 3HP dc series motor. In this chapter the design of the convertor, and control circuit and its operation has been given.

3.1 POWER CIRCUIT

The power circuit, shown in figure III-1, consists of a single phase, half controlled convertor, with freewheeling diode. Common cathode configuration has been used. The line transient suppression circuit has been used for the over voltage protection of thyristors and diodes.

3.1.1 Selection Of Power Circuit Components[10]-

Specifications of dc series motor:

220V, 12.8A 3 HP

1450 rpm Max. 3500 rpm

Supply voltage is 230 V, 50 Hz.

Therefore peak inverse voltage on thyristors and diodes will be $\sqrt{2} \times 230 = 325$ Volts. Allowing a safety factor of, say 2,-SO that thyristors and diodes can comfortably take a reasonable transient overvoltage, devices with 600 V ratings can be used.

D.C. motor current rating is 12.8A. Allowing an overload capacity of twice full load current, 26A rated thyristors and diodes may be used. Since conduction is not over full 180^o, a derating of 15% is usually considered. So 28A thyristors and diodes for bridge circuit will be satisfactory.

Since the current rating of the freewheeling diode need only be 70% of bridge circuit device, a 20A diode for the same is chosen.[7]

Overvoltage protection[7] is provided by using a surge suppression circuit, consisting of 4 µF, 400V a.c. capacitor in series with a 10 Ohms, 2W resistor, connected across input terminals. A 50 K, 3 W resistor is connected across the capacitor which provides a path for discharging stored energy.

Overcurrent protection is obtained by using a fuse whose I^2t rating is less than that of thyristors.

Specifications of thyristors and diodes actually used are given in Appendix A.

3.2 CONTROL CIRCUIT[9]

The control circuit consists of a unijunction transistor relaxation oscillator. The output pulses of this oscillator are used to control the firing delay angle of the thyristors.

For the control circuit shown in figure III-2, the rectified pulses from bridge rectifier(A) are clipped to square waves of about 18V by zener (two 9.1 zeners in series). These rectangular pulses are used for charging the capacitor C_c. The rate of charging is decided by resistance R_C. The voltage across capacitor will try to rise upto V_B i.e. 18V, but when it reaches a value ηV_B, uJT goes into conduction and capacitor discharges through emitter and base 1 of uJT and the resistance R_{B1}. Thus a pulse output is obtained. Since at the end of each half cycle the input to charging circuit goes to zero, the pulses appear at the same instant during each half cycle. The pulses are given to the gates of thyristors through diodeo D_7 and D_8.

The design of the control circuit is carried out in the following way.

3.2.1 UJT RELAXATION OSCILLATOR

Specifications of 2N2646 UJT

R_{BBO}	Inter base resistance (KΩ) at the rate of V_{BB} = 3V, I_E = 0	4.7 - 9.1
η	Stand off ratio @ V_{BB}=10V	0.56 - 0.75
I_V	Valley current minimum (mA.)	4
I_P	peak point emitter current (μA)	5
I_{EO}	Emitter reverse current maximum(μA) T_j = 25° @ V_{B2E}=30V	12
V_{OB1}	Base one peak pulse voltage minimum (V)	3

For thyristor 28TB6,

P_G	Average dc gate power (W)	1
I_{GT}	Gate trigger current (mA)	100.

Maximum gate voltage which will not trigger any device is 250 mV.

Design:- Thyristor turn on time say 5 μS, and taking gate Power to be 2W,

Turn on energy = $2 \times 5 \times 10^{-6} = 10^{-7}$ watt seconds.

$$\therefore \frac{1}{2} (C\ \eta^2\ V_b^2) = 10^{-7}$$

$$\therefore \quad C_{min} = \frac{2 \times 10^{-7}}{0.56^2 \times 18^2} \simeq 2\ \mu F.$$

So selecting $C_c = 0.3\ \mu F$

Now $T = RC \ln \frac{1}{1 - \eta}$

control required is from 0 to 180° i.e. 10 ms (50 Hz)

$$\text{i.e.} \quad 10 \times 10^{-3} S = R \times 0.3 \times 10^{-6} \times \frac{1}{1 - 0.56}$$

$$\therefore \quad R_{max} = 36\ K$$

and minimum value considering delay of 0.5 mS.

$R_{min} = 2\ K$

So R_C consists of 100 K potentiometer in series with 2.2K.

Choosing 100 Ohms for R_{B1}.

$$R_{B2} = \frac{10{,}000}{\eta\ V_B} \simeq 1.5\ K$$

3.2.2 SYNCHRONIZATION(9)

Zener TSZ 9.1 - 9.1V, R_z ... @ 10 mA, 12 Ω, Pd = 0.75W.

Bridge rectifier (A) using BYX127 diodes (1A current rating and PIV1200) is connected to supply through an isolating transformer. The half sinusoids are clipped to square waves of 18V by two zeners, 1SZ9.1, in series. The rest of the voltage is dropped across a series resistance R_S(8 K , 20 W). These rectangular pulses are applied to the charging circuit of oscillator, wherein the capacitor is discharged at the end of each half cycle, and hence the pulses will be synchronised with the supply and fire at the same instant during each half cycle.

The output pulses of UJT are fed to thyristor gates through diodes (BYX126).

3.2.3 DESIGN OF ISOLATING TRANSFORMER[11]

Allowing for any future additions to control circuitry , a 20VA, 1:1 ratio power transformer has been designed.

<u>CORE</u>

$$T_e = \text{turns per Volt} = 14, \quad E = 4.44 f \phi_m T$$

$$\phi_m = \frac{1}{4.44 f T_e} = \frac{1}{4.44 \times 50 \times 14}$$

A_1 = net iron cross section required $= \frac{10^4}{4.44 \times 50 \times 14} = 3.22c$

Gross iron cross section $A_G = \frac{A_1}{0.9} = 3.58 \text{ cm}^2$

Using a square section, width of core $A = \sqrt{3.58} = 1.9$cm.

WINDING

Primary current $I_p = \frac{20}{230} \approx 100$ mA (Say)

Using a current density of 2.3A /mm^2

area of conductor ap $= \frac{0.1}{2.3} = 0.0435$ mm^2

Diameter of bare conductor $d_p = \sqrt{\frac{4}{\pi} \times 0.0435}$

$= 0.236$ mm

Diameter of enamelled wire = 0.302

Number of turns T_p = 230 x 14 = 3220 turns.

The specifications for secondary winding are same.

WINDOW AREA

Space factor $= 0.8 \left(\frac{0.236}{0.302}\right)^2 = 0.625$

W_p window space for primary winding $= \frac{3220 \times 0.236}{0.625}$

$= 122$ mm^2.

A_w = window area = 1.2(122 + 122) = 292 mm^2

Using E and I stampings.

A = 2.5 cm, L = 3.3 cm, W = 1.25 cm.

0.236 mm bare dia super enamelled copper wire has been used.

3.3 CONVERTOR

A half controlled circuit with freewheeling diode is shown in figure III-3. When the upper terminal is positive and thyristor T1 is triggered, the load current flows through T1 and D2. At the end of half cycle load current is transferred to freewheeling diode D_F and T_1 is line commutated. The process repeats during the next half cycle with T2 and D1 conducting. The average output voltage is given by

$$V_{av} = \frac{V_m}{\pi} (1 + \cos \alpha)$$

and α is set by resistance R_C in control circuit.

3.4 CONVERTOR AND MOTOR

For starting R_C is kept maximum and convertor output voltage is zero. Then R_C is progressively x cutout until the desired speed is obtained. The speed control is obtained by varying the armature voltage which in turn can be achieved by varying R_C.

APPENDIX -A

The following available components have been used in the power circuit.

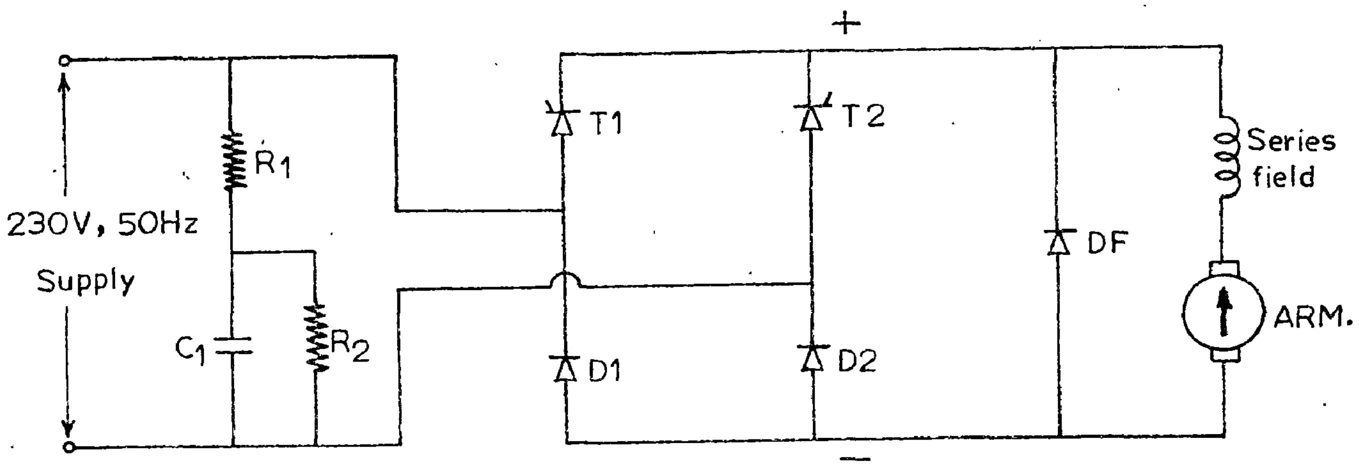
4R15 - Power diodes for bridge circuit and freewheeling.

Maximum average forward current	15A
PIV	320V.

28TB5 - Convertor grade SCR - Mind rectifiers

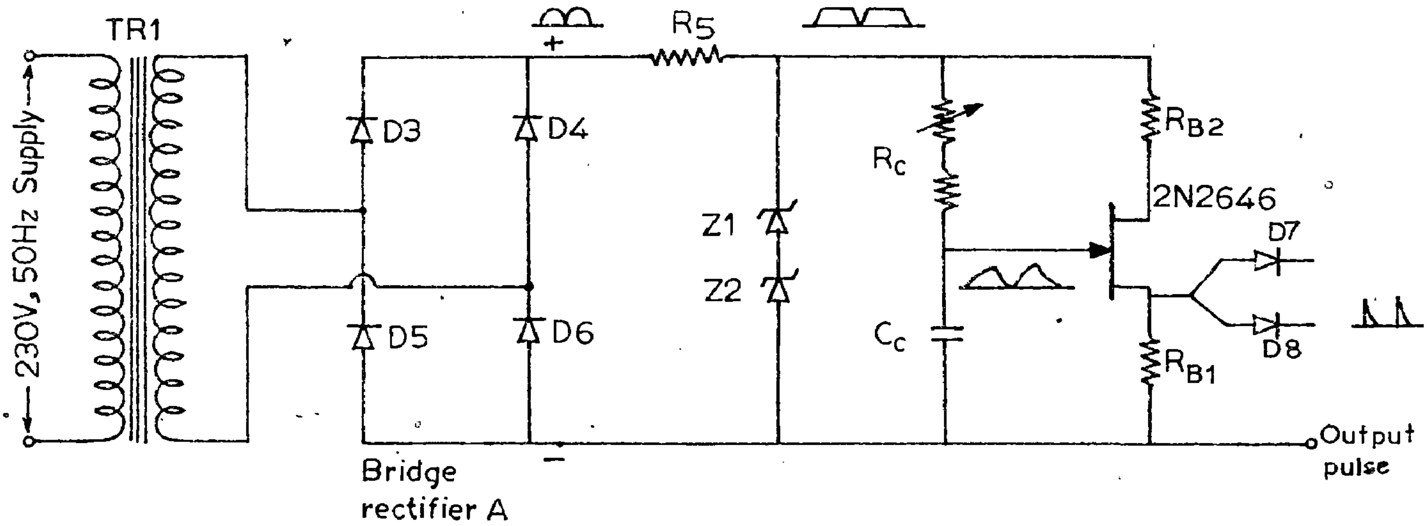
I_{TCAV}	30A.	PIV 600	
$I_{T(AV)}$	37A		Average value of on state current.
I_T	47A		Continuous(direct) on-state current
I^2t	10 ms	1.52	A^2 secs x 10^3
	3 ms	1.13	A^2 secs x 10^3
V_T	1.85	V	instantaneous total value of on-state voltage.
i_T	95A		instantaneous on-state current to produce V_T.
R_{jb}	0.66	°C/W	Maximum junction to case thermal impedence for a device with a maximum forward voltage drop characteristics.
R_{mtg}	0.25	°C/W	Contact thermal resistance between base of device and heatsink mounting when recommended mounting torque is utilised.
I_{GT}	100 mA at 25°C		gate trigger current.

I_{FGM}	5A	peak forward gate current.
V_{FGM}	12V	peak forward gate voltage.
V_{RG}	-5V	reverse gate voltage.
P_{GM}	20W	peak gate power
P_G	1W	Average dc gate power.
T_{bd}	-30 to 125°C	
T_{stg}	-40 to 150°C	
I_D	15 mA	Continuous(direct) off state current.
I_R	15 mA	Continuous(direct) reverse blocking current.
I_L	150 mA	Latching current.
Wt	33 gms	
Torque	0.48 kgf.m.	
V_{BO}	600V	breakover voltage.



T1, T2	=	Thyristor 28TB6
D1, D2, DF	=	Diode 4N15
R_1	=	10 Ω, 2W
R_2	=	50K, 3 W
C_1	=	4 μF, 400V A.C.

Figure III-1 _ Convertor power circuit .



TR1 = 230V, 20VA, 1:1 Ratio transformer

D3 to D6 = Diode BYX127

R_5 = 8K, 2W

Z1, Z2 = TSZ 9.1

R_c = 10K Potentiometer in series with 2.2K

C_c = 0.3 μF

R_{B1} = 100 Ω

R_{B2} = 1.5 K

D7, D8 = Diode BYX126

Figure III-2 _ Control circuit .

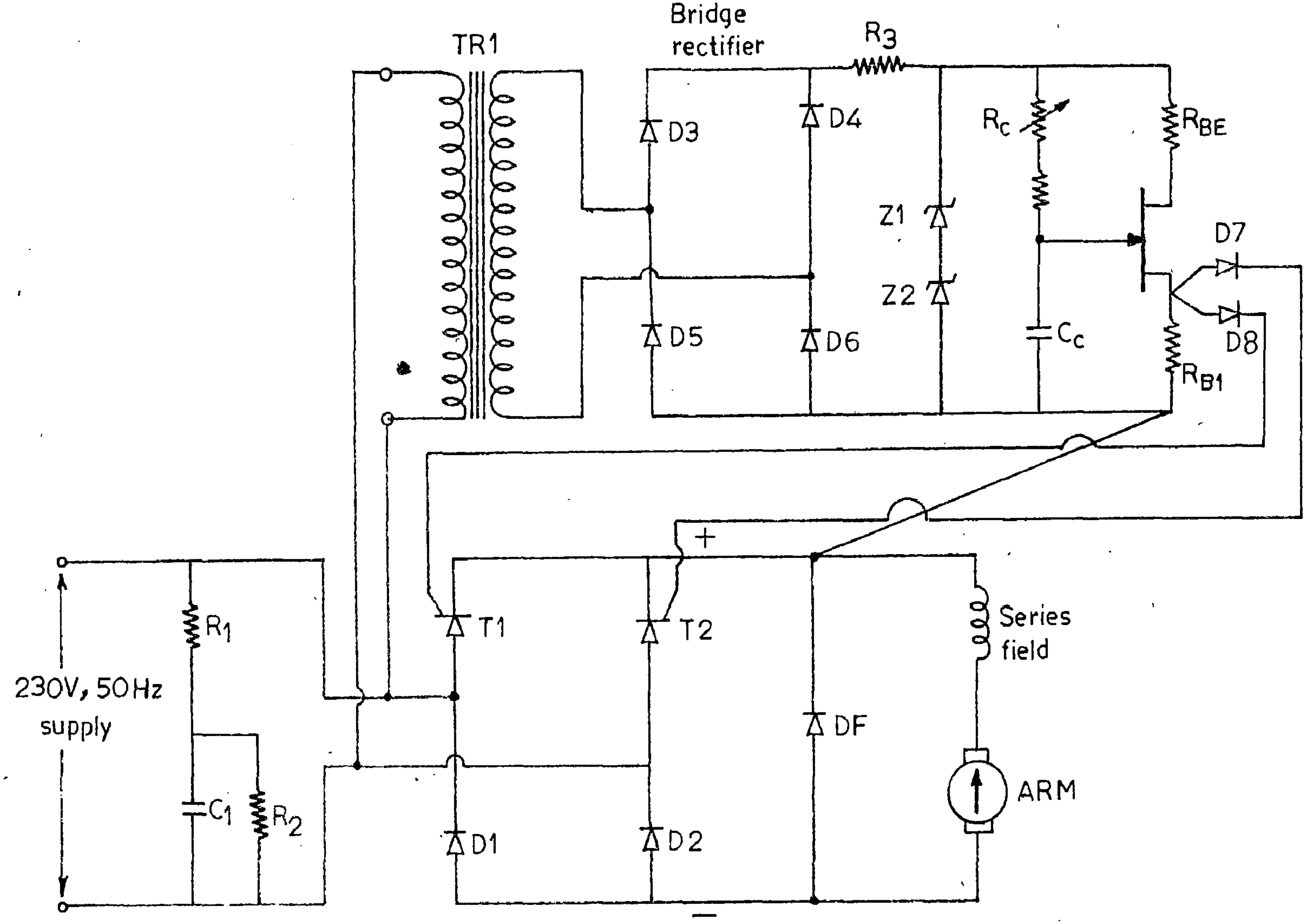


Figure III-3 _ Half controlled convertor for D.C. series motor.

CHAPTER-IV

PERFORMANCE CALCULATION

This chapter deals with the experimental verification of the performance equations deduced in Chapter II. Oscillographic records of armature voltage, armature current and line current are given for different firing angles and loads and compared with the computed ones.

4.1 PERFORMANCE EQUATIONS OF THE MOTOR

Performance equations deduced in Chapter II are given below:

Voltage applied to the motor

$$v = V_m \sin wt \quad \ldots\ldots \quad \alpha < wt < \pi \quad \ldots\ldots \quad (1)$$

Average voltage applied to the motor

$$V_{av} = \frac{V_m}{\pi}(1 + \cos\alpha) \quad \ldots\ldots \quad (2)$$

The variation of armature current with time is given by

$$i = \frac{V_m}{Z}\sin(wt-\theta)\left[u(t-t\alpha) - u(t-T/2)\right]$$

$$+\frac{V_m}{Z}\sin(\theta-\alpha)e^{-\left(\frac{wt-\alpha}{\tan\theta}\right)}\cdot u(t-t_\alpha)$$

$$+\frac{V_m}{Z}\sin\theta\, e^{-\left(\frac{wt-\pi}{\tan\theta}\right)}\cdot u(t-T/2) + i_o e^{-\left(\frac{wt}{\tan\theta}\right)} \ldots (3)$$

$$i_o = \frac{1}{(1-e^{-\pi/\tan\theta})}\;\frac{V_m}{Z}\;\sin\theta + \sin(\theta-\alpha)e^{-\left(\frac{\pi-\alpha}{\tan\theta}\right)} \quad \ldots (4)$$

where,

$$\tan\theta = \frac{\omega L}{R + KW} \quad \ldots\ldots \quad (5)$$

$$Z = \sqrt{(R + KW)^2 + (\omega L)^2} \quad \ldots\ldots \quad (6)$$

Hence

$$I_{av} = \frac{V_{av}}{R + K\,\omega} \quad \ldots\ldots \quad (7)$$

And

$$I^2_{rms} = \frac{V_m^2}{2\pi\, Z^2} \Big\{ (\pi - \alpha) + \cos(2\theta - \alpha)\sin\alpha$$

$$+ \frac{4\sin\theta\sin\alpha}{(1 - e^{-\pi/\tan\theta})} \left[\sin(\theta - \alpha) + \sin\theta\, e^{-\alpha/\tan\theta}\right]$$

$$+ \frac{\tan\theta}{(1 - e^{-\pi/\tan\theta})} \Big[(\sin^2(\theta - \alpha) + \sin^2\theta)(1 + e^{-\pi/\tan\theta})$$

$$+ 2\sin(\theta - \alpha)\sin\theta\,(e^{-\alpha/\tan\theta} + e^{-(\frac{\pi - \alpha}{\tan\theta})}) \Big] \Big\} \quad \ldots (8)$$

Now electromagnetic torque developed

$$T_e = k\, I^2_{rms} \quad \ldots\ldots \quad (9)$$

and

$$T_e = A + B\,\omega + T_L \quad \ldots\ldots \quad (10)$$

The variation of line current with time is given by

$$i_L = \frac{V_m}{Z}\sin(wt - \theta) + \frac{V_m}{Z}\sin(\theta - \alpha)\, e^{-(\frac{wt - \alpha}{\tan\theta})} + i_0 e^{-(\frac{wt}{\tan\theta}}$$

$$\text{-------} \alpha < wt \quad \pi \quad \ldots (11)$$

Hence,

$$I^2_{L\,rms} = \frac{V_m^2}{2\pi\, Z^2} \Big\{ (\pi - \alpha) + \cos(2\theta - \alpha)\sin\alpha$$

$$+ \frac{4\sin\theta\sin\alpha}{(1 - e^{-\pi/\tan\theta})} \left[\sin(\theta - \alpha) + \sin\theta\, e^{-\alpha/\tan\theta}\right]$$

$$+ \frac{\tan\theta}{(1 - e^{-\pi/\tan\theta})^2} \left(\sin(\theta - \alpha) + \sin\theta\, e^{-\alpha/\tan\theta}\right)^2$$

$$\left(1 - e^{-2(\frac{\pi - \alpha}{\tan\theta})}\right) \Big] \Big\} \quad \ldots\ldots \quad (12)$$

Input power factor, cos ϕ, is given by

$$\cos\phi = \frac{\text{power output}}{\text{volt ampere input}} = \frac{V_{av}\, I_{av}}{V_L\, I_L} \quad \ldots. \; (13)$$

Where, V_{av} and I_{av} are given by expressions (2) and (5), V_L is rms value of line voltage and I_L rms line current and is obtained from (10).

To determine the displacement and distortion factors Fourier coefficients are necessary.

$$a_1 = \frac{V_m}{\pi Z} \Big[\sin(\theta - \alpha)\sin\alpha - (\pi - \alpha)\sin\theta$$

$$+ \frac{2\sin\theta}{(1 - e^{-\pi/\tan\theta})} \Big[(\sin(\theta-\alpha) + \sin\theta\, e^{-\alpha/\tan\theta})$$

$$(\cos(\alpha+\theta) + \cos\theta\, e^{-(\frac{\pi-\alpha}{\tan\theta})}) \Big] \Big] \quad \ldots. \; (14)$$

$$b_1 = \frac{V_m}{\pi Z} \Big[\cos(\theta-\alpha)\sin\alpha - (\pi - \alpha)\sin\theta$$

$$+ \frac{2\sin\theta}{(1 - e^{-\pi/\tan\theta})} \Big[(\sin(\theta-\alpha) + \sin\theta\, e^{-\alpha/\tan\theta})$$

$$(\sin(\alpha+\theta) + \sin\theta\, e^{-(\frac{\pi-\alpha}{\tan\theta})}) \Big] \Big] \quad \ldots. \; (15)$$

Therefore fundamental component of line current is given by

$$I_{L_1} = \sqrt{(a_1^2 + b_1^2)/2} \quad \ldots. \; (16)$$

The displacement angle is defined as the angle between line voltage and fundamental component of line current.

$$\phi_1 = \tan^{-1}(a_1/b_1) \quad \ldots\ldots \quad (17)$$

And cosine of the displacement angle, ϕ_1, is called displacement factor or fundamental power factor.

$$\text{Hence displacement factor} = \cos\phi_1 \quad \ldots \quad (18)$$

Distortion factor is defined as the ratio of fundamental component of line current to rms value of line current.

$$\text{distortion factor } \mu = \frac{I_{L1}}{I_L} \quad \ldots\ldots \quad (19)$$

4.2 DC SERIES MOTOR CONSTANTS

The dc series motor parameters determined from tests are given below.

$R = R_a + R_f$ = total armature circuit resistance in ohms = 2.6

$L = L_a + L_f$ = total armature circuit inductance in henries = 0.121

K = rotational voltage coefficient in volts/ampere/radian/Sec = 0.1637

A = 1.4 N-m

B = 0.0032 N-m / radian.

4.3 COMPUTATION

The time variation of armature voltage, armature current and line current for two different triggering angles and loads from expressions (1),(3) and (11) respectively is tabulated in Table 1.

The performance quantities, viz, average current, armature rms current, torque, line current, power factor etc. are calculated for different triggering angles from expressions given in section 4.1 and are listed in Table II.

4.4 EXPERIMENT

The circuit diagram is shown in figure 4.1. The triggering angle α is measured from oscillograph. The observations are recorded in Table III.

4.5 WAVEFORMS

From Table I waveforms of armature voltage, current and line current are drawn in figures IV-2 to IV 4 and corresponding Oscillograph records are given in figure IV-5 to IV-7.

4.6 CHARACTERISTICS

The following characteristics are drawn from Table II. On the same graph the chracteristics obtained experimentally (Table III) are presented.

(a) Speed Vs rms value of motor armature current - figure IV-8.

(b) Speed Vs load torque - figure IV-9.

(c) Line current vs load torque - figure IV-10.
The following characteristics from Table II are also drawn.

(d) Power factor vs load torque- figure IV-11.

(e) Displacement factor vs load torque - figure IV-12.

(f) distortion factor vs load torque - figure IV-13.

TABLE-I

(A) $\alpha = 32.3^{\circ}$, $V_m = 325$ Volts

Sl. No.	wt in degrees	v=armature voltage in volts.	N=1280 rpm, T_L = 13N-m		N=2500 rpm, T_L =2.92 N	
			i in amperes	i_L amperes	i in ampere	i_L in amperes
1	2	3	4	5	6	7
1.	0	0	7.7	0	3.65	0
2.	15	0	6.5	0	2.67	0
3.	32.3	174V	5.35	5.35	1.86	1.86
4.	45	230V	5.55	5.55	2.47	2.47
5.	60	281	6.14	6.14	3.345	3.345
6.	75	314	7.39	7.39	4.29	4.29
7.	90	325	8.3	8.3	5.0	5.0
8.	105	314			5.55	5.55
9.	120	281	9.53	9.53	5.84	5.84
10.	135	230	9.7	9.7	5.84	5.84
11.	150	162.5	9.42	5.387	5.387	5.387
12.	165	81	8.73	8.73	4.677	4.677
13.	180	0	7.7	7.7	3.65	3.65

(B) $\alpha = 97.3^{\circ}$ $V_m = 325$ volts.

SlNo.	wt in degrees	Armature voltage v in volts	N = 480 rpm T_L = 6 N-m	
			i amperes	in i_L amperes
1	2	3	4	5
1.	0	0	9.74	0
2.	15	0	9.05	0
3.	30	0	8.39	0

1	2	3	4	5
4.	45	0	7.79	0
5.	60	0	7.21	0
6.	75	0	6.71	0
7.	97.3	32.1	6.0	6.0
8.	105	314	7.09	7.09
9.	120	281	8.4	8.4
10.	135	230	9.49	9.49
11.	150	162.5	10.03	10.03
12.	165	81	10.24	10.24
13.	180	0	9.74	9.74

TABLE-II

Sl. No.	N in rpm	I_{AV} in amperes	I_{rms} in amperes	$T_o = KI^2_{rms}$	$T_L = T_o - (A+B)$	I_L in amper
1	2	3	4	5	6	7
$\alpha = 32.5^o$ $V_{av} = 192.5$ volts						
1.	900	10.59	10.60	18.709	17.0	10.38
2.	1200	8.238	8.366	11.455	9.6	8.02
3.	1500	6.741	6.88	7.772	5.87	6.58
4.	1800	5.705	5.87	5.646	3.65	5.62
5.	2100	4.945	5.13	4.305	2.2	4.93
6.	2400	4.363	4.56	3.402	1.2	4.4
$\alpha = 57.6^o$ $V_{av} = 160.5$ V						
7.	600	12.33	12.43	25.34	23.7	12.12
8.	900	8.81	8.95	13.15	11.49	8.37
9.	1200	6.85	7.04	8.12	6.32	6.5
10.	1500	5.4	5.81	5.56	3.66	5.39
11.	1800	4.75	4.99	4.08	2.00	4.64
12.	2100	4.12	4.38	3.14	1.04	4.11
13.	2400	3.63	3.92	2.51	0.4	3.7
$\alpha = 75.5$, $V_{av} = 130.5$						
14.	600	10.13	16.86	15.26	9.62	9.62
15.	900	7.16	7.33	8.8	7.1	6.64
16.	1200	5.57	5.78	5.48	3.60	5.18
17.	1500	4.56	4.80	3.78	1.88	4.325
18/	1800	3.85	4.13	2.8	0.8	3.78

TABLE-II (Continued)

Sl. No.	Input power factor cos φ	Fourier Coefficients a_{1v}	b_1	$I_{L1} = \sqrt{\frac{(a_1^2 + b_1^2)}{2}}$ in amps	Displa-cement factor cos $φ_1$	Dist orti fact $I_{L1}/$
1	8	9	10	11	12	1
$\alpha = 32.3$ $V_{av} = 192.5$						
1.	0.852	-4.99	12.68	9.63	0.93	0.9
2.	0.861	-4.12	9.98	7.63	0.924	0.
3.	0.859	-3.53	8.27	6.36	0.92	0.
4.	0.850	-3.10	7.10	5.50	0.916	0.
5.	0.84	-2.76	6.25	4.83	0.915	0.
6.	0.83	-2.49	5.59	4.33	0.914	0.
$\alpha = 57.6^\circ$, $V_{av} = 160.5$ V						
7.	0.71	-7.90	12.27	10.32	0.84	0.
8.	0.734	-5.97	8.91	7.59	0.83	0.
9.	0.736	-4.88	7.07	6.07	0.823	0.
10.	0.727	-4.15	5.92	5.11	0.819	0.
11.	0.713	-3.63	5.13	4.44	0.816	0.
12.	0.698	-3.23	4.56	3.95	0.816	0.
13.	0.684	-2.91	4.12	3.57	0.816	0.
$\alpha = 75.5^\circ$, $V_{av} = 130.5$						
14.	0.602	-7.26	8.16	7.72	0.746	0.
15.	0.612	-5.49	5.97	5.73	0.737	0.
16.	0.611	-4.49	4.77	4.63	0.728	0.
17.	0.598	-3.84	4.03	3.94	0.722	0.
18.	0.582	-3.38	3.52	3.45	0.722	0.

TABLE -II(continued)

1	2	3	4	5	6	7
$\alpha = 97.3^o$		$V_{av} = 91$ V				
19.	600	6.99	7.11	8.30	6.7	6.72
20.	900	5.0	5.16	4.37	2.67	4.63
21.	1200	3.89	4.10	2.75	0.95	3.60
$\alpha = 114^o$		$V_{av} = 62$ V				
22.	300	7.92	7.78	10.45	8.95	9.45
23.	600	4.76	4.86	3.88	2.28	5.13
24.	900	3.40	3.54	2.06	0.36	3.53

TABLE-II (Continued)

1	8	9	10	11	12	13
$\alpha = 97.3$, $V_{av} = 91V$						
19.	0.412	-5.18	4.02	4.64	0.613	0.69
20.	0.427	-3.94	2.96	3.49	0.6	0.752
21.	0.427	-3.25	2.40	2.86	0.593	0.795
$\alpha = 114^{o}$, $V_{av} = 62$ V						
22.	0.226	-5.08	3.04	4.18	0.515	0.442
23.	0.253	-3.27	1.88	2.67	0.499	0.52
24.	0.261	-2.50	1.40	2.03	0.486	0.575

TABLE-III

Voltage applied = 230 V, 50 Hz

Flywheel diameter = 11.5 inches.

Sl. No.	Speed in rpm	Armature voltage in volts	Armature current in amperes.	Line current in amperes.	Brake load (W_1-W_2) in lbs.	Load torque T_L in N-m.
1	2	3	4	5	6	7
$\alpha = 32.3^o$						
1.	2500	190	4.5	4.5	(5.5 - 3.3)	1.3
2.	1850	188	6.0	6.0	(11 - 5)	3.9
3.	1500	187	8.5	8.1	(16 - 6)	6.5
4.	1300	185	11.0	10.4	(22.5 - 7)	10.1
5.	1200	185	12.3	11.7	(27 - 8)	12.35
$\alpha = 57.6^o$						
6.	2400	165	3.5	3.6	(4 - 2)	1.3
7.	1460		6.2	6	(13-7)	3.9
8.	1240		7.8	7.4	(16-9)	4.55
[illegible]	[illegible]		[illegible]			

TABLE - III (Continued)

1	2	3	4	5	6	7
9.	1100		9.4	8.5	(22-10)	7.8
10.	950	145	11.5	10.4	(27-11)	10.4
11.						
$\alpha = 75.5^{o}$						
11.	2000	125	3.5	3.3	(3 -2)	0.65
12.	1300		4.8	4.4	(9 -5)	2.6
13.	900		7.7	6.9	(17-8)	5.85
14.	740	110	9.6	8.5	(25-10)	9.75
$\alpha = 97.3^{o}$						
15	1210	90	3.8	3.5	(5-3.5)	0.975
16.	730	84	6.4	5.5	(13-7)	3.9
17.	530	84	9.0	8.4	(19-9)	6.5
18.	360	81	12.3	9.7	(30-10)	13

TABLE-III(Continued)

1	2	3	4	5	6	7
$\alpha = 114^o$						
19.	1000	57	2.7	2.3	(2-1)	0.65
20.	640		4.1	3.3	(6-2.5)	2.28
21.	370		7.1	5.3	(14-6)	5.2
22.	240	55	10.2	7.3	(23-7)	10.4

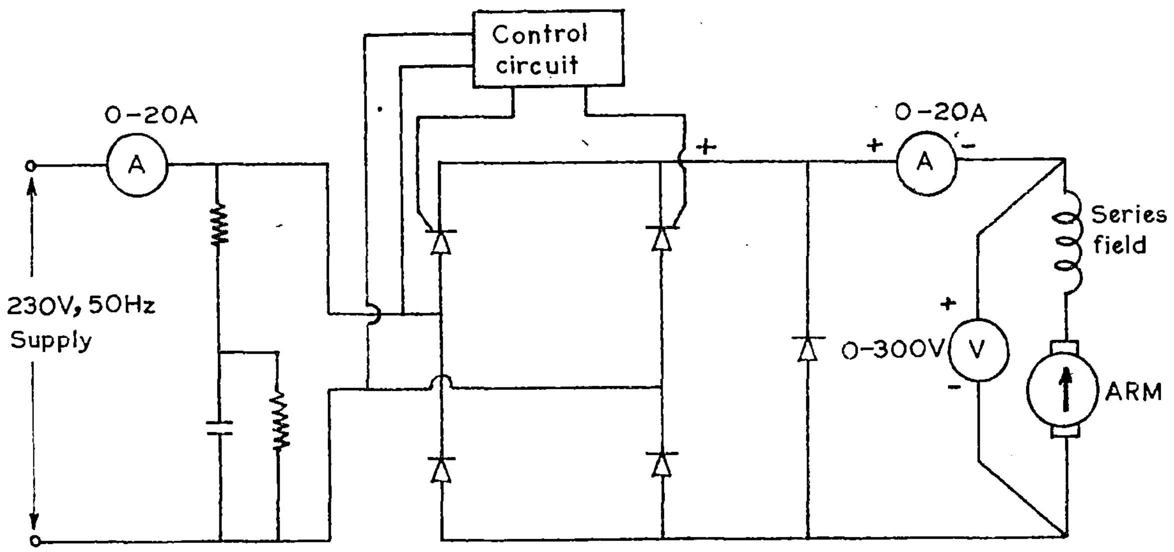


Figure IV-1 _ Convertor controlled D.C. series motor-load test.

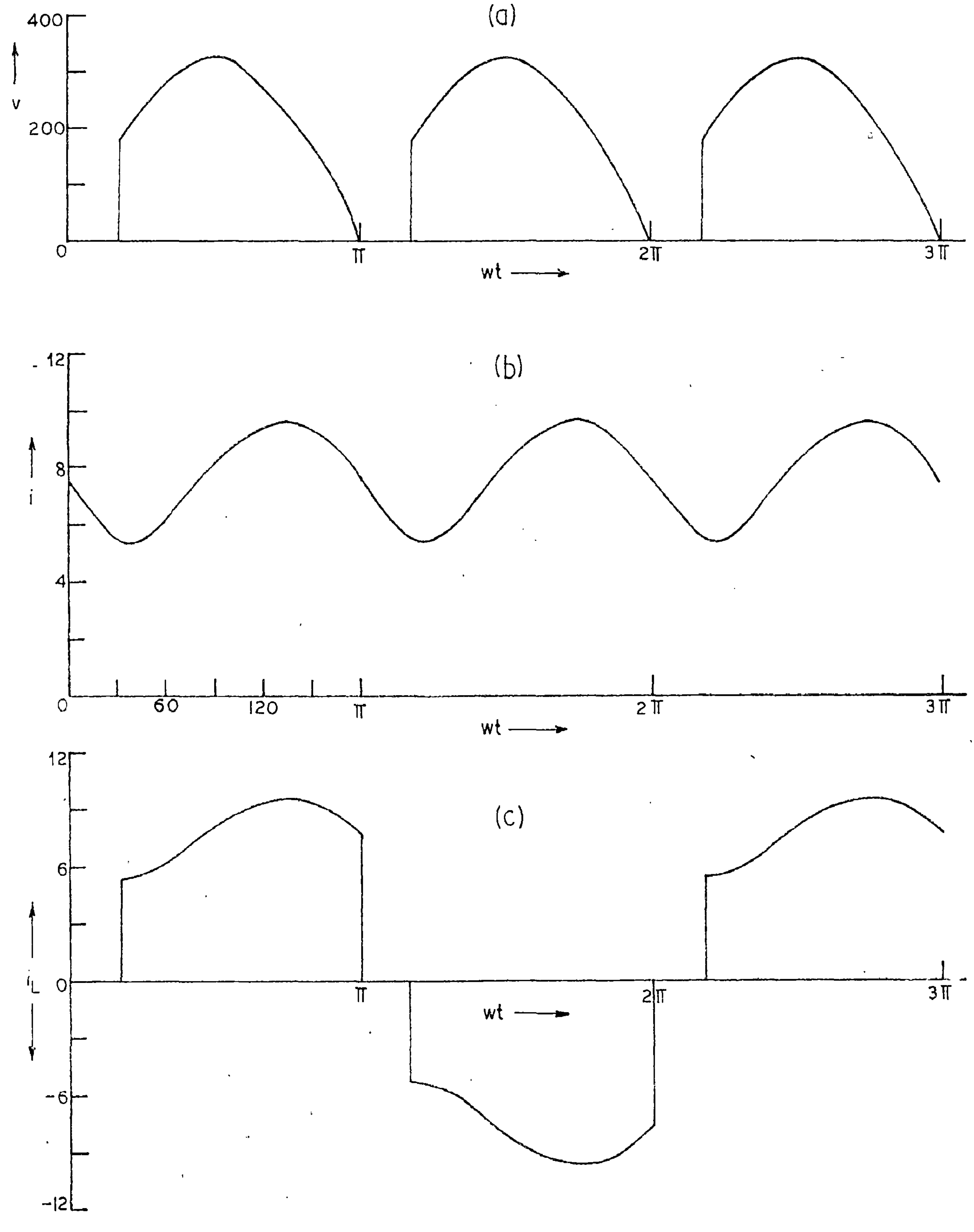


Figure IV-2. (a) Armature voltage, (b) Armature current and (c) Line current waveforms.
$\alpha = 32.3°$, N = 1280, T_L = 13.0 N-m

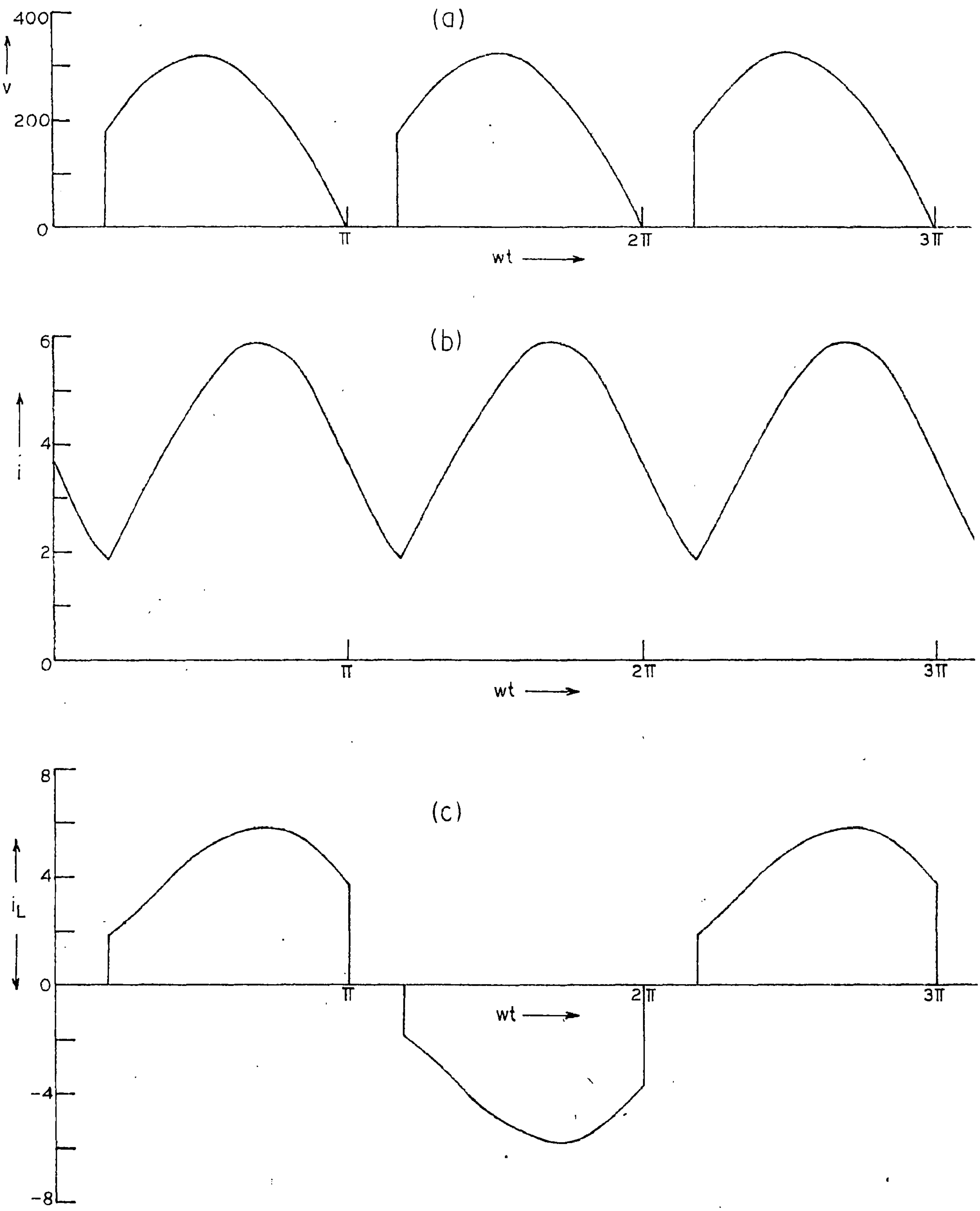


Figure IV-3_ (a) Armature voltage (b) Armature current and (c) Line current waveforms.

$\alpha = 32.3^\circ$ N = 2500 $T_L \doteq 2.92$ N-m

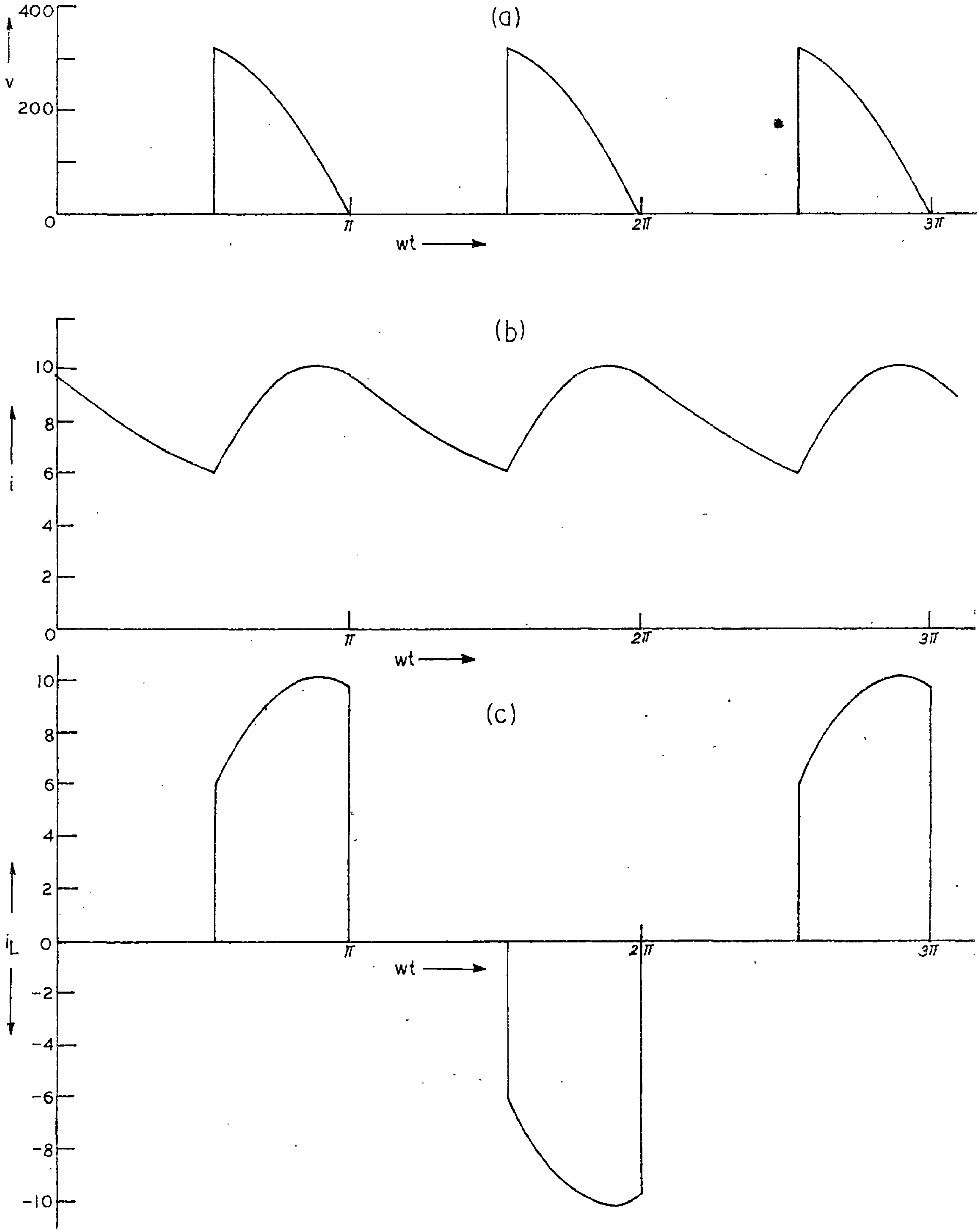
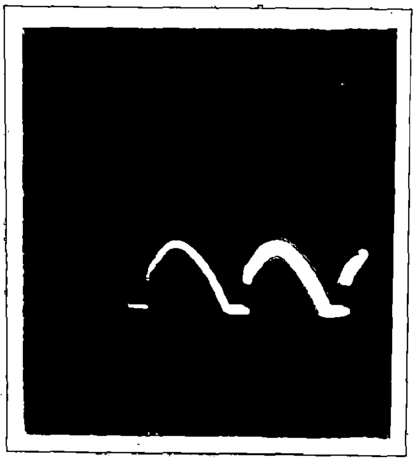
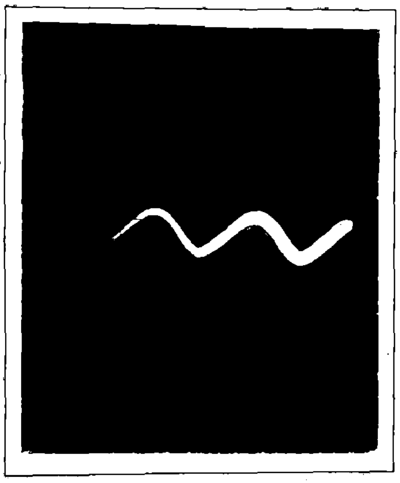


Figure IV-4 _ (a) Armature voltage, (b) Armature current and (c) Line current waveforms.

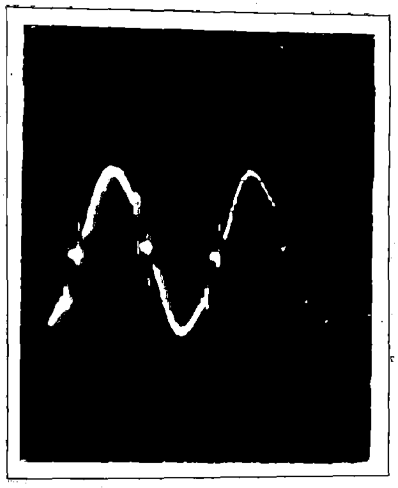
$\alpha = 97.3°$, N = 480 R.P.M., $T_L = 6$ N-m



(a) Armature voltage



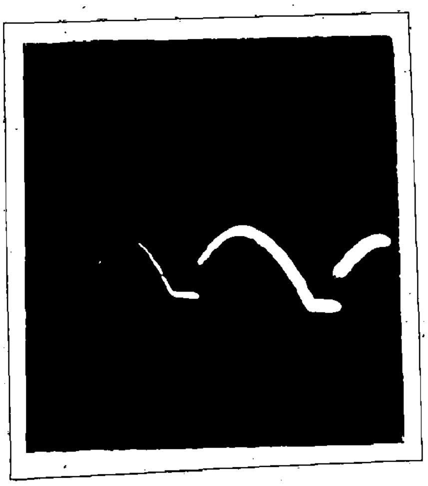
(b) Armature Current



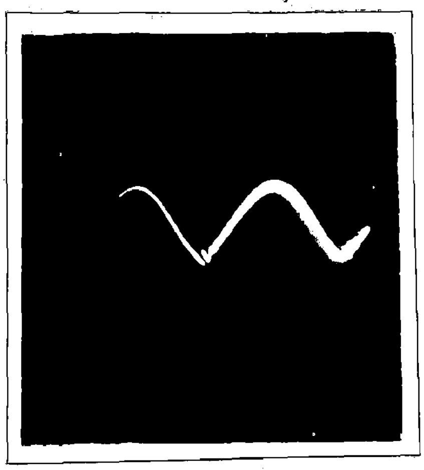
(c) Line Current

FIGURE IV-5 OSCILLOGRAPHS

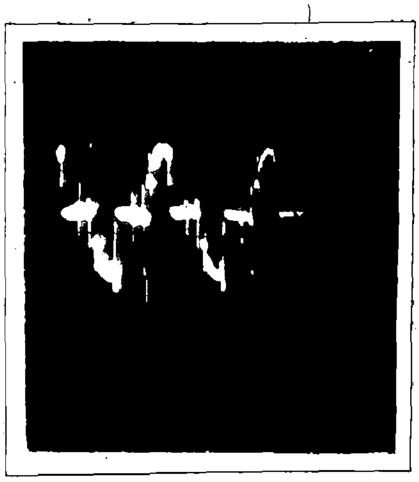
$\alpha = 32.3^0$ N = 1280 rpm T_L = 13.0 N-m



(a) Armature Voltage



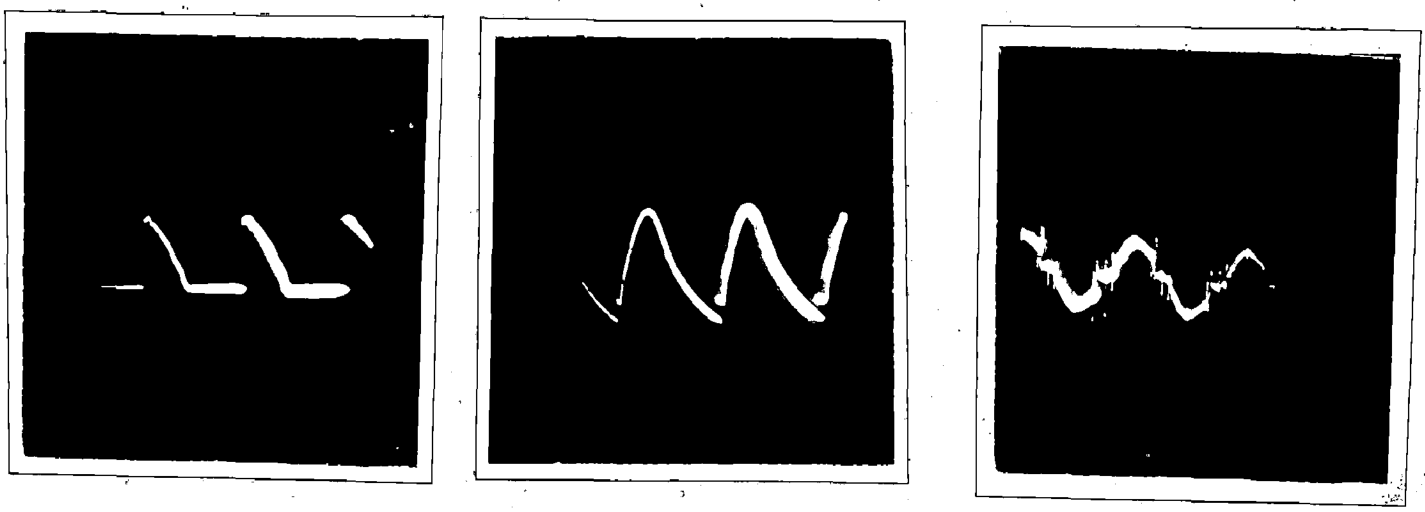
(b) Armature Current



(c) Line Current.

FIGURE IV-6 OSCILLOGRAPHS

$\alpha = 32.3^0$ N = 2500 rpm T_L = 2.92 N-m.



(a) Armature Voltage

(b) Armature Current

(c) Line Current.

FIGURE IV-7 OSCILLOGRAPHS

$\alpha = 97.3^{\circ}$ $N = 480$ rpm $T_L = 6$ N-m

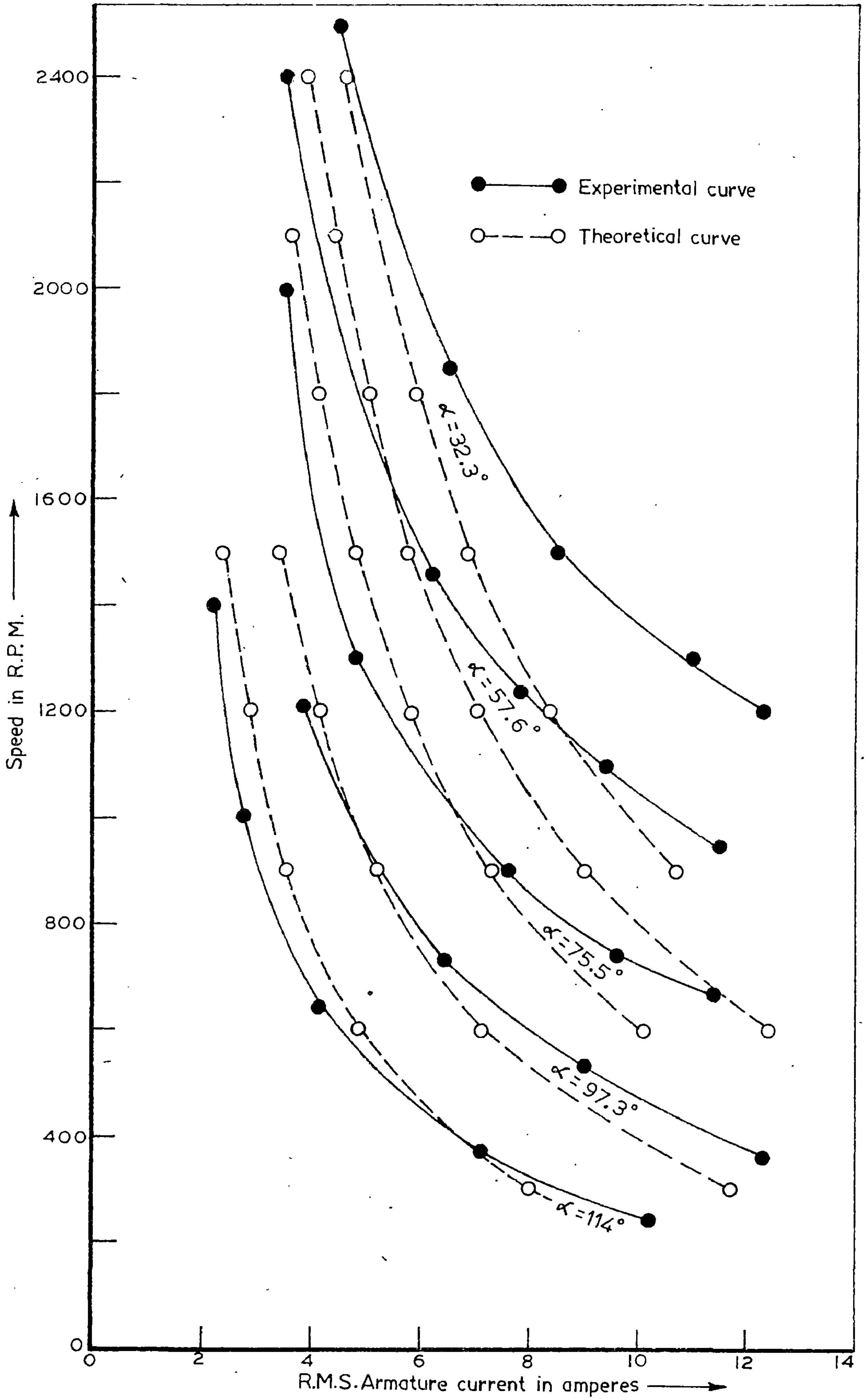

Experimental curve
Theoretical curve
α = 32.3°
α = 57.6°
α = 75.5°
α = 97.3°
α = 114°
Speed in R.P.M.
R.M.S. Armature current in amperes
0
400
800
1200
1600
2000
2400
2
4
6
8
10
12
14

Figure IV - 8

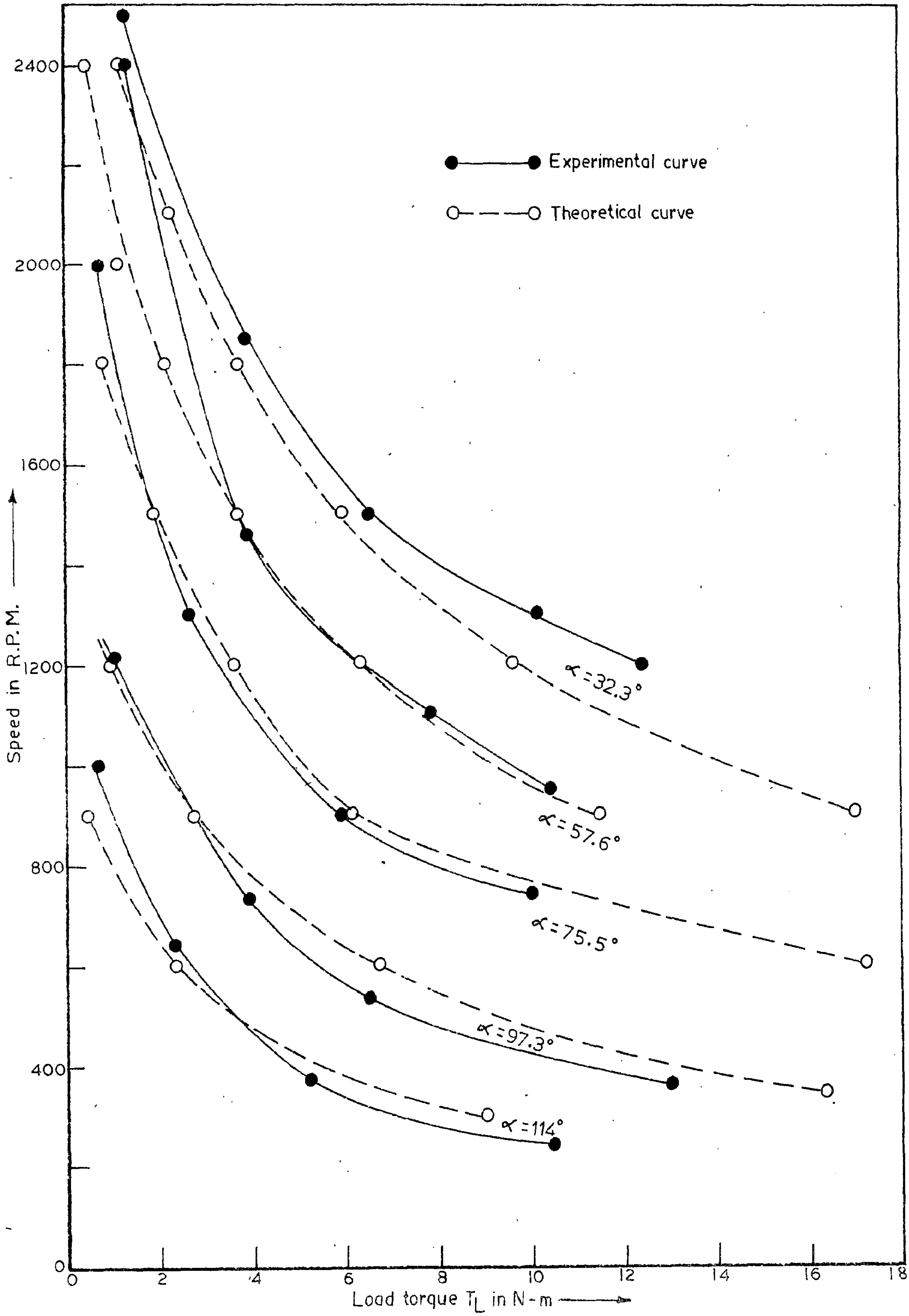

Experimental curve
Theoretical curve
2400
2000
1600
1200
800
400
0
Speed in R.P.M.
0
2
4
6
8
10
12
14
16
18
Load torque T_L in N-m
α = 32.3°
α = 57.6°
α = 75.5°
α = 97.3°
α = 114°

Figure IV-9

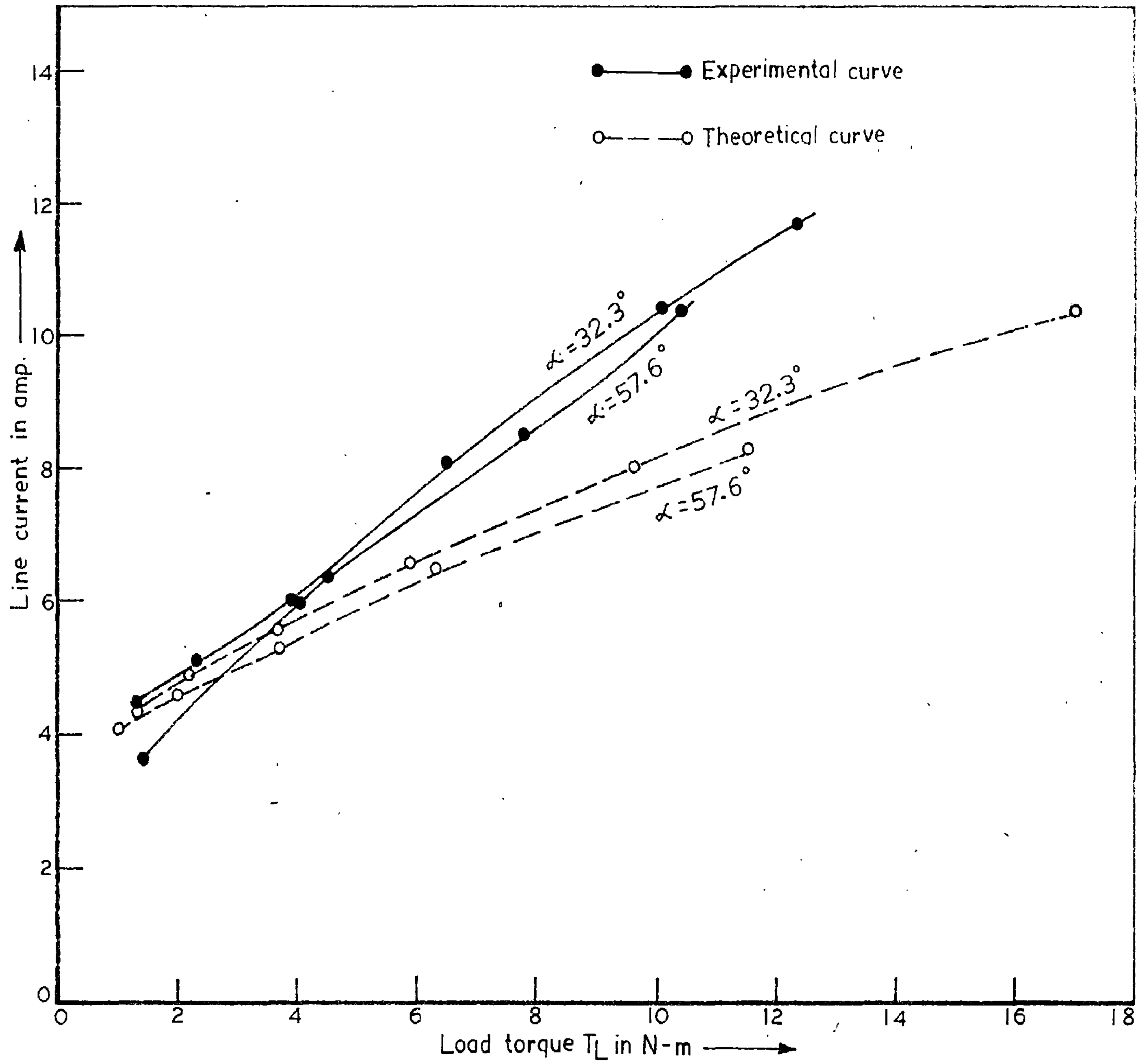
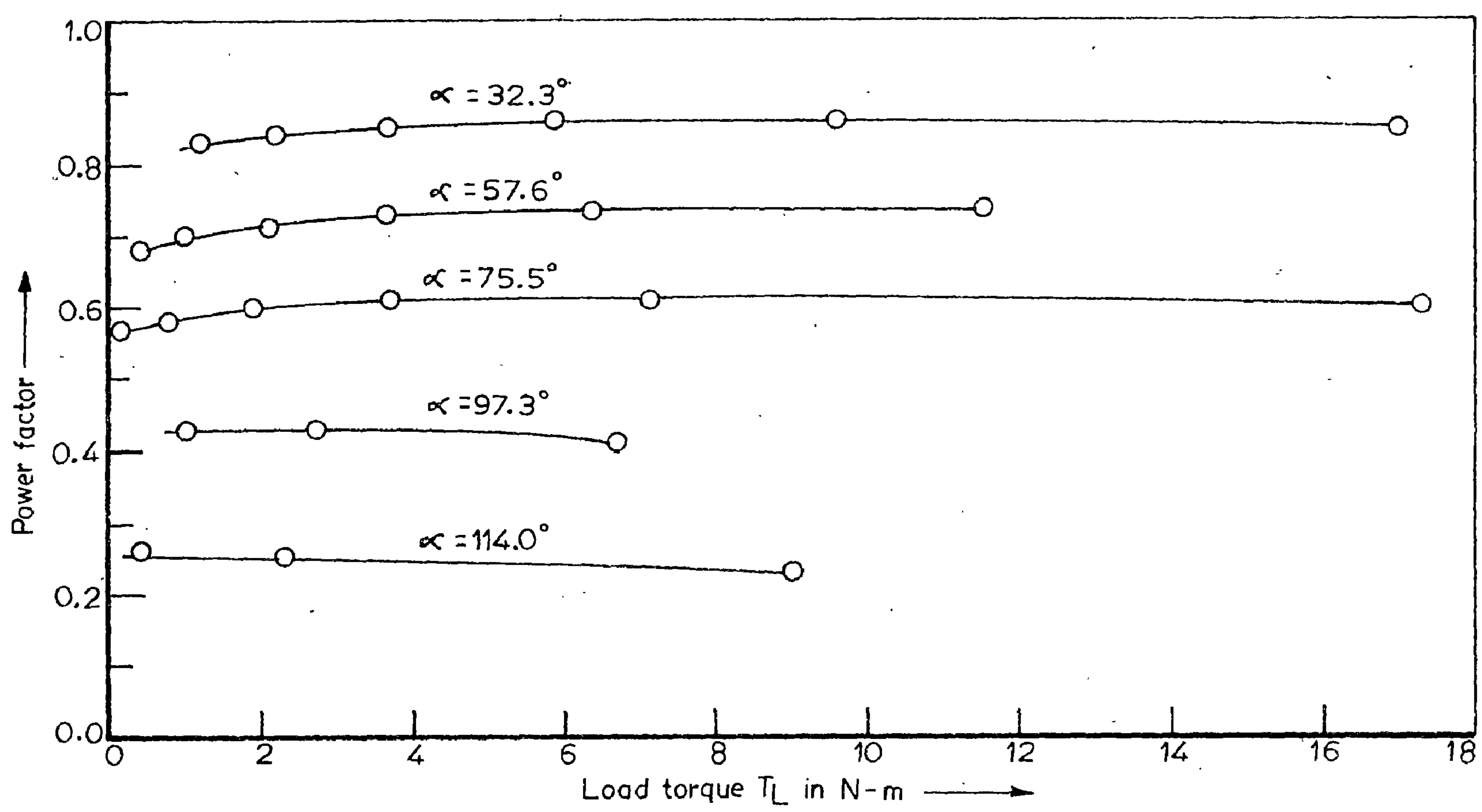
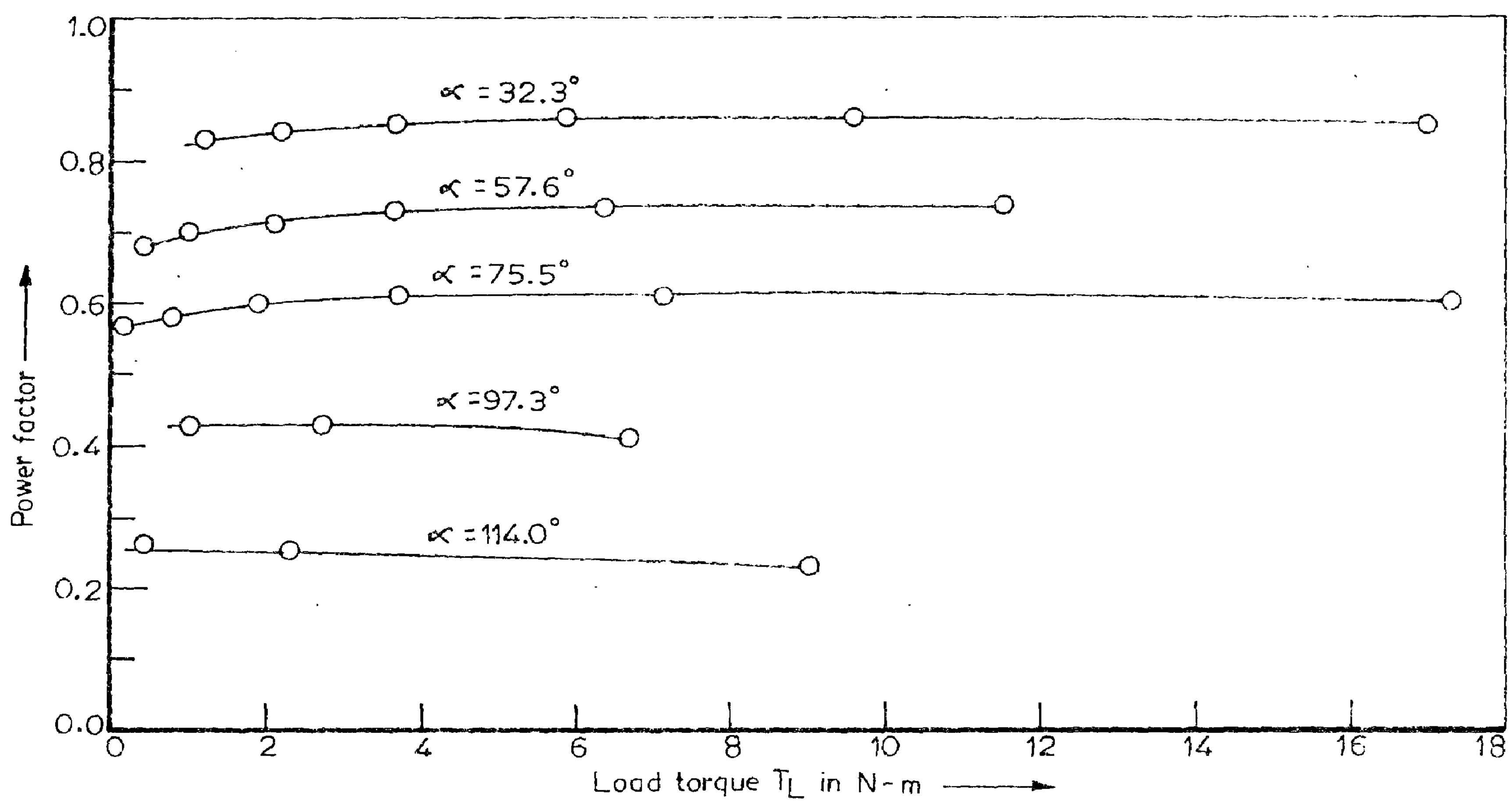

Experimental curve
Theoretical curve
Line current in amp.
Load torque T_L in N-m
α = 32.3°
α = 57.6°
α = 32.3°
α = 57.6°
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
14
16
18

Figure IV-10



1.0
0.8
0.6
0.4
0.2
0.0
Power factor
α = 32.3°
α = 57.6°
α = 75.5°
α = 97.3°
α = 114.0°
0
2
4
6
8
10
12
14
16
18
Load torque TL in N-m

Figure IV -11



1.0
0.8
0.6
0.4
0.2
0.0
Power factor
∝ = 32.3°
∝ = 57.6°
∝ = 75.5°
∝ = 97.3°
∝ = 114.0°
0
2
4
6
8
10
12
14
16
18
Load torque T_L in N-m

Figure IV -11

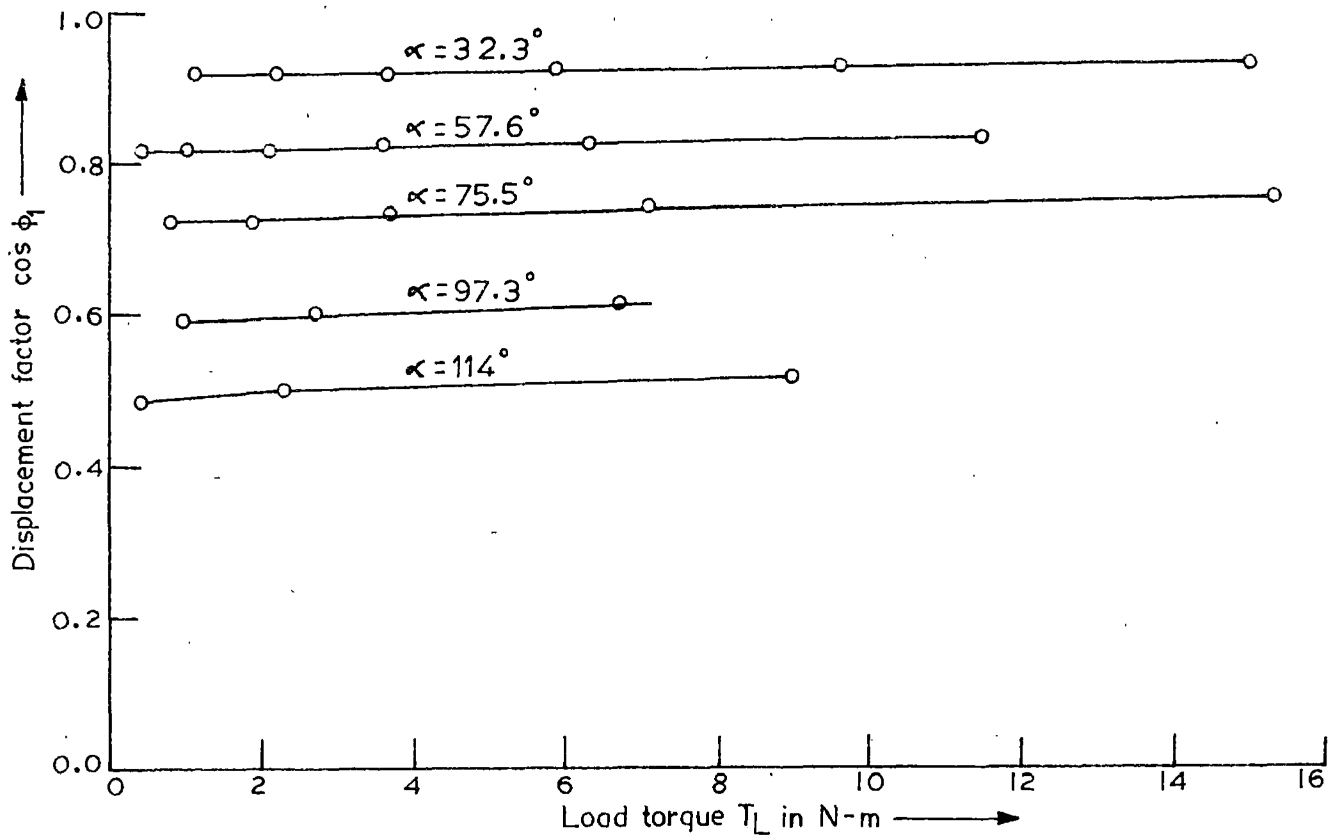


Figure IV-12 - Displacement factor vs. load torque.

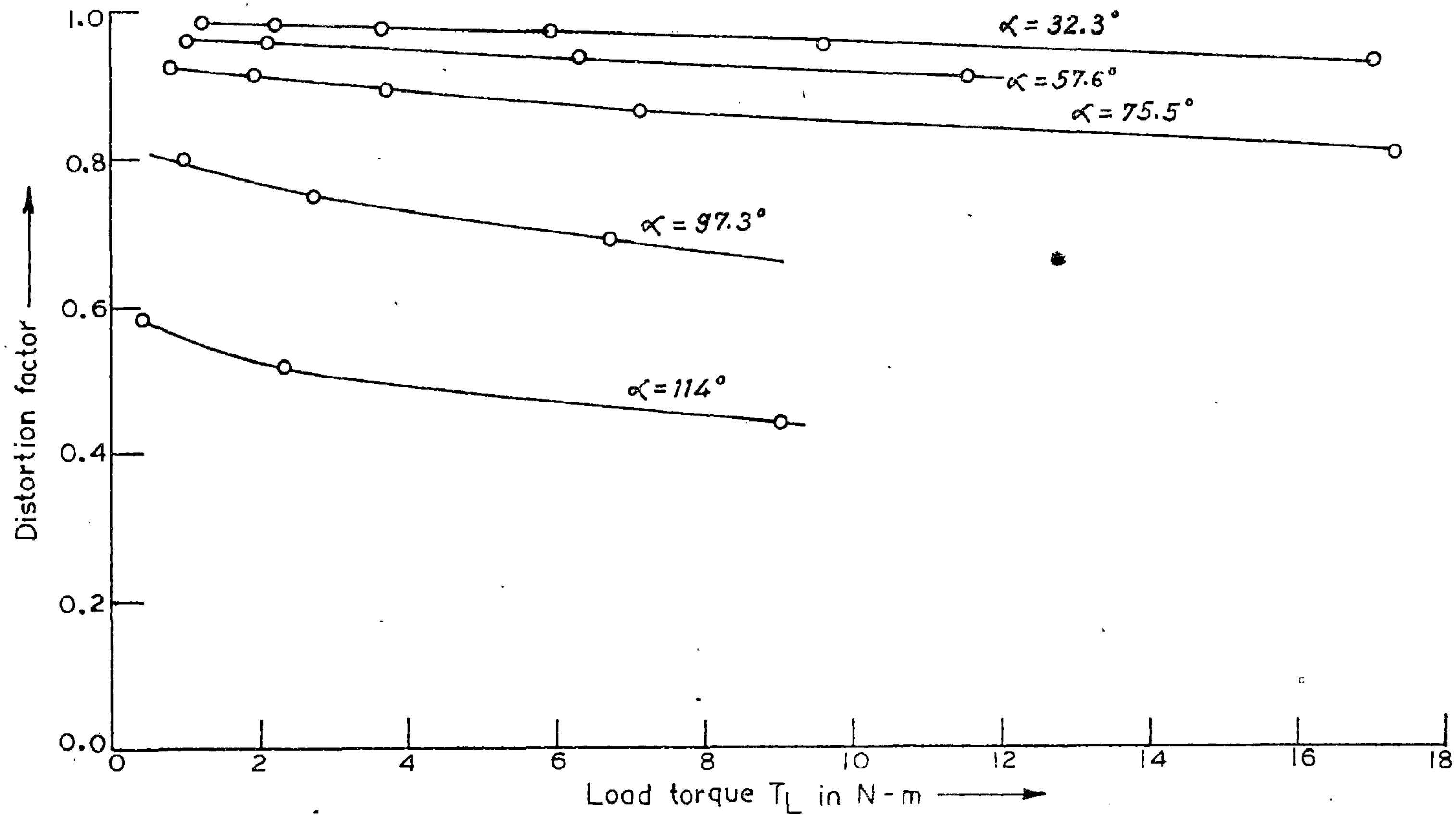


Figure IV-13 _ Distortion factor vs. load torque .

CHAPTER-V

CONCLUSION AND DISCUSSION

CONCLUSION

A half controlled convertor with freewheeling diode has been designed, fabricated and tested. It is possible to vary the output voltage smoothly from 0 to 190 volts. Hence efficient starting and speed control of d.c. series motor by armature voltage control is possible.

Performance equations of a pulse controlled d.c. series motor have been deduced. Using these equations the following characteristics are drawn.

(1) Armature current VS speed.

(2) Speed VS torque

(3) Line current VS torque.

These characteristics are compared with experimentally obtained characteristics. Closer comparision between theoretical and experimental results suggests that these can be used for calculating the performance of the motor.

In addition, the Fourier coefficients of line current are presented. From these the displacement and distortion factors are obtained.

DISCUSSION

By using series or shunt transistor regulators in convertor control circuit, it is possible to obtain soft starting and overload protections. Tachogenerator feedback can be used to control triggering angle α and hence better speed regulation with changes in load can be achieved.

In the analysis a constant rotational voltage coefficient has been assumed. Accuracy of the results improve if the non-linear relation between current and induced emf is accounted for in the following way.

The average value of current for a particular speed and triggering angle α by assuming rotational voltage coefficient K is evaluated. The value of average current is tested from magnetization characteristics whether the assumed value of K is satisfactory. If such is not the case, the value of K is read from magnetization characteristic and average value of current is calculated again. This is continued until convergence occurs. This value of K is used in other equations for rms value of current, line current, torque etc.

The brush contact resistance, which actually decreases with increase in armature current, has been clubbed with armature resistance and has been assumed constant. The brush contact resistance can be obtained from actual tests and can be used in the expressions.

The armature inductance decreases with increase in armature current, and expressions for the same are available. The field inductance varies with armature current this drop can be taken into account by using $N_S \frac{d\phi}{dt}$, where N_S is number of series field turns and ϕ is working flux.

REFERENCES

PAPERS

(1) S.R. Doradla and P. C. Sen, "Solid State Series motor drive", IEEE Transactions- Vol. IECI-22 no. 2, May 1975, pp.164 to 171.

(2) P.C. Sen and S.R. Doradla, "Symmetrical and extinction angle control of solid state series motor drive," IEEE Transactions - Vol.IECI-23 no.1, February 1976, pp.31 to 38.

(3) P.D. Damle and G.K. Dubey, "Analysis of Chopper fed d.c. series motor", IEEE Transactions- Vol.IECI-23 no.1, February, 1976.

(4) P.W. Franklin, "Theory of the d.c. motor controlled by power pulses - Part I motor operation", IEEE Transactions - Vol.PAS-91 no.1, pp.249-53.

(5) M. Ramamoorty and B. Ilango, "A new approach to the steady state analysis of single-pulse-fired Thyristor controlled D.C. motors". Journal of Institution of Engineers(India), EL Vol.52, April, 1972.

BOOKS

(6) D.K. Cheng, "Analysis of Linear Systems".

(7) Mullard, "Power Engineering Using Thyristors-Vol.I".

(8) Department of Electrical Engineering, I.I.T, Bombay, "Short term course on Solid State Power Control-Lecture notes".