SHADED-POLE FLAT LINEAR INDUCTION MOTOR

A Thesis submitted to the Cape
Technikon in fulfilment of the
requirements for the Master's
Diploma in Technology (Heavy
Current).

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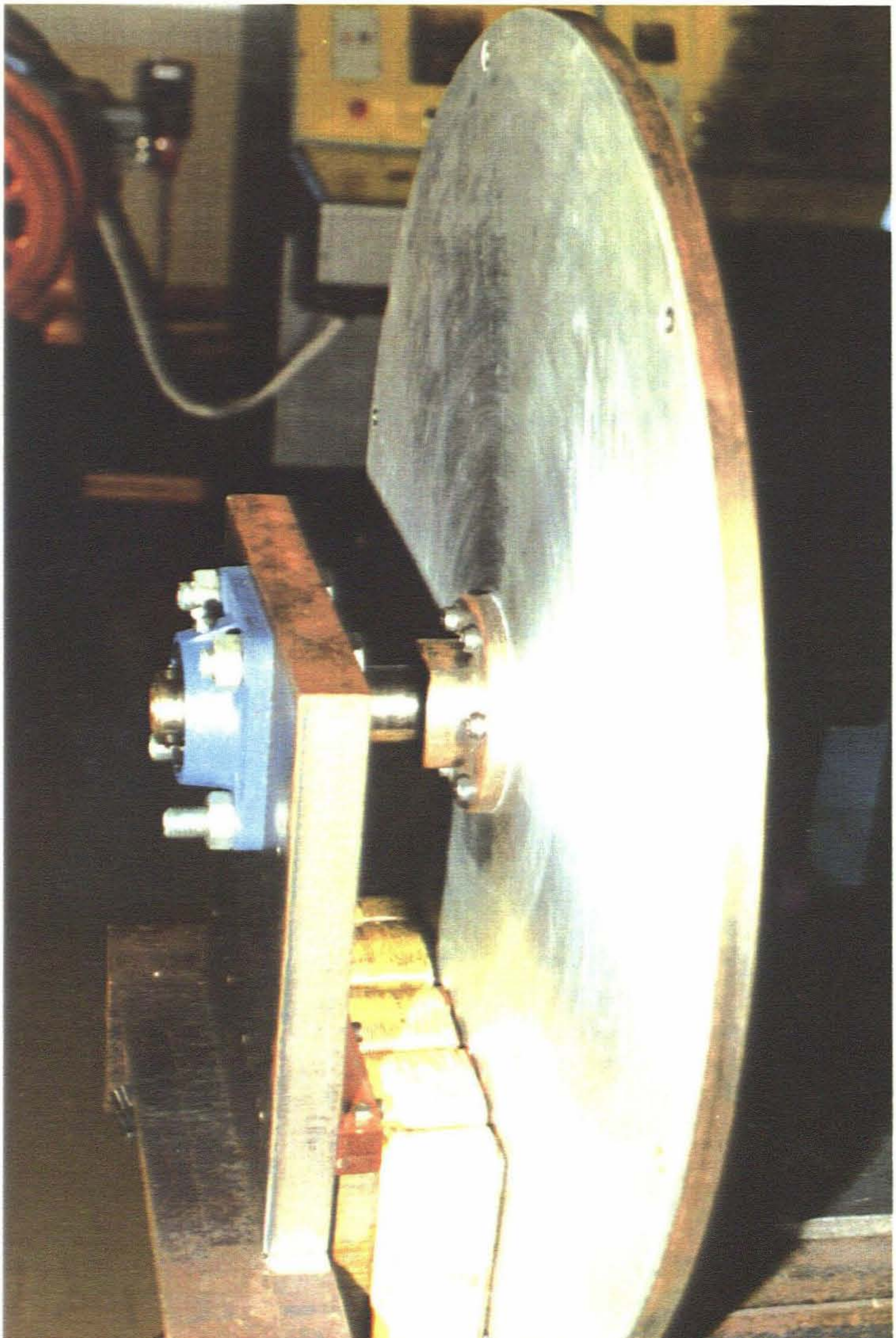

ABSTRACT

Linear induction motors are built for numerous applications. Their robustness, gearfree-link to the load and the fact that speed is not a function of the number of poles (as in round machines) are only a few advantages. As every single phase motor needs some starting aid, so does a linear induction drive. For round machines, capacitors or shaded poles are usually used. A capacitor can be damaged electrically, which is a rare occurrence for shading rings. A useful combination of these advantages is a linear induction motor which is gearless and uses the shaded pole principle as a starting aid.

In order to simplify the designing process, a computer program (Fortran) was written. The main objective on the electrical side was to obtain low input power, high power factor and high efficiency.

In order to find the performance curves, torque measurements were made. Although the principles of torque measurements are well known the device to measure torque for this machine was not available and had to be constructed.

Material obtainable in South Africa was used, so that the motor could be reproduced at any time. This work should provide a valuable foundation for further research in this direction.

TERMS OF REFERENCE

The objective is to design and build a shaded-pole flat linear induction motor. A computer program is to be written in order to simulate the motor and to simplify the design process, as well as finding the necessary performance curves.

The above mentioned points are to be carried out as a thesis, to be submitted in July 1991, for the completion of a Master's Diploma at the Cape Technikon.

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NOMENCLATURE

a = accelleration of mass, inertia test (m/s^2)

A_{cu} = area of copper wire (m^2)

b_p = width of pole (m)

B_g = flux density in air gap (T)

$\cos\phi$ = power factor

d = thickness of aluminium disk (m)

d_w = diameter of wire with insulation (m)

E_1 = assumed initial primary EMF (V)

f = frequency (Hz)

F_r = force to overcome friction and windage resistance (N)

g = air gap (m)

h = thickness of iron disk (m)

h_{ov} = winding overhang (m)

h_p = height of winding space (m)

h_s = height of shading ring slot (m)

h_y = height of yoke (m)

H_l = magnetic field intensity in the limb (A/m)

H_s = magnetic field intensity in the iron disk (A/m)

H_y = magnetic field intensity in the yoke (A/m)

I_{Fe} = iron loss current (A)

I_o = no load current (A)

I_1 = primary current (A)

I_μ = magnetization current (A)

$j = \sqrt{-1}$ = imaginary unit

J = current density (A/m^2)

k_c = Carter's factor

k_d = distribution factor

k_n = saturation factor

k_p = pitch factor

k_{rn} = Russell and Norsworthy factor

k_{tr} = transfer coeficient

K_w = winding factor

l = width of core (m)

l_{av} = average length of one turn (m)

l_1 = effective winding space (m)

l_2 = available winding space (m)

L_i = length of core (m)

m_{Fe} = mass of core (kg)

m_I = mass used in inertia test (kg)

m_s = mass needed to start rotating disk with uniform velocity (kg)

m_t = total mass of disk and shaft (kg)

m_1 = number of phases

N = speed (rpm)

N_p = number of turns per pole

N_1 = total number of turns

p = number of pole pairs

P_{elect} = secondary I^2R losses (W)

P_{Fe} = iron loss in core (W)

P_I = input power (W)

P_L = total power loss (W)

P_{1cu} = copper loss in primary (W)

P_{2cu} = total transfered power in air gap (W)

r = radius of shaft used for inertia test (m)

r_g = radius of gyration (m)

R_{Fe} = iron loss resistance (Ω)

R_1 = primary resistance (Ω)

s = slip

S_d = distance that the weight for inertia test has dropped (m)

t = time that the mass took to drop in the inertia test (s)

t_p = thickness of insulation paper between windigs (m)

u = initial velocity (m/s)

V_{Fe} = core volume (m^3)

V_1 = input voltage (V)

w_s = width of shading pole slot (m)

w_1 = initial angular velocity, inertia test (rad/s^2)

w_2 = final angular velocity, inertia test (rad/s^2)

X_m = mutual inductance (Ω)

X_1 = primary leakage reactance (Ω)

Z_{Al} = impedance of aluminium reaction rail refered to primary (Ω)

Z'_{Fe} = impedance of iron reaction rail refered to primary (Ω)

Z_t = total impedance of motor (Ω)

Z'_2 = total impedance of reaction rail refered to primary (Ω)

α = angular acceleration (rad/s^2)

α_{Al} = propagation constant for aluminium (m^{-1})

α_{Fe} = propagation constant for iron (m^{-1})

γ_{cu} = specific weight of aluminium (kp/m^3)

γ_{Fe} = specific weight of sheet steel (kp/m^3)

ΔP_{Fe} = unit loss based on 0.4T in the air gap (W/kg)

η = efficiency

μ_{Fe} = complex permeability in reaction rail (Hm)

μ_o = permeability of free space (H/m)

μ_{rs} = relative surface permeability iron disk

μ' = real component of μ_{rs}

μ'' = imaginary component of μ_{rs}

ρ_{Fe} = density of steel (kg/m^3)

σ_{Al} = conductivity of aluminium (S/m)

σ_{cu} = conductivity of copper (S/m)

σ_{Fe} = conductivity of steel (S/m)

σ_1 = leakage factor

σ'_{Al} = equivalent conductivity of aluminium disk (S/m)

τ = pole pitch (m)

τ_{Al} = temperature constant of aluminium at t=20°C

τ_{cu} = temperature constant of copper at t=20°C

τ_{Fesh} = temperature constant of sheet steel at t=20°C

τ_{Feso} = temperature constant of solid steel at t=20°C

Φ_g = air gap flux (Wb)

Φ_t = total flux in core (Wb)

ω = angular velocity (rad/s)

1. INTRODUCTION

Just as electromagnetic forces produce a rotary motion in an electric machine, electromagnetic forces may be used to produce linear motion. In principle there is a linear electric machine for every rotary machine.

The main difference between linear electric machines and its rotary counterpart is best explained by an imaginary process whereby an induction motor is transformed into a linear induction motor (LIM) by cutting the stator and the rotor of the rotary motor in a radial plane and unrolling it. This produces an open air gap with an entry point and an exit point in the linear induction-motor.

I believe that a need exists for the development and manufacture of a single-phase linear machine, because three-phase power is not normally available for domestic use. The three-phase induction motor, the two phase induction motor and some single-phase induction motors are similarly constructed. The essential elements for the production of a rotating or moving field in these induction motors are the time displacement of the exciting current and the space displacement of the winding. The single-phase induction motor that falls into this category usually uses a capacitor for the phase displacement.

The shaded-pole induction motor is a very popular choice for use where only fractional horse-power is required. It is very simple in construction, low in cost, extremely rugged and very reliable because it does not need commutator brushes, a centrifugal switch, a starting capacitor, collector rings, governor or contacts of any sort. All these advantages and the fact that the shaded-pole principle has not been investigated in conjunction with linear induction motors, justifies this theses.

The stator core with slots and teeth of linear induction motors can be replaced by a simpler flat salient pole magnetic circuit. The secondary magnetic circuit can be a simple conductive disk which is much cheaper and simpler than the rotor of an inductive machine. An additional advantage, especially in turntables, is the elimination of a gear box. These advantages in a linear induction motor are reason enough to adapt its performance characteristics to drive various large and small machines.

The disadvantages of the linear induction motors are a small power factor and a small starting torque. This is due to a large air gap and an open air gap. For the shaded-pole linear induction motor the starting torque is even lower. This is due to the phase split being less than 90 degrees as a result of various practical imperfections.

2. CONSTRUCTION

2.1 Construction

Figure 1 shows the basic construction of the shaded-pole flat linear induction motor. It consists basically of two parts, namely a flat magnetic core (6) and a round conductive disk (1;2).

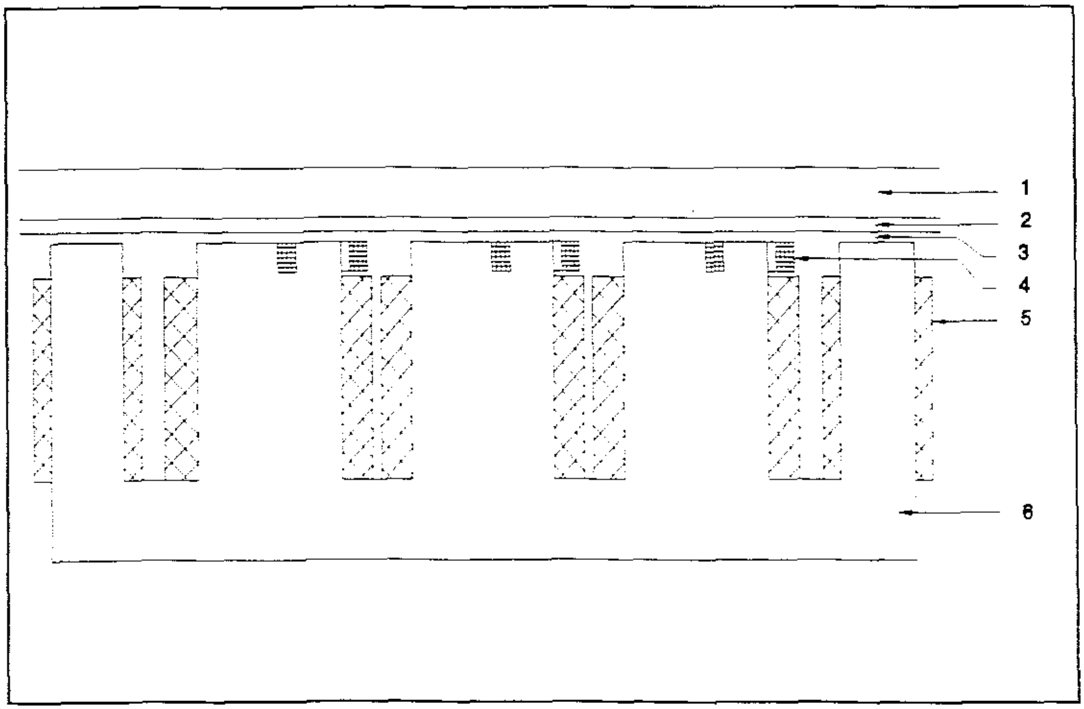


Figure 1 Basic construction of the shaded-pole flat linear induction motor

A laminated core was constructed out of standard H18, 0.5mm, Non Orientated Silicon Steel (N.O.S.S.) transformer laminations. The laminations, which are aligned in the direction of the field lines, are insulated from each other by a thin layer of varnish.

Laminating an iron core means an increase in permeability and decrease in conductivity, this consequently reduces the magnitude of the eddy current paths.

A shaded four pole flat linear induction motor core (Figure 1,6), was constructed by laminating two blocks of laminations under high pressure with strong epoxy glue (HY4076 and AV4076). A support frame was then built to keep the laminations together and to prevent them from fringing while slots where milled into the poles. The slots have to be open, as this reduces the leakage flux between the auxiliary and main windings and therefore allows more effective flux to flow through the air gap.

Shaded-pole copper rings (Figure 1,4) were then constructed to fit tightly into the slots. This was done to keep the main windings in place and to ensure that the shaded-pole copper rings do not become detached when vibrations occur. The shaded-pole copper rings were soldered in a very clean environment with silver solder. It is important to solder the seams with a material that has a high melting point to prevent disintegration during extreme operating conditions. The main windings were then wound (Figure 1,5), taking the space needed for the shaded-pole copper rings into consideration. The direction in which the coils are wound, is important in creating north and south poles.

The assembly of the core was as follows. First the coils were slipped over the limbs, taking care that the correct south and north poles were created. The coil was then insulated with special insulating paper (DMD-Mitron) from the limb and from the yoke. After this the shaded-pole copper rings where forced into the slots.

The following procedure was followed to secure all the various parts and thereby preventing magnetic vibrations. First the core was placed into the oven and heated to 160 degrees, so as to obtain a homogeneous temperature throughout the core. Then the core was dipped in a special transformer resin (Isonol 31) until all air bubbles disappeared. The high temperature of the core ensures that the resin in the vicinity of the core becomes thinner and is able to fill up every air gap that exists between laminations of the core and the windings of the armature coils. Finally the core was baked to dry and harden the resin. This is necessary to keep all the parts in place during extreme running conditions.

The round conductive disk is much cheaper and easer to construct than its counterpart, the squirrel cage induction motor rotor. The secondary disk was constructed out of a 10mm mild steel disk to which a 3mm aluminium cap was laminated.

Figure 2 shows the whole assembly of the motor. The magnetic core and the conductive disk are mounted on the supportive frame in such a way that the air gap and distance of the core from the centre of the disk to the edge of the disk can be changed for different tests.

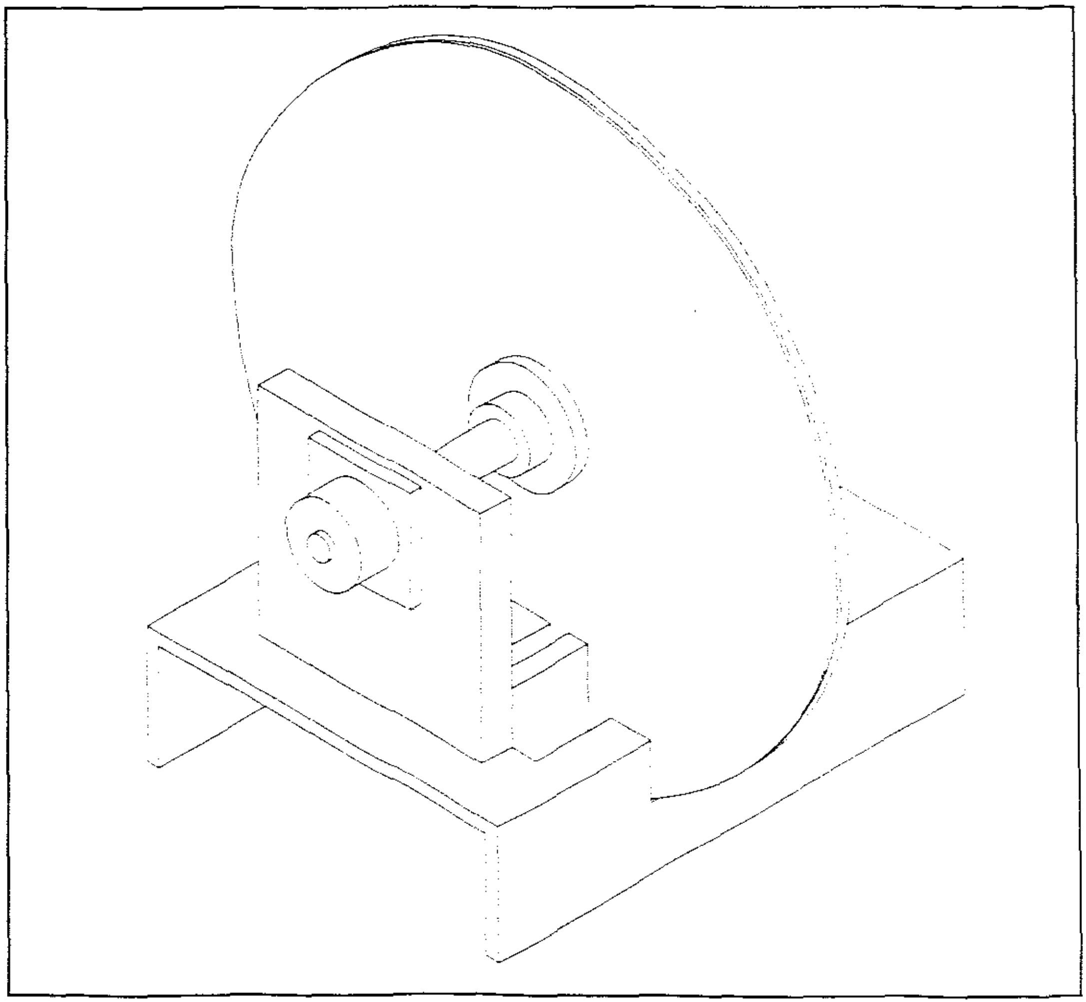


Figure 2 Assembly of the shaded-pole flat linear induction motor

2.2 Moving Magnetic field

The induced current in the shading-ring-coil causes the flux in the shaded portion of the pole to lag the flux in the other portion. The result is a travelling magnetic field from the direction of the unshaded portion to the shaded portion of the pole. This travelling magnetic field induces currents to flow in the round aluminium disk. The secondary currents in turn create their own magnetic field, and the interaction between the two magnetic fields causes the thrust. The 10mm mild steel disk has a flux depth penetration of 7.11mm (Appendix 3) and ensures that the flux lines return by the shortest path into the core and therefor reduce the total reluctance of the field circuit which reduces the excitation for the flux.

To enable eddy currents to be fully established, the secondary disk should at least be half a pole pitch larger than the primary core in all direction. Another consideration when deciding on the size of the disk, is the distance of the primary core from the centre of the disk. The core should be situated as far away as physically possible, to ensure that the braking forces do not become to large.

3. DESIGN OF SHADED-POLE FLAT LIM

3.1 Formulae used in the design

To start the design of the shaded-pole flat linear induction motor the main dimensions of the core have to be chosen tentatively from the output graphs. After a standard transformer lamination has been chosen most dimensions like L_i, τ, b_p, h_y, h_s, h_p and l are fixed.

(i) volume of the core

$$V_{Fe} = L_i\ (l\ h_y + 4\ \tau\ (\tau - b_p) - 3\ h_s\ w_s) \qquad \textbf{(1)}$$

mass of core

$$m_{Fe} = V_{Fe}\ \rho_{Fe} \qquad \textbf{(2)}$$

iron core loss (multiplied by 1.5 to take additional core losses like those for bolts and sharp edges into account)

$$P_{Fe} = \Delta P_{Fe}\ m_{Fe}\ 1.5 \qquad \textbf{(3)}$$

(ii) total flux (the flux of the air gap was chosen tentatively from the final current density, i.e. when the air gap flux is to high the current density will become to high)

$$\Phi_t = b_p\ L_i\ B_g\ \sigma_l \qquad \textbf{(4)}$$

(iii) total number of turns (E_1 was determined via the iterative method - refer to Flowchart in section 3.3, page 31)

$$N_1 = \frac{|E_1|}{4.44\ K_w\ f\ \Phi_t} \tag{5}$$

number of turns for one pole

$$N_p = \frac{N_1}{2\ p} \tag{6}$$

transfer coefficient (reference 4)

$$k_{tr} = \frac{2\ m_1\ (N_1\ K_w)^2}{p} \tag{7}$$

(iv) available winding space

$$l_2 = \frac{\tau - b_p}{2} \tag{8}$$

effective winding space

$$l_1 = \frac{N_p\ d_w\ (d_w + t_p)}{h_p} \tag{9}$$

average length of one turn

$$l_{av} = 2\ (L_i + b_p + 2\ l_1) \tag{10}$$

(v) primary resistance

$$R_1 = \frac{l_{av} N_1}{\sigma_{cu} A_{cu}} \tag{11}$$

primary resistance at a temperature of 75°

$$R_1 = R_1 \frac{\tau_{cu} + 75}{\tau_{cu} + 20} \tag{12}$$

mutual inductance (reference 1)

$$X_m = 12.8 \text{ f } p \ (N_p K_w)^2 \frac{\tau \ L_i}{k_n \ k_c \ g} 10^{-6} \tag{13}$$

primary leakage reactance (reference 1)

$$X_1 = 0.8 \ (\sigma_l - 1) \ X_m \tag{14}$$

iron loss resistance

$$R_{Fe} = \frac{E_1^2}{P_{Fe}} \tag{15}$$

(reference 4)

$$\beta = \frac{\pi}{\tau} \tag{16}$$

winding overhang

$$h_{ov} = \frac{\tau}{2} \tag{17}$$

$$w = \tau + L_i \tag{18}$$

Russel - Norsworthy factor (this factor takes care of edge effects in high conductivity nonmagnetic layers, reference 4)

$$k_{rn} = 1 - \frac{\tanh\left(\beta \frac{w}{2}\right)}{\beta \frac{w}{2} \left(1 + \tanh\left(\beta \frac{w}{2}\right) \tanh(\beta h_{ov})\right)} \tag{19}$$

conductivity of aluminium

$$\sigma_{Al} = \sigma_{Al} \left(\frac{\tau_{Al} + 20}{\tau_{Al} + 75}\right) \tag{20}$$

equivalent conductivity of aluminium disk (reference 2)

$$\sigma_{Al} = k_{rn}\, \sigma_{Al} \tag{21}$$

propagation constant for aluminium (reference 2)

$$\chi_{Al} = \sqrt{(j\, s\, \omega\, \mu_c\, \sigma_{Al}) + \left(\frac{\pi}{\tau}\right)^2} \tag{22}$$

impedance of the aluminium reaction rail referred to the primary (reference 2)

$$Z'_{Al} = ktr \frac{j\ s\ \omega\ \mu_o}{\chi_{Al}} \frac{1}{\tanh(\chi_{Al}\ d)} \frac{L_i}{\tau} \qquad \textbf{(23)}$$

complex permeability in reaction rail (takes into account saturation and hysteresis and is a function of the magnetic field strength, (reference 2 & 3)

$$\mu_{Fe} = \mu_o\ \mu_{IS}\ (\mu' - \mu'') \qquad \textbf{(24)}$$

propagation constant for iron (reference 2)

$$\chi_{Fe} = \sqrt{(j\ s\ \omega\ \mu_{Fe}\ \sigma_{Fe}) + \frac{\pi}{\tau}} \qquad \textbf{(25)}$$

the influence of the transverse edge effect on the secondary impedance can be taken into account by the coefficient k_z (reference 2)

$$k_z = 1 - \left[\frac{g}{L_i}\right] \frac{2\ \tau}{\pi\ w} \left[1 - \exp\left[\frac{-(\pi\ w)}{2\ L_i}\right]\right] \qquad \textbf{(26)}$$

impedance of laminated ferromagnetic reaction rail reverted to the primary (reference 2)

$$Z'_{Fe} = k_{tr} \frac{j\ s\ \omega\ \mu_{Fe}}{\chi_{Fe}} \frac{1}{\tanh(\chi_{Fe}\ h)} \frac{L_i\ k_z}{\tau} \qquad \textbf{(27)}$$

total impedance of reaction rail referred to primary

$$Z_2' = \frac{Z_{Al}' \, Z_{Fe}'}{Z_{Al}' + Z_{Fe}'} \left[\frac{1}{s}\right] \qquad (28)$$

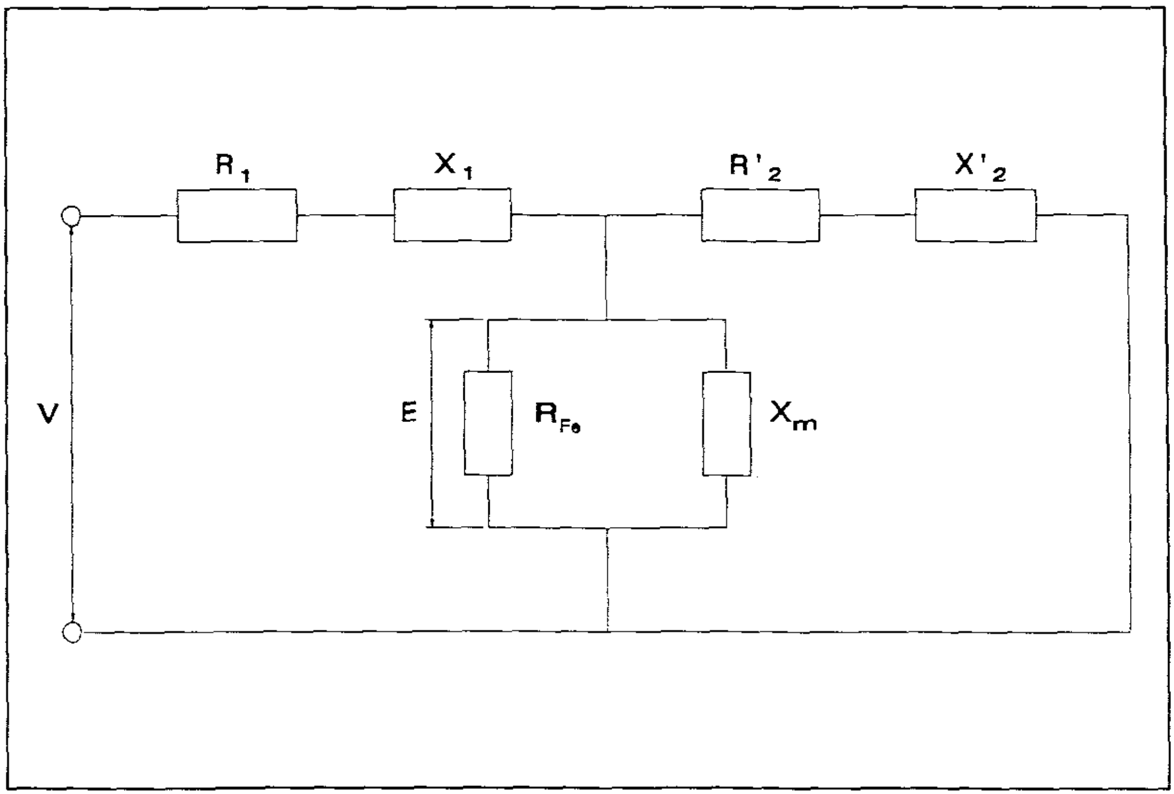


Figure 3 Equivalent circuit for a linear inductive motor with negligible small end effect (low speed).

(vi) total impedance of motor (derived from figure 3)

$$Z_t = (R_1 + jX_1) + \left[\frac{R_{Fe}\left[\dfrac{jX_m \, Z_2'}{jX_m + Z_2'}\right]}{R_{Fe} + \left[\dfrac{jX_m \, Z_2'}{jX_m + Z_2'}\right]}\right] \qquad (29)$$

(vii) primary current

$$I_1 = \frac{V_1}{Z_t} \tag{30}$$

current density

$$J = \frac{|I_1|}{A_{cu}} \tag{31}$$

(viii) EMF induced in the primary

$$E_1 = V_1 - |I_1| \, |R_1 + j\,X_1| \tag{32}$$

(ix) magnetizing current

$$I_\mu = \frac{|E_1|}{X_m} \tag{33}$$

iron loss current

$$I_{Fe} = \frac{|E_1|}{R_{FE}} \tag{34}$$

no load current

$$I_o = I_{Fe} - j\,I_\mu \tag{35}$$

secondary current

$$I_2' = I_1 - I_o \tag{36}$$

(x) iron loss in the core

$$P_{Fe} = I_{Fe}^2 \, R_{Fe} \tag{37}$$

copper loss in the primary

$$P_{1cu} = |I_1| \, R_1 \tag{38}$$

total power transferred across the air gap from the secondary

$$P_{2cu} = |I_2'| \, R_2' \; s \tag{39}$$

secondary I^2 R losses

$$P_{elect} = |I_2'^2| \, R_2' \tag{40}$$

Thrust

$$Thrust = \frac{P_{elect}}{2 \, f \, \tau} \tag{41}$$

(xi) total power loss

$$P_L = P_{Fe} + P_{1cu} + P_{2cu} \tag{42}$$

(xii) power factor

$$\cos \phi = \cos\left[\left[\angle \, (I1) \; \frac{180}{\pi} \right] \frac{\pi}{180} \right] \tag{43}$$

(xiii) Input power

$$P_I = V_1 \, |I_1| \cos\phi \tag{44}$$

(xvi) efficiency

$$\eta = 1 - \frac{P_L}{P_I} \tag{45}$$

3.2 CALCULATIONS

The following calculations are based on the formulas in section 3.1, where the calculation numbers correspond to the formula numbers. The single-phase shaded-pole LIM was constructed according to the dimensions used in the calculations. Refer to the input values in section 4.1.

(i) Volume according to formula (1).

$$\begin{aligned} V_{Fe} &= 0.09\ (0.192*0.016\ +\ 4*0.048* \\ &\quad (0.048\ -\ 0.032)\ -\ 3*0.005*0.005) \\ &= 5.462*10^{-4}\ (m^3) \end{aligned} \tag{1}$$

mass of core according to formula (2)

$$\begin{aligned} m_{Fe} &= 5.462*10^{-4}*7.8*10^{3} \\ &= 4.26\ (kg) \end{aligned} \tag{2}$$

iron core loss

$$P_{Fe} = 0.6 * 4.26 * 1.5 \\ = 3.834\ (W) \tag{3}$$

(ii) total flux

$$\Phi_t = .032 * 0.09 * 0.4 * 1.15 \\ = 0.001\ (Wb) \tag{4}$$

(iii) The induced voltage was found via the iterative method. Refer to the flowchart in section 3.3 to follow the iterative loop.

$$E_1 = 153.597\ (V)$$

total number of turns

$$N_1 = \frac{153.597}{4.44 * 1 * 50 * 0.001} \\ = 522.251 \tag{5}$$

number of turns for one pole

$$N_p = \frac{522.251}{2 * 2} \\ = 130.563 \tag{6}$$

transfer coefficient

$$k_{tr} = \frac{2*2*(522.251*1)^2}{2} = 5.455*10^5 \tag{7}$$

(iv) available winding space

$$l_2 = \frac{0.048-0.032}{2} = 0.008\ (m) \tag{8}$$

effective winding space

$$l_1 = \frac{130.563*0.001*(0.001+6*10^{-4})}{0.043} = 0.007\ (m) \tag{9}$$

average length of one turn

$$l_{av} = 2*(0.09+0.032+2*0.007) = 0.272\ (m) \tag{10}$$

(v) primary resistance

$$R_1 = \frac{0.272*522.251}{5.6*10^7*1.227*10^{-6}} = 2.068\ (\Omega) \tag{11}$$

primary resistance at a temperature of 75°

$$R_1 = 2.068 * \frac{235+75}{235+20} = 2.514\ (\Omega) \tag{12}$$

primary inductance

$$X_m = 12.8*50*2*(130.563*1)^2 * \frac{0.048*0.009}{1.1*1*0.002}*10^{-6} = 42.846\ (\Omega) \tag{13}$$

primary leakage reactance

$$X_1 = 0.8*(1.15-1)*42.846 = 5.142\ (\Omega) \tag{14}$$

iron loss resistance

$$R_{Fe} = \frac{153.597^2}{3.834} = 6.153 * 10^3\ (\Omega) \tag{15}$$

$$\beta = \frac{3.142}{0.048} = 65.45\ (rad/m) \tag{16}$$

winding overhang

$$h_{ov} = \frac{0.048}{2} = 0.024\ (m) \tag{17}$$

$$w = 0.048 + 0.09 = 0.138\ (m) \tag{18}$$

Russel - Norsworthy factor

$$k_{rn} = 1 - \frac{\tanh\left(65.45 * \frac{0.138}{2}\right)}{65.45 * \frac{0.138}{2}} * \frac{1}{\left[1 + \tanh\left(65.45 * \frac{0.138}{2}\right) * \tanh(65.45 * 0.024)\right]} = 0.885 \tag{19}$$

conductivity of aluminium

$$\sigma_{Al} = 3.6 * 10^7 * \left[\frac{245 + 20}{245 + 75}\right] = 2.981 * 10^7\ (S/m) \tag{20}$$

equivalent conductivity of the aluminium disk

$$\sigma_{Al} = 0.885 * 2.981 * 10^7 = 2.637 * 10^7\ (S/m) \tag{21}$$

propagation constant for aluminium

$$\chi_{Al} = \sqrt{(j*50*314.159*1.257*10^{-6}*2.637*10^{7}) + \left[\frac{\pi}{0.048}\right]^{2}}$$
$$= 88.15 + 59.049j \ (1/m) \tag{22}$$

impedance of aluminium reaction rail

$$Z_{Al} = 5.455*10^{5}*\frac{(j*1*314.159*1.257*10^{-6})}{(88.15+59.049j)}*$$
$$\frac{1}{\tanh[(88.15+59.049j)*0.002]}*\frac{0.09}{0.048} \tag{23}$$
$$= 16.586 + 7.094j \ (\Omega)$$

complex permeability in reaction rail

$$\mu_{Fe} = 1.257*10^{-6}*200*(1.23-0.69j)$$
$$= 3.091*10^{-4} - 1.734*10^{-4}j \ (H/m) \tag{24}$$

propagation constant for iron

$$\chi_{Fe} = \sqrt{(j*50*314.159*(3.091*10^{-4}-1.734*10^{-4}j)) + \left[\frac{\pi}{0.048}\right]^{2}} \tag{25}$$
$$= 646.361 + 375.63j \ (1/m)$$

transverse edge effect coefficient

$$k_{z} = 1-\left[\frac{0.002}{0.09}\right]*\frac{2*0.048}{\pi*0.138}*$$
$$\left[1-\exp\left[\frac{-\pi*0.138}{2*0.09}\right]\right] \tag{26}$$
$$= 1.179$$

impedance of laminated ferromagnetic material

$$Z'_{Fe} = 5.455*10^5 * \frac{j*1*314.159*(3.091*10^{-4}-1.734*10^{-4})}{(6.46.361+375.63j)} * \frac{1}{\tanh((646.361+375.63j)*0.005)} * \frac{0.09*1.179}{0.048} = 154.173 + 91.355j \ (\Omega) \qquad \textbf{(27)}$$

total impedance of reaction rail

$$Z'_2 = \frac{(16.586+7.094j)*(154.173+91.355j)}{(16.586+7.094j)+(154.173+91.355j)} * \left[\frac{1}{1}\right] = 15.002 + 6.629j \ (\Omega) \qquad \textbf{(28)}$$

(iv) total impedance of motor

$$Z_t = (2.068+5.142j) + \left[\frac{6.153*10^3*\left[\frac{42.846j*(15.002+6.629j)}{42.846j+(15.002+6.629j)}\right]}{6.153*10^3+\left[\frac{42.846j+(15.002+6.629j)}{42.846j+(15.002+6.629j)}\right]}\right] = 12.813 + 13.977j \ (\Omega) \qquad \textbf{(29)}$$

(vii) primary current

$$I_1 = \frac{220}{(12.813+13.977j)} = 7.84 - 8.553j = 11.603\angle{-47.49} \ (A) \qquad \textbf{(30)}$$

current density

$$J = \frac{11.603}{1.227*10^{6}} = 9.455*10^{-6} \ (A/m^{2}) \quad (31)$$

(viii) EMF induced in primary

$$\begin{aligned} E_1 &= 220-11.603*(|2.514+5.142j|) \\ &= 220-11.603*5.723 \\ &= 153.597 \ (V) \end{aligned} \quad (32)$$

(ix) magnetizing current

$$I_{\mu} = \frac{153.597}{42.846} = 3.585 \ (A) \quad (33)$$

iron loss current

$$I_{Fe} = \frac{153.597}{6.153*10^{3}} = 0.025 \ (A) \quad (34)$$

no load current

$$I_o = 0.025-3.585j \ (A) \quad (35)$$

secondary current

$$\begin{aligned} I_2^{\prime} &= (7.84-8.553j) - (0.025-3.585j) \\ &= 7.816 - 4.968j \ (A) \end{aligned} \quad (36)$$

(x) iron loss in the core

$$P_{Fe} = 0.025^2 * 6.153 * 10^3 \qquad (37)$$
$$= 3.834 \ (W)$$

copper loss in the primary

$$P_{1cu} = 11.603^2 * 2.514 \qquad (38)$$
$$= 338.394 \ (W)$$

total power transferred across the air gap from the secondary

$$P_{2cu} = 9.261^2 * 15.002 * 1 \qquad (39)$$
$$= 1.287 * 10^3 (W)$$

secondary I^2R losses

$$P_{elect} = 9.261^2 * 15.002 \qquad (40)$$
$$= 1.287 * 10^3 \ (W)$$

Thrust

$$Thrust = \frac{1.287 * 10^3}{2 * 50 * 0.048} \qquad (41)$$
$$= 268.039 \ (N)$$

(xi) total power loss

$$P_L = 3.834 + 338.394 + 1.287 * 10^3 \qquad (42)$$
$$= 1.629 * 10^3 \ (W)$$

(xii) power factor

$$\cos\phi = \cos\left[\left[-0.829 * \frac{180}{\pi}\right] * \frac{\pi}{180}\right] \tag{43}$$

$$= 0.676$$

(xiii) input power

$$P_I = 220 * 11.603 * 0.676 \tag{44}$$

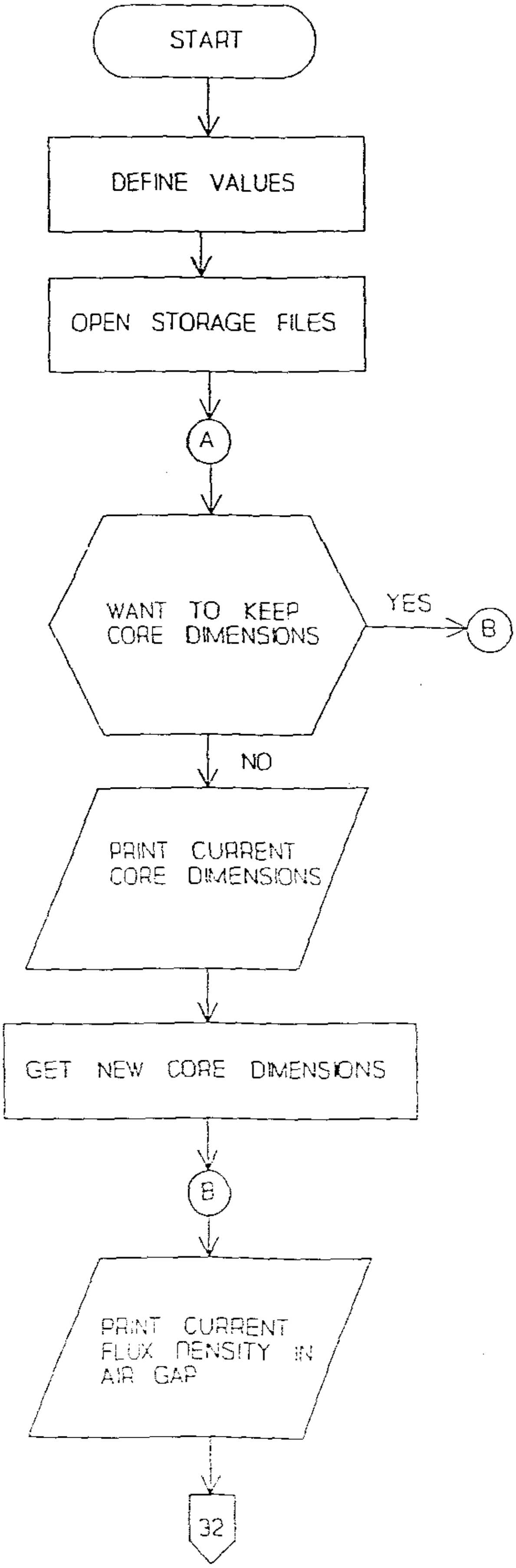
$$= 1.725 * 10^3 \ (W)$$

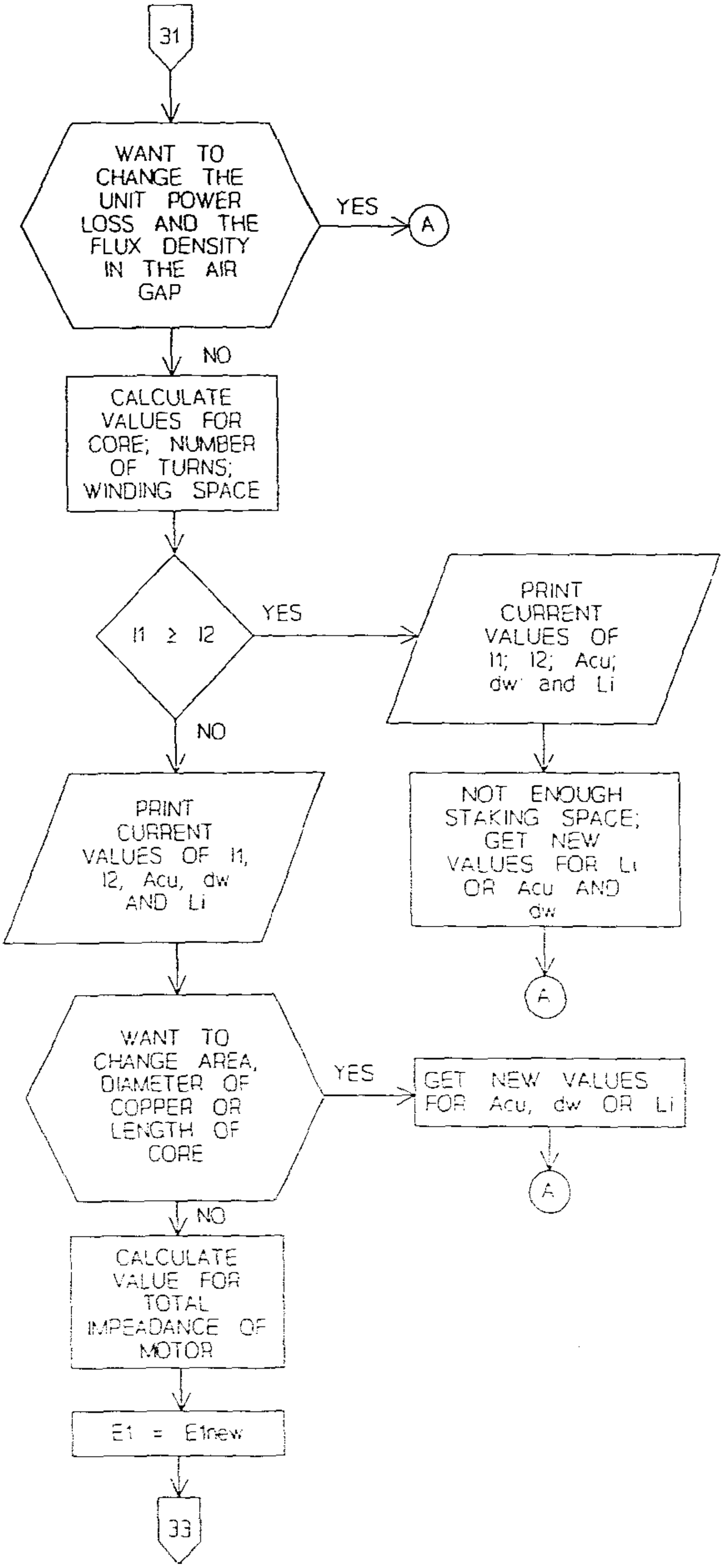
(xvi) efficiency

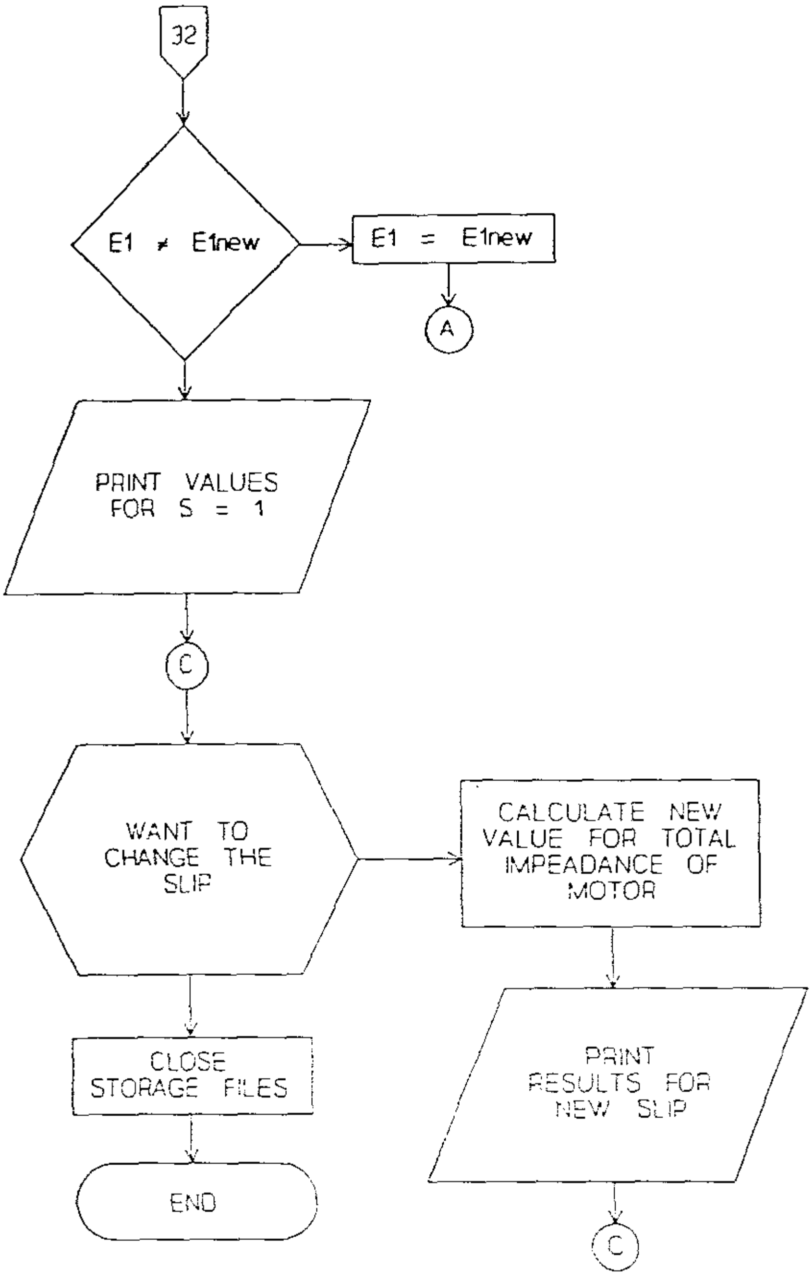
$$\eta = 1 - \frac{1.629 * 10^3}{1.725 * 10^3} \tag{45}$$

$$= 0.056$$

3.3 Flowchart




31
WANT TO CHANGE THE UNIT POWER LOSS AND THE FLUX DENSITY IN THE AIR GAP
YES
A
NO
CALCULATE VALUES FOR CORE; NUMBER OF TURNS; WINDING SPACE
I1 ≥ I2
YES
PRINT CURRENT VALUES OF I1; I2; Acu; dw and Li
NOT ENOUGH STAKING SPACE; GET NEW VALUES FOR Li OR Acu AND dw
A
NO
PRINT CURRENT VALUES OF I1, I2, Acu, dw AND Li
WANT TO CHANGE AREA, DIAMETER OF COPPER OR LENGTH OF CORE
YES
GET NEW VALUES FOR Acu, dw OR Li
A
NO
CALCULATE VALUE FOR TOTAL IMPEADANCE OF MOTOR
E1 = E1new
33



The computer program was written in Fortran and can be found in Appendix 1. The computed results can be found in Appendix 2.

4. EXAMPLE OF CALCULATIONS

4.1 Input data

A_{cu} = $1.2272 * 10^{-6}$ (m^2)

B_g = 0.4 (T)

b_p = 0.032 (m)

d = 0.002 (m)

d_w = 0.00125 (m)

E_1 = 153.597 (V)

f = 50 (Hz)

g = 0.002 (m)

h = 0.005 (m)

h_p = 0.043 (m)

h_s = 0.005 (m)

h_y = 0.016 (m)

H_1 = 112 (A/m)

H_s = 6000 (A/m)

k_c = 1

k_n = 1.1

K_w = 1

l = 0.192 (m)

L_i = 0.09 (m)

m_1 = 2

p = 2

s = 1

t_p = 0.0006 (m)

V_1 = 220 (V)

$w_s = 0.005$ (m)

$\gamma_{cu} = 8920$ (kp/m^3)

$\gamma_{Fe} = 7800$ (kp/m^3)

$\Delta P_{Fe} = 0.6$ (W/kg)

$\mu_o = 4 * \pi * 10^{-7}$ (H/m)

$\mu_{rs} = 200$

$\mu' = 1.23$

$\mu'' = 0.69$

$\rho_{Fe} = 7800$ (kg/m^3)

$\sigma_{Al} = 36 * 10^6$ (S/m)

$\sigma_{cu} = 56 * 10^6$ (S/m)

$\sigma_{Fe} = 5 * 10^6$ (S/m)

$\sigma_1 = 1.15$

$\tau = 0.048$ (m)

$\tau_{Al} = 245$ (°C)

$\tau_{cu} = 235$ (°C)

$\tau_{Fesh} = 202$ (°C)

$\tau_{Feso} = 230$ (°C)

$\omega = 2 * \pi * f$

4.2 Results

Results for the slip between 1 and 0 are given in tabular form below. They were calculated with the simulating program found in Appendix 1.

Table 1 Results from simulating program in Appendix 1

Slip	cos ϕ	n	I_μ (A)	J (A/m^2)
1.00	0.676	0.056	3.584	9.45e+06
0.95	0.665	0.091	3.619	9.24e+06
0.90	0.654	0.127	3.653	9.03e+06
0.85	0.641	0.162	3.687	8.82e+06
0.80	0.627	0.198	3.721	8.62e+06
0.75	0.612	0.233	3.754	8.42e+06
0.70	0.595	0.268	3.786	8.22e+06
0.65	0.576	0.303	3.817	8.03e+06
0.60	0.555	0.337	3.848	7.84e+06
0.55	0.532	0.371	3.877	7.66e+06
0.50	0.507	0.403	3.905	7.49e+06
0.45	0.480	0.435	3.932	7.33e+06
0.40	0.449	0.464	3.957	7.18e+06
0.35	0.416	0.491	3.980	7.04e+06
0.30	0.381	0.514	4.001	6.91e+06
0.25	0.342	0.531	4.020	6.79e+06
0.20	0.300	0.538	4.036	6.70e+06
0.15	0.255	0.528	4.050	6.61e+06
0.10	0.206	0.486	4.060	6.55e+06

Table 2 Results from simulating program in Appendix 1

Slip	P_1 (W)	P_{In} (W)	P_{elect} (W)	Thrust (N)
1.00	1628.185	1724.30	1286.21	267.96
0.95	1508.547	1660.17	1243.65	259.09
0.90	1392.372	1594.79	1199.72	249.94
0.85	1279.859	1528.16	1154.39	240.50
0.80	1171.21	1460.27	1107.59	230.75
0.75	1066.628	1391.11	1059.27	220.68
0.70	966.3248	1320.69	1009.37	210.29
0.65	870.5121	1248.98	957.79	199.54
0.60	779.4088	1175.99	904.43	188.42
0.55	693.2388	1101.70	849.14	176.90
0.50	612.2343	1026.09	791.75	164.95
0.45	536.6393	949.13	732.03	152.51
0.40	466.7172	870.79	669.67	139.51
0.35	402.7597	791.00	604.28	125.89
0.30	345.1045	709.67	535.37	111.53
0.25	294.1567	626.65	462.31	96.31
0.20	250.4183	541.70	384.37	80.08
0.15	214.5179	454.41	300.70	62.65
0.10	187.2295	364.02	210.34	43.82

4.3 Nameplate

Table 3 Typical nameplate values used in design

Dimensions	
length of core	0.09 (m)
hight of core	0.064 (m)
width of core	0.192 (m)
weight of core	4.26 (kg)
weight of aluminium and mild steel disk	9.5 (kg)
diameter of aluminium and mild steel disk	0.52 (m)
thickness of aluminium cap	3 (mm)
thickness of mild steel disk	10 (mm)
diameter of secondary rotor	0.52 (m)
cross sectional area of shaded pole ring	0.0024 (m^2)

Electrical Information	
number of phases	1
frequency	50 (Hz)
voltage	220 (V)
current	11.603 (A)
resistance	12.813 (Ω)
speed	84 (rpm)

Motor Information	
stator motor	single-phase shaded-pole
stator core	laminated (H18, 0.5mm, Non Orientated Silicon Steel)
rotor disk	aluminium cap laminated to mild steel disk
slot insulation	DMD-Mitron (6510)
shaded pole	copper soldered with silver solder

4.4 Characteristic curves

The followig graphs are based on the tabulated values in section 4.2.

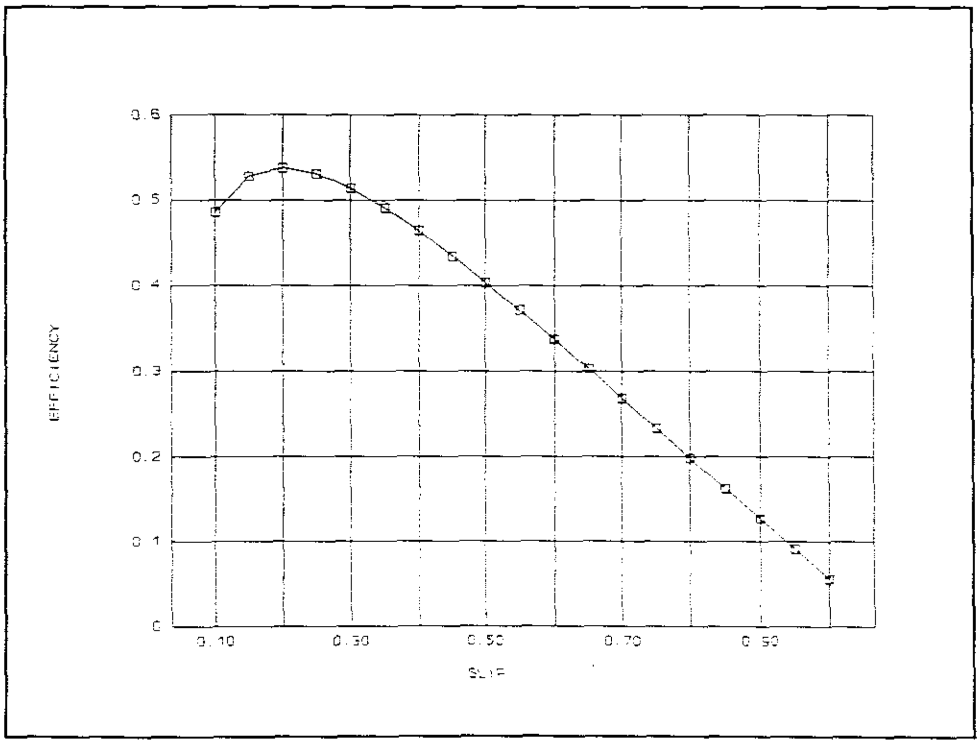


Figure 4 Efficiency versus slip

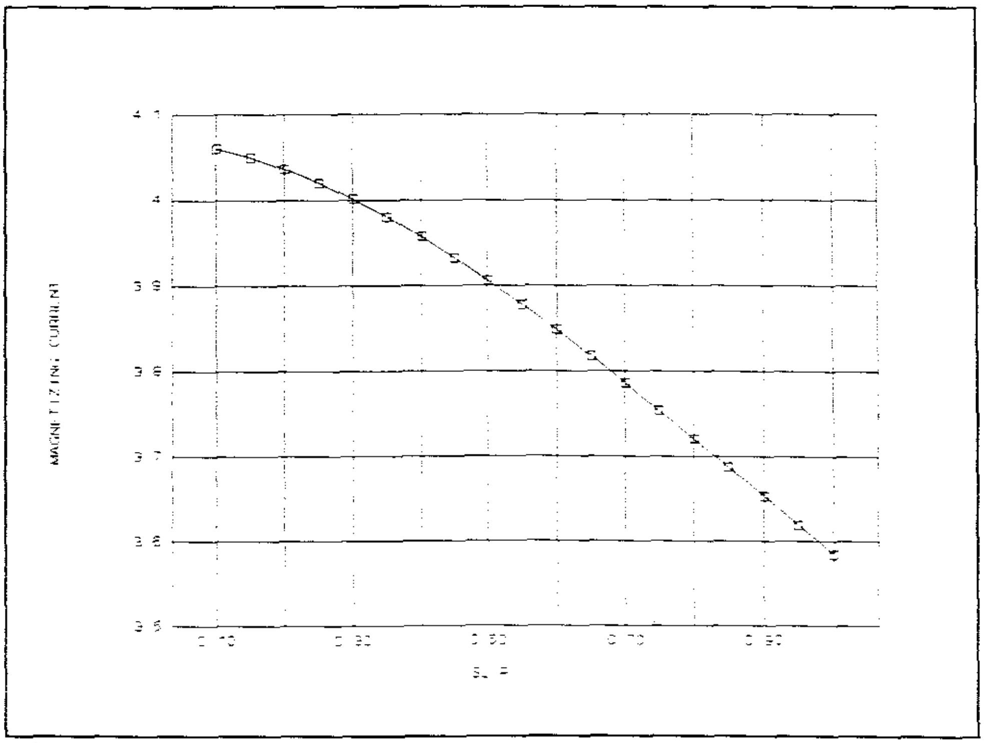


Figure 5 Magnetizing current versus slip

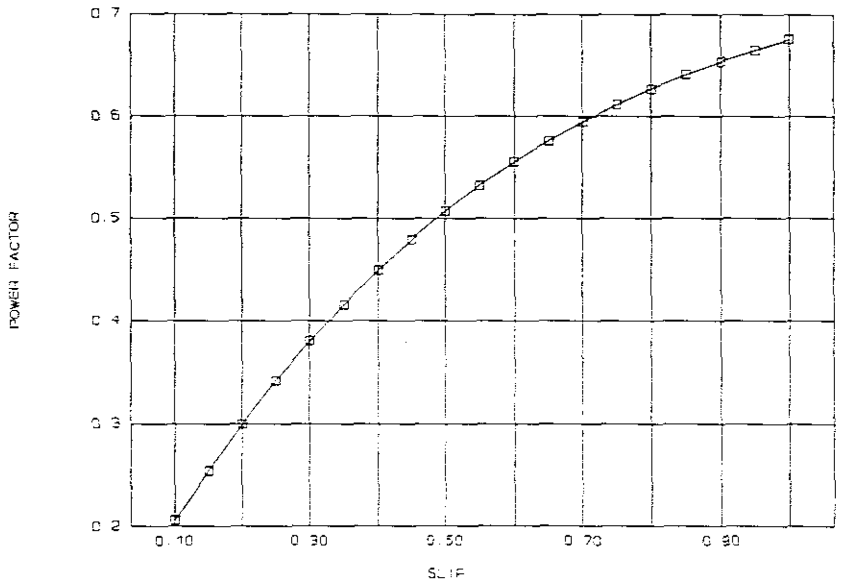


Figure 6 Power factor versus slip

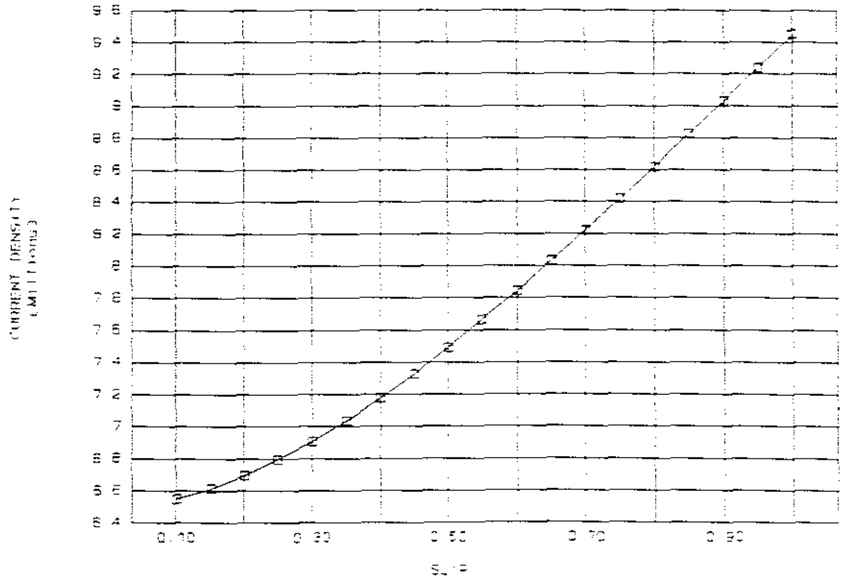


Figure 7 Current density versus slip

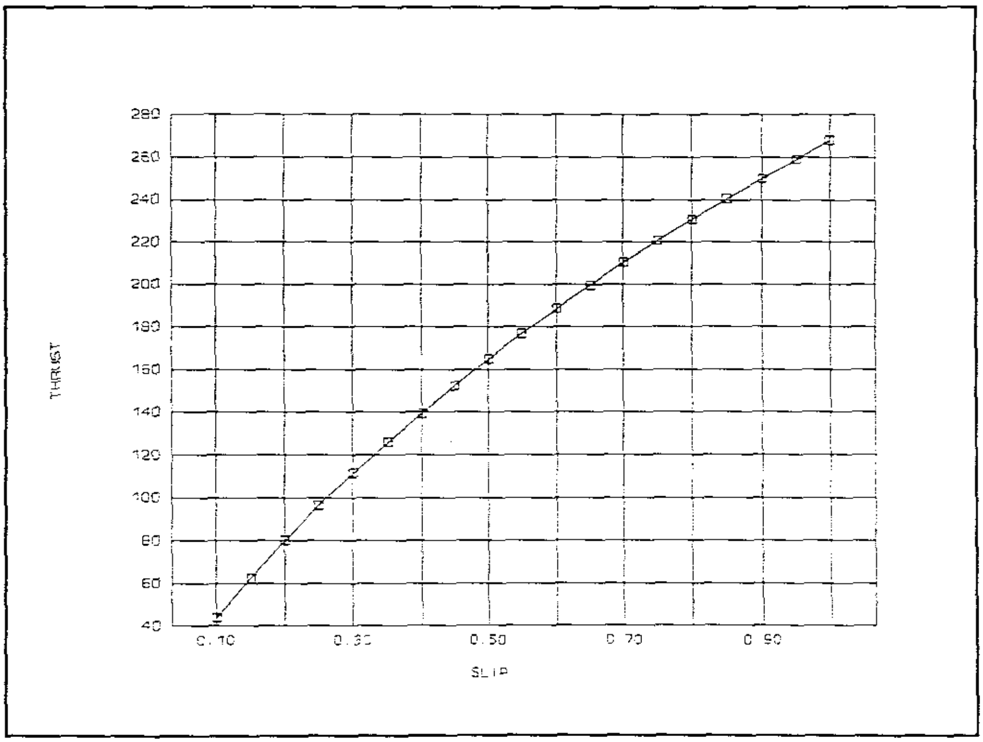


Figure 8 Thrust versus slip

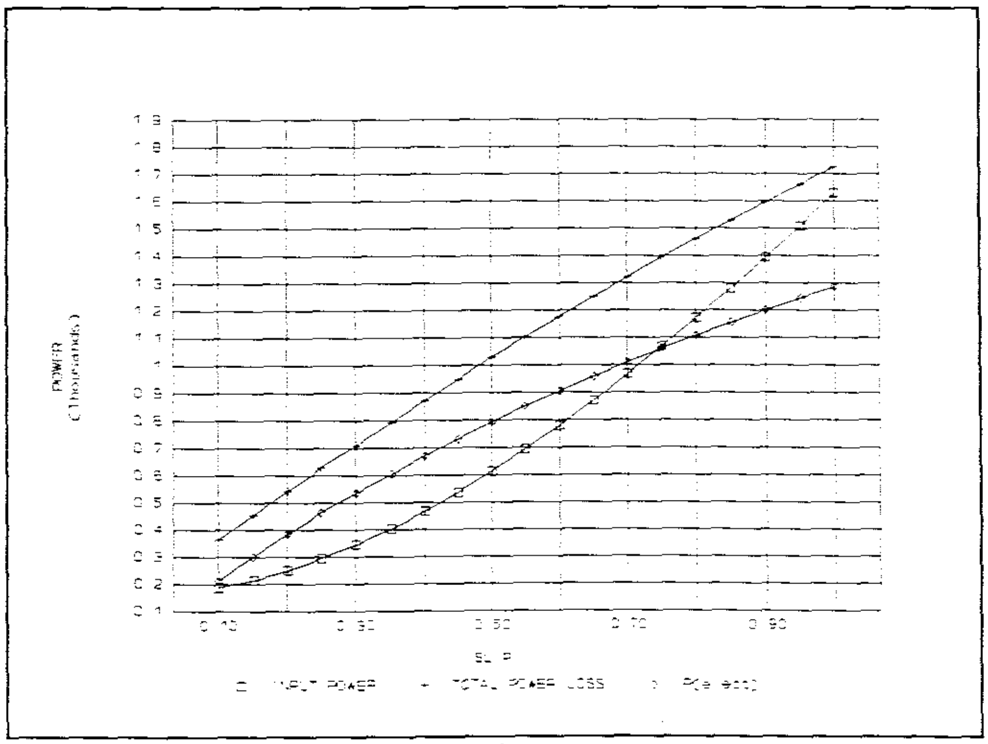


Figure 9 Power versus slip

4.5 Figures

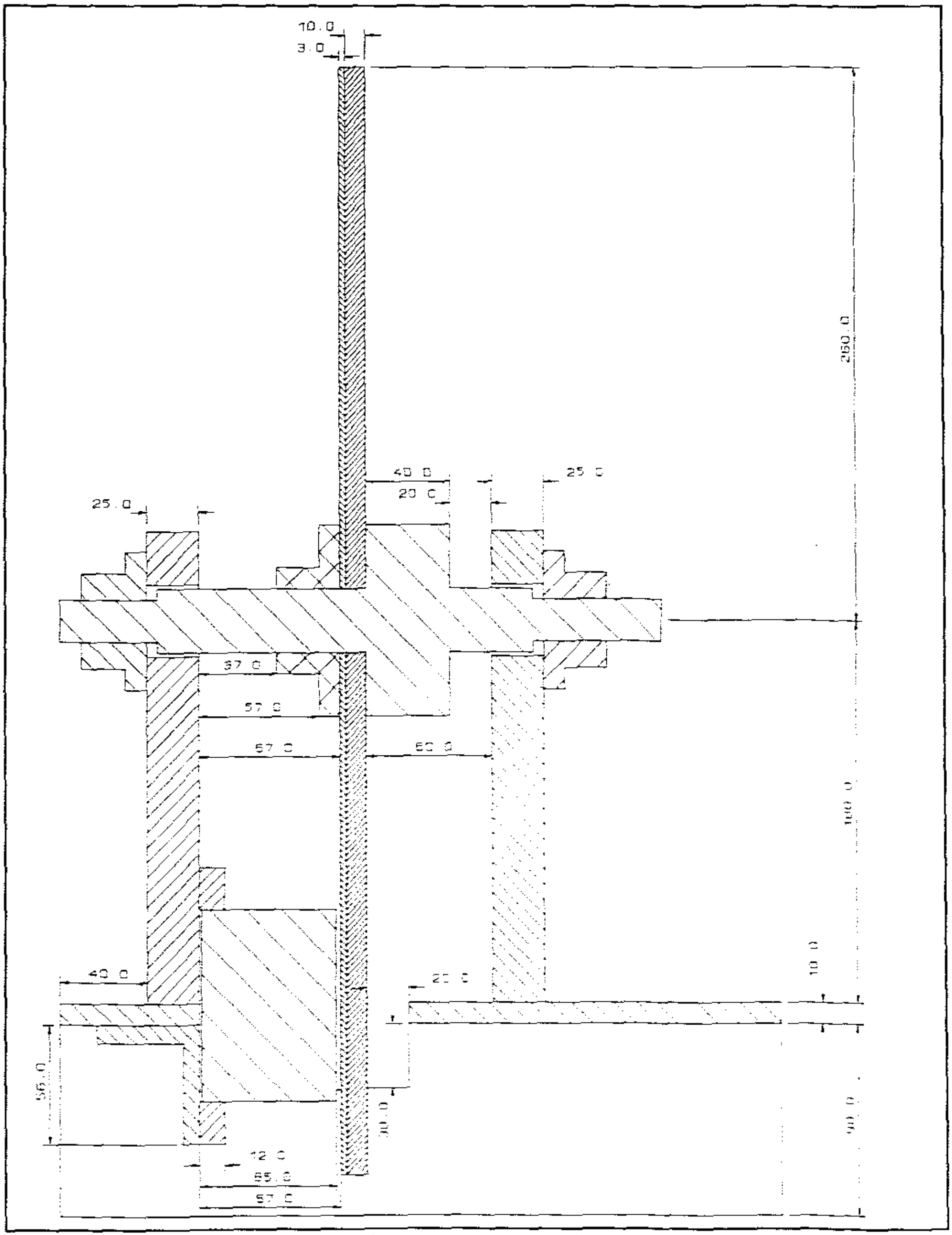


Figure 10 Sectional view of the single-phase shaded-pole linear induction motor.

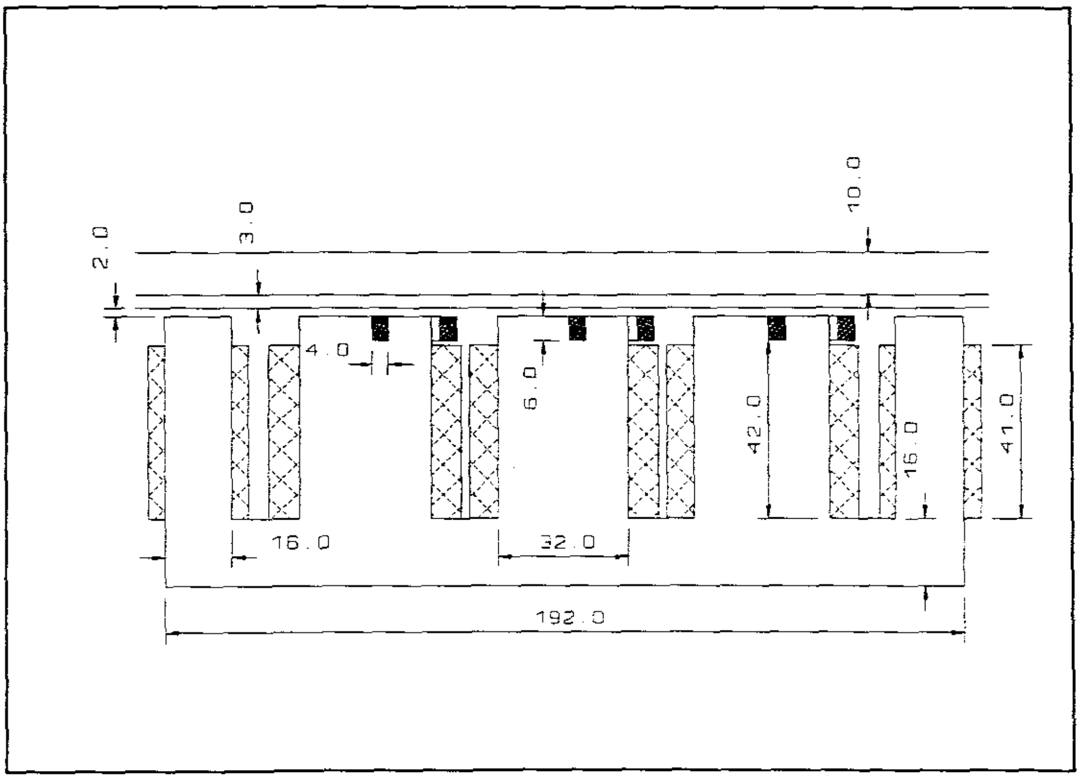


Figure 11 Constuction of stator core, aluminium cap and mild steel rotor disk

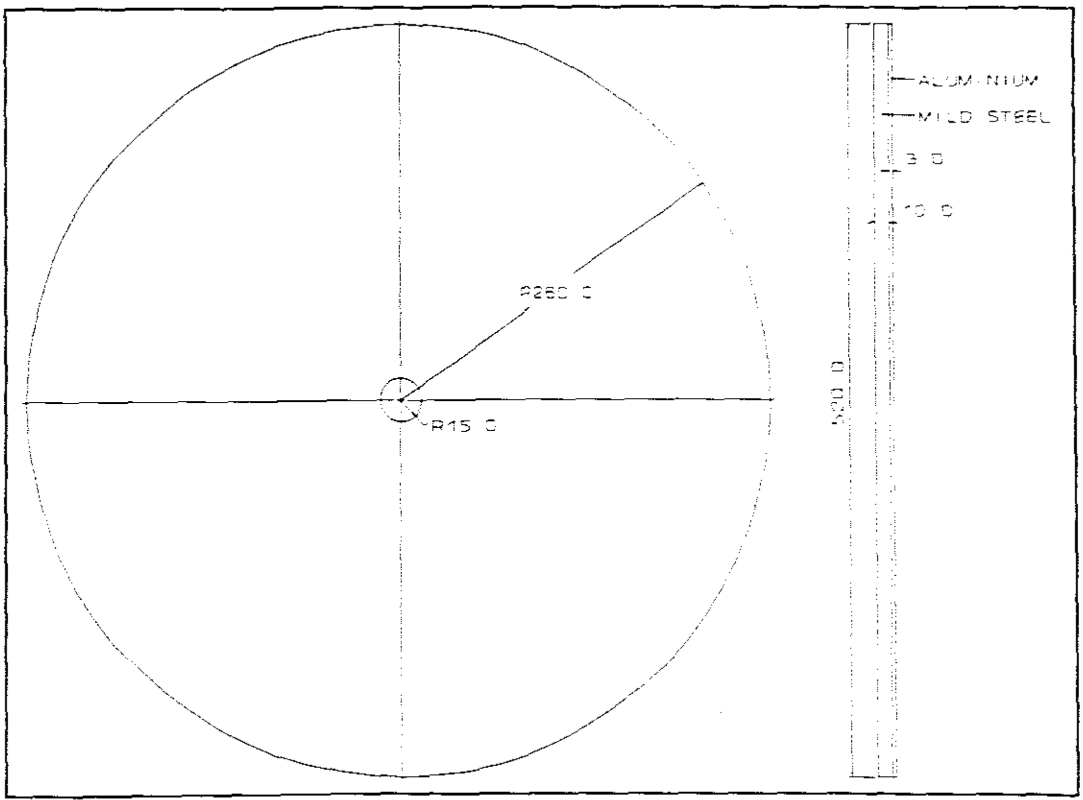


Figure 12 Aluminium and mild steel disk forming secondary rotor

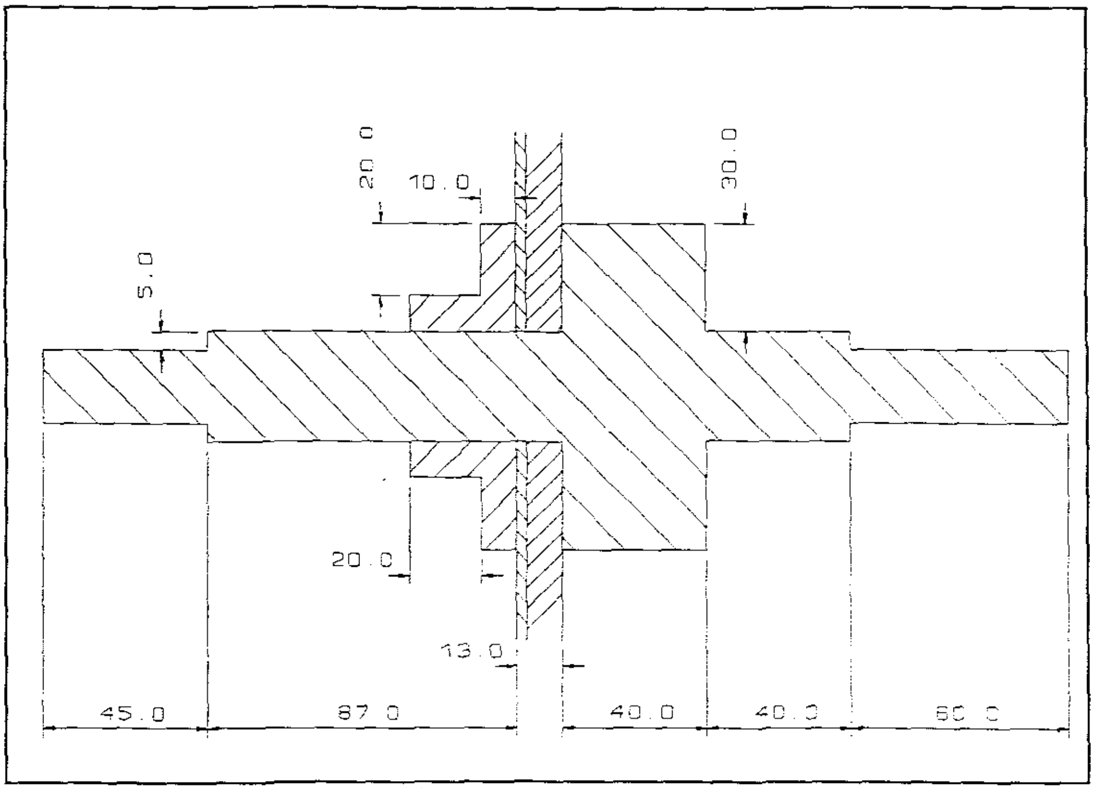


Figure 13 Sectional view of the shaft. The shaft was constructed in this specific way, so as to withstand the attraction force exerted onto the aluminium and mild steel disk by the stator core.

5. TESTING

To determine the characteristic curves of the single-phase single-pole LIM , a no-load, a short-circuit and a torque test was done. The inertia of the disk was found by applying a test normally used for flywheels.

5.1 No-load test

The power factor was calculated from readings of the input power and the input current as the supply of the motor was increased in steps.

5.1.1 Measured results

Table 4 No-load test

V_1 (V)	I_1 (A)	P_I (W)	POWER FACTOR
0	0	0	
10	0.56	5.8	1.00
20	1.1	16	0.73
30	1.62	32	0.66
40	2.18	54	0.62
50	2.79	78	0.56
60	3.33	105	0.53
70	3.8	140	0.53
80	4.45	180	0.51
90	4.9	225	0.51
100	5.46	270	0.49
110	5.9	320	0.49
120	6.52	380	0.49

130	6.9	450	0.50
140	7.4	520	0.50
150	8	600	0.50
160	8.5	660	0.49
170	9	760	0.50
180	9.5	840	0.49
190	10	920	0.48
200	10.25	1020	0.50
210	10.68	1100	0.49
220	11.06	1200	0.49

5.1.2 Characteristic curves

The following graphs show clearly that a supply of 50V is needed to overcome windage and friction losses.

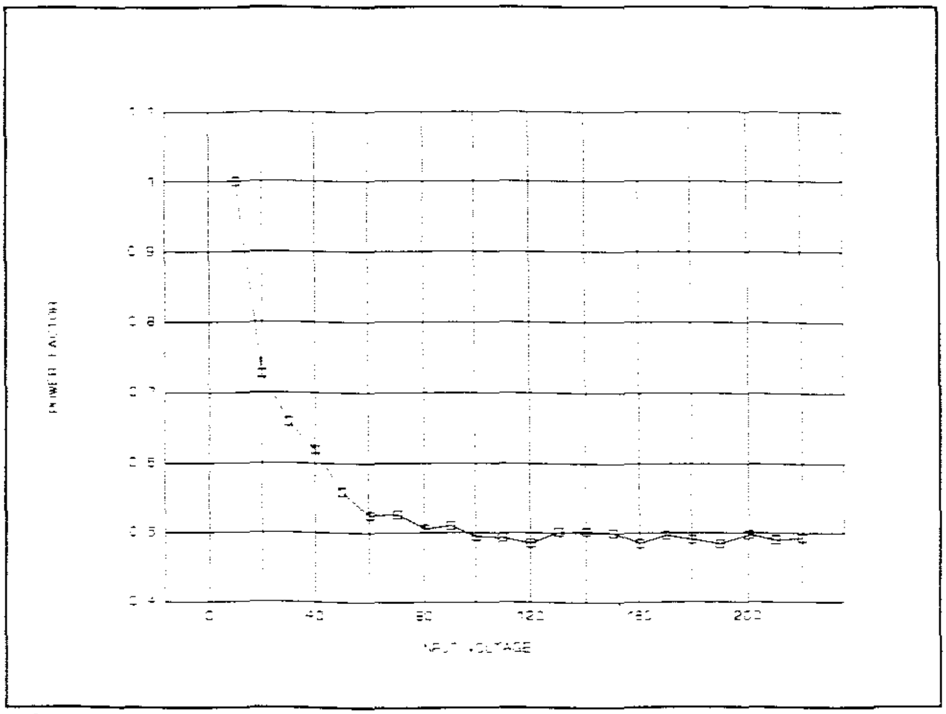


Figure 14 Power factor versus input voltage

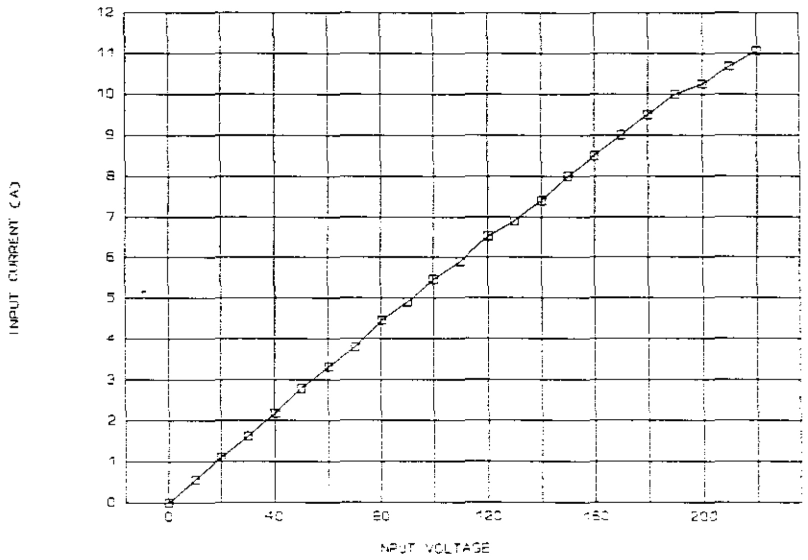


Figure 15 Input current versus input voltage

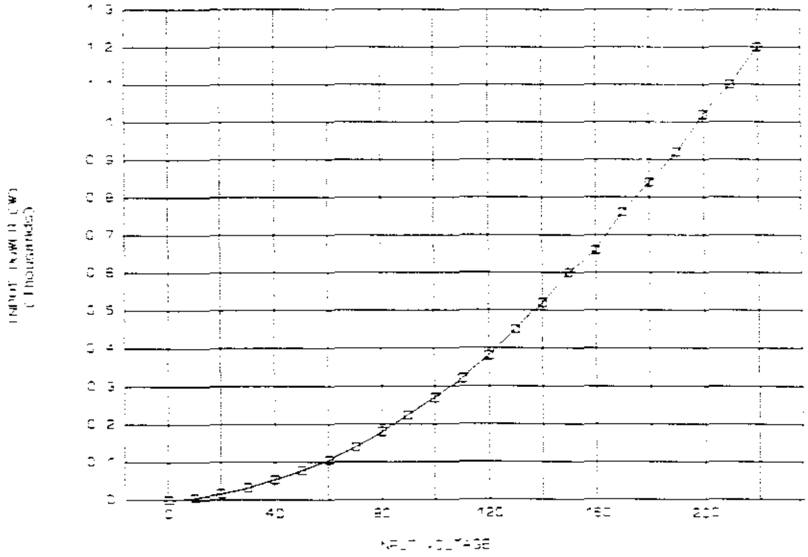


Figure 16 Input power versus input voltage

5.2 Short-circuit test

An adjustable scale was connected to the rotor disk (figure 17). Each reading was taken with the scale perpendicular to the center of the disk. As the supply voltage was raised in small increments, readings of the input power, input current and of the scale were taken.

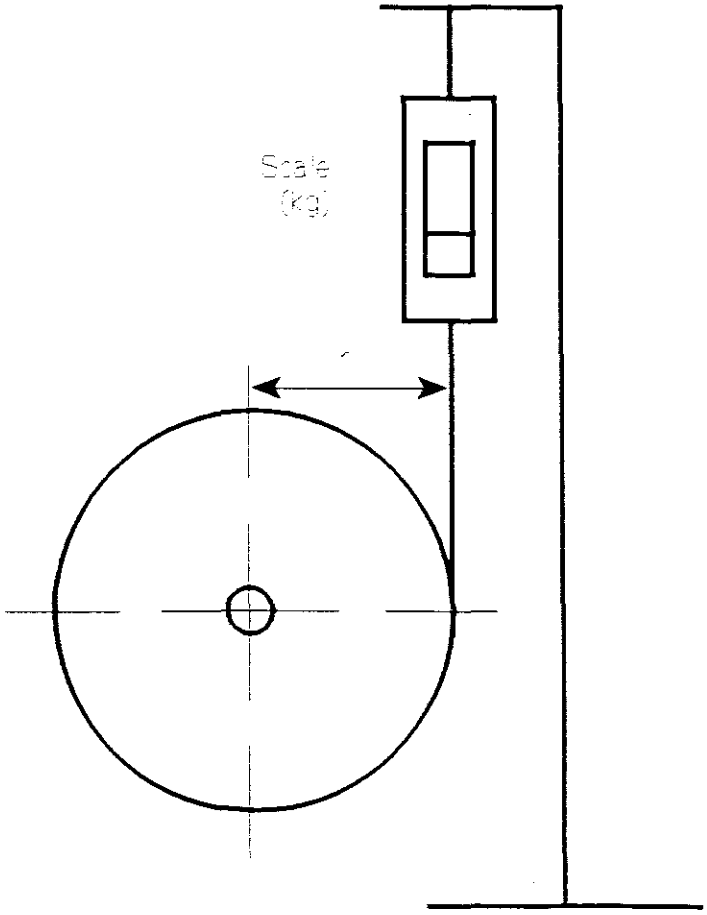


Figure 17 Torque measurement for blocked rotor

5.2.1 Input data

$g = 9.81$ (m/s^2)

$I_1 = 11.9$ (A)

$m = 1.24$ (kg)

$P_I = 1200$ (W)

$r = 0.25$ (m)

$V_1 = 220$ (V)

5.2.2 Calculations

Force

$$\begin{aligned} F &= m\,g \\ &= 1.24 * 9.81 \qquad (1) \\ &= 12.16\ (N) \end{aligned}$$

Torque

$$\begin{aligned} T &= F\,r \\ &= 12.16 * 0.25 \qquad (2) \\ &= 3.0411\,(Nm) \end{aligned}$$

Power Factor

$$\begin{aligned} \cos\phi &= \frac{P_I}{V_1\ I_1} \\ &= \frac{1200}{220 * 11.9} \qquad (3) \\ &= 0.485 \end{aligned}$$

5.2.3 Results

Table 5 Short-circuit test

V_1 (V)	I_1 (A)	P_I (W)	m (kg)	Power Factor	T (Nm)
0	0	0			
10	0.57	3		0.526	
20	1.11	7.2		0.324	
30	1.64	24.5		0.498	
40	2.18	42		0.482	
50	2.79	67	0.010	0.480	0.025
60	3.33	100	0.050	0.501	0.123
70	3.88	135	0.102	0.497	0.250
80	4.5	185	0.145	0.514	0.356
90	4.92	230	0.195	0.519	0.478
100	5.42	280	0.255	0.517	0.625
110	5.94	345	0.320	0.528	0.785
120	6.47	400	0.385	0.515	0.944
130	7	460	0.470	0.505	1.153
140	7.52	520	0.545	0.494	1.337
150	8.01	600	0.620	0.499	1.521
160	8.51	660	0.700	0.485	1.717
170	9.09	750	0.790	0.485	1.937
180	9.62	840	0.880	0.485	2.158
190	10.1	920	0.960	0.479	2.354
200	10.7	1020	1.050	0.477	2.575
210	11.4	1100	1.150	0.459	2.820
220	11.9	1200	1.240	0.458	3.041

5.2.4 Characteristic curves

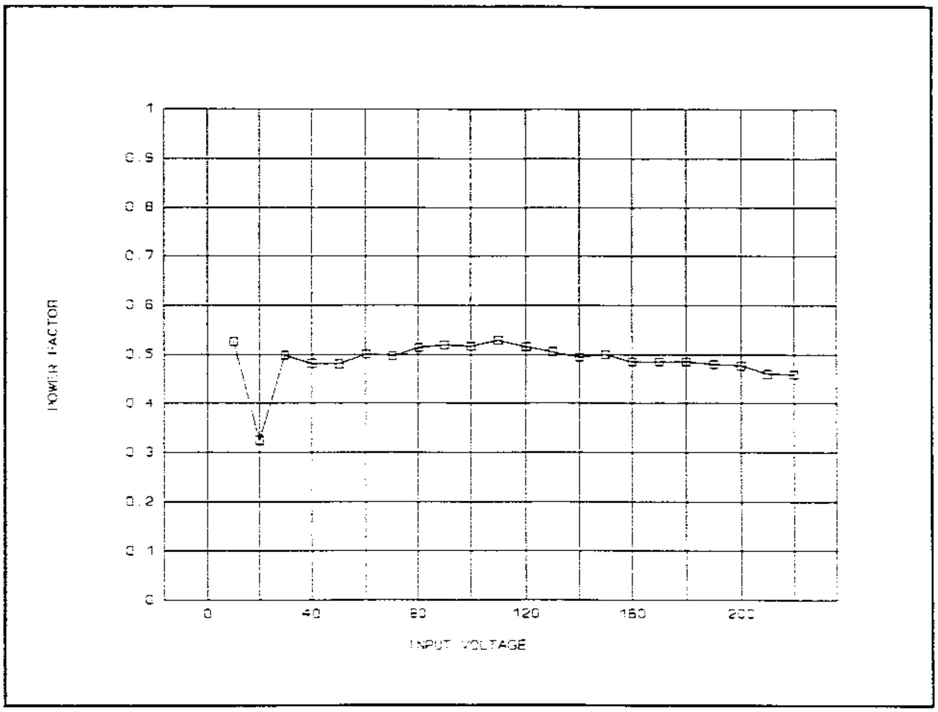


Figure 18 Power factor versus input voltage

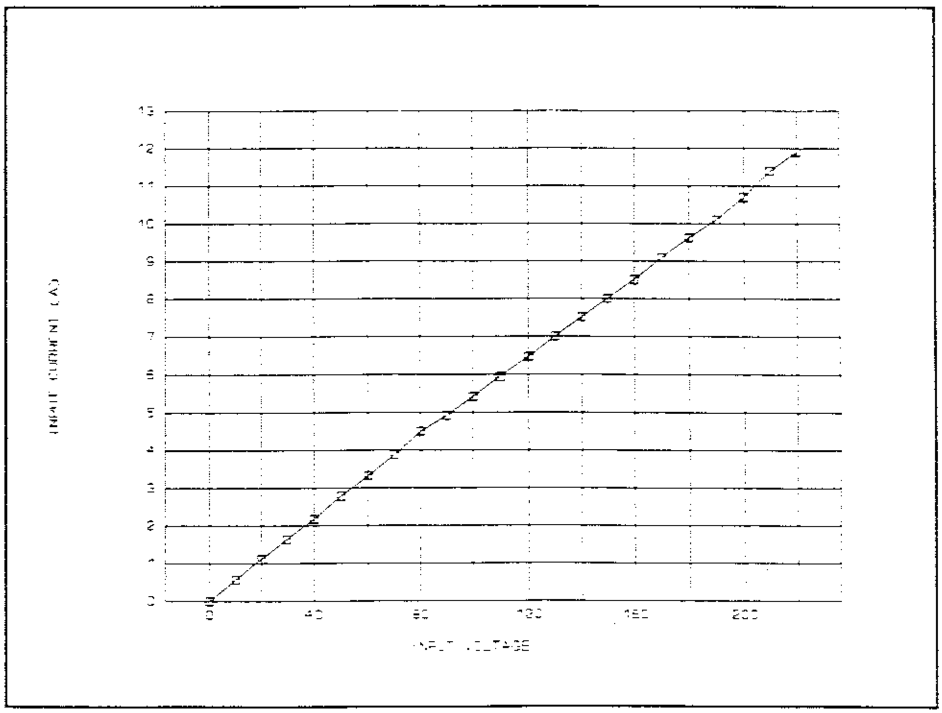


Figure 19 Input current versus input voltage

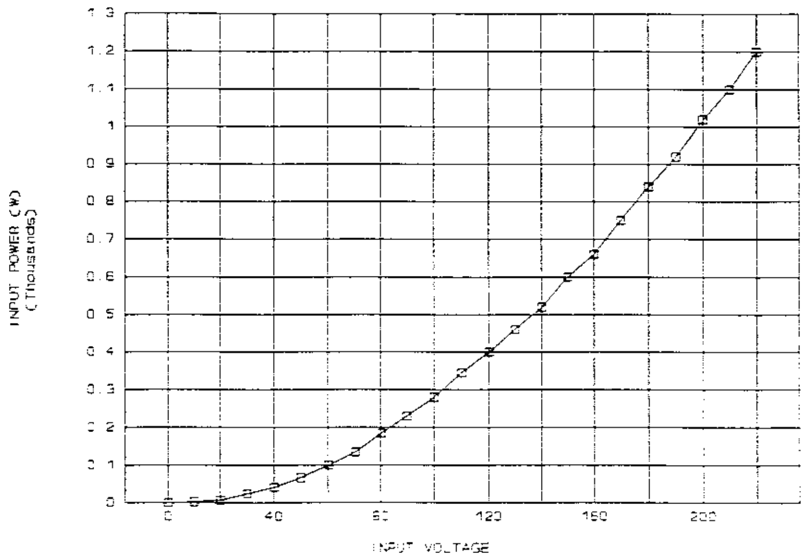


Figure 20 Input power versus input current

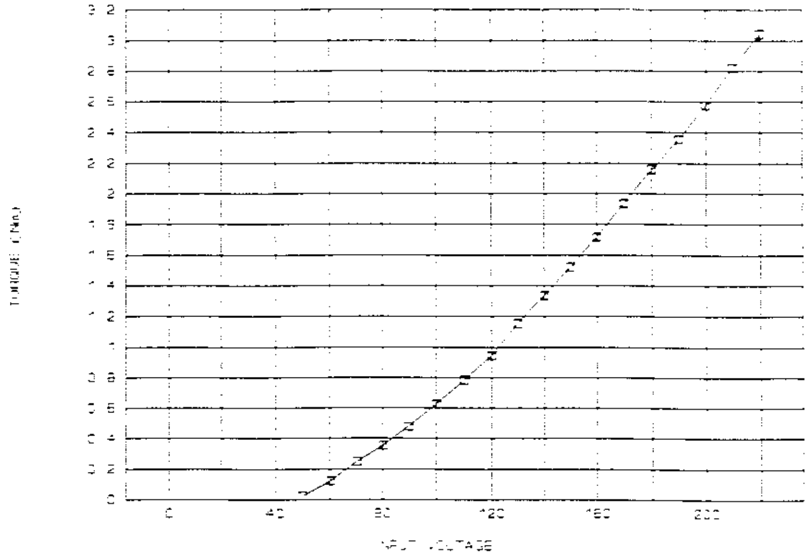


Figure 21 Torque versus input power

5.3 Load test

A rope was wound around a part of the shaft and connected perpendicularly to the axis of the shaft and to the scale. The other side of the rope was connected to a known weight. The weight was situated directly beneath the scale (Figure 22).

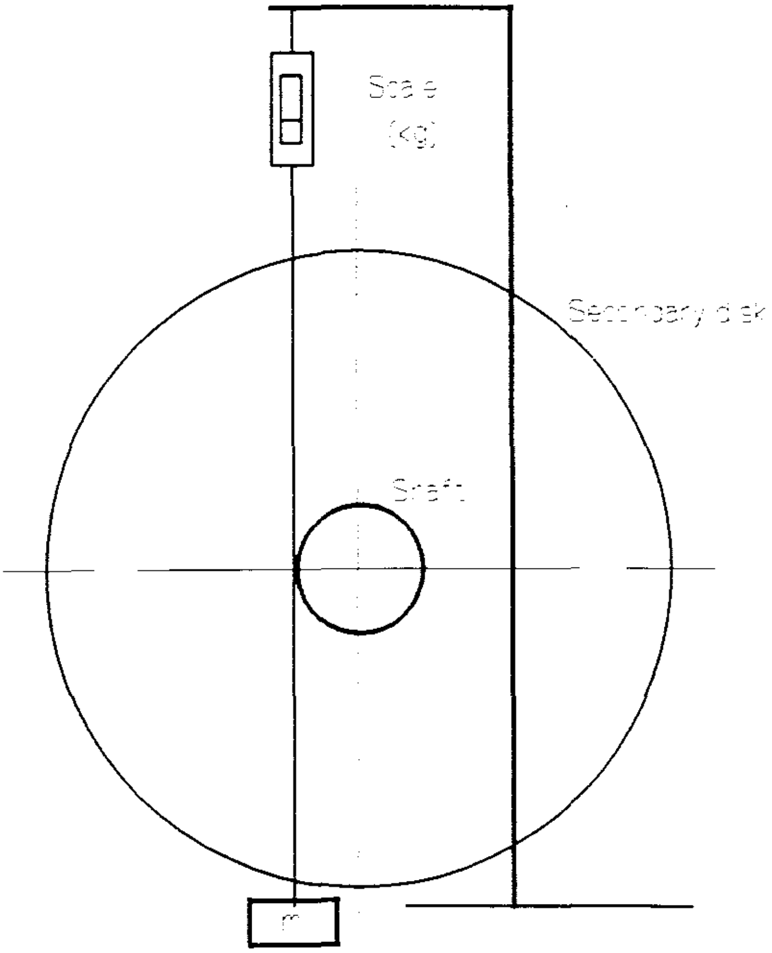


Figure 22 Load test

5.3.1 Input Data

I_1 = 8.009 (A)

P_I = 598.75 (W)

N = 25 (rpm)

V_1 = 150 (V)

W_s = 3.8 (kg)

W_g = 1.5 (kg)

5.3.2 Calculations

Force used for braking the disk

$$\begin{aligned} F_b &= (W_s - W_g)\ g \\ &= (3.8 - 1.5) * 9.81 \qquad (1) \\ &= 22.56\,(N) \end{aligned}$$

Torque due to braking force

$$\begin{aligned} T &= F_b\ r_b \\ &= 22.56 * 0.0425 \qquad (2) \\ &= 0.959\,(Nm) \end{aligned}$$

Output power

$$\begin{aligned} P_L &= \frac{2\ \pi\ N\ T}{60} \\ &= \frac{2 * \pi * 25 * 0.959}{60} \qquad (3) \\ &= 2.51\ (W) \end{aligned}$$

efficiency

$$\eta = \frac{P_L}{P_I} = \frac{2.51}{598.75} = 0.0042 \qquad (4)$$

power factor

$$\cos \phi = \frac{P_I}{V_1 \, I_1} = \frac{598.75}{150 * 8.009} = 0.498 \qquad (5)$$

5.3.3 Results

Table 6 Load test

T (Nm)	Speed (rpm)	P_L (W)	P_I (W)	I_1 (A)
0.000	90	0.00	580	8.000
0.117	84.9	1.04	581.25	8.001
0.183	80.5	1.55	582.5	8.001
0.233	76.5	1.87	583.75	8.002
0.296	74	2.29	585	8.003
0.342	70	2.51	586.25	8.003
0.467	64	3.13	587.5	8.004
0.542	59	3.35	588.75	8.004
0.592	54.5	3.38	590	8.005
0.650	51	3.47	591.25	8.006

0.688	48	3.46	592.5	8.006
0.750	43	3.38	593.75	8.007
0.834	39.5	3.45	595	8.008
0.876	35	3.21	596.25	8.008
0.934	30	2.93	597.5	8.009
0.959	25	2.51	598.75	8.009

Table 7 Load test

T (Nm)	Speed (rpm)	Efficiency	Power factor
0.000	90	0.0000	0.483
0.117	84.9	0.0018	0.484
0.183	80.5	0.0027	0.485
0.233	76.5	0.0032	0.486
0.296	74	0.0039	0.487
0.342	70	0.0043	0.488
0.467	64	0.0053	0.489
0.542	59	0.0057	0.490
0.592	54.5	0.0057	0.491
0.650	51	0.0059	0.492
0.688	48	0.0058	0.493
0.750	43	0.0057	0.494
0.834	39.5	0.0058	0.495
0.876	35	0.0054	0.496
0.934	30	0.0049	0.497
0.959	25	0.0042	0.498

5.3.4 Characteristic curves

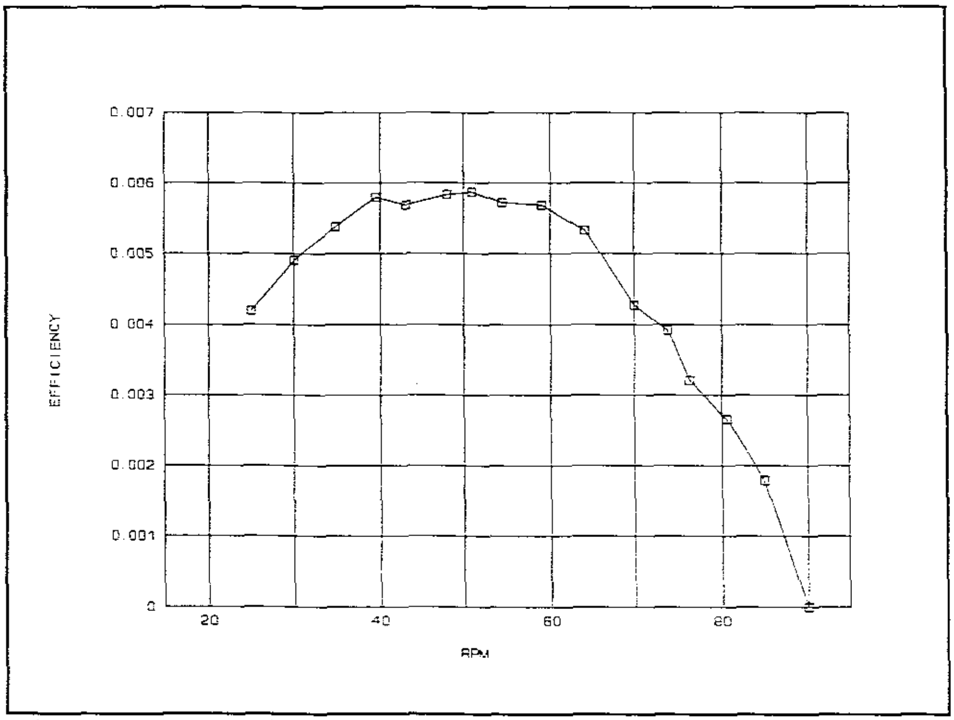


Figure 23 Efficiency versus speed

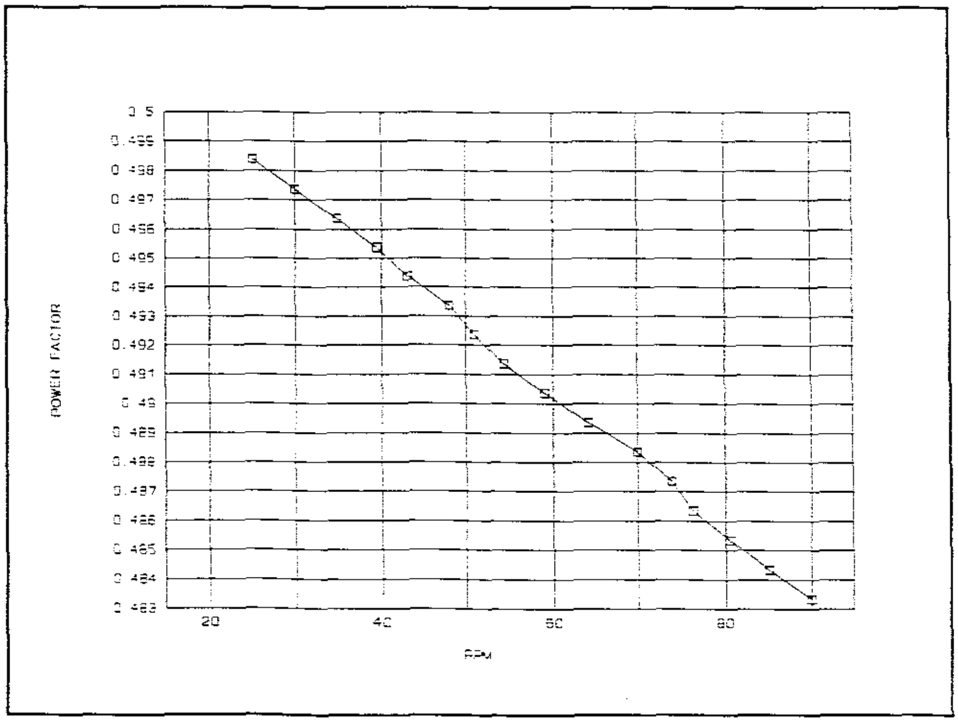


Figure 24 Power factor versus speed

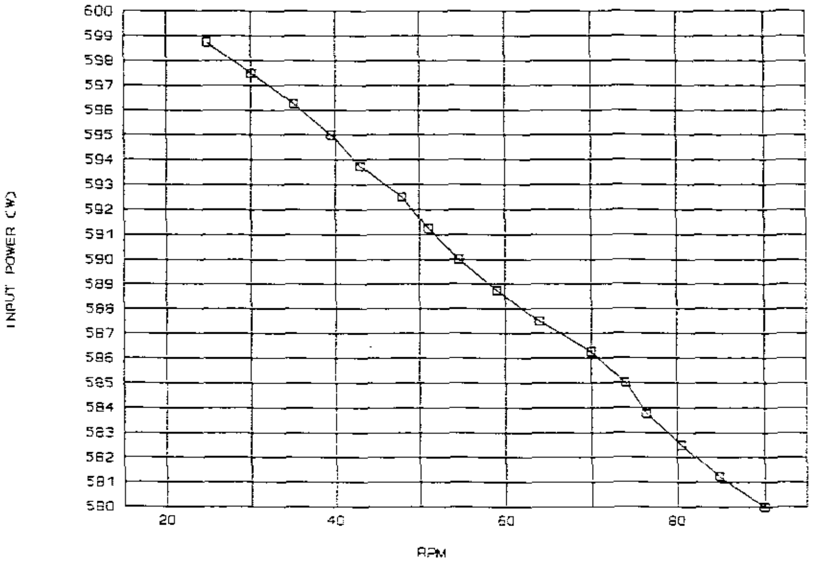


Figure 25 Input power versus speed

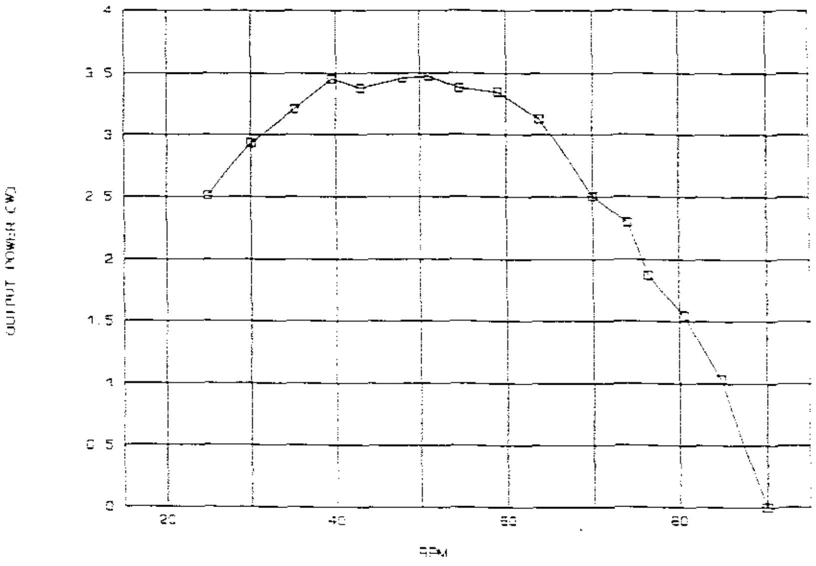


Figure 26 Output power versus speed

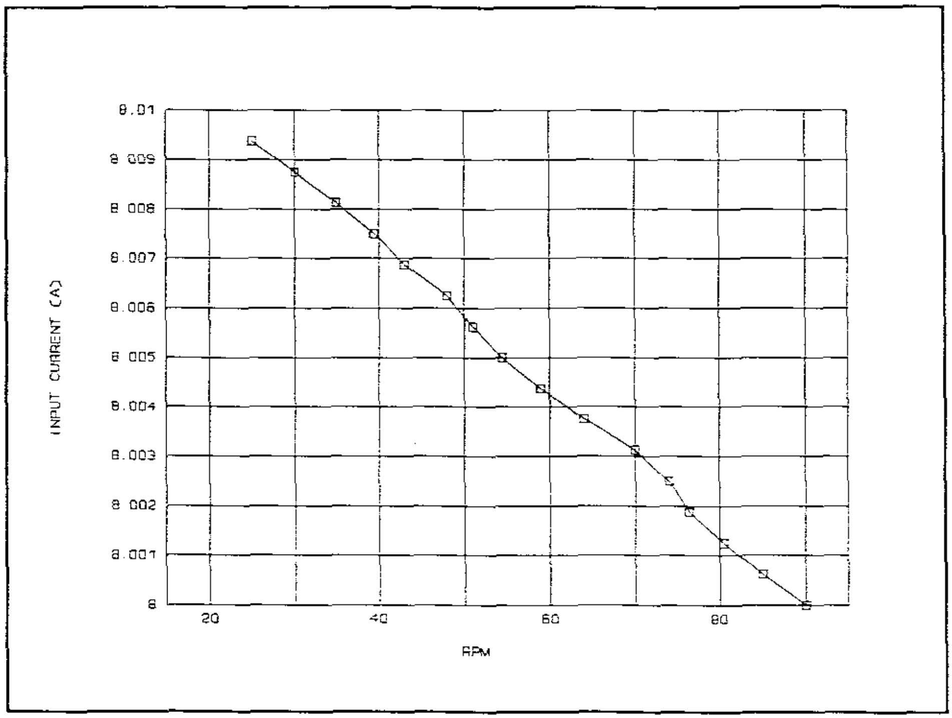


Figure 27 Input current versus speed

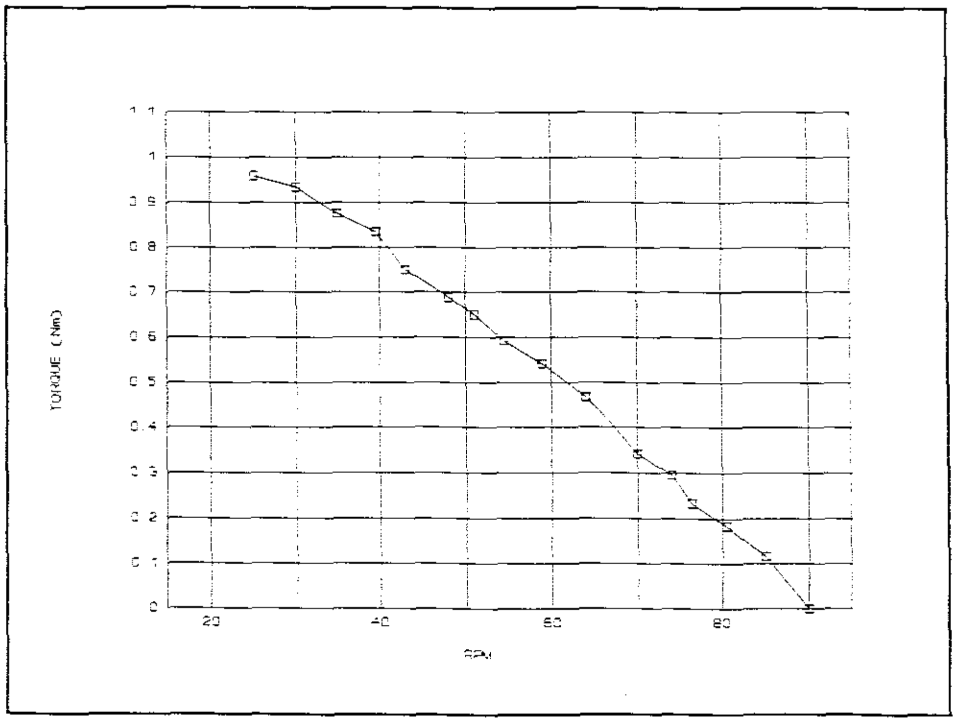


Figure 28 Torque versus speed

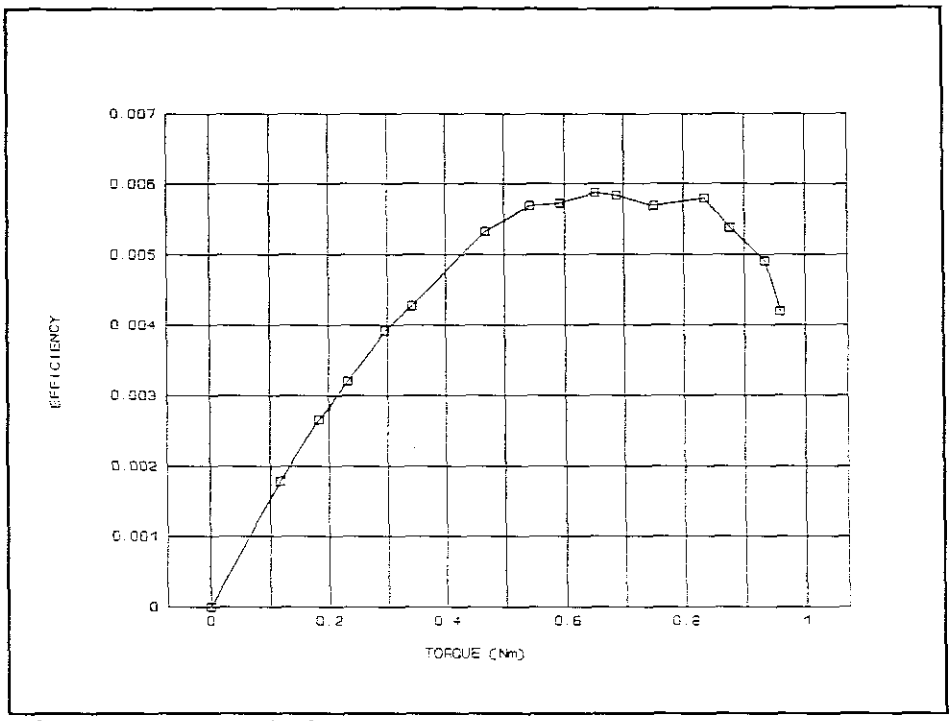


Figure 29 Efficiency versus torque

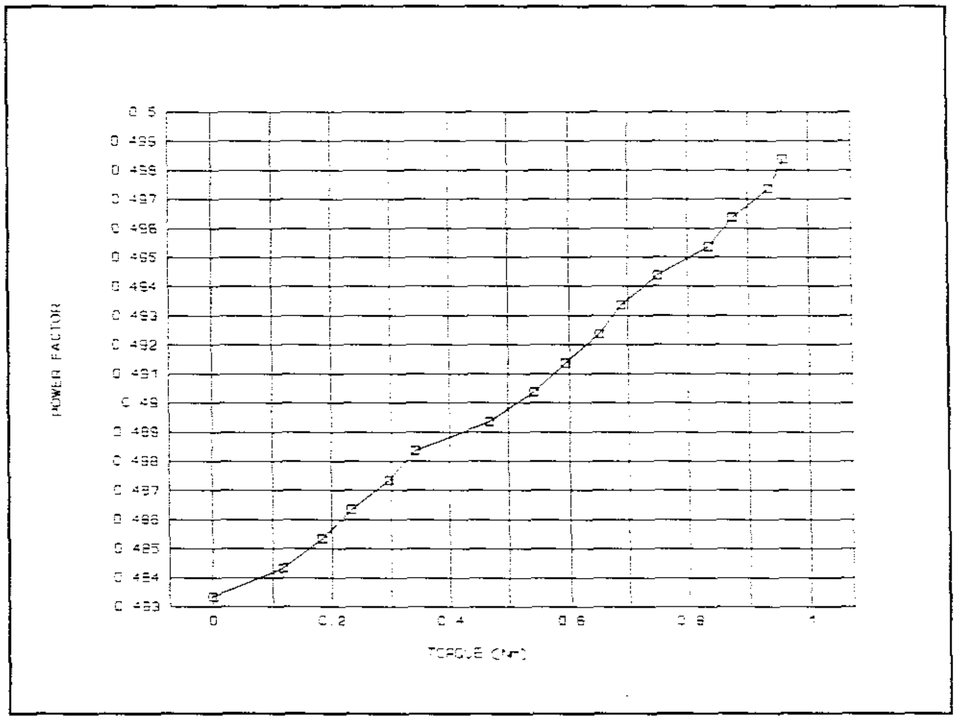


Figure 30 Power factor versus torque

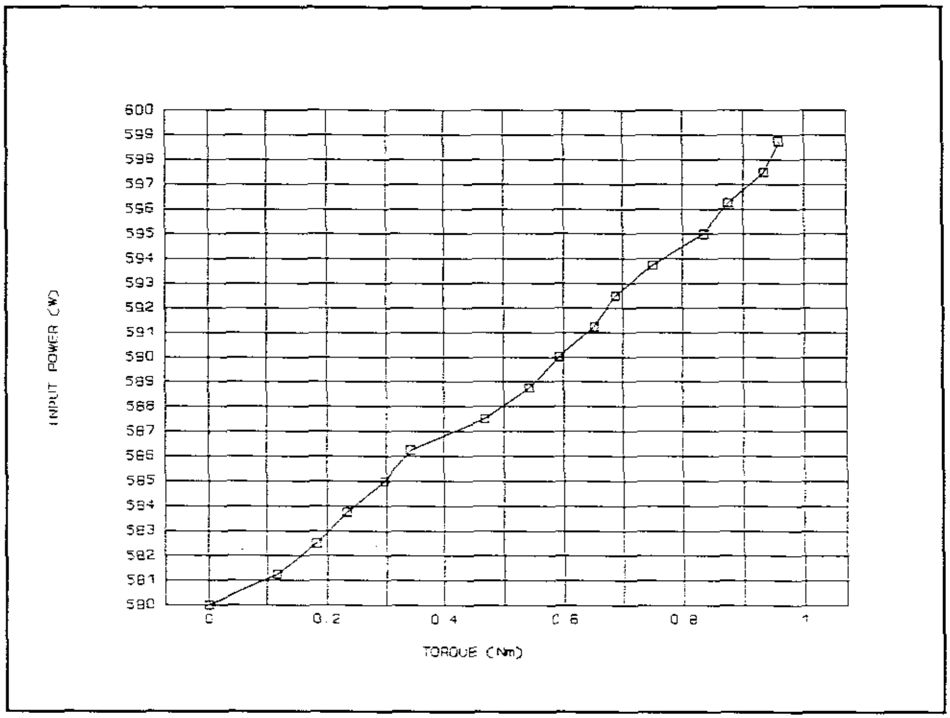


Figure 31 Input power versus torque

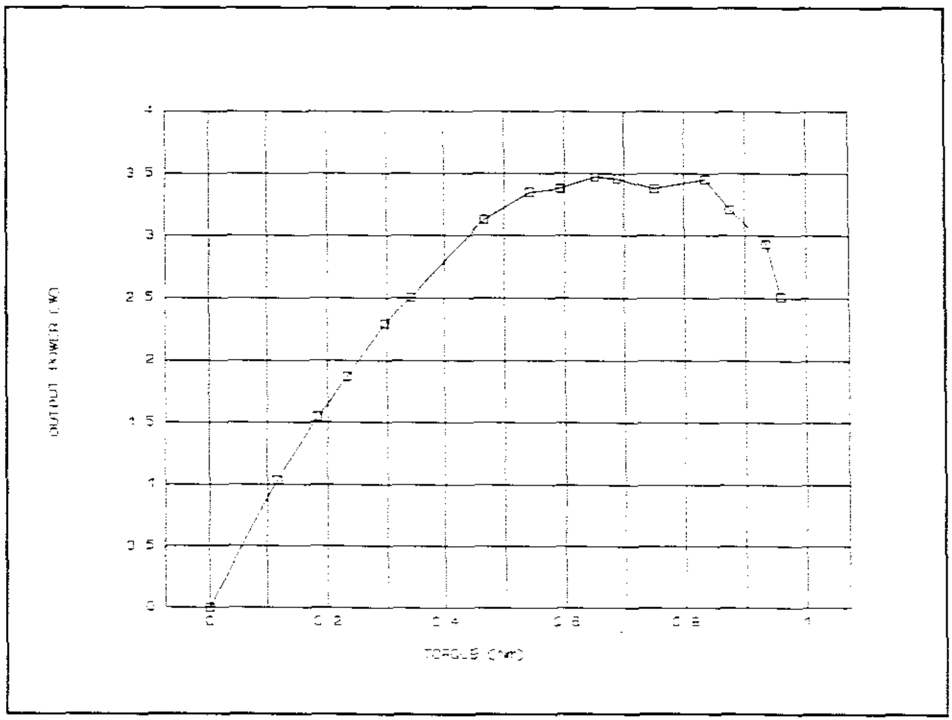


Figure 32 Output power versus torque

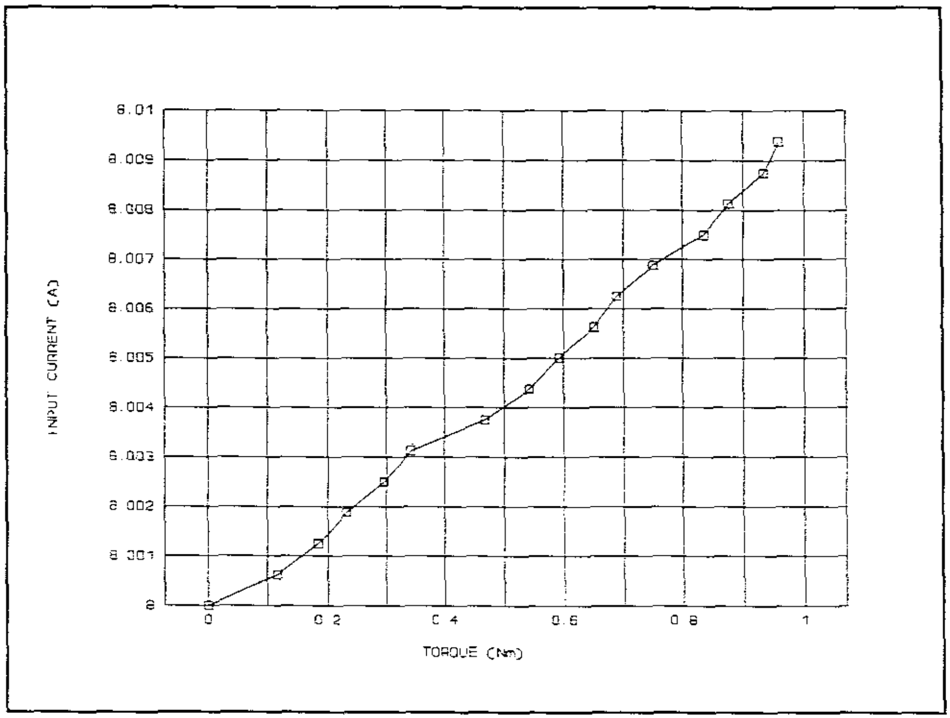


Figure 33 Input current versus torque

5.4 INERTIA

The windage and frictional resistance was found by winding a rope around the shaft and attaching weights of various masses to the loose end. The force of these resistances is given by the (mass * g) that only sets the shaft in motion and does not accelerate it.

The inertia was found by adding a greater known mass to the rope and timing the fall through a known vertical distance with a stopwatch. This experiment was done with various weights to compare the results.

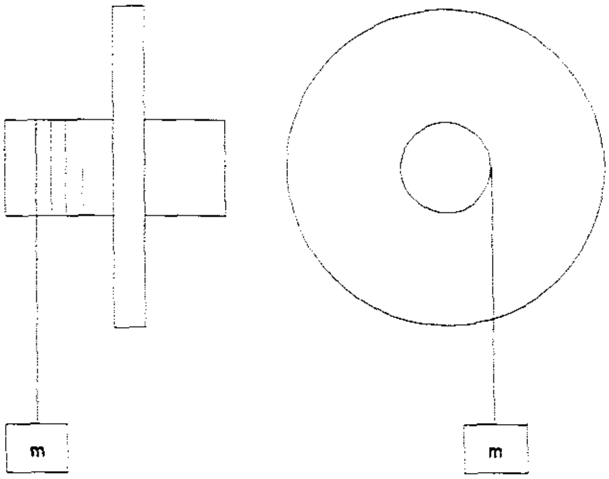


Figure 34 Diagram for the Inertia test.

5.4.1 Input data

d_a = 0.042 (m)

m_t = 9.5 (kg)

m_s = 0.2 (kg)

m_I = 0.6 (kg)

r 0.042 (m)

S_d = 0.542 (m)

t = 10.82 (s)

ω_1 = 0 (rad/s)

5.4.2 Calculations

(i) acceleration of the 0.6kg mass

$$S_d = u\ t + 0.5\ a\ t^2 \tag{1}$$

therefore

$$a = \frac{2*(0.542 - 0 * 10.82)}{10.82^2}$$

$$= 9.259 * 10^{-3}\ (m/s)$$

(ii) acceleration of the secondary disk

$$\alpha = \frac{a}{r} \tag{2}$$

$$\alpha = \frac{9.259 * 10^{-3}}{0.042}$$

$$= 0.22\ (rad/s^2)$$

(iii) friction and windage resistance force

$$F_r = m_2\, g \qquad (3)$$

$$F_r = 0.25 * 9.81$$
$$= 2.453\ (N)$$

(iv) Resultant force due to the motion and the 0.6kg mass

$$F = m_3\ (g - a) \qquad (4)$$

$$F = 0.6 * (9.81 - 9.259 * 10^{-3})$$
$$= 5.88\,(N)$$

(v) force in the cord to accelerate the disk

$$F_a = F - F_r \qquad (5)$$

$$F_a = 5.88 - 2.453$$
$$= 3.428\ (N)$$

(vi) accelerating torque

$$T_a = F_a\, r \qquad (6)$$

$$T_a = 3.428 * 0.042$$
$$= 0.144 \ (Nm)$$

(vii) Moment of Inertia

$$I = \frac{T}{\alpha} \tag{7}$$

$$I = \frac{3.428}{0.22}$$
$$= 0.653 \ (kg/m^2)$$

(viii) Radius of gyration

$$r_g = \sqrt{\frac{I}{m_1}} \tag{8}$$

$$r_g = \sqrt{\frac{0.653}{9.5}}$$
$$= 0.262 \ (m)$$

5.4.3 Calculate run-out-time

(i) final angular velocity

$$\omega_1 = \frac{2 \ \pi \ N}{60} \tag{9}$$

$$\omega_1 = \frac{2*\pi*84}{60}$$

$$= 8.692 \ (rad/s)$$

(ii) Torque due to friction

$$T_r = m_2 \, g \, r \tag{10}$$

$$T_r = 0.25 * 9.81 * 0.042$$

$$= 0.103 \ (Nm)$$

(iii) angular velocity

$$\alpha = \frac{T_r}{I} \tag{11}$$

$$\alpha = \frac{0.103}{0.653}$$

$$= 0.158 \ (rad/s^2)$$

(iv) time for the disk to come to a stand still

$$t = \frac{\omega_1}{\alpha} \tag{12}$$

$$t = \frac{8.692}{0.158}$$

$$= 55.77 \ (s)$$

5.4.4 Measured run-out time

The motor was run up to rated speed, after which the input power was cut and the speed measured every 5 seconds.

5.4.4.1 Measured results

Table 8 Run-out-time

Time (s)	Speed (RPM)	Velocity (m/s)
0	84	2.3750
5	77	2.1771
10	69	1.9509
15	62	1.7530
20	54	1.5268
25	47	1.3288
30	40	1.1309
35	33	0.9330
40	25	0.7068
45	18	0.5089
50	12	0.3392
55	6	0.1696
60	0	0

5.4.4.2 Graph

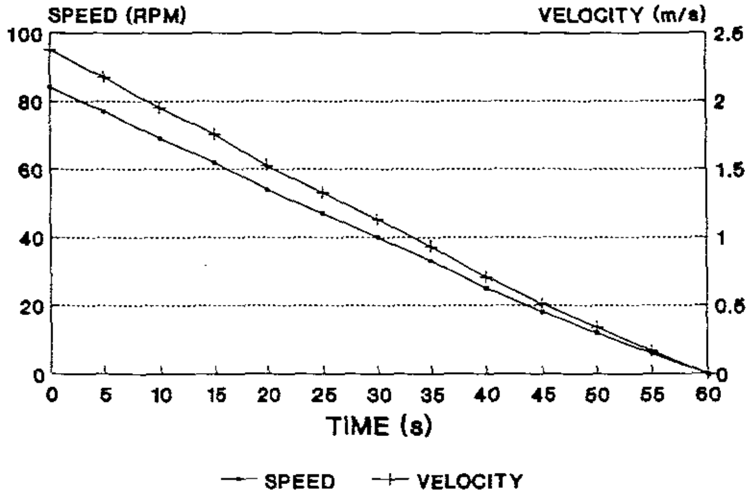


Figure 35 Speed and velocity versus time

6. CONCLUSION

In this thesis the characteristics of the shaded-pole induction motor and the 3 phase single-sided linear induction motor were used to design the shaded-pole flat linear induction motor.

Since the design was limited to materials that were available locally, compromises could not be avoided. For example when a standard transformer lamination is chosen, most dimensions are fixed, including the pole pitch and the winding space.

Due to the fact that an iterative method was used to find the induced EMF and to alleviate the decision making process, the CAD approach was of great help.

The characteristic curves show clearly that the disadvantages of this motor are a low power factor, a small starting torque and a low efficiency. This is due to a large and open air gap and the fact that the shaded poles do not produce a 90 degree phase shift.

It was found that the distance from the core to the centre of the secondary disk plays an important role in the performance of the motor. The braking forces induced by the core onto the aluminium cap reduce as the distance between the two is increased.

Although efficiency, power factor and starting torque of this motor are worse then for normal induction motors, I think that this design holds a lot of potential where only a single phase supply is available and the advantages of a single-sided induction motor are needed.

LIST OF REFERENCES

1. J. Gieras and G. Frydrychowicz-Jastrzebska, Einfluß des Raumwinkels zwischen Haupt- und Hilfsphase auf die Betriebscharakteristik des Induktionsmotors mit geteilten Polen, Z.electr.Inform.-u. Energietechnik, Leipzig 12, 1982, No 6, pp.545-557

2. Jacek F. Gieras, Design of Single-Sided Linear Induction Motors for propulsion of Wheel-On-Rail Vehicles, Dept. of Electrical & Electronic Engineering, University of Cape Town

3. Davy Linear Motors Limited, Equipment Specifications

4. Jacek F. Gieras, Graham E. Dawson and Anthony R. Eastham, Performance Calculation for Single-Sided Linear Induction motors with a Double-Layer Reaction Rail Under Constant Current Excitation, IEEE Transactions on Magnetics, voll. mag 22, No 1, January 1986

5. J. D. Walker, Applied Mechanics, SI edition

APPENDIX 1

```
C LINEAR MOTOR
      REAL l,TAU,CFE,Li,ws,hy,hs,bp,Bg,ol,ocu,Acu,lav,R1
      REAL VFE,V1,E1,N1,Kw,f,p,Np,ktr,m1,dw,hp,l1,tp,tcu
      REAL l2,mFE,PFE,Xm,kn,kc,g,X1,BETA,PI,hov,w,krn
      REAL oAL,tAL,s,wav,FLUXd,PERrs,PER1,PER2,oFE,kz,e
      REAL c,h,RFE,uPFE,E1new,J1T,R,nl,nTAU,nhy,nhs,nws
      REAL nbp,nhp,ALi,AAcu,Adw,Iu,IFe,P2cu,Pelect
      REAL Thrust,PL,cosA,eff,Pin,PERo,P1cu
      COMPLEX xAL,j,ZAL,a,b,PERFE,xFE,ZFE,Zt,Z2,I1,Z1
      COMPLEX Io,I2
      INTEGER COUNT,LOOP,CHANGE,ANSWER,VALUE,SWITCH,SLIP
      INTEGER ANDER,NICHT,NOCH,CHOICE,ANTWORD,SCHALTER
      INTEGER WERT,SKAKEL
      OPEN(1,STATUS='SCRATCH')
      OPEN(3,STATUS='NEW')
      OPEN(4,STATUS='NEW')
      OPEN(7,STATUS='NEW')
      OPEN(8,STATUS='NEW')
      ANDER=0
      NICHT=0
      NOCH=0
      SKAKEL=0
      SWITCH=0
      SCHALTER=0
      WERT=0
      COUNT=0
```

```
      LOOP=0
      CHANGE=0
      E1=170.00
20    IF (ANDER.EQ.0) Li=0.09
30    IF (CHANGE.EQ.0) THEN
           Acu=0.0000012272
           dw=0.00125
      ENDIF
      IF (SWITCH.EQ.1) GOTO 70
40    l=0.192
      TAU=0.048
      ws=0.005
      hy=0.016
      hs=0.005
      hp=0.043
      bp=0.032
      IF (SKAKEL.EQ.1) GOTO 70
      IF (NOCH.EQ.1) GOTO 70
      PRINT*,'DO YOU WANT TO KEEP CORE DIMENSIONS
                [YES=1/NO=2]'
      READ*,DYW
50    IF (DYW.EQ.1.0) THEN
           NOCH=1
           GOTO 70
      ENDIF
60    IF (DYW.EQ.2) THEN
      PRINT*,'THE CURRENT DIMENSIONS ARE GIVEN IN THE
                FOLLOWING ORDER:'
```

```
     PRINT*,'              l, TAU, hy, hs, hp, bp, ws'
     PRINT*,l,TAU,hy,hs,hp,bp,ws
     PRINT*,'PLEASE ENTER NEW DIMENSIONS, KEEPING THE
               SAME ORDER AND SEPERATED BY A COMMA'
     READ*,l,TAU,hy,hs,hp,bp,ws
     WRITE (7,*) l,TAU,hy,hs,hp,bp,ws
     SWITCH=1
     ENDIF
70   CONTINUE
     IF (SWITCH.EQ.1) THEN
          REWIND 7
          READ (7,*) l,TAU,hy,hs,hp,bp,ws
     ENDIF
     IF (ANDER.EQ.1) THEN
          REWIND 3
          READ (3,*) Li
     ENDIF
     IF (CHANGE.EQ.1) THEN
          REWIND 4
          READ (4,*) Acu,dw
     ENDIF
     IF (SCHALTER.EQ.1) THEN
          REWIND 8
          READ (8,*) Bg,uPFE
     ENDIF
75   CONTINUE
     IF (SCHALTER.EQ.1) GOTO 78
     Bg=0.4
```

```
      uPFE=0.6

      IF (WERT.EQ.1) GOTO 78

      PRINT*,'AT THE MOMENT Bg = ',Bg,'

                AND W/Kg = ',uPFE

      PRINT*,'DO YOU WANT TO CHANGE Bg AND W/Kg

                [YES=1/NO=2]'

      READ*,ANTWORD

      IF (ANTWORD.EQ.1) THEN

           PRINT*,'ENTER NEW VALUE FOR Bg AND W/Kg'

           READ*,Bg,uPFE

           WRITE (8,*) Bg,uPFE

           SCHALTER=1

           GOTO 20

      ELSE IF (ANTWORD.EQ.2) THEN

           WERT=1

           GOTO 78

      ENDIF

 78   CONTINUE

      ol=1.15

      V1=220.0

      s=1.0

      CFE=7800.0

      Kw=1.0

      f=50.0

      p=2.0

      m1=2.0

      tp=0.0006

      ocu=56000000.0
```

```
      tcu=235.0
      kc=1.0
      kn=1.1
      g=0.002
      PIE=3.141593
      oAL=36000000.0
      tAL=245.0
      wav=2*PIE*f
      PERo=4.0E-7*PIE
      j=CSQRT(CMPLX(-1))
      d=0.002
      PERrs=200.0
      PER1=1.23
      PER2=0.69
      oFE=5.0E6
      h=0.005
C     FORMULA ORIENTATED
      VFE=Li*(l*hy+4*TAU*(TAU-bp)-3*hs*ws)
      mFE=VFE*CFE
      PFE=uPFE*mFE*1.5
      FLUX=bp*Li*Bg*ol
      N1=E1/(4.44*Kw*f*FLUX)
      Np=N1/(2*p)
      ktr=(2*m1*(N1*Kw)**2)/p
      l1=(Np*dw/hp)*(dw+tp)
      lav=2*(Li+bp+(2*l1))
      l2=(TAU-bp)/2
80    IF (l1.GE.l2) THEN
```

```
        PRINT*,'THERE IS NOT ENOUGH STAKINGSPACE'
        PRINT*,'AND l1 = ',l1,' AND l2 = ',l2
        PRINT*,'AT THIS MOMENT Li = ',Li,'
                  AND Acu = ',Acu
        PRINT*,'YOU ARE ALLOWED TO CHANGE ONLY
                  Li OR Acu'
        PRINT*,'WHICH ONE DO YOU WANT TO CHANGE?'
        PRINT*,'ENTER 1 FOR Li OR 2 FOR Acu'
        READ*,CHOICE
90      IF (CHOICE.EQ.1) THEN
             CLOSE(3)
             PRINT*,'ENTER NEW VALUE FOR Li'
             READ*,Li
             OPEN(3)
             WRITE (3,*) Li
             ANDER=1
             SKAKEL=1
             GOTO 20
        ELSE IF (CHOICE.EQ.2) THEN
             CLOSE(4)
             PRINT*,'ENTER NEW VALUE FOR Acu
                       AND FOR dw'
             READ*,Acu,dw
                  OPEN(4)
             WRITE (4,*) Acu,dw
             CHANGE=1
             SKAKEL=1
             GOTO 20
```

```
        ENDIF
110   ELSE IF (l1.LT.l2) THEN
        IF (NICHT.EQ.1) GOTO 150
        PRINT*,'AT THIS MOMENT Li = ',Li,'
                  AND Acu = ',Acu
        PRINT*,'AND l1 = ',l1,' AND l2 = ',l2


        PRINT*,'DO YOU WANT TO CHANGE THE VALUES?
                  [YES=1/NO=2]'
        READ*,VALUE
120     IF (VALUE.EQ.1) THEN
             PRINT*,'YOU ARE ALLOWED TO CHANGE ONLY
                       Li OR Acu'
             PRINT*,'WHICH ONE DO YOU WANT TO CHANGE?'
             PRINT*,'ENTER 1 FOR Li OR 2 FOR Acu'
             READ*,ANSWER
130          IF (ANSWER.EQ.1) THEN
                  CLOSE(3)
                  PRINT*,'ENTER NEW VALUE FOR Li'
                  READ*,Li
                  OPEN(3)
                  WRITE (3,*) Li
                  ANDER=1
                  SKAKEL=1
                  GOTO 20
140          ELSE IF (ANSWER.EQ.2) THEN
                  CLOSE(4)
                  PRINT*,'ENTER NEW VALUE FOR Acu
```

```
                    AND FOR dw'
              READ*,Acu,dw
              OPEN(4)
              WRITE (4,*) Acu,dw
              CHANGE=1
              SKAKEL=1
              GOTO 20
          ENDIF
      ELSE IF (VALUE.EQ.2) THEN
          NICHT=1
          GOTO 150
      ENDIF
  ENDIF
150  CONTINUE
  R1=(lav*N1)/(ocu*Acu)
  R1=R1*(tcu+75.0)/(tcu+20.0)
  Xm=12.8*f*p*(Np*Kw)**2*TAU*Li/(kn*kc*g*1000000.0)
  X1=0.8*(ol-1.0)*Xm
  BETA=PIE/TAU
  hov=TAU/2
  w=TAU+Li
  krn=1-((TANH(BETA*w/2))/
 1((BETA*W/2)*(1+TANH(BETA*w/2)*TANH(BETA*hov)))
  oAL=oAL*krn*((tAL+20)/(tAL+75))
  xAL=CSQRT((s*j*wav*PERo*oAL)+((PIE/TAU)*(PIE/TAU)))
  b=xAL*d
  a=(CEXP(b)-CEXP((-1)*b))/
 1(CEXP(b)+CEXP((-1)*b))
```

```
     ZAL=(ktr*j*s*wav*PERo*Li)/(xAL*TAU*a)
     PERFE=PERo*PERrs*(PER1-PER2*j)
     xFE=CSQRT((s*j*wav*PERFE*oFE)+
   1/((PIE/TAU)*(PIE/TAU)))
     kz=1-(g/Li)+((2*TAU)/(PIE*w))*(1-
   1/(EXP(((-1)*PIE*w)/(2*Li))))
     e=xFE*h
     c=(CEXP(e)-CEXP((-1)*e))/
    1(CEXP(e)+CEXP((-1)*e))
     ZFE=(ktr*j*s*wav*PERFE*Li*kz)/(xFE*TAU*c)
     Z2=((ZAL*ZFE)/(ZAL+ZFE))*(1/s)
     RFE=(E1*E1)/PFE
     Zt=(R1+(j*X1))+((RFE*((j*Xm*Z2)/((j*Xm)+Z2)))
   1/(RFE+((j*Xm*Z2)/((j*Xm)+Z2))))
     I1=V1/Zt
     J1=CABS(I1)/Acu
     R=CABS(I1)
     Z1=R1+(j*X1)
     T=CABS(Z1)
     E1new=V1-(R*T)
     PRINT*,'WHEN S=1,  E1new = ',E1new
160  IF (E1new.NE.E1) THEN
          E1=E1new
          COUNT=COUNT+1
          GOTO 20
     ENDIF
180  CONTINUE
     PRINT*,'                                             '
```

```
      PRINT*,'ENTER A VALUE FOR S [0<S<1]'
      READ*,s
190   IF (s.NE.1.0) THEN
195        xAL=CSQRT((s*j*wav*PERo*oAL)+
     1          ((PIE/TAU)*(PIE/TAU)))
           b=xAL*d
           a=(CEXP(b)-CEXP((-1)*b))/
     1          (CEXP(b)+CEXP((-1)*b))
           ZAL=(ktr*j*s*wav*PERo*Li)/(xAL*TAU*a)
           PERFE=PERo*PERrs*(PER1-PER2*j)
           xFE=CSQRT((s*j*wav*PERFE*oFE)+
      1         ((PIE/TAU)*(PIE/TAU)))
           kz=1-(g/Li)+((2*TAU)/(PIE*w))*
      1         (1-(EXP(((-1)*PIE*w)/(2*Li))))
           e=xFE*h
           c=(CEXP(e)-CEXP((-1)*e))/
      1         (CEXP(e)+CEXP((-1)*e))
           ZFE=(ktr*j*s*wav*PERFE*Li*kz)/(xFE*TAU*c)
           Z2=((ZAL*ZFE)/(ZAL+ZFE))*(1/s)
           RFE=(E1*E1)/PFE
           Zt=(R1+(j*X1))+((RFE*((j*Xm*Z2)/((j*Xm)+Z2)))
      1         /(RFE+((j*Xm*Z2)/((j*Xm)+Z2))))
           I1=V1/Zt
           J1=CABS(I1)/Acu
           R=CABS(I1)
           Z1=R1+(j*X1)
           T=CABS(Z1)
           E1new=V1-(R*T)
```

```
          PRINT*,'THE NEW ITERATION FOR E1new =',E1new
200      IF (E1new.NE.E1) THEN
               E1=E1new
               GOTO 195
          ELSE
               GOTO 210
          ENDIF
     ELSE
          GOTO 210
     ENDIF
210       WRITE(*,220)E1new,COUNT
220       FORMAT('  E1new = ',F10.6,'  AFTER',I3,'
                    INTERATIONS')
230       WRITE(*,240)N1,Np
240       FORMAT('  N1 = ',F4.0,'   AND   Np = ',F4.0)
          Iu=E1new/Xm
          IFe=E1new/RFe
          Io=IFe-(Iu*j)
          I2=I1-Io
          PFE=(IFe**2)*RFE
          P1cu=CABS(I1*I1)*R1
          P2cu=CABS(I2*I2)*REAL(Z2)*s
          Pelect=CABS(I2*I2)*REAL(Z2)
          Thrust=Pelect/(2*f*TAU)
          PL=PFe+P1cu+P2cu
          cosA=COS((ATAN(AIMAG(I1)/REAL(I1))*
     1    (180/PIE))*PIE/180)
          Pin=V1*R*cosA
```

```
      eff=1-(PL/Pin)
      PRINT*,'    '
      PRINT*,'    '
      PRINT*,'    '
      PRINT*,'    I1 =',R,'       Iu =',Iu
      PRINT*,'Pelect =',Pelect,'  PL =',PL,'
           Pin =',Pin
      PRINT*,' Thrust=',Thrust
      PRINT*,'  eff =',eff
      PRINT*,' cosA =',cosA
      PRINT*,'     J =',J1
      PRINT*,'  '
      PRINT*,'  '
      PRINT*,'DO YOU WANT TO CHANGE THE SLIP
           [YES=1/NO=2] '
      READ*,SLIP
      IF (SLIP.EQ.1) THEN
           GOTO 180
      ELSE IF (SLIP.EQ.2) THEN
           CLOSE(1)
           CLOSE(3)
           CLOSE(4)
           CLOSE(7)
           CLOSE(8)
      ENDIF
END
```

APPENDIX 2

Sample run of program

```
A:\>LM

DO YOU WANT TO KEEP CORE DIMENSIONS [YES=1/NO=2]

1

AT THE MOMENT Bg = 4.0000E-01  AND W/Kg = 6.0000E-01

DO YOU WANT TO CHANGE Bg AND W/Kg [YES=1/NO=2]

2

AT THIS MOMENT Li = 9.0000E-02 AND Acu = 1.2272E-06

AND l1 = 7.7713E-03 AND l2 = 7.9999E-03

DO YOU WANT TO CHANGE THE VALUES? [YES=1/NO=2]

2

ENTER A VALUE FOR S [0<S<1]

1

E1new = 153.6131  AFTER  5 INTERATIONS

N1 = 522.   AND   Np = 131.

I1 = 11.5976          Iu = 3.5844

Pelect = 1286.2110   PL = 1628.1850   Pin = 1724.2960

Thrust= 267.9607

eff  = 5.5739E-02

cosA = 6.7580E-01

J = 9450505.00


DO YOU WANT TO CHANGE THE SLIP [YES=1/NO=2]

1

ENTER A VALUE FOR S [0<S<1]

0.8
```

```
E1new = 159.448700  AFTER  5 INTERATIONS

N1 = 522.   AND   Np = 131.

I1 = 10.5781          Iu = 3.7206

Pelect = 1107.5890   PL = 1171.2100   Pin = 1460.2690

Thrust= 230.7478

eff = 1.9794E-01

cosA = 6.274791E-01

J = 8619766.00

DO YOU WANT TO CHANGE THE SLIP [YES=1/NO=2]

1

ENTER A VALUE FOR S [0<S<1]

0.55

E1new = 166.163000  AFTER  5 INTERATIONS

N1 = 522.   AND   Np = 131.

I1 = 9.4052           Iu = 3.8773

Pelect = 849.1395    PL = 693.2388   Pin = 1101.7000

Thrust=     176.9041

eff =   3.7075E-01

cosA =   5.3244E-01

J = 7663960.00

DO YOU WANT TO CHANGE THE SLIP [YES=1/NO=2]

1

ENTER A VALUE FOR S [0<S<1]

0.1

E1new = 173.9980  AFTER  5 INTERATIONS

N1 = 522.   AND   Np = 131.

I1 = 8.0364           Iu = 4.0601

Pelect = 210.3370    PL = 187.2295   Pin = 364.0162
```

```
Thrust = 43.8202

eff = 4.8565E-01

cosA = 2.0588E-01

J = 6548609.00

DO YOU WANT TO CHANGE THE SLIP [YES=1/NO=2]

1
```

Sample run for different Design

```
DO YOU WANT TO KEEP CORE DIMENSIONS [YES=1/NO=2]

2

THE CURRENT DIMENSIONS ARE GIVEN IN THE FOLLOWING ORDER:

           l, TAU, hy, hs, hp, bp, ws

   1.9200E-01    4.8000E-02    1.6000E-02    5.0000E-03

   4.3000E-02    3.2000E-02    5.0000E-03

PLEASE ENTER NEW DIMENSIONS, KEEPING THE SAME ORDER AND

SEPERATED BY A COMMA

0.192,0.048,0.018,0.005,0.043,0.032,0.005

AT THE MOMENT Bg = 4.0000E-01  AND W/Kg = 6.0000E-01

DO YOU WANT TO CHANGE Bg AND W/Kg [YES=1/NO=2]

1

ENTER NEW VALUE FOR Bg AND W/Kg

0.6,0.92

AT THIS MOMENT Li = 9.0000E-02 AND Acu = 1.2272E-06

AND l1 = 5.1809E-03 AND l2 = 7.9999E-03

DO YOU WANT TO CHANGE THE VALUES? [YES=1/NO=2]

1

YOU ARE ALLOWED TO CHANGE ONLY Li OR Acu
```

```
WHICH ONE DO YOU WANT TO CHANGE?

ENTER 1 FOR Li OR 2 FOR Acu

ENTER NEW VALUE FOR Bg AND W/Kg

0.6,0.92

AT THIS MOMENT Li = 9.0000E-02 AND Acu = 1.2272E-06

AND l1 = 5.1809E-03 AND l2 = 7.9999E-03

DO YOU WANT TO CHANGE THE VALUES? [YES=1/NO=2]

1

YOU ARE ALLOWED TO CHANGE ONLY Li OR Acu

WHICH ONE DO YOU WANT TO CHANGE?

ENTER 1 FOR Li OR 2 FOR Acu

1

ENTER NEW VALUE FOR Li

0.04

THERE IS NOT ENOUGH STAKINGSPACE

AND l1 = 1.1657E-02 AND l2 = 7.9999E-03

AT THIS MOMENT Li = 4.0000E-02 AND Acu = 1.2272E-06

YOU ARE ALLOWED TO CHANGE ONLY Li OR Acu

WHICH ONE DO YOU WANT TO CHANGE?

ENTER 1 FOR Li OR 2 FOR Acu

2

ENTER NEW VALUE FOR Acu AND FOR dw

0.0000005176,0.00089

AT THIS MOMENT Li = 4.0000E-02 AND Acu = 5.1760E-07

AND l1 = 6.6847E-03 AND l2 = 7.9999E-03

DO YOU WANT TO CHANGE THE VALUES? [YES=1/NO=2]

2

ENTER A VALUE FOR S [0<S<1]
```

```
1

E1new = 141.815300  AFTER  9 INTERATIONS

N1 = 723.   AND   Np = 181.

I1 = 11.6990          Iu =3.8826

Pelect = 1227.2710   PL = 1920.5430   Pin = 1911.2130

Thrust= 255.6814

eff = -4.8817E-03

cosA = 7.4256E-01

J = 2.2602E+07

DO YOU WANT TO CHANGE THE SLIP [YES=1/NO=2]

1

ENTER A VALUE FOR S [0<S<1]

0.1

E1new = 159.0340  AFTER  9 INTERATIONS

N1 = 723.   AND   Np = 181.

I1 = 9.1225          Iu = 4.54112

Pelect = 261.6733    PL = 448.7939   Pin = 625.0469

Thrust= 54.5152

eff = 2.8198E-01

cosA = 3.1143E-01

J = 1.7624E+07

DO YOU WANT TO CHANGE THE SLIP [YES=1/NO=2]
```

From the above sample run it can be seen that the current desity is much to high for the selected wire diameter.

APPENDIX 3

Depth of Penetration

The depth of penetration of the magnetic field into the mild steel disk was calculated in the following way.

$$\delta = \frac{1}{\sqrt{f \pi \mu_0 \sigma_{Fe}}}$$

$$= \frac{1}{\sqrt{50 * \pi * 200 * 4 * \pi * 10^{-7} * 5 * 10^{5}}}$$

$$= 0.00711 (m)$$

$$= 7.11 (mm)$$

As the mild steel disk is 10mm thick, the disk is not saturated by the magnetic field.