A BRUSHLESS,DIRECT-DRIVE,WIND-TURBINE ALTERNATOR

A Thesis

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In

Electrical Engineering

By

Calvin Wai Chiu Cheung

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A dissertation submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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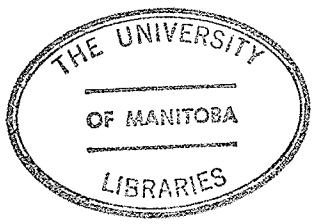

ABSTRACT

A design concept for low-speed brushless wind turbine alternators is introduced. A prototype machine was built and tested to demonstrate the concept. Optimal designs were obtained by a Direct Search optimisation method. An alternate design is suggested and compared with the prototype design. A range of recommended rated power outputs is suggested for each design.

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act	Threshold electrical loading.
acf	Furling electrical loading.
a	number of circuit in stator.
af	number of circuit in field.
As	Area of the slot.
Asc	Conductor size of the field winding.
Ascs	Conductor size of the stator winding.
ATmg	Ampere turns per pole at the main gap.
ATar	Demagnetizing A.T. per pole for armature reaction.
ATfd	Total A.T. per pole pair for the field.
Bt	Average threshold air gap flux density.
Bf	Average furling air gap flux density.
Cpp	Number of coils per phase.
Clt	Stator I^2R loss at threshold.
Clf	Stator I^2R loss at furling.
Db	Stator bore diameter.
Dens	Density of laminations.
Ef	Exciter voltage.
f(x)	Function of x.
Ft	Threshold frequency.
Ff	Furling frequency.
g(x)	Constraint function.
Gt	Threshold output coefficient.
Gf	Furling output coefficient.
ht	Slot depth.

Ift	Threshold full load current.
Iff	Furling full load current.
Ipp	Stator current per path.
Jf	Field current density.
Js	Stator current density.
Kd	Distribution factor.
Ke	Coil-span factor.
Ked	Eddy current loss ratio.
Ks	Skewing factor.
Kw	Winding factor.
L	Stator core length.
Lm	Stator mean turn length.
Lf	Mean turn of field winding.
Lt	Mutual leakage inductance.
nt	Threshold r.p.s.
nf	Furling r.p.s.
Nt	Threshold r.p.m.
Nf	Furling r.p.m.
Ns	Number of slots.
Nc	Number of conductors per slot.
p	The pth power of a function.
P	Number of poles.
Pf	Power factor.
Plf	Field I^2R loss.
Pe	Iron loss.
Pc	Power transfered by conduction.
Pr	Power transferred by radiation.

Pv	Power transferred by convection.
P(X,Fs)	Objective function.
Qt	Threshold KVA output.
Qf	Furling KVA output.
Rp	Stator resistance per path.
Rph	Stator resistance per phase.
Rf	Field resistance per circuit.
Sf	Space factor.
Spi	Slots per phase with in phase coils.
Spo	Slots per phase with out of phase coils.
Sp	Slots per pole.
T1	Final temperature of the machine.
T2	Ambient temperature of the air.
Tpc	Number of turns per coil.
Tph	Number of turns per phase.
Tpf	Number of field turns per circuit.
Vp	E.M.F. per phase.
Vt	Rotor peripheral threshold speed.
Vf	Rotor peripheral furling speed.
wt	Weight of iron.
Wt	Threshold rated output power.
Wf	Furling rated output power.
Wo	Slot width.
Xo	Slot mutual reactance.
Xoh	Overhang leakage reactance.
Xs	Slot self leakage reactance.
Xst	Total slot leakage reactance.

ys	Slot pitch.
ys′	Effective slot pitch.
ϵ	Short pitch angle.
ϵm	Emissivity of material.
δ	Angle between coils emf in electrical radian.
Φ	Average flux per pole.
β	Skew angle.
τ	Pole pitch.
ρ	Resistivity of copper at 75^0C.
ρs	Resistivity of iron at 75^0C.
λs	Slot leakage flux.
λab	Slot mutual leakage flux.
μo	Permeability of air.

Chapter I

INTRODUCTION

1.1 General

The generation of electrical power from the wind has received attention in recent years in Canada. Both the National Research Council and the Bristol Aerospace Limited have developed the vertical axis windmill for power generation.[1] Due to the cold climate and the inaccessibility of large areas of Canada, the requirement of regular maintenance on the brushes and the slip rings limits the use of conventional alternators in windmill applications. Thus, the development of a maintenance-free alternator in remote, unmanned locations is desirable. The objective of this thesis is to develop an efficient, direct-drive, fully controllable brushless alternator for the vertical axis windmill application.

The average wind speed in Canada lies in the 7 to 13 m.p.h. range. For a 8.7 ft diameter vertical axis wind turbine, the shaft speed is about 100 to 150 r.p.m. The mechanical power that can be obtained is about 60 to 200 watts. Since only a small amount of power is extracted from the wind, a speed-up transmission is not desirable because the frictional loss in the gears constitutes a great portion

of the power generated. The ideal machine for this application should have the following characteristics :

(1) Capability of low speed operation (40-200 r.p.m.) with reasonable efficiency (75% or above),
(2) Controllable self excitation,
(3) Capability of self starting,
(4) No slip rings.

A direct-drive, fully controllable, brushless alternator will satisfy the above characteristics.

1.2 Factors Affecting The Performance of The Wind Power System

Theoretically, the mechanical power extracted from wind is proportional to the area intercepted by the turbine and the cube of wind speed. A large amount of mechanical power is expected from an efficient turbine situated in a strong wind location. However, due to the low power coefficient, about 0.35, of the wind turbines, only a small portion of the available power is obtained from the wind. Figure 1.1 shows the theoretical electrical power output of the vertical axis windmill with a 75% efficient generator coupled to it. Since the mechanical power output from the turbine is low, any additional of speed-up mechanism loss

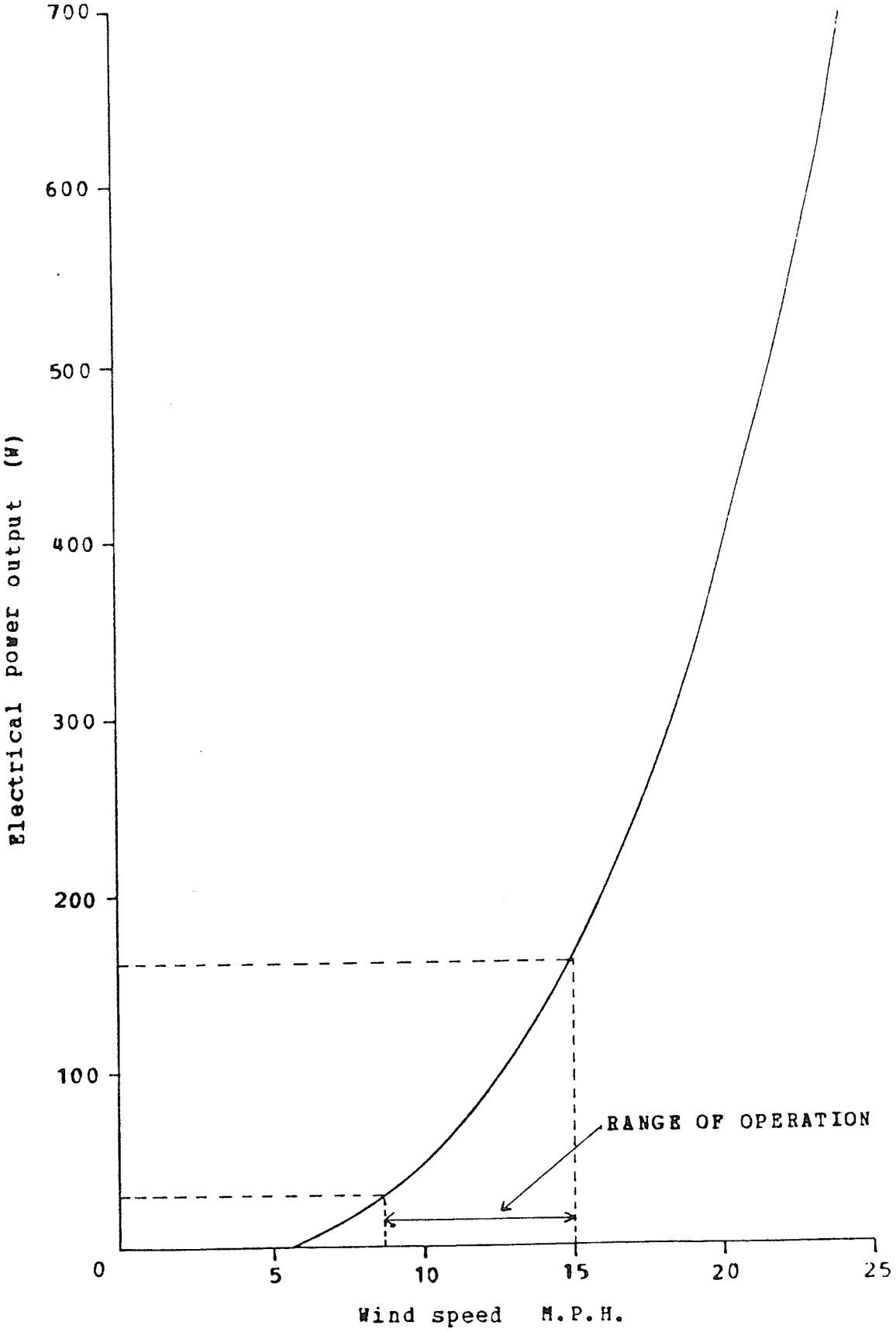


Figure 1.1: The Electrical Power Output of The Windmill

will further reduce the mechanical power input to the alternator. The brushes and the bearings also constitute some losses in mechanical power.

The vertical axis turbine has a low starting and accelerating torque. If a 10:1 ratio speed-up transmission is applied, the starting torque required is ten times the friction torque of the alternator plus the friction torque of the gearbox. For such a high torque, the wind turbine may not be able to start or to accelerate.

A direct-coupled machine can ease the starting and accelerating problems. However, due to the low shaft speed (100-150 r.p.m.) of the turbine, an alternator with larger diameter is required.

Due to the variation of the wind speed, a controllable field excitation can provide an easy way to match the machine to the load over a wide range of speed. The capabilities of self start and self excitation are also necessary for the application of the windmill in remote locations where an alternate electrical supply is not available.

The intermittent operating characteristic of the windmill may cause additional problems in a cold environment. The

cold weather in winter, and the all year round cold climate in the Arctic, creates a starting problem for the generator. When the windmill stops due to insufficient wind, there is a danger of frosting the brushes and the slip rings.

The brushes and the slip rings of a conventional sychronous alternator require regular maintenance such as :

(1) Cleaning and machining of the slip rings,
(2) Replacing the degraded slip rings due to corrosive environment, and
(3) Adjusting, cleaning and replacing the brushes.

When the windmills are used in remote areas, the maintenance cost tends to be high. The maintenance cost can therefore be minimized if the brushless alternators are used instead.

In order to accomplish a high efficiency wind power system, a direct-drive, fully controllable brushless alternator is desired.

1.3 Types of Brushless Alternator

There are four main types of brushless machines :

(1) Permanent magnet machine;

(2) Rotating rectifier brushless machine;

(3) Inductor alternator; and

(3) Stationary field brushless machine.

(1) Permanent magnet machine

The permanent magnet machines have no control over the field excitation. To maintain a constant voltage for various wind speed, a regulator rated at full output power must be incorporated between the alternator and load. The cogging or detenting forces cause starting problems when coupled to a low torque wind turbine. In addition, the cost of the permanent magnets is comparatively expensive. Apart from these disadvantages, the permanent magnet machine is comparatively small and light weight and has an inherently high efficiency.

(2) Rotating rectifier brushless machine

This type of machine has a fully controllable field. It is essentially two machines on the same shaft. The stator of the exciter provides field to induce votlage in the rotor winding. The voltages are rectified and fed to the rotor field of the alternator. Thus, the field excitation of the alternator can be controlled by adjusting the stator current of the exciter.

This alternator requires the design of two machines and therefore is costly. Because of the probable inefficiency of two machines, the overall efficiency will be reduced, hence it is not economical for low rating alternators.

(3) Inductor alternator

Present designs are limited to high speed, high frequency, single-phase alternators. Currently a parallel study is underway to investigate the applicability of the Guy-type inductor alternator for wind turbines.

(4) Stationary field brushless machine

This type of alternator is similar to the Lundell machine, except there is no winding in its rotor. Fig 1.2 shows two configurations of this type of alternator. The field is provided by concentrated axial winding about the shaft or the inside of the frame. A magnetic field is produced across the auxiliary airgap on the rotor, hence voltage is induced on the stator phase winding. The main advantage of this machine is that no brushes are required, and yet the excitation is fully controllable. Since the rotor is simply of the claw-poles type, it is economical to manufacture.

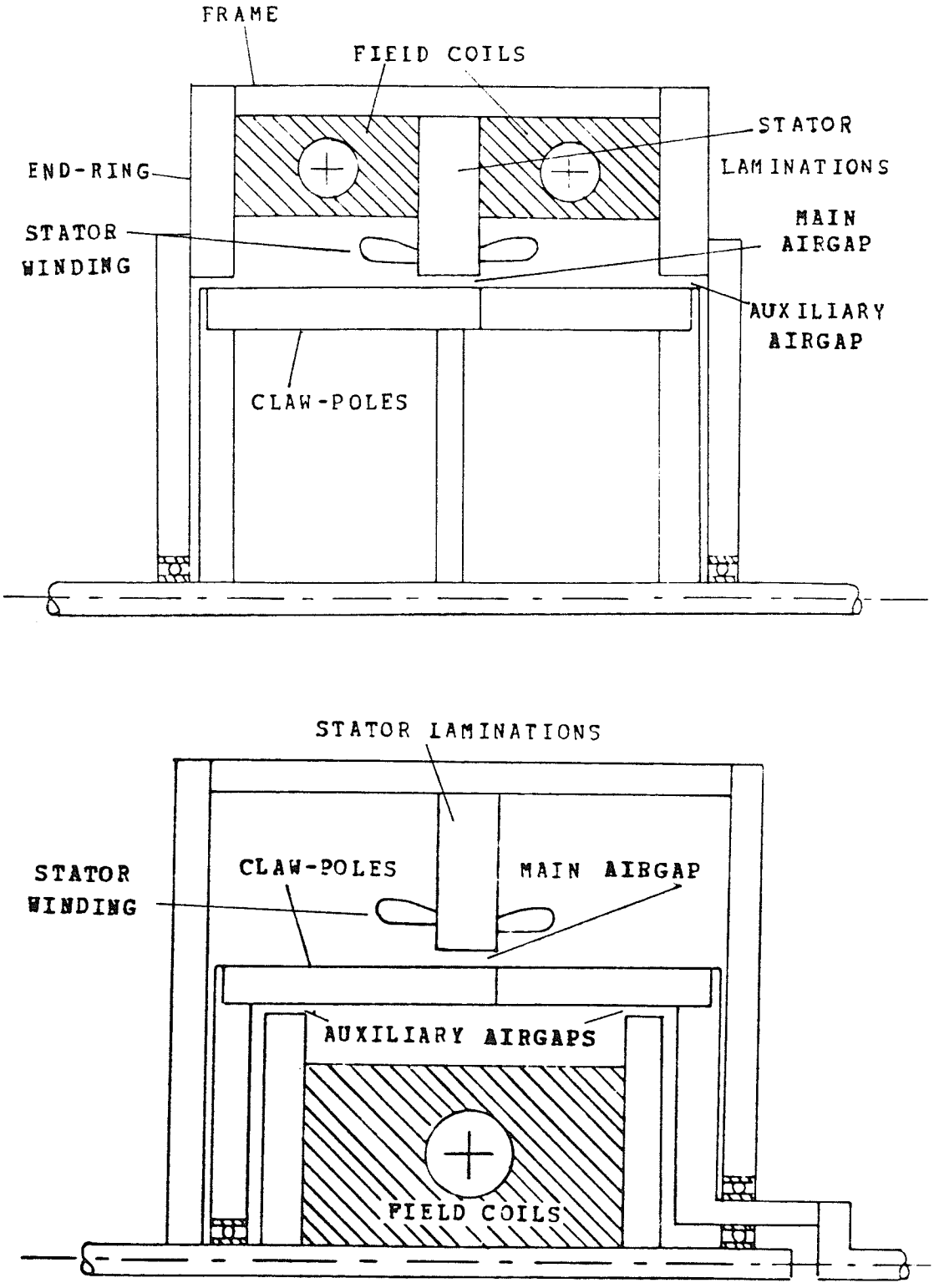


Figure 1.2: Stationary Field Brushless Machines

1.4 Scope of The Thesis

A reliable, simple and fully controllable brushless alternator for windmill applications is desirable for unmanned locations and the cold weather in Canada. The development of a stationary field, brushless alternator capable to operate at reasonable efficieny (75% or more) over a wide range of wind speeds is the main theme of this thesis.

The studies of the development are as follows :

(1) Concept and theory of the design,

(2) Sample design of a prototype machine,

(3) Tests on the prototype,

(4) Final design,

(5) Optimal design, and

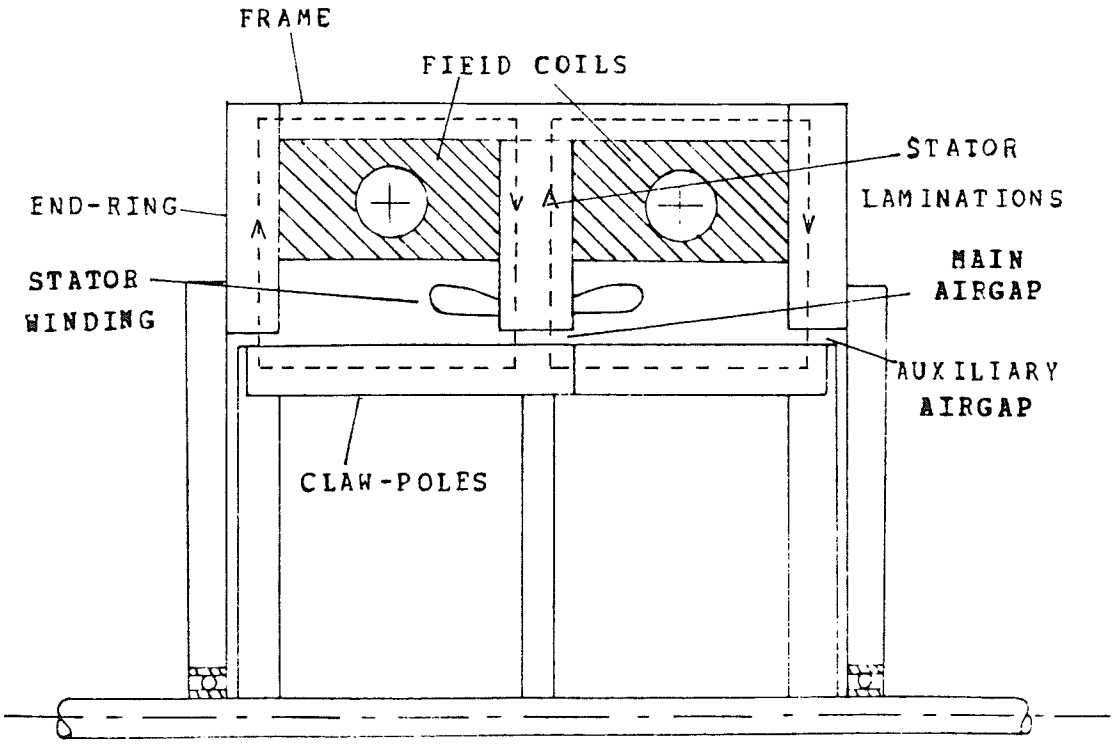
(6) Alternate designs.

Chapter II

BRUSHLESS LUNDELL ALTERNATORS

2.1 General

A brushless Lundell alternator is a modified conventional Lundell machine[2 3]. Fig. 2.1 shows the main feature of a brushless Lundell alternator. The rotor is similiar to the Lundell type with claw-poles, but the field winding is stationary instead of rotating. Thus, no brushes are required for feeding current to the field winding. The field winding is placed along the inside surface of the frame on both sides of the stator back core. The frame and the end-rings are made of magnetic materials to form part of the magnetic path for saving material. The stator winding is the conventional three-phase winding. The magnetic path is shown by broken lines. There are two auxiliary airgaps between the end-rings and the rotor pole-claws. The main magnetic flux, produced by the field coils at the frame, travels along the frame to the first end-ring. The magnetic flux passes through the first auxiliary airgap to the pole claws (say, North poles). Here the flux distributes among the poles and penetrates into the stator through the main airgap. The flux goes circumferentially along the stator back core and returns through the main airgap at one pole pitch apart to the South poles. Here the flux crosses the



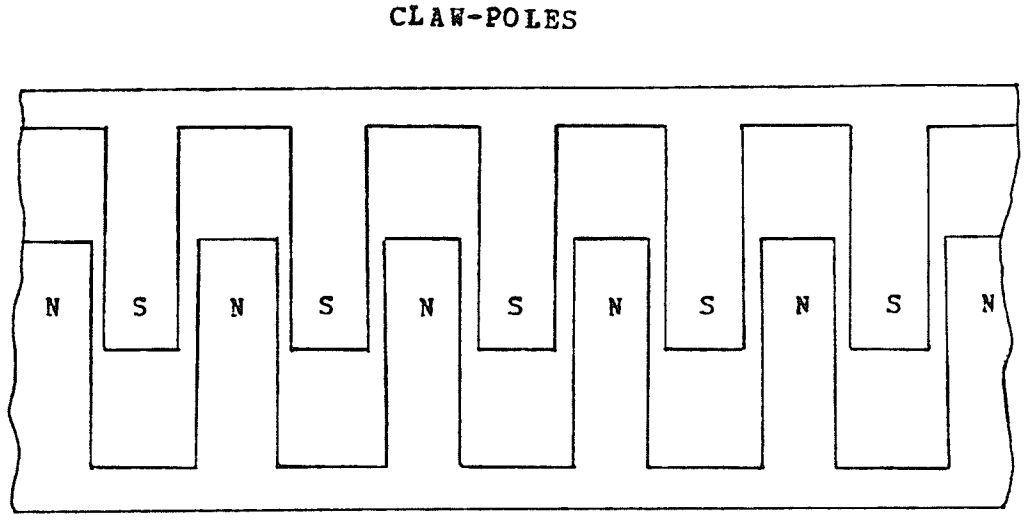


Figure 2.1: Brushless Lundell Alternator

second auxiliary airgap to the second end-ring and returns to the frame, thus completing the full magnetic circuit.

The stator has a three-phase double-layer lap winding. This machine has three different rated open circuit voltage outputs, as will be discussed later, and hence requires at least four identical winding sections. The teeth are tapered and the slots are rectangular in shape. The stator core laminations are skewed one slot pitch.

2.2 Design Procedure

A design must meet a set of specifications and constraints. The specifications are usually the following: rated power, rated voltage, power factor, efficiency, frequency and the r.p.m. of the machine. Generally, the constraints are efficiency, the cost and the weight of the machine. For this thesis the design specifications are describied in Chapter Three. The design procedure is divided into seven major parts :

(1) Poles and frequency,

(2) Main dimensions,

(3) Stator winding design,

(4) Leakage reactance,

(5) Magnetic circuit,

(6) Field winding design,

(7) Losses and efficiency.

Each part of the design procedure will be discussed in the succeeding sections.

2.3 Poles and Frequency

A windmill is a variable speed prime mover so the alternator has to operate over a range of speed. The lowest operating speed of the alternator is designated as the threshold speed and the highest as the furling speed. The actual furling (or maximum) speed of the wind turbine may be considerably higher. The number of poles of the machine is first estimated by using the given frequency at furling, Ff, and the r.p.m. at furling, Nf, with the expression :

$$P = \frac{120.Ff}{Nf} \qquad (2.1)$$

From Equation (2.1), the closest even number of poles, P, is used to compute the exact frequencies at furling and threshold. The frequency is expressed as :

$$Ff = \frac{P.Nf}{120} \quad \text{or} \quad Ft = \frac{P.Nt}{120} \quad (Hz) \qquad (2.2)$$

where Ff and Ft are frequency at furling and threshold respectively.

2.4 Main Dimensions

After the number of poles and frequencies are computed, the main dimensions can be determined. First, an average airgap flux density, B, for the machine is assumed. The average flux per pole is therefore expressed as

$$\Phi = \frac{\pi.Db.L.B}{P} \quad (Wb/Pole) \tag{2.3}$$

where Db is the stator bore diameter,

L is the core length.

The angular speeds of the machine at threshold and furling are :

$$nt = \frac{Nt}{60} \quad (rev./sec.) \tag{2.4}$$

$$nf = \frac{Nf}{60} \quad (rev./sec.) \tag{2.5}$$

The e.m.f. per phase is given by

$$Vp = 4.44\ \Phi.F.Tph.Kw$$

$$= 2.22\ \pi.Db.L.Tph.Kw.B.n \quad (V) \tag{2.6}$$

where F is the operating frequency,

n is the angular speed,

Kw is the winding factor,

and Tph is the number of turns per phase.

If Db, L, Tph, Kw are all fixed, Vp is directly proportional to B and n, i.e.,

$$Vp \propto B.n \tag{2.7}$$

For a constant voltage machine, Vp is almost constant between nf and nt, and therefore B has to be varied accordingly. The threshold flux density, Bt, is thus related to the furling flux density, Bf, by

$$Bt = \frac{nf.Bf}{nt} \quad (T) \tag{2.8}$$

Since nf > nt, therefore Bt > Bf. To prevent saturation at low speed operation, the threshold airgap flux density, Bt, is first chosen and then Bf is obtained from Equation 2.8.

The electrical loading, ampere conductor per meter of the airgap surface, at threshold and furling is defined as

$$act = \frac{6.Tph.Ift}{\pi.Db} \quad (a.c./m.) \tag{2.9}$$

where Ift is the threshold full load current.

$$acf = \frac{6.Tph.Iff}{\pi.Db} \quad (a.c./m) \tag{2.10}$$

where Iff is the furling full load current.

From Equations 2.6, 2.8, 2.9, 2.10, the KVA output at threshold and furling of the machine can be expressed as

$$Qt = 10.955\ Db^2.L.nt.act.Bt.Kw \quad (KVA) \tag{2.11}$$

$$Qf = 10.955\ Db^2.L.nf.acf.Bf.Kw \quad (KVA) \tag{2.12}$$

The output coefficient for threshold is defined as

$$Gt = \frac{Qt}{Db^2.L.nt}$$

$$= 10.955\ act.Bt.Kw \times 10^{-3} \tag{2.13}$$

and for furling as:

$$Gf = \frac{Qf}{Db^2.L.nf}$$

$$= 10.955\ acf.Bf.Kw \times 10^{-3} \tag{2.14}$$

From Equations 2.13 and 2.14, the ratio of the output coefficient at threshold and furling is expressed as

$$\frac{Gf}{Gt} = \frac{Qf.nt}{Qt.nf} \tag{2.15}$$

The ratio between act and acf is obtained from Equations 2.8, 2.11 and 2.12 as

$$\frac{acf}{act} = \frac{Qt}{Qf} \qquad (2.16)$$

Since Qt and Qf are specified outputs, the electrical loadings at threshold and furling have to be different and the difference depends on the ratio of Qt and Qf. By calculating the ratio Qf/Ff, the estimated value of electrical loading at furling , acf, can be obtained[4]. The electeical loading at threshold , act, is evaluated from Equation 2.16. The output coefficients at furling and threshold are calculated from Equations 2.13 and 2.14, with an estimated winding factor Kw between 0.8 to 1.0, usually 0.9.

From Equation 2.13, the bore diameter, Db, of the machine is given by

$$Db = \frac{(P.Qtx10^{-3})^{1\ 3}}{(Kr.\pi.nt.Gt)} \quad (m.) \qquad (2.17)$$

where Kr is the ratio of armature length L to pole-pitch.

$$Kr = \frac{L}{\tau} = \frac{L}{\pi.Db/P} \qquad (2.18)$$

Generally, Kr is chosen between 0.8 to 2.5.[4] After the stator bore diameter is determined, the length of the stator core can be computed with the expression

$$L = \frac{Qtx10^{-3}}{nt.Gt.Db^2} \quad (m.) \tag{2.19}$$

In Equations 2.17 and 2.19, the threshold value is used for calculation, because the airgap flux density at threshold is higher than that at furling. If Bf is used for calculation, saturation may occur in the iron when the machine is operating at low speed. The iron loss and leakage flux would also be high.

The rotor peripheral speed is used to check the mechanical safety of the machine. The rotor peripheral speed at threshold and furling are :

$$Vt = \pi.Db.nt \quad (m./sec.) \tag{2.20}$$

$$Vf = \pi.Db.nf \quad (m./sec.) \tag{2.21}$$

The rotor peripheral speed can reach up to about 30 to 60 m/s[5], but for mechanical rigidty, it is perferable to limit it to less than 15 m/s. For the design procedure peripheral speed is used as a constraint. If it exceeds the mechanical

safety limits, a new ratio of armature length to pole pitch has to be chosen. The stator bore diameter and core length are recomputed again until the mechanical safety is satisfied.

2.5 Stator Winding Design

When a machine is designed for multiple output voltages, a number of parallel circuits are required. For a 'm' phase machine with 'a' number of parallel paths, the number of slots Ns must be a multiple of m.a, i.e.,

$$\frac{Ns}{m.a} = \text{integer} \qquad (2.22)$$

The number of slots depends on the type of winding desired. In general, the integral slot winding has an integral number of slots per pole per phase, while for the fractional slot winding, the number of slots per pole per phase can be a fraction.

After the number of slots is determined, the slot pitch is calculated using the expression

$$ys = \frac{\pi.Db}{Ns} \qquad (2.23)$$

Choosing the ratio between tooth width and slot pitch of about 0.3 to 0.7, the tooth pitch is calculated. If the flux density in the tooth is higher than 1.8T, saturation may occur. A ratio between tooth pitch and slot pitch must therefore be changed to a higher value.

There are many choices of armature windings. The most commonly used winding is a double layer lap winding with short-pitched coils. The advantages of double layer lap winding are :

(a) ease of manufacturing

(b) fractional slotting can be used

(c) chorded spans are obtained

A double-layer lap winding is used in this design. A phase spread of 60^0 or 120^0 is chosen to fix the coil span. The electrical space phase angle between coil axes is then calculated. The distribution factor Kd of the winding is computed by the expression

$$Kd = \frac{\text{Sin}(k.\delta)/2}{k.\text{Sin}\,\delta/2} \qquad (2.24)$$

where k is the number of coils per pole per phase.

δ is the angle between coils emf.

The coil-span factor ke is obtained by the Equation

$$Ke = \cos\epsilon/2 \tag{2.25}$$

where ϵ is the angle by which a coil is short pitched.

The stator laminations are skewed one slot pitch to prevent cogging. The skew factor is

$$Ks = \frac{\mathrm{Sin}\beta/2}{\beta/2} \tag{2.26}$$

where $\beta = \tan^{-1}(ys/L)$

where ys is the slot pitch,

L is the core length.

The winding factor is expressed as

$$Kw = Kd.Ke.Ks \tag{2.27}$$

After determining the winding factor Kw, the estimated Kw is replaced with the calculated value. The stator bore diameter, Db, core length, L, electrical loading and output coefficient are computed from Equations 2.9, 2.10, 2.13, 2.14, 2.17, and 2.19. If the electrical loading and output coefficient are too large, the main dimensions have to be recalculated.

The number of turns required at furling and threshold is

calculated with the following expression

$$Tph = \frac{Vp \times 1.05}{0.11624\ n.Kw.B.Db.L} \qquad (2.28)$$

where n is the angular speed,

B is the airgap flux density.

The factor 1.05 allows for a first estimate for the voltage drop in the winding under full load. The larger number of turns between furling and threshold is used.

The full load current at furling and threshold is obtained by the expressions

$$Ift = \frac{Wt}{m.Pf.Vp} \quad (A) \qquad (2.29)$$

where Wt is the rated output power at threshold,

Pf is the power factor,

m is the number of phase.

$$Iff = \frac{Wf}{m.Pf.Vp} \quad (A) \qquad (2.30)$$

where Wf is the rated output power at furling.

The furling current is used to calculate the conductor size.

For 'a' parallel paths, the current per path at furling is

$$Ipp = \frac{Iff}{a} \quad (A) \tag{2.31}$$

The number of coils per path per phase is

$$Cpp = \frac{Ns}{m.a} \tag{2.32}$$

The number of turns per coil is

$$Tpc = \frac{Tph}{Cpp} \tag{2.33}$$

The number of conductor per slot is

$$Nc = 2.Tpc \tag{2.34}$$

A current density, Js, and a space factor, Sf, are assumed to calculate the slot area, As, and the slot depth, ht. The conductor size is expressed as

$$Ascs = \frac{Ipp}{Js} \quad (m.^2) \tag{2.35}$$

The area of the slot required is

$$As = \frac{Ascs.Nc}{Sf} \quad (m.^2) \tag{2.36}$$

where a space factor, Sf, of between 0.4 to 0.5 was chosen.

The slot depth is expressed as

$$ht = \frac{As}{Wo} \quad (m.) \tag{2.37}$$

where Wo is the slot width

If ht is too big, either the current density Js or the slot width Wo has to be increased. The current density Js can be increased if it is within the current density limit. However, the I^2R loss of the winding is directly proportional to the square of the current density, therefore a small current density is recommended. If the slot width is increased, saturation may occur in the teeth. In the case when both current density and slot width cannot be changed, the stator bore diameter and the core length have to be increased.

2.5.1 Copper Loss In Stator

The mean length of a coil is estimated with the method suggested by Kuhlmann[4]. The shape of an armature coil for synchronous machine is shown in Fig 2.2. The length of the mean-turn is expressed as

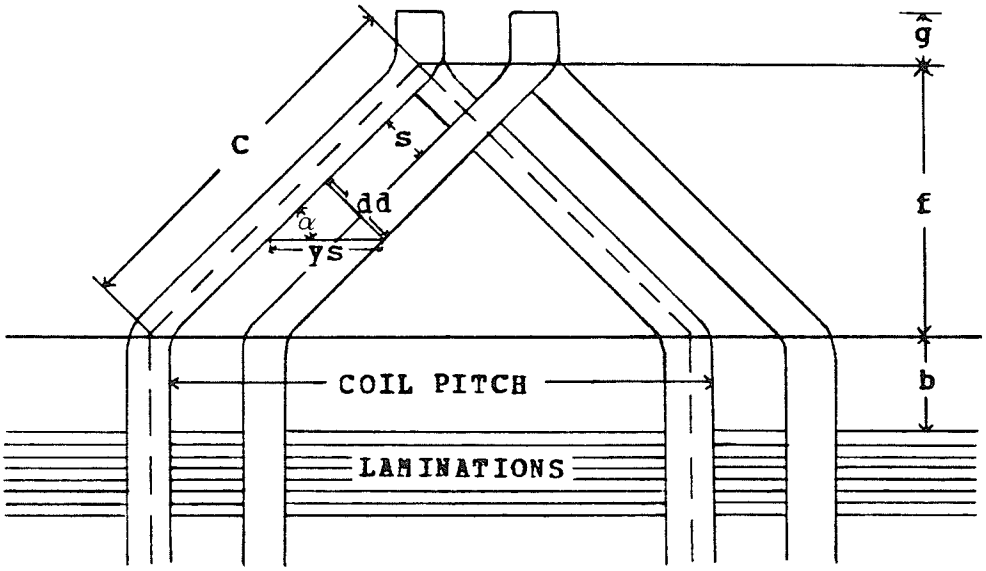


Figure 2.2: The Shape of Armature Coils

$$Lm = 2 \left\{ \frac{\pi.(Db + ht).cp}{(P.\cos\alpha)} + 2b + ht + L \right\} \quad (m.) \quad (2.38)$$

where cp = (coil pitch)/(slot per pole)

$\alpha = \sin^{-1}(dd/ys)$

dd = Wo + s

b is the coil extension,

s is the coil clearance,

L is the core length,

ht is the slot depth.

Total length of coils per path is

$$Lp = Lm.Tpc.Cpp \qquad (m.) \tag{2.39}$$

The resistance per path at 75^0C is

$$Rp = \frac{\rho.Lp}{Ascs} \qquad (Ohm) \tag{2.40}$$

where ρ is the resistivity of copper at 75^0C.

The resistance per phase is written as

$$Rph = \frac{Rp}{a} \qquad (Ohm) \tag{2.41}$$

The I^2R losses at furling and threshold can be calculated with following expressions

$$Clf = m.Iff^2.Rph \qquad (W) \tag{2.42}$$

$$Clt = m.Ift^2.Rph \qquad (W) \tag{2.43}$$

2.6 Leakage Reactance

2.6.1 Slot Leakage Reactance

Fig 2.3 shows a slot with double-layer winding. The mmf of the slot currents will set up leakage flux in each of the five paths indicated in the diagram. These fluxes are

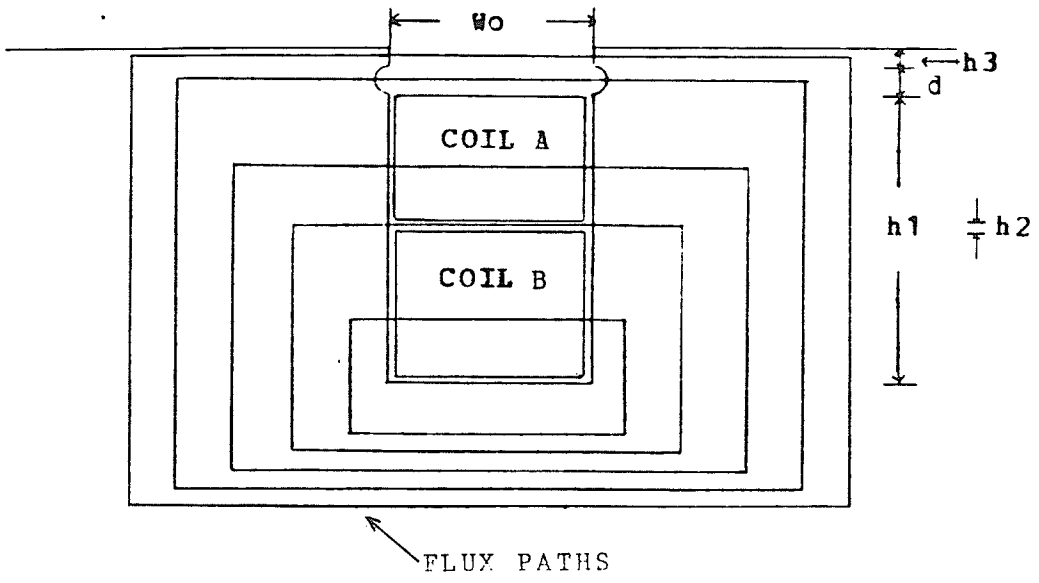


Figure 2.3: Slot Leakage Flux With Double-Layer Winding

computed with the assumption that the fluxes pass straight across the slots and the reluctance of the iron paths is negligible. For calculating the slot leakage flux, there are two cases to be considered:

(a) Full pitch coils--coil A and coil B are of the same phase.

(b) Short pitch coil--coil A and coil B are out of phase.

(a) Full pitch coil

Since coil A and coil B are coils of the same phase, the currents in the slot are also in phase. The deriviation of the leakage flux per slot per length of core is similar to Alger[6] and Landsdorf[7]. It is expressed as

$$\lambda s = 4.Tpc^2.\mu o\{ \frac{h3}{Wo} + \frac{d}{Wo+d} + \frac{h1}{3.Wo} - \frac{h2}{12.WO} \} \quad (2.44)$$

where μo is the permeability of air.

The leakage reactance for in phase coils is

$$Xs = 2.\pi.F.L.\lambda s.Spi \quad (Ohm) \quad (2.45)$$

where spi is the number of slots per phase.

(b) Short pitch coil

In this case, some slots has in phase coils so Equation 2.44 can be applied. For those slots with out of phase coils, assume the current in coil A leads the current in coil B by an angle θ ($2\pi/3$ for three-phase). The method suggested by Langdorf is used[7]. The self-inductance of coil A is proportional to the leakage flux λa. λa is expressed as

$$\lambda a = Tpc^2.\mu o\{ \frac{h3}{Wo} + \frac{d}{Wo+d} + \frac{h1 - h2}{6.Wo} \} \quad (2.46)$$

The self inductance of coil B is proportional to the leakage flux λb. λb is expressed as

$$\lambda b = Tpc^2 . \mu o \{ \frac{h3}{Wo} + \frac{d}{Wo+d} + \frac{2.h1 + h2}{3.Wo} \} \qquad (2.47)$$

The mutual inductance of coil A due to the unit current in coil B is proportional to the mutual flux leakage λab. The mutual leakage flux is

$$\lambda ab = Tpc^2 . \mu o \{ \frac{h1 - h2}{4.Wo} + \frac{h3}{Wo} + \frac{d}{d+Wo} \} \qquad (2.48)$$

The mutual leakage flux λab of coil B due to the unit current in coil A is equal to the mutual leakage flux λab. The leakage inductance of coil A and coil B are derived in Appendix I and they can be expressed as

$$La = (\lambda a^2 + \lambda ab^2 + 2.\lambda a.\lambda ab.\cos\theta)^{1/2} \qquad (2.49)$$

$$Lb = (\lambda b^2 + \lambda ba^2 + 2.\lambda b.\lambda ba.\cos\theta)^{1/2} \qquad (2.50)$$

The total leakage inductance per slot is

$$LT = La + Lb \qquad (2.51)$$

Therefore the leakage reactor per phase due to out of phase coils in a slot is

$$Xo = 2\ F.L.LT.Spo \qquad (2.52)$$

where Spo is slots per phase with out of phase coil,

F is the frequency at furling or threshold.

In general, some of the slots of fractional-pitch winding will be occupied by coil sides of the same phase. Thus, the total slot leakage reactance is the sum of Equation 2.45 and 2.52

$$Xst = Xo + Xs \tag{2.53}$$

2.6.2 Overhang Leakage Reactance

There are only empirical formulae for calculating overhang leakage reactance. The overhang leakage reactance is estimated with an empirical formula suggested by Alger[6].

$$Xoh = \frac{38.4\pi.F.\mu o.Tpc^{2}.Db.Ns.(3p - 1)}{2.p} \tag{2.54}$$

where p is the coil pitch fraction.

The zig-zag leakage and the differential leakage are usually small enough to be ignored. Therefore, the total leakage considered is the sum of the slot leakage reactance and the overhang reactance. The total leakage reactance per phase is

$$XT = Xoh + Xst \tag{2.55}$$

2.7 Magnetic Circuit

The total ampere turns per pole required is the sum of the ampere turns for each part. The flux per pole is expressed as

$$\Phi = Bt.\tau.L \quad (Wb) \tag{2.56}$$

where τ is the pole-pitch.

The fluxes in different parts are determined accordingly. Assume the average flux densities in the stator back core, frame, end-rings and poles as Bc, Bf, Ber, and Bp respectively. The estimated flux densities are dependent on the magnetic characteristic of the material. For an optimum use of the material, high flux density is desired; but due to magnetic saturation, a value below 1.8T is usually chosen.

The required cross-sectional area A of each component of the magnetic circuit can be calculated by the Equation

$$A = \frac{\Psi}{B} \quad (m.^2) \tag{2.57}$$

where Ψ is the flux in that part of magnetic circuit,

B is the flux density.

Hence the dimension of each part of the magnetic circuit is obtained.

2.7.1 Total Ampere Turns Per Phase

The magnetic characteristic of materials are obtained by experiment. The ampere turns per pole of each part of the magnetic path, except the main airgap, is the length of that part multiplied by the corresponding magnetic field intensity from the magnetic curves. The presence of the slots increases the gap reluctance so the effective airgap reluctance has to be determined. A method suggested by M.G. Say is to find an effective contracted slot pitch with the expression

$$ys' = ys - KoWo \tag{2.58}$$

where Ko is the Carter coefficient.

Carter coefficient Ko is obtained from the Carter's curve from the ratio of slot width to gap length. Hence the effective pole area becomes

$$Ap = ys'.L.Sp \tag{2.59}$$

where Sp is slots per pole.

The effective airgap flux density is

$$Bg = \frac{\Phi}{Ap} \tag{2.60}$$

The ampere turns per pole at the main airgap is

$$ATmg = \frac{Lg.Bg}{\mu o} \qquad (2.61)$$

where Lg is the length of the air gap.

The sum of the total ampere turns in series is the total required ampere turns per pole for the magnetic circuit. The demagnetizing ampere turns per pole for armature reaction is

$$ATar = 1.35\ Kw.Tph.Iff/P \qquad (2.62)$$

The total A.T. per pole pair ATfd for the field is equal twice the sum of the total A.T. of the magnetic circuit and the A.T. of armature reaction.

2.8 Field Winding Design

The rectified output voltage is used as the exciter voltage Ef. Since there are several rated output voltages, a number of parallel field circuits are required.

The cross-section area of the field winding is expressed as

$$Acf = \frac{ATfd}{Sf.Jf} \quad (m.^2) \qquad (2.63)$$

where Sf is the space factor (between 0.4 to 0.5),

Jf is the current density.

A current density, Jf, is chosen to calculate Acf. Allow sixty percent of the stator back core for placing the field winding and calculate the length of the frame.

The conductor size is expressed as

$$Asc = \frac{ATfd.\rho.Lf}{af.Ef} \quad (m.^2) \tag{2.64}$$

where ρ is the resistivity of copper at 75^0C,

af is the number of parallel paths,

Lf is the mean turn.

The number of turns required for each path is

$$Tpf = \frac{ATfd}{af.Asc.Jf} \tag{2.65}$$

The resistance per path is expressed as

$$Rf = \frac{\rho.lf.Tpf}{Asc} \quad (Ohm) \tag{2.66}$$

The total I^2R loss of the field is

$$Plf = ATfd.\rho.Lf.Jf \quad (W) \tag{2.67}$$

2.9 Iron Loss

The iron loss is calculated in the two separate parts: the teeth and the core. The weight of the teeth and the core are calculated. The iron loss is expressed as

$$Pe = \frac{1.65\ B^2.F^2.t^2.wt}{\rho s.Dens} \quad (W) \qquad (2.68)$$

where B is the average flux density,

F is the frequency of the machine,

t is the thickness of the lamination,

wt is the weight,

Dens is the density of the laminations,

ρs is the resistivity of the material.

Substitute the weight and the flux density of the teeth and core into Equation 2.68 accordingly. The total iron loss is the sum of the iron loss of the teeth and the stator core.

2.10 Eddy Loss

The Equation suggested by M.G.Say is used to calculate the eddy current loss in the conductors in slots. First, estimate the width of copper 'bb' occupied in the slot. Then find the number of layers of conductor 'c' in the slot. The

average eddy current loss ratio is expressed as

$$Ked = (\sigma.h)^4(c^2/9) \qquad (2.69)$$

where

$$\sigma = \left(\frac{\pi.\mu o.F.bb}{2.\rho.Wo} \right)^{1/2}$$

The average eddy current loss is equal to Ked multiplied by the I^2R loss of the conductors in the slots.

2.11 Temperature Rise

The power loss in the windings are dissipated as heat. The loss heat is transferred by a combination of conduction, radiation and convection. Assume the machine as a homogeneous body with surface area A, the power transferred by conduction across the interface between air and machine surface is

$$Pc = Kc(T1 - T2).A \quad (W) \qquad (2.70)$$

where Kc is the coefficient of air (10 to 50),

T1 is the final temperature inside the machine,

T2 is the ambient temperature of the air.

The power transferred by radiation is

$$Pr = 5.7 \times 10^{-8} \epsilon m(T1^4-T2^4).A \quad (W) \qquad (2.71)$$

where ϵm is the emissivity of the material.

The power transferred by convection is

$$Pv = 2.ap^{1/2}(T1-T2)^{5/4}.A \quad (W) \qquad (2.72)$$

where ap is the number of atmosphere pressure

The final temperature T1 is obtained by using an iteration method on Equations 2.70, 2.71 and 2.72.

2.12 Efficiency

The losses in various part of the machine are summed up. The efficiencies at furling and threshold is calculated from the Equation

$$Eff = 1 - \frac{PL}{PL+W} \quad (\%) \qquad (2.73)$$

where PL is the total power loss,

W is the rated output power.

The above design procedures are applied for a sample design in the following chapter.

Chapter III

SAMPLE DESIGN

3.1 Specification For Design

A set of specifications has been chosen for the sample design to demonstrate the concept and the feasibility of the proposed design. The specifications are given in Table 3.1. There were some limitations on the design due to the constraint of the available material. The armature laminations and the frame are available, which fix the stator bore diameter, the slot number, the tooth width and the length of the frame. The design procedure discussed earlier has therefore to be modified. A computer program is written for the purpose of design and is given in Appendix II.

TABLE 3.1

Specifications of Design

	Threshold	Furling
Speed (r.p.m.)	: 87	174
Full load power (W)	: 20	160
Power factor	: 0.6	0.6
Phase voltage (V)	: 8,16,32	8,16,32
Number of phase	: 3	3

Details of available stator laminations :

Bore Diameter Db - 0.3046 m.

Outside Diameter Dos - 0.4315 m.

Number of Slots - 72

Slot Pitch ys - 0.016 m.

Slot Width Wo - 0.008 m.

Slot Depth ht - 0.03 m.

Teeth - tapered

The length of the frame, Lf, is 0.11 m. and the thickness, Tf, is 0.011 m. The stator core length, L, is chosen at 0.02538 m. Twenty four poles are chosen to give an output frequency of 17.4 Hz at the threshold, and 34.8 Hz at furling. The peripheral speeds at furling and threshold are checked by Equations 2.20 and 2.21, and found to be 2.77 m/s and 1.38 m/s respectively. They satisfy the requirement that the peripheral speed be less than 15 m/s.

The design schedule is shown in Table 3.2.

3.2 Stator Winding

Since the number of poles chosen is 24, it gives one slot per pole per phase. The phase spread is 60^0. Integral slot double-layer lap winding is used. Full pitch coils are used such that the distribution factor and coil span factor

TABLE 3.2

Design Schedule

	8 V. OUTPUT		16 V. OUTPUT		32 V. OUTPUT	
	THRESHOLD	FOPLING	THRESHOLD	FOPLING	THRESHOLD	FOPLING
RATING						
FULL LOAD (VA)	33.33333	266.66650	33.33333	266.66650	33.33333	266.66650
FULL LOAD POWER (W)	20.00000	160.00000	20.00000	160.00000	20.00000	160.00000
LINE VOLTAGE (V)	13.85640	13.85640	27.71280	27.71280	55.42560	55.42560
PHASE VOLTAGE (V)	8.00000	8.00000	16.00000	16.00000	32.00000	32.00000
CURRENT PER PHASE (A)	1.38889	11.11112	0.69444	5.55556	0.34722	2.77778
POWER FACTOR	0.60000	0.60000	0.60000	0.60000	0.60000	0.60000
FREQUENCY (HZ)	17.39999	34.79999	17.39999	34.79999	17.39999	34.79999
SPEED (RPM)	87.00000	174.00000	87.00000	174.00000	87.00000	174.00000
NUMBER OF POLES	24.00000	24.00000	24.00000	24.00000	24.00000	24.00000
MAIN DIMENSIONS						
MAGNETIC LOADING (T)	0.60000	0.30000	0.60000	0.30000	0.60000	0.30000
ELECTRIC LOADING (AC/M)	1487.115	11896.910	1487.115	11896.910	1487.115	11896.910
OUTPUT COEFFICIENT (KVA/RPS/M**3)	0.9765E 01	0.3906E 02	0.9765E 01	0.3906E 02	0.9765E 01	0.3906E 02
STATOR BORE DIAMETER (M)	0.3046E 00	0.3046E 00	0.3046E 00	0.3046E 00	0.3046E 00	0.3046E 00
STSTOR OUTSIDE DIAMETER (M)	0.4300E 00	0.4300E 00	0.4300E 00	0.4300E 00	0.4300E 00	0.4300E 00
GROSS CORE LENGTH (M)	0.2538E-01	0.2538E-01	0.2538E-01	0.2538E-01	0.2538E-01	0.2538E-01
IRON LENGTH (M)	0.2284E-01	0.2284E-01	0.2284E-01	0.2284E-01	0.2284E-01	0.2284E-01
POLE PITCH (M)	0.3987E-01	0.3987E-01	0.3987E-01	0.3987E-01	0.3987E-01	0.3987E-01
FRAME OUTSIDE DIAMETER (M)	0.4520E 00	0.4520E 00	0.4520E 00	0.4520E 00	0.4520E 00	0.4520E 00
THICKNESS OF THE FRAME (M)	0.1100E-01	0.1100E-01	0.1100E-01	0.1100E-01	0.1100E-01	0.1100E-01
LENGTH OF THE FRAME (M)	0.1100E 00	0.1100E 00	0.1100E 00	0.1100E 00	0.1100E 00	0.1100E 00
END-RING OUTSIDE DIAMETER (M)	0.4520E 00	0.4520E 00	0.4520E 00	0.4520E 00	0.4520E 00	0.4520E 00
END-RING INSIDE DIAMETER (M)	0.3046E 00	0.3046E 00	0.3046E 00	0.3046E 00	0.3046E 00	0.3046E 00
THICKNESS OF THE END-RING (M)	0.1142E-01	0.1142E-01	0.1142E-01	0.1142E-01	0.1142E-01	0.1142E-01
STATOR						
WINDING	TWO LAYERS PER SLOT					
NUMBER OF PARALLEL CIRCUIT	4.00000	4.00000	2.00000	2.00000	1.00000	1.00000
NUMBER OF SLOTS	72.00000	72.00000	72.00000	72.00000	72.00000	72.00000
SLOTS/POLE/PHASE	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
CONDUCTORS/SLOT	66.39871	66.39871	66.39871	66.39871	66.39871	66.39871
TURNS/PARALLEL CIRCUIT	199.19610	199.19610	398.39200	398.39200	796.78440	796.78440
PITCH FACTOR	0.96600	0.96600	0.96600	0.96600	0.96600	0.96600
DISTRIBUTION FACTOR	0.96600	0.96600	0.96600	0.96600	0.96600	0.96600
WINDING FACTOR	0.99900	0.99900	0.99900	0.99900	0.99900	0.99900
CONDUCTOR SIZE (M**2)	0.1314E-05	0.1314E-05	0.1314E-05	0.1314E-05	0.1314E-05	0.1314E-05
CURRENT DENSITY (A/M**2)	0.2114E 07	0.2114E 07	0.2114E 07	0.2114E 07	0.2114E 07	0.2114E 07
SLOT PITCH (M)	0.1329E-01	0.1329E-01	0.1329E-01	0.1329E-01	0.1329E-01	0.1329E-01
SLOT WIDTH (M)	0.8000E-02	0.8000E-02	0.8000E-02	0.8000E-02	0.8000E-02	0.8000E-02
SLOT DEPTH (M)	0.3000E-01	0.3000E-01	0.3000E-01	0.3000E-01	0.3000E-01	0.3000E-01
TOOTH WIDTH (M)	0.5316E-02	0.5316E-02	0.5316E-02	0.5316E-02	0.5316E-02	0.5316E-02
RESISTANCE/PHASE (OHM)	0.2632E 00	0.2632E 00	0.1053E 01	0.1053E 01	0.4210E 01	0.4210E 01
I**2R LOSS (W)	1.52289	97.46897	1.52289	97.46897	1.52289	97.46897
EDDY CURRENT LOSS (W)	0.00058	0.14952	0.00058	0.14952	0.00058	0.14952
STRAY LOSS (W)	0.30469	19.52289	0.30469	19.52289	0.30469	19.52289
LEAKAGE REACTANCE (OHM)	0.29589	0.59178	0.42575	0.85150	0.68549	1.37096
ROTOR						
TYPE	:LUNDELL TYPE					
POLE ARC (M)	0.2791E-01	0.2791E-01	0.2791E-01	0.2791E-01	0.2791E-01	0.2791E-01
THICKNESS OF THE POLE (M)	0.2447E-01	0.2447E-01	0.2447E-01	0.2447E-01	0.2447E-01	0.2447E-01
LENGTH OF POLE-SHOE (M)	0.6769E-01	0.6769E-01	0.6769E-01	0.6769E-01	0.6769E-01	0.6769E-01
FIELD TURNS	77.64662	77.64662	77.64662	77.64662	77.64662	77.64662
NUMBER OF PARALLEL CIRCUIT	4.00000	4.00000	2.00000	2.00000	1.00000	1.00000
CONDUCTOR SIZE (M**2)	0.1757E-05	0.1757E-05	0.1757E-05	0.1757E-05	0.1757E-05	0.1757E-05
FIELD CURRENT (A)	40.06757	27.55853	20.03378	13.77927	10.01689	6.88963
CURRENT DENSITY (A/M**2)	0.5700E 07	0.5700E 07	0.5700E 07	0.5700E 07	0.5700E 07	0.5700E 07
RESISTANCE (OHM)	0.29949	0.29949	1.19798	1.19798	4.79190	4.79190
I**2R LOSS (W)	480.81030	227.45750	480.81030	227.45750	480.81030	227.45750
PERIPHERAL VELOCITY (M/S)	1.38736	2.77473	1.38736	2.77473	1.38736	2.77473
MAGNETISATION						
FLUX/POLE (WB)	0.5464E-03	0.2732E-03	0.5464E-03	0.2732E-03	0.5464E-03	0.2732E-03
CORE FLUX DENSITY (T)	0.1885E 00	0.1885E 00	0.1885E 00	0.1885E 00	0.1885E 00	0.1885E 00
TOOTH FLUX DENSITY (T)	0.6644E 00	0.6644E 00	0.6644E 00	0.6644E 00	0.6644E 00	0.6644E 00
FRAME FLUX DENSITY (T)	0.7500E 00	0.7500E 00	0.7500E 00	0.7500E 00	0.7500E 00	0.7500E 00
GAP LENGTH AT STATOR (M)	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
GAP LENGTH AT END-RING (M)	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
FIELD A.T./POLE	1555.5540	1069.9130	1555.5540	1069.9130	1555.5540	1069.9130
ARMATURE A.T./POLE	15.5466	124.3731	15.5466	124.3731	15.5466	124.3731
WEIGHT OF THE MACHINE						
WEIGHT OF STATOR WINDING	9.2429	9.2429	9.2429	9.2429	9.2429	9.2429
WEIGHT OF FIELD WINDING	6.2718	6.2718	6.2718	6.2718	6.2718	6.2718
WEIGHT OF THE STATOR CORE	12.7297	12.7297	12.7297	12.7297	12.7297	12.7297
WEIGHT OF THE FRAME	12.9084	12.9084	12.9084	12.9084	12.9084	12.9084
WEIGHT OF THE POLES	20.0000	20.0000	20.0000	20.0000	20.0000	20.0000
WEIGHT OF THE POLE SUPPORT	0.6611	0.6611	0.6611	0.6611	0.6611	0.6611
WEIGHT OF THE END RING	12.7715	12.7715	12.7715	12.7715	12.7715	12.7715
TOTAL WEIGHT	63.1288	63.1288	63.1288	63.1288	63.1288	63.1288
EFFICIENCY						
TEMPERATURE RISE (C)	20.0000	15.0000	20.0000	15.0000	20.0000	15.0000
TEMPERATURE INSIDE THE MACHINE (C)	45.0000	40.0000	45.0000	40.0000	45.0000	40.0000
IRON LOSS	0.2502	0.2502	0.2502	0.2502	0.2502	0.2502
STATOR I**2R LOSS (W)	1.5229	97.4650	1.5229	97.4650	1.5229	97.4650
EDDY CURRENT LOSS (W)	0.0006	0.1495	0.0006	0.1495	0.0006	0.1495
STRAY LOSS (W)	0.3047	19.5229	0.3047	19.5229	0.3047	19.5229
FIELD I**2R LOSS (W)	480.8103	227.4575	480.8103	227.4575	480.8103	227.4575
TOTAL LOSS (W)	482.8884	344.8047	482.8884	344.8047	482.8884	344.8047
EFFICIENCY (%)	3.9770	31.6929	3.9770	31.6929	3.9770	31.6929

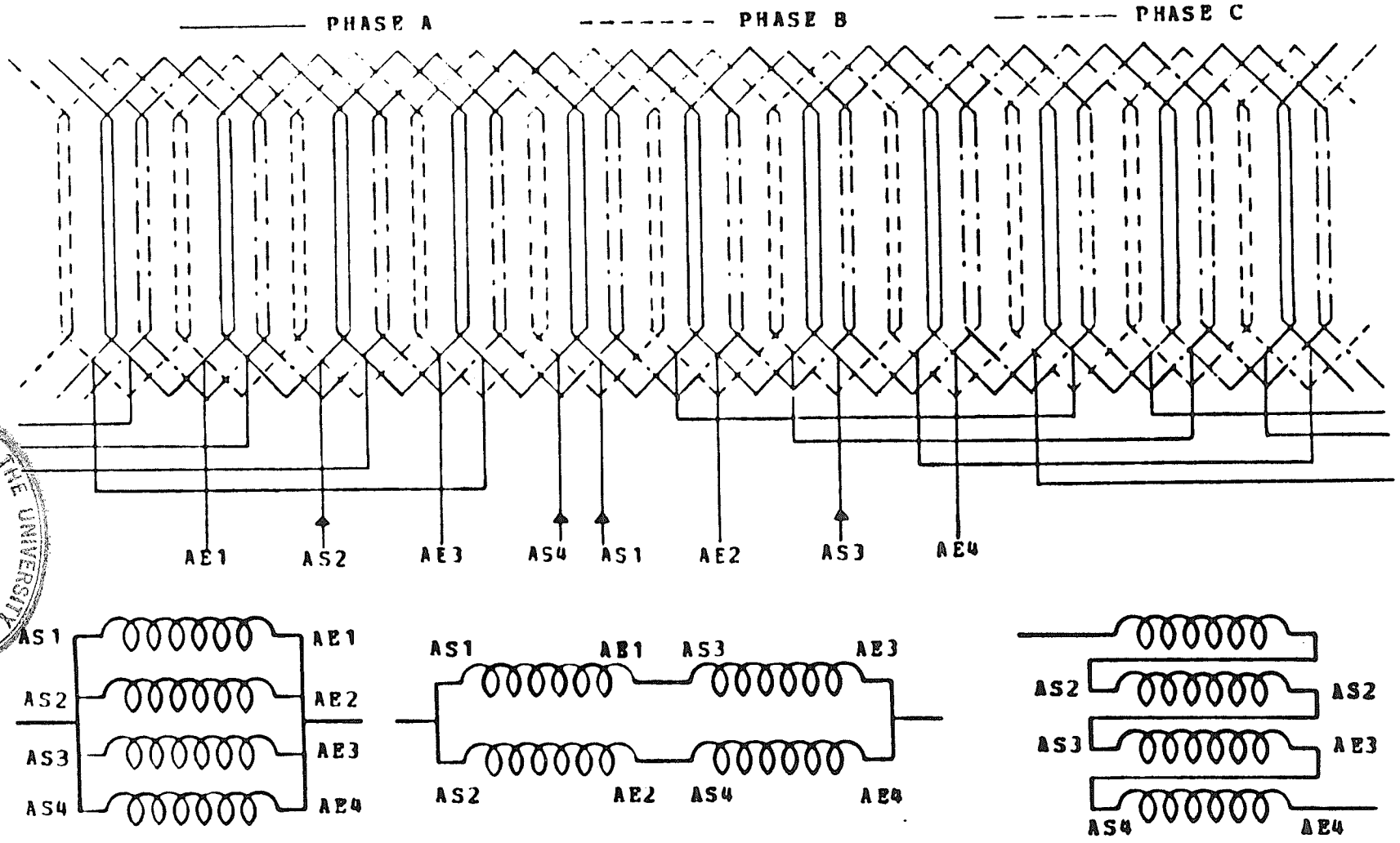
are equal to one. The stator laminations are skewed by one slot pitch. The skew factor obtained from Equation 2.26 is 0.99. Hence the winding factor is equal to 0.966.

There are three rated output voltages and the minimum number of parallel paths required is four. The winding diagram is shown in Fig. 3.1. The number of turns per phase is equal to 198. A space factor of 0.4 is used in calculating the conductor size. The conductor size is 0.1289×10^{-6} m. The resistance and the I^2R loss of stator winding are calculated from Equations 2.40, 2.41, 2.42 and 2.43. The leakage reactance per phase is obtained from Equations 2.44 and 2.55 because all the coils are full pitch coils.

3.3 Magnetic Circuit

The average airgap flux density at threshold for the main airgap and the auxilary airgaps are all equal to 0.6 T. The average flux density in the pole and in the end-ring are chosen to be 0.4 T and 0.675 T. The pole width is taken as 0.7 of the pole pitch. The average flux per pole is calculated from Equation 2.56. From Equation 2.57 the thickness of the pole and the end-rings are determined.

The ampere turns of each part are calculated. The armature reaction is determined by Equation 2.61. The total



8 V CONNECTION OF PHASE A 16 V CONNECTION OF PHASE A 32 V CONNECTION OF PHASE A

Figure 3.1: Stator Winding of The Machine

ampere turns per pole pair turns out to be 3500 A.T.

3.4 Field Winding

There are three exciter voltages, so four parallel circuits are required. Since the frame and the stator back core are fixed, the cross-section area of the field winding is also fixed.

A 0.4 space factor is used for calculation. A current density greater than 5.7×10^6 A/m^2 is required to fit in the area provided. Since the field loss depends on the current density, JF, the minimum value of 5.7×10^6 A/m^2 is used. From Equations 2.63 and 2.64 the conductor size and the number of turns per path are 0.21×10^{-5} m^2 and 78. The I^2R loss of field winding is obtained from Equation 2.66.

3.5 Performance

The efficiency at furling and threshold are calculated to be 31.7% and 4.0% respectively. The weight of the machine is 63 Kg. The temperature rise inside the machine is 45^0C at threshold and 40^0C at furling. The performance of the machine is not satisfactory because of the limitations of the material.

A prototype machine of the sample design was built

despite the unsatisfactory performance. The main purpose of fabrication of the machine is to demonstrate the concept of the design, to test the design procedure and to verify the calculations.

3.6 Measurment of Material Properties

The magnetic characteristics of the material are not known. A specimen of the stator laminations and the frame were tested in the laboratory to obtain the magnetic characteristics of the material.

The experiment set up is shown in Fig. 3.2. The test specimen had two coils around it. The primary coil was connected to the power supply through the amplifier and a two-way switch. The secondary coil was connected to the integrator of the analog computer and then to a X-Y plotter. Since the integral of the secondary voltage with respect to time is equal to the flux linkage in the specimen, the output from the integrator would give the change in flux. A d.c. current was supplied to the primary side. By changing the current direction with the switch, a change in flux was recorded in the plotter. The field intensity was calculated by dividing the ampere turns of the primary coil by the mean length of the specimen. The corresponding flux density was derived from the amplitude of the curve, the number of turns

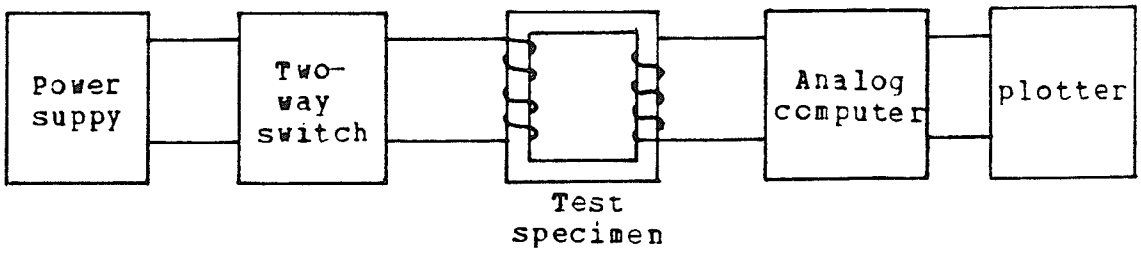


Figure 3.2: Experimental Set-Up of Material Properties Measurment

in the secondary side and the cross-section area of the specimen. By using different input currents and calculating the corresponding field intensity and flux density, the magnetic characteristic curve of the material was plotted. Fig. 3.3 and Fig. 3.4 show the magnetic characteristics of the laminations and the frame respectively. These two curves were used in the preceeding design and the computer design program.

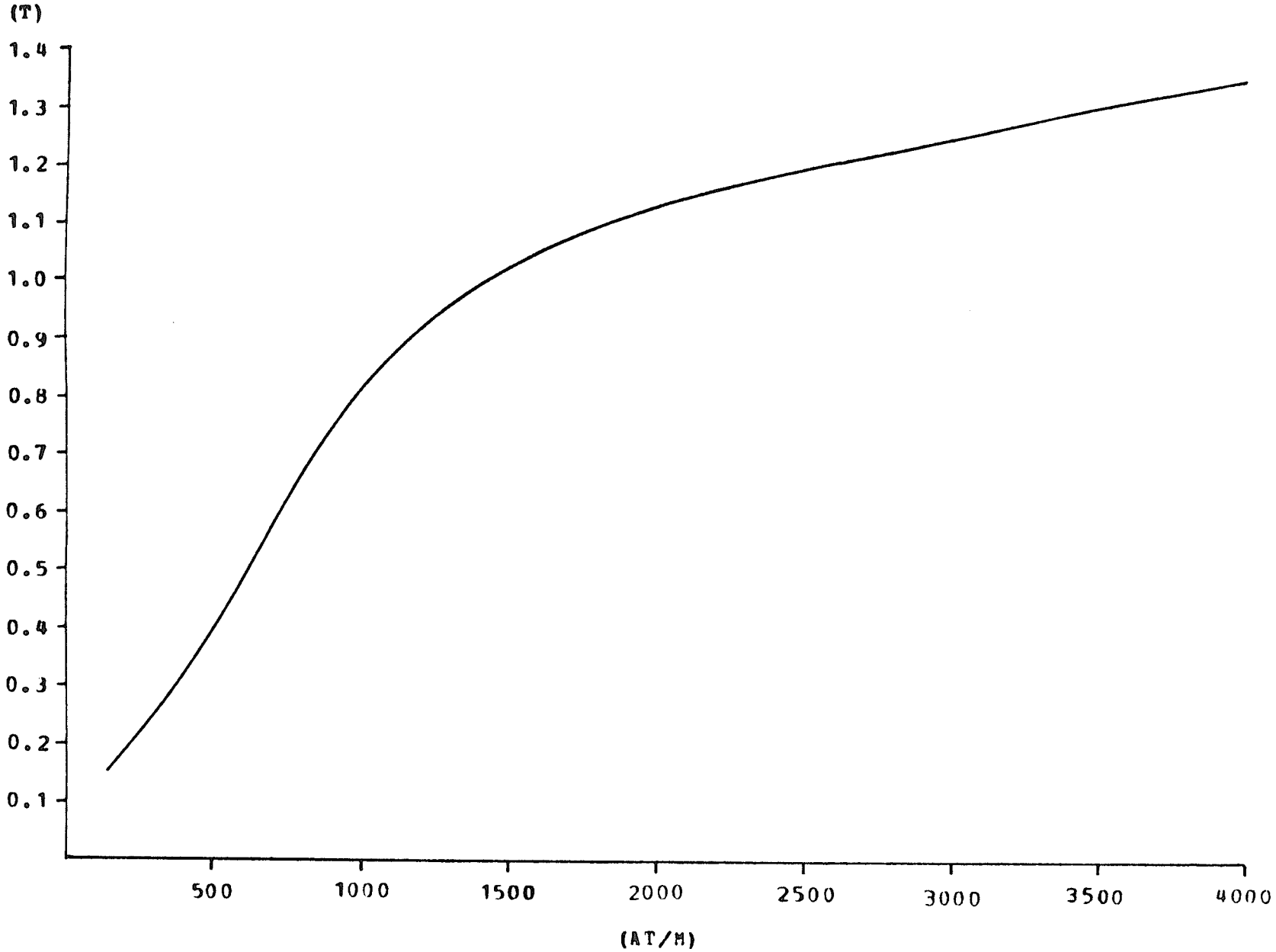


Figure 3.3: Magnetic Characteristic of The Stator Laminations

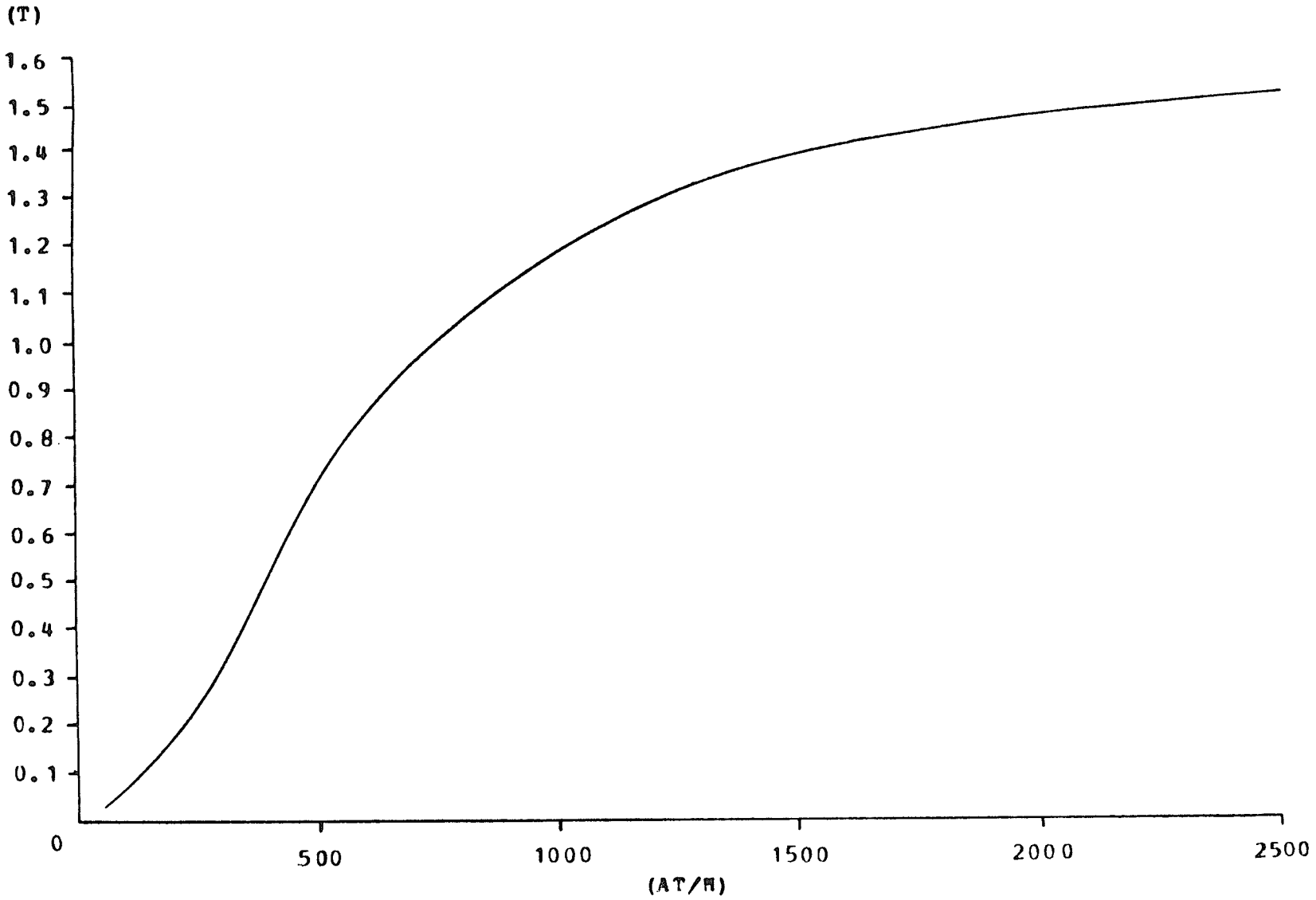


Figure 3.4: Magnetic Characteristic of The Frame

Chapter IV

TESTS ON THE PROTOTYPE MACHINE

4.1 Introduction

The prototype brushless machine was tested in the laboratory instead of testing it on the existing windmill, due to uncontrollable wind speed in the natural setting. A d.c. motor, with the Ward-Leonard speed control, was used as the prime mover. Three tests had been applied to the machine :

(1) Open-Circuit Test,

(2) Short-Circuit Test,

(3) Zero Power Factor Test.

The test results were compared with the computer simulation results in order to demonstrate the accuracy of the computer program.

4.2 Open-Circuit Test

There are three different stator connections to provide three rated voltages of 8 V, 16 V and 32 V. The open-circuit tests were performed on each connection at constant threshold speed and constant furling speed separately. Fig. 4.1 to Fig. 4.3 show the open-circuit test results with 8 V, 16 V and 32 V connections respectively.

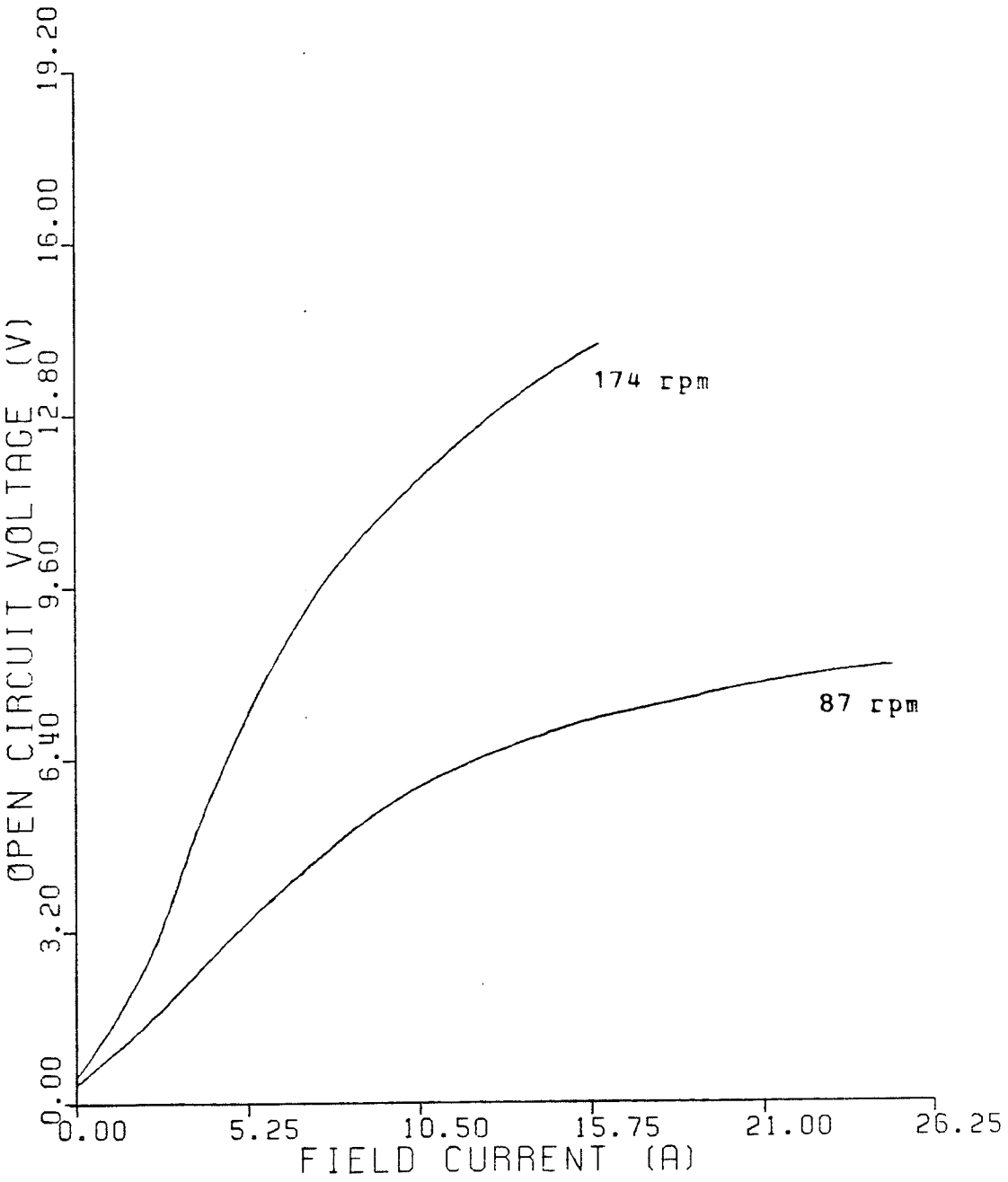


Figure 4.1: Open-Circuit Test With 8 V Connection

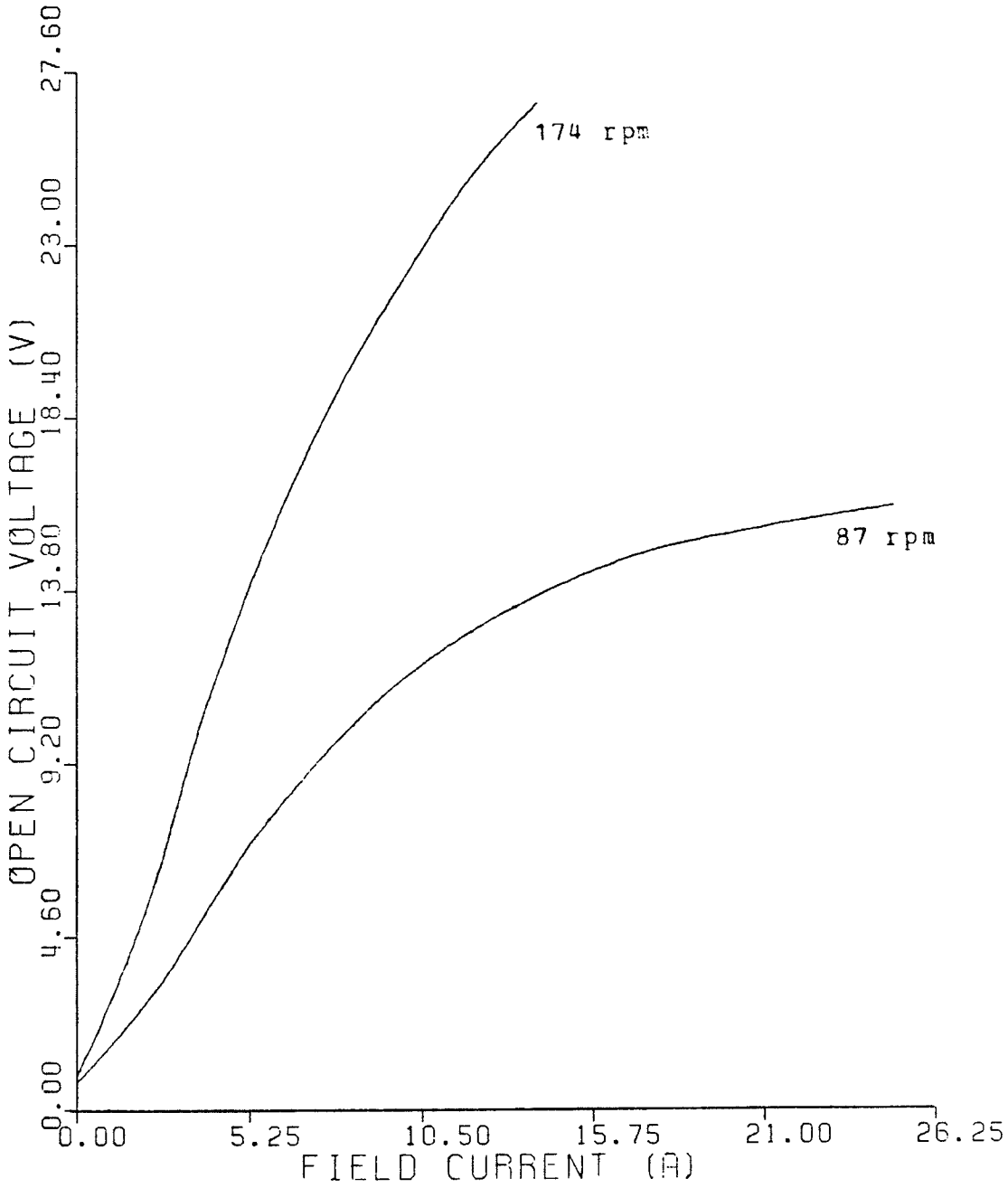


Figure 4.2: Open-Circuit Test With 16 V Connection

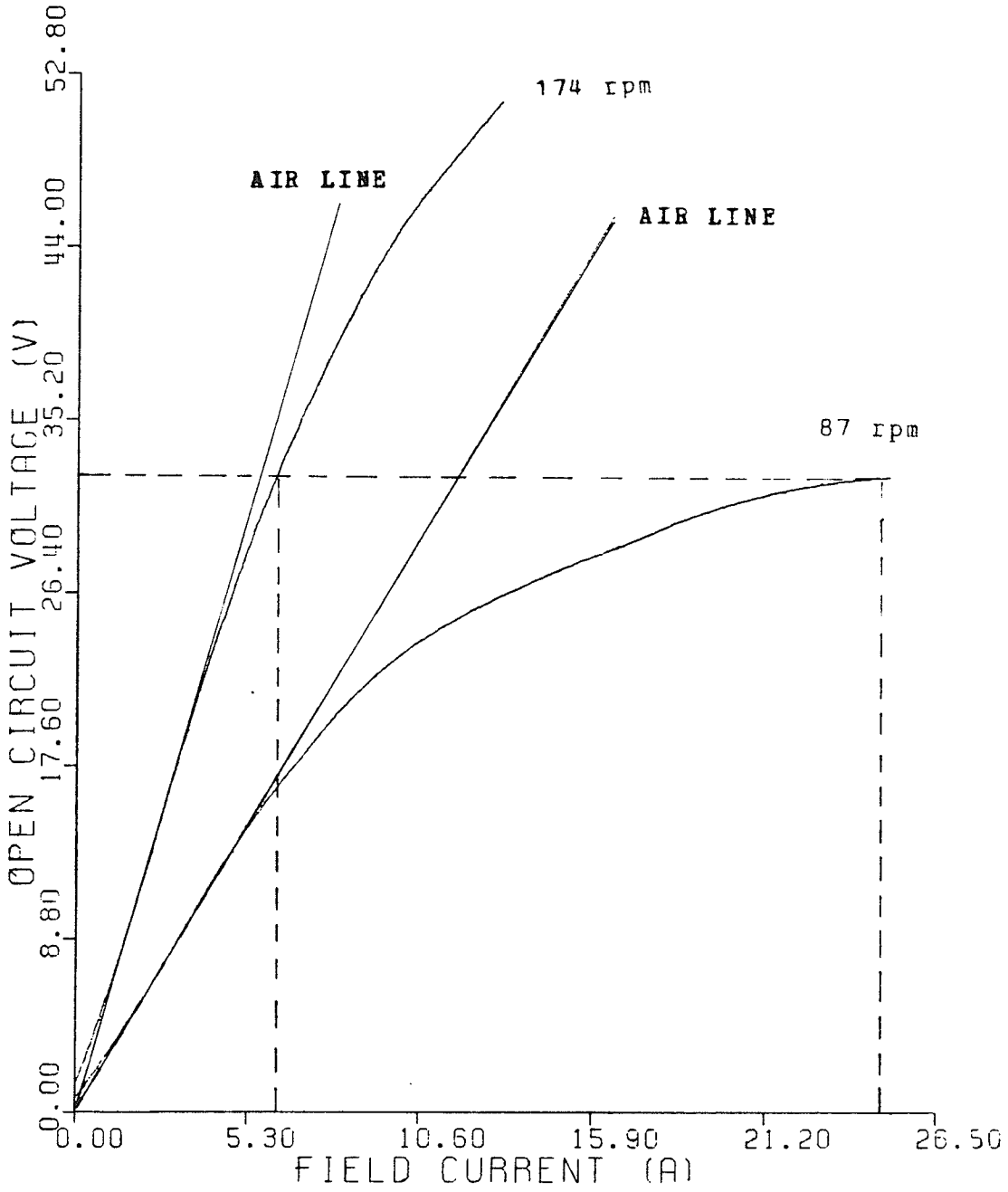


Figure 4.3: Open-Circuit Test With 32 V Connection

At furling speed, the open-circuit test results are close to the calculated value, while at threshold speed, the test results are not comparable to the expected values. Table 4.1 shows the discrepances between the test results and the calculated results at rated voltage with the 32 V connection. It also shows the ampere-turns required for the airgaps from the airgap-line analysis. The average flux per pole in the machine at furling and threshold was slightly different from the calculated values. At low speed, the mmf required for the iron path was much higher than expected. It indicated that some parts of the iron path were heavily saturated during low speed operation.

TABLE 4.1

Discrepance Between Test And Calculated Results

	Furling	Threshold
Calculated field A.T.	1891	3080
Tested field A.T.	1903.2	7488
% difference in A.T.	0.65%	143%
A.T. from air line	1716	3588
A.T. for iron	187.2	3900
Flux per pole (wb)	$2.51X10^{-4}$	$5.25X10^{-4}$
Calculated flux per pole (wb)	$2.732X10^{-4}$	$5.46X10^{-4}$
% difference in flux/pole	8%	3.9%

The teeth of the stator were found to be saturated at low speed due to the change in pole arc dimension. In the original design, the pole arc was 70% of the pole pitch, but due to some changes made to ease the fabrication, the pole arc was reduced to 64% of the pole pitch. Apparently, instead of three teeth under each each pole, there were only two teeth under each pole all the time. Most of the flux went directly to the teeth right under the pole arc, thus caused very high flux density in the teeth.

At furling speed, the average flux per pole was low, so there was no significant effect on the open-circuit characteristic. But at threshold speed, the average flux per pole was doubled, so the flux density in the teeth was doubled accordingly. The average flux density in the teeth at rated open-circuit voltage was 1.9 T. Because of the saturation in the teeth, a much higher mmf was required to obtain the rated open-circuit voltage.

4.3 Short-Circuit Test

Fig. 4.4 to Fig. 4.6 show the short-circuit test results with the 8V, 16V and 32V connections respectively. Higher field excitation than the calculated values were found in the short-circuit tests. At rated short-circuit current with the 32V connection, at furling speed, the field current was 17% higher than the calculated value of 3.42 A, and at

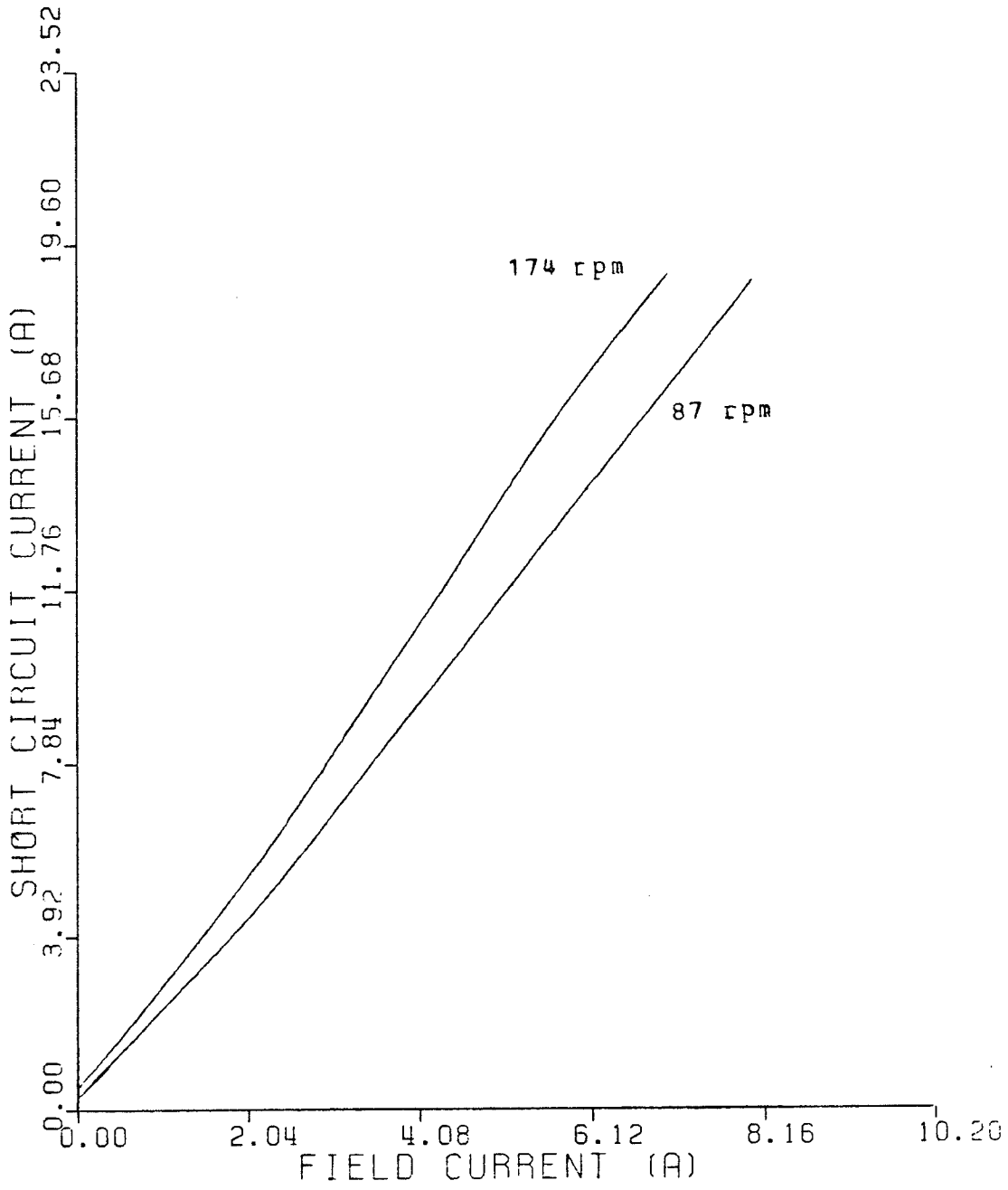


Figure 4.4: Short-Circuit Test With 8 V Connection

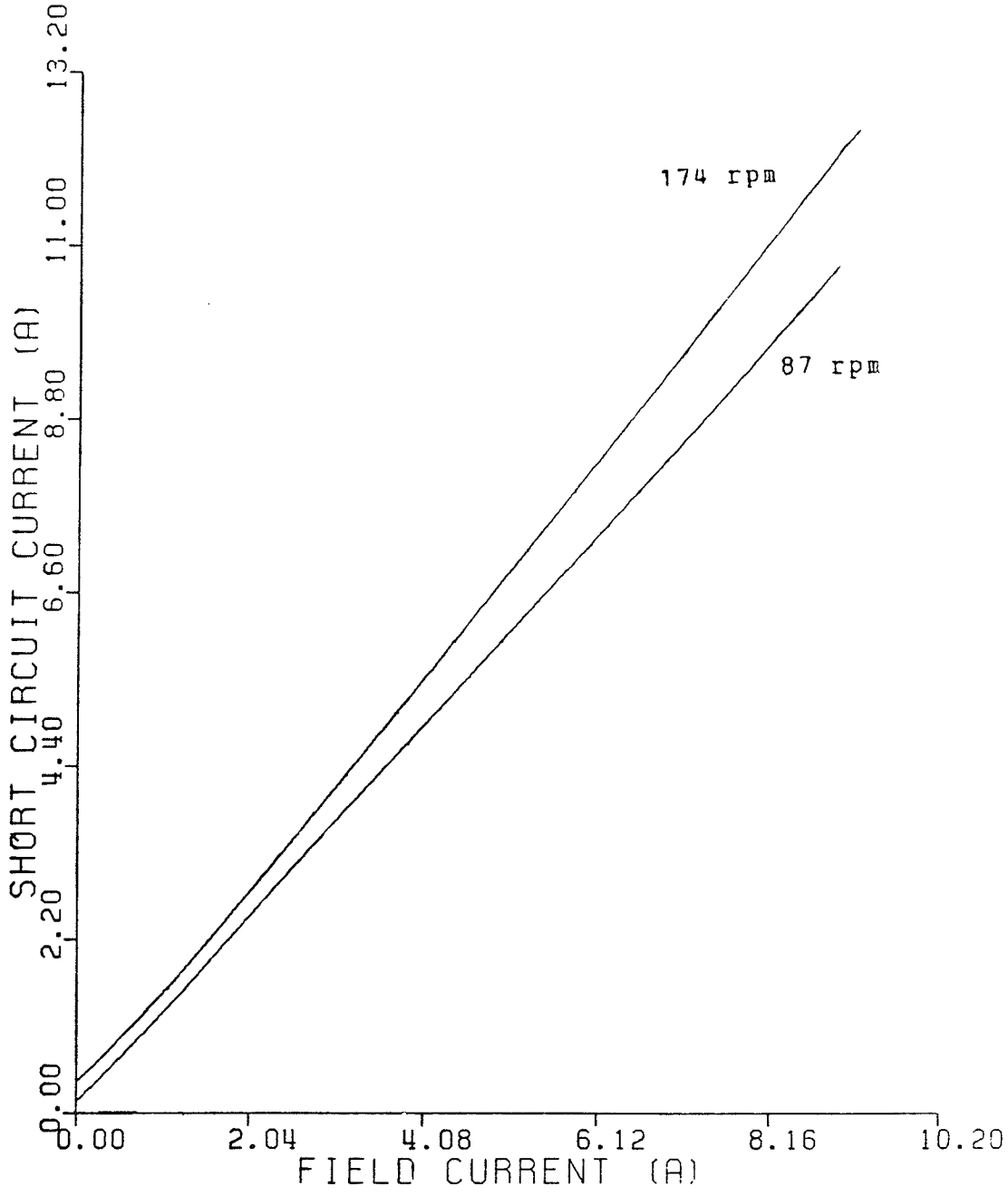


Figure 4.5: Short-Circuit Test With 16 V Connection

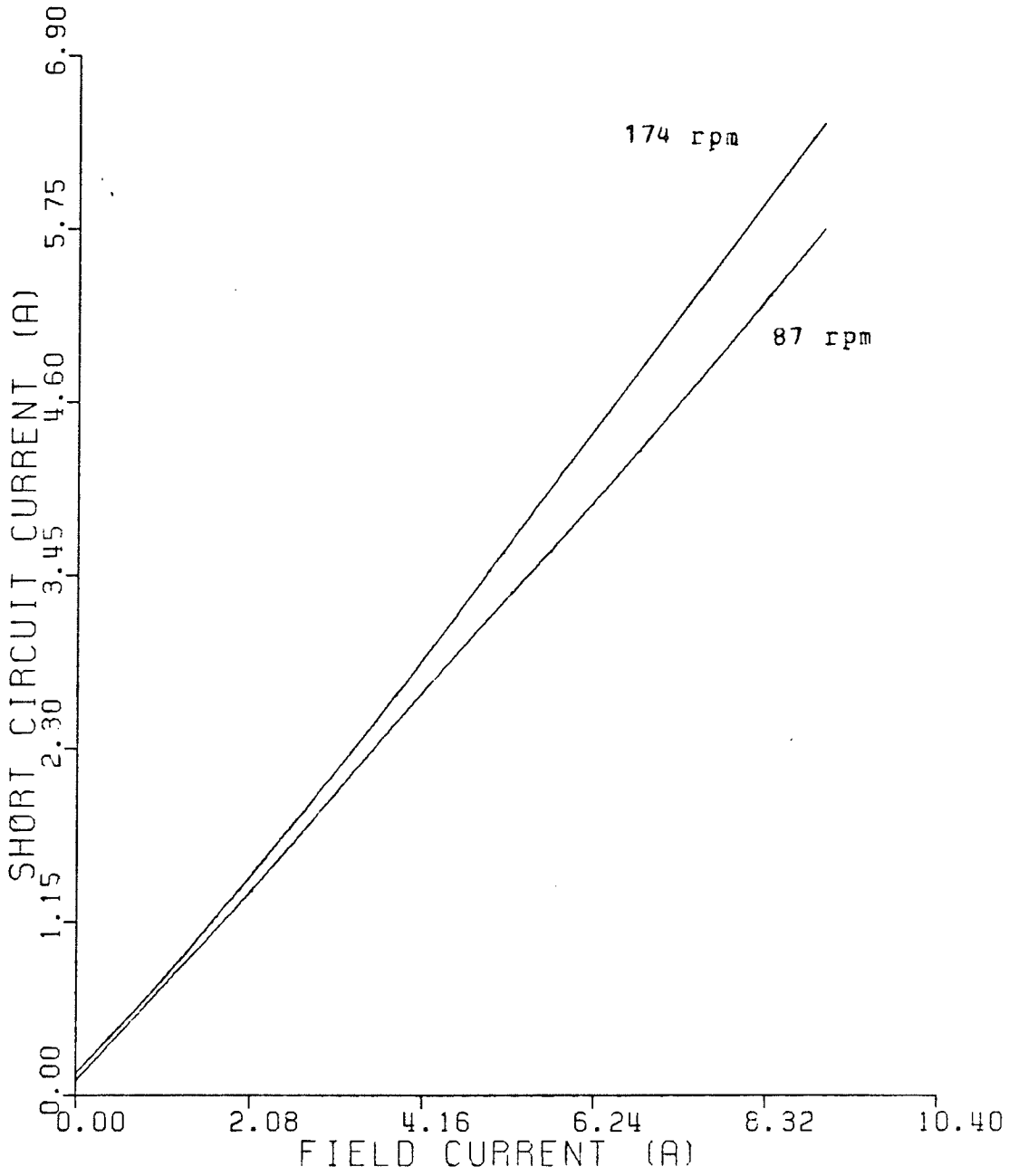


Figure 4.6: Short-Circuit Test With 32 V Connection

threshold speed, the field current was 6.3% higher than the calculated value of 0.5 A. The cause of higher field excitation needed was due to higher synchronous reactance of the machine. Since the synchronous reactance includes the effects of flux leakage and armature reaction, the cause of the discrepancy will be identified after obtaining the equivalent circuit of the machine.

4.4 Equivalent Circuit of The Machine

The equivalent circuit of the machine was obtained from the open-circuit test, short-circuit test and the zero power factor test. Fig. 4.7 shows the curves of the zero power factor load test and the open-circuit test at furling speed with 32V connection. A constant stator current of 54% the rated value was used in the this test. The resistance, Rs, of the stator winding was measured by d.c. current at operating temperature. The synchronous reactance was calculated from the ratio of open-circuit voltage at rated value and the short-circuit current with the same field excitation. The synchronous reactance was further separated by the Potier triangle method into the leakage reactance, Xl, and the magnetising reactance, Xa, due to armature reaction. Fig. 4.8 shows the equivalent circuit of the machine at furling with 32V connection.

The resistance of the winding was 2.4% lower than the

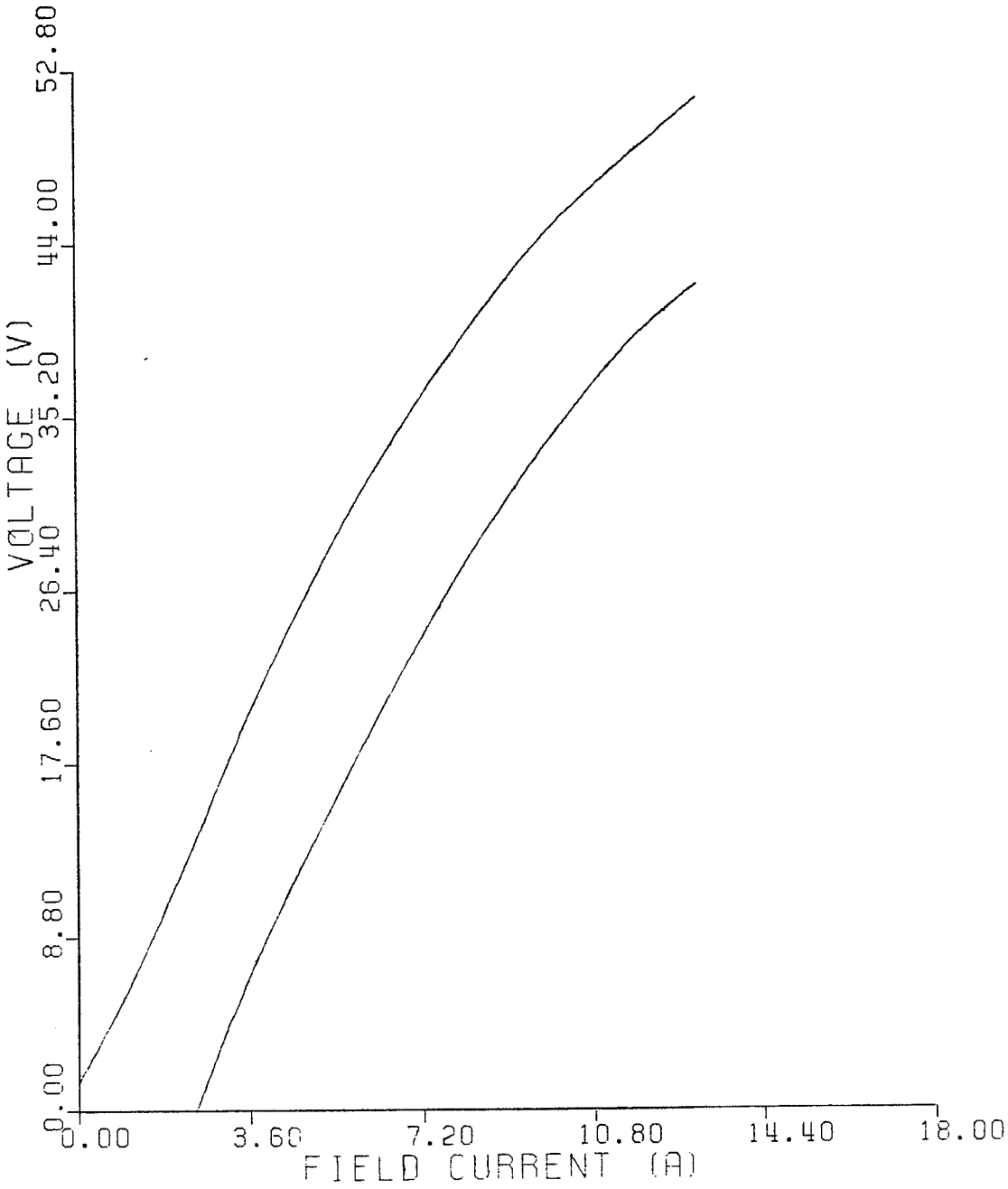


Figure 4.7: Inductive Load Test With 32 V Connection

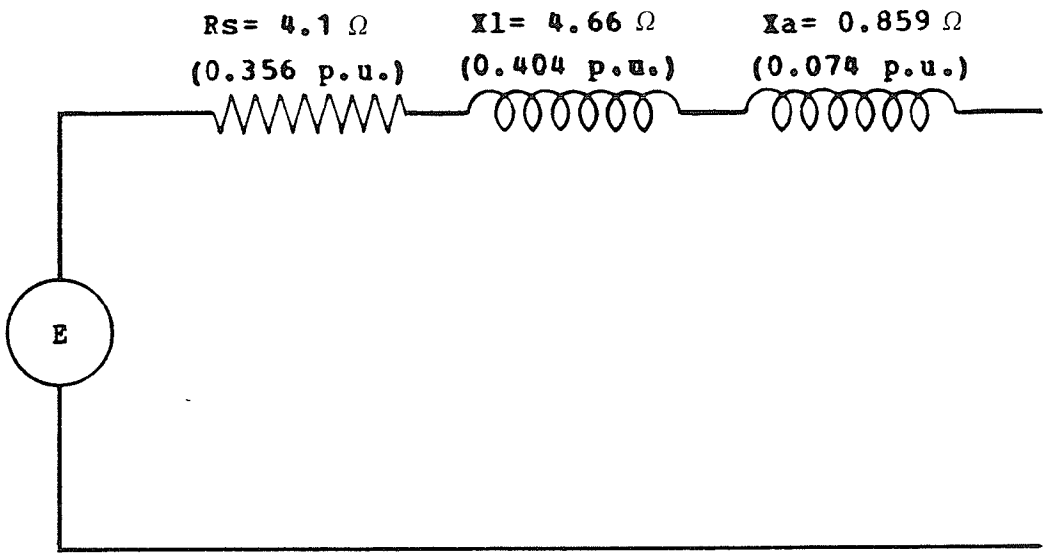


Figure 4.8: Equivalent Circuit of The Machine With 32 V Connection

calculated value. Since the resistance was measured by d.c. current, the skin effect and the eddy current loss in the winding were not included in the measurment, therefore a lower resistance was obtained. The armature reaction was 5.7% lower than the expected value. The leakage reactance was 290% higher than the calculated value. The low calculated leakage reactance was due to the under estimation of the overhang leakage reactance, based on an empirical formula, and neglect of the zig-zag leakage and the differential leakage reactances. Therefore, a lower

calculated leakage reactance was obtained. Since a complete field analysis of the overhang, zig-zag and differential leakage flux is outside the scope of the thesis, the exact expression will not be derived. The empirical formula will continue be used in the design in later chapters but the overhang leakage reactance will be multipied by a factor of three to include the zig-zag and differential leakage reactances.

Although the actual performance of the prototype machine did not meet the requirments of the original design, the computer results were reasonably accurate. Except for the overhang leakage reactance, the other parameters were within 6% accuracy. The tooth saturation was completely due to the difference between the design and actual dimensions of the machine.

Chapter V

OPTIMUM DESIGN OF BRUSHLESS ALTERNATORS

The design in the previous chapter, due to the limitation of the available materials, is not an efficient one. Improvement is made in this section to obtain an optimal design. The main objective is to improve the efficiency and reduce the weight of the machine. A suitable range of power output is suggested in this section.

There are some drawbacks in the previous design. The I^2R loss in the field winding is high because of the fixed stator outside diameter and the frame size. The full load I^2R loss of the stator winding is also high due to the fixed slot size. To improve the field and stator losses, a shorter mean turn and lower current density are desired.

The new design is based on the following improvements :

(1) reduced mean turn length, and

(2) reduced current densities of field and stator.

The frame length is made longer so that a larger conductor cross-section for the field can be accommodated. The stator bore and outside diameter are smaller so that the mean turn is shorter. The stator winding is designed again using fractional pitch winding. The mean turn is only around one core tooth. Fig. 5.1 shows the diagram of the

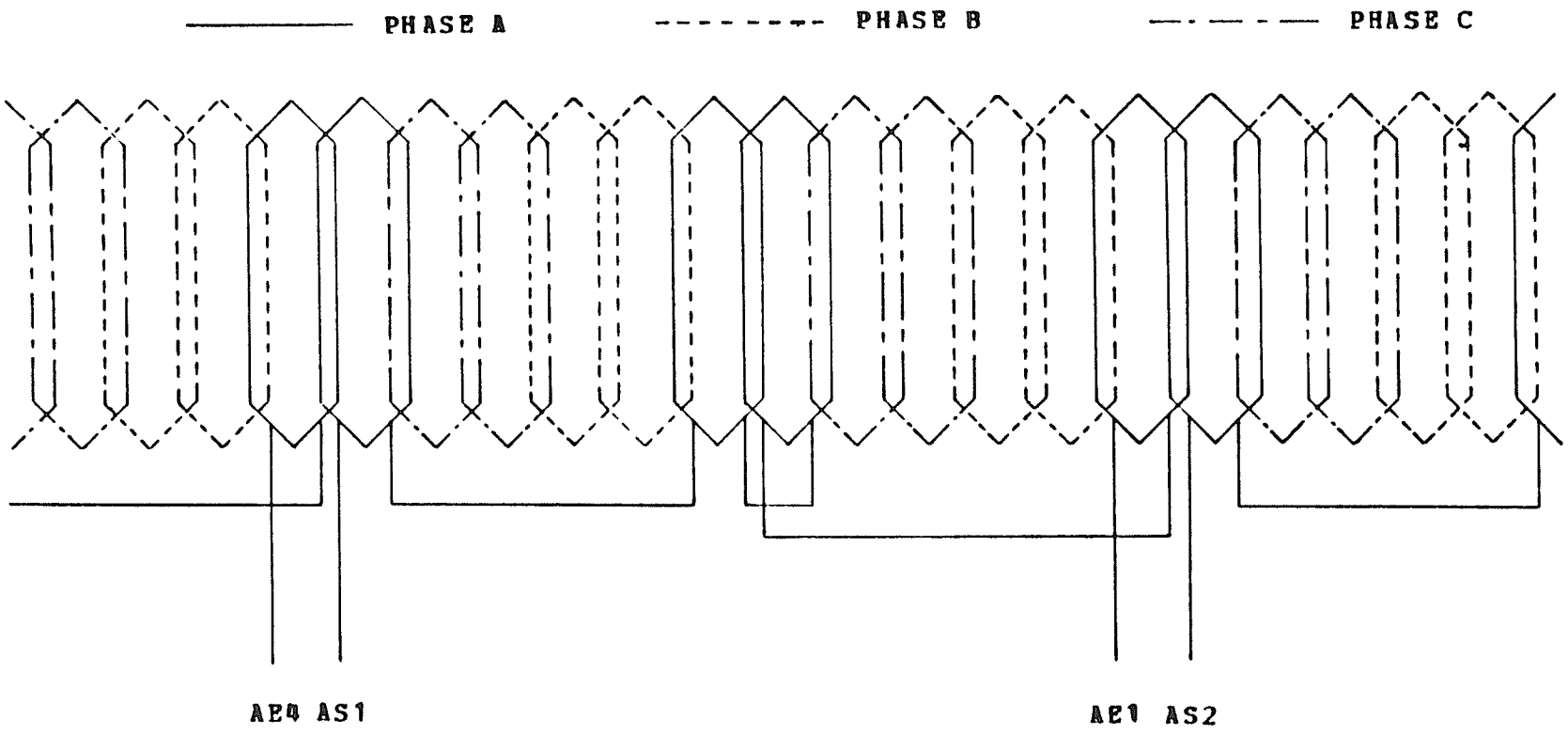


Figure 5.1: Stator Winding of New Design

TABLE 5.1

New Design Parameters

Full load power (W)	: 20-160
Core length (m)	: 0.3867
Stator bore diameter (m)	: 0.1969
Stator outside diameter (m)	: 0.3662
Number of slots	: 48
number of poles	: 40
Length of the frame (m)	: 1.178
Thickness of the frame (m)	: 0.00733
Stator current density (A/m^2)	: $1.5X10^6$
Field current density (A/m^2)	: $0.75X10^6$
Total weight (Kg)	: 243.3
Efficiency at furling (%)	: 70.63
Efficiency at threshold (%)	: 22.56

stator winding. The new design is shown in Table 5.1

This design has a better performance than the last design but the weight of the machine is heavier. The efficiencies at furling and threshold are higher, however they are still not within the feasible range of over 75% efficiency at all speeds. In order to obtain an optimal feasible design, this design is used as the starting original design in the optimisation program. Six independent parameters are chosen as the variables.

5.1 Effects of Some Parameters on Machine Performance

The performance of the machine depends on many parameters. Among all these factors, only six major parameters are considered :

(a) Average airgap flux density,

(b) Stator bore diameter,

(c) Stator core length,

(d) Current density of stator winding,

(e) Current density of field winding, and

(f) Stator core flux density.

To show the effects of the above parameters, each parameter is varied in steps in the original design program. Figure 5.2 to 5.7 show the performance of the machine with each parameter varying alone while the rest are fixed. It can be shown that for a particular range, the efficiency is higher and the weight is lighter. In order to improve the performance, all six parameters are varied. An optimisation technique is applied to obtain the feasible design.

5.2 Optimisation

The main purpose of optimisation is to minimize the cost or the weight of the machine while meeting the specifications. Different optimisation techniques have been used for different applications in the past. The least pth

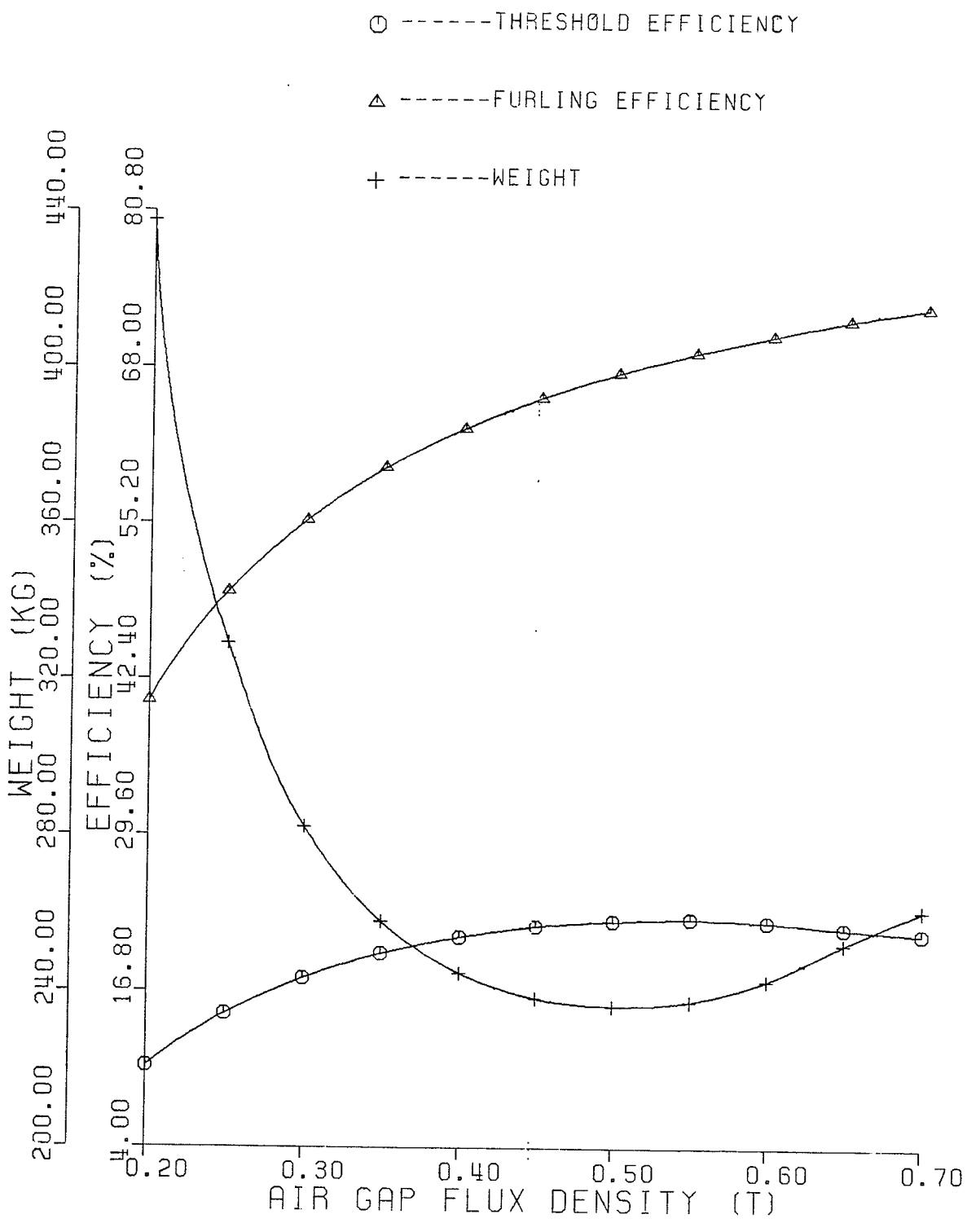


Figure 5.2: Air Gap Flux Vs. Efficiency And Weight

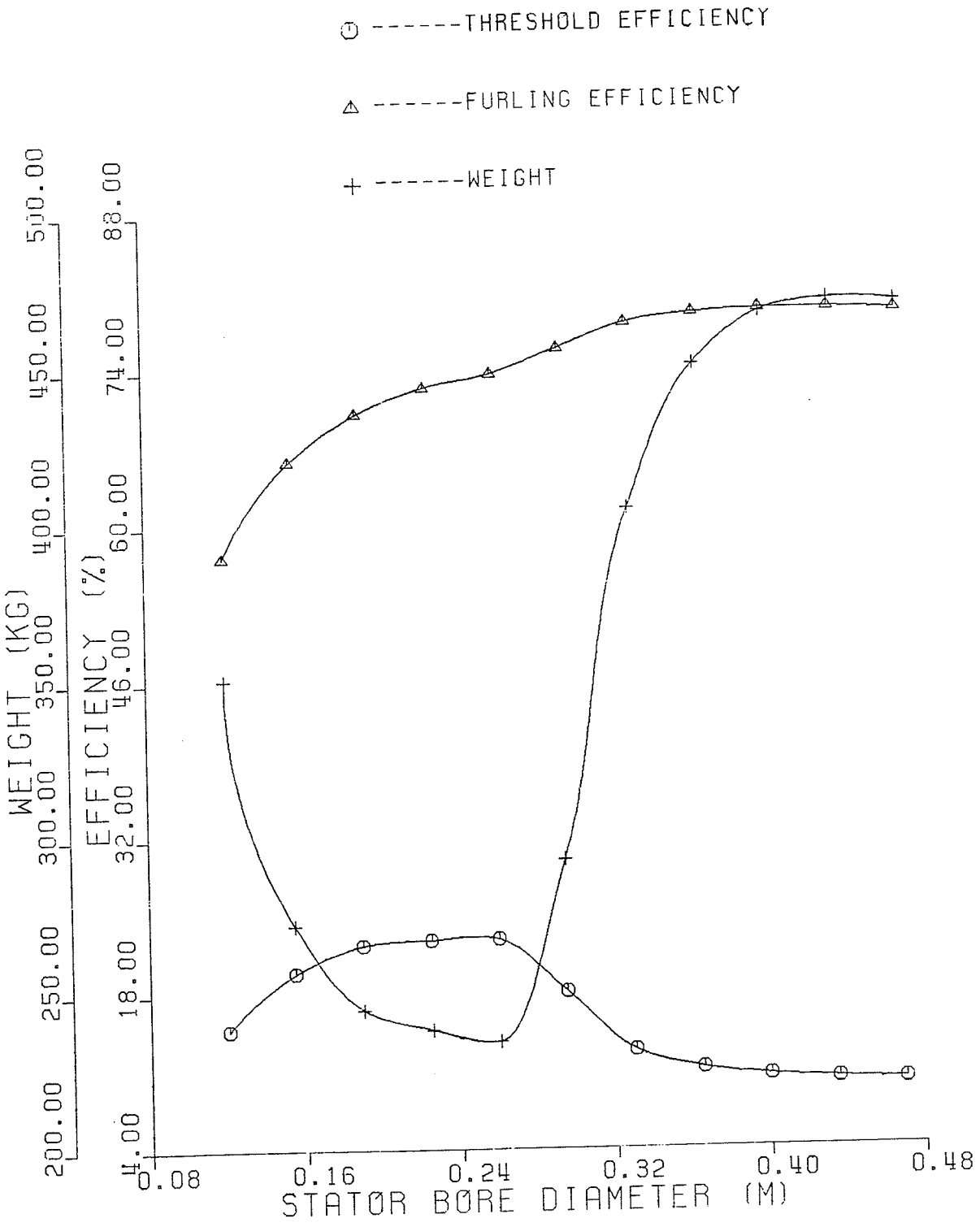


Figure 5.3: Stator Bore Diameter Vs. Efficiency And Weight

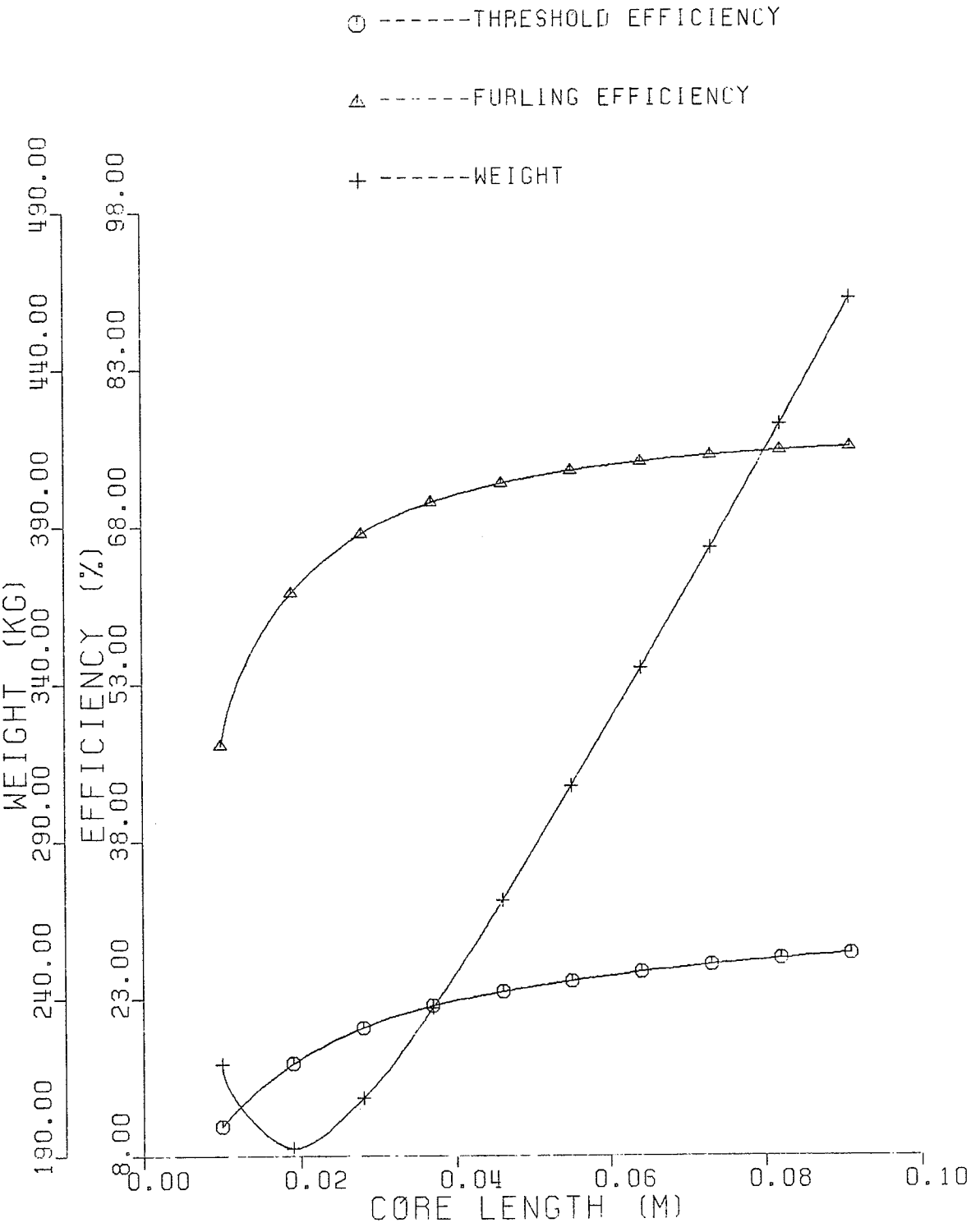


Figure 5.4: Stator Core Length Vs. Efficiency And Weight

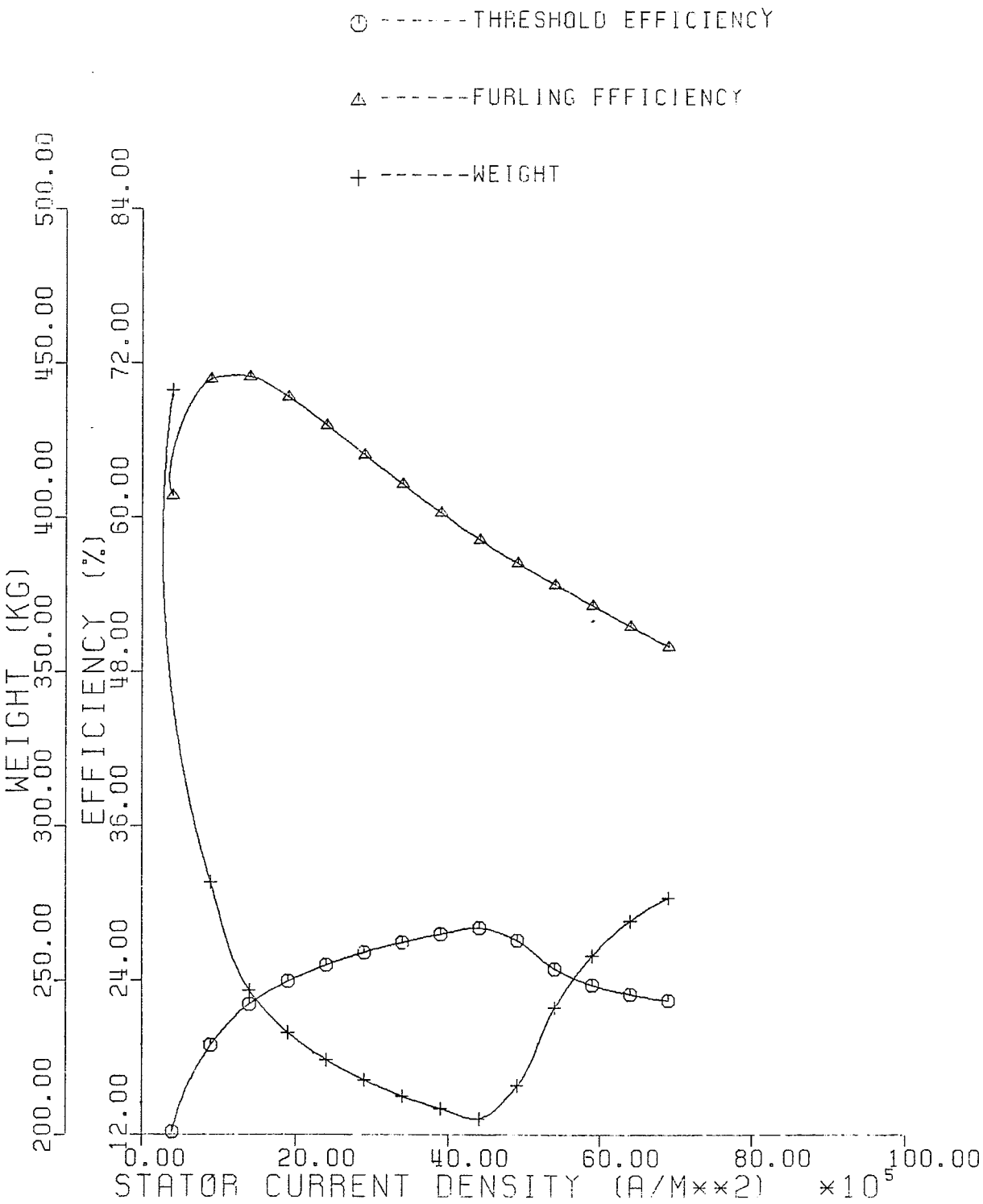


Figure 5.5: Stator Current Density Vs. Efficiency And Weight

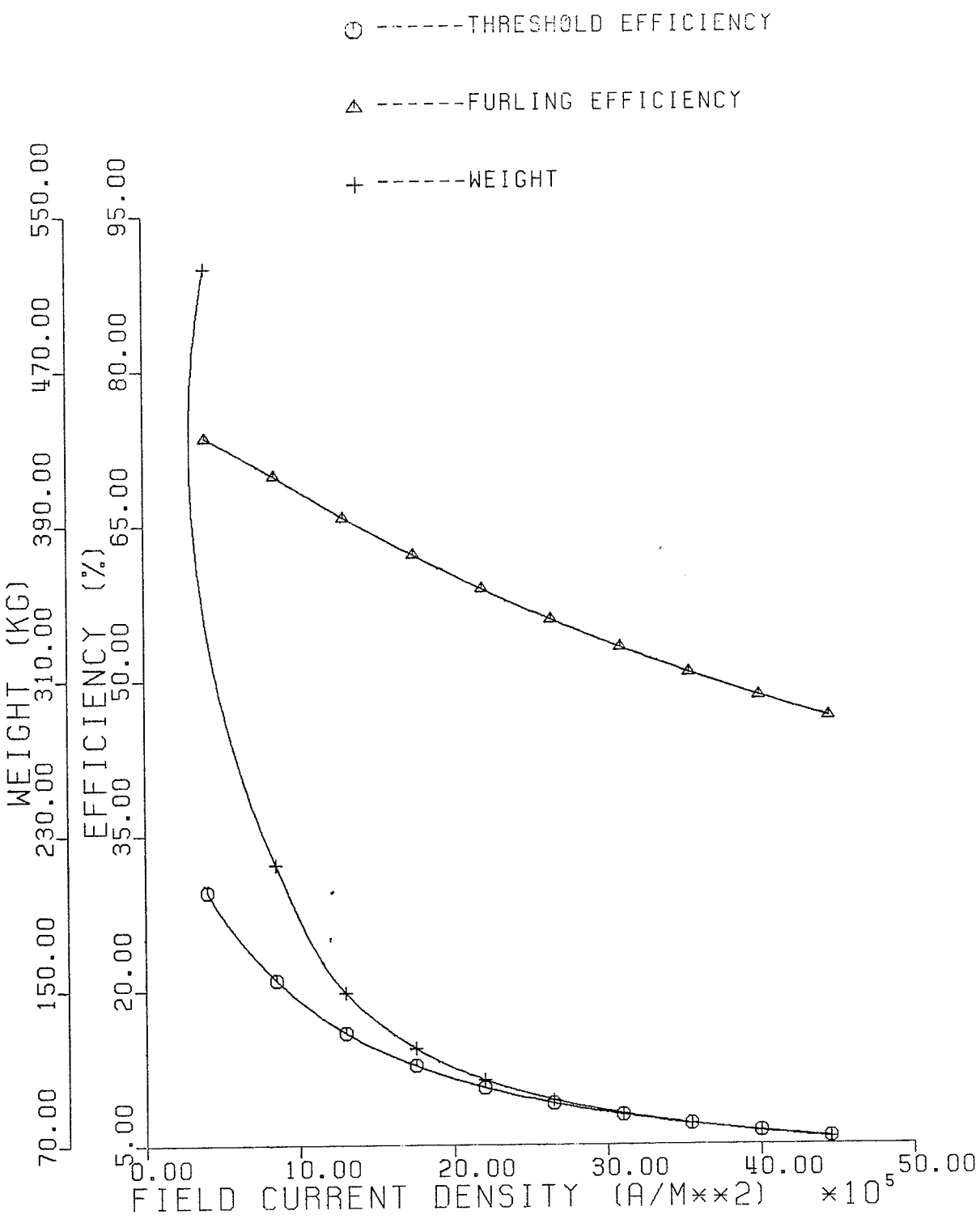


Figure 5.6: Field Current Density Vs. Efficiency And Weight

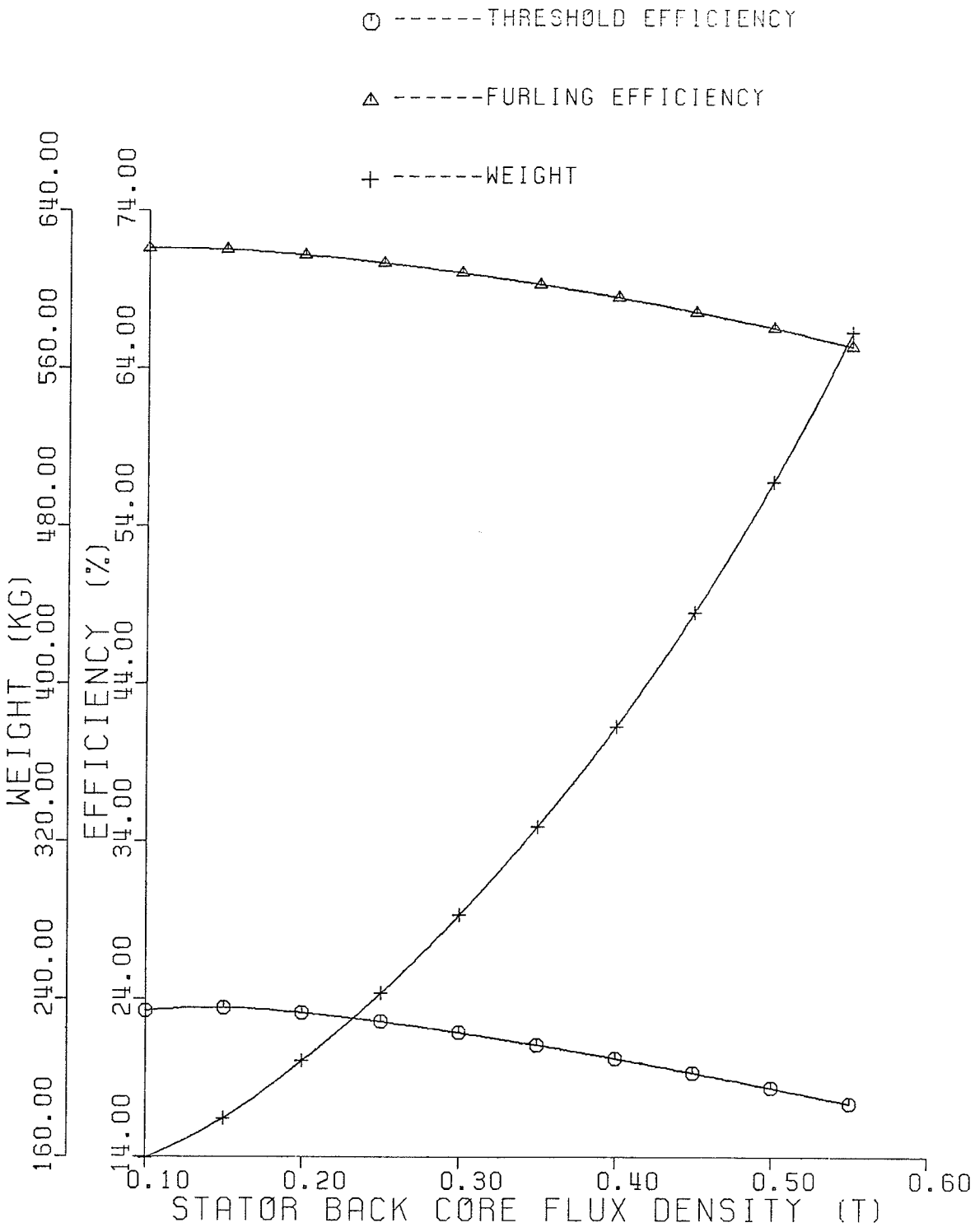


Figure 5.7: Stator Back Core Vs. Efficiency And Weight

approximation method[8] with a direct search technique[9] was used in this particular study.

A design which satisfies all the specifications is called a feasible design. Many other techniques require to start from a feasible design, but with this method it can also start from a nonfeasible design. This reduces the effort to obtain a feasible design from a synthesis program. The efficiency of the direct search method was found to be high for machine desigining[10].

5.2.1 Optimisation Problems

The basic mathmetical optimisation problem is to minimize a scalar quantity which is the value of a function of n variables x1,x2,x3.....,xn, i.e.,

$$E = f(X) \tag{5.1}$$

where $X = (x1,x2,x3.....,xn)^T$

The function f is referred to as the function to be minimized and the vector X is a set of independent parameters. There are constraints attached to some of the parameters. A common constraint on the variable xi is the upper and lower bound in the form

$$xli \leq xi \leq xui \tag{5.2}$$

where xli and xui are the lower and upper bounds.

Most inequality constraints can be put into a constraint function of the form

$$g(x1,x2,\ldots,xn) \leq n \tag{5.3}$$

For the case of upper and lower limits, the expression (5.2) is replaced by two expressions:

$$xi - xui \leq 0 \tag{5.4}$$

$$xli - xi \leq 0 \tag{5.5}$$

The region of search in which all the constraints are satisfied is the feasible region. The choice of independent parameters depends on individual design. In this particular design the six parameters mentioned in the last section were chosen.

5.2.2 Objective Function

The objective function reduces the constrained problem into an unconstrained problem. The best known sequential unconstrained minimization technique of Fiacco and McCormick[11] was shown not so efficient compared to least pth approximation method of Bandler and Charalambous[10].

The least pth approximation method was used to formulate the objective function. In this method, the function to be

minimized is formed into a constraint function.

$$g(x) = Fs - F(x) \tag{5.6}$$

where Fs is the specified constrained value desired.

The objective function is defined as

$$P(X,Fs) = M(X) \left[\sum_{i \epsilon K} \left(\frac{\alpha i . gi}{M(X)} \right)^{q} \right]^{\frac{1}{q}} \tag{5.7}$$

where $M(x) = \text{Max} \{ \alpha i . gi(x) \}$

αi is a position scaling factor for the i^{th} constraint function,

$q = p.\text{sign}(M)$, $p \geq 1$

$gi(x)$ is the constraint function,

$K(x) = [\ i,\ gi(x)>0,\ i \epsilon I\ ]$ for $M>0$,

$K(x) = I$ for $M<0$,

I is the index set $1,2,3....,m$.

There are two cases to be considered:

(I) $M>0$, some constraints are violated, and

(II) $M<0$, all constraints are satisfied.

Case I

When some of the constraints are violated, $M>0$, the objective function is the pth root of the sum of only the violated constraints raised to the pth power. The index

set, K(X), that controls the sample points, is dependent on X. The sample points are included if the corresponding constraints are violated, and excluded when the corresponding constraints are satisfied. The value of p determines the weight placed on the larger constraints. When the value of p is larger the maximum violated constraint would be emphasized. Since the value of p is positive the minimization method will attempt to minimize the largest constraint.

Case II

For the case when all the constraints are satified, M<0, all the sample points are included in the objective function. This time, the value of q is negative so the least negative constraints will be emphasized. The minimization method will attempt to reduce the value of the constraints function exceeding the specification as much as possible. The design will move away from all the constraint boundaries and enter the centre of the feasible region.

The value of p used in the program varied from one to nine. With larger value of p, the design converged faster to the feasible region. But for values higher than ten, error may occur due to underflowing of computer when the constraint functions approached zero.

5.3 Specified Constraint Value And Scaling Factors

The specified constraints for this study were the weight of the machine and the efficiencies at furling and threshold. The specified weight was initially set at a low value. The specified efficiencies at furling and threshold were both set at 75% for the first run. The specified weight is adjusted accordingly after the minimum value of the objective function is reached. If the feasible region is reached, the specified weight is reduced, otherwise the weight will increase.

A method proposed by Morrison[12] for optimisation by least squares was used to select the value of the specified constraint. The constraint value is updated after each optimisation sequence by the formula:

$$Fs(i+1) = Fs(i) + P(x,Fs(i)) \qquad (5.8)$$

Where $P(x,Fs(i))$ is the minimum value of the objective function from the i^{th} optimisation sequence.

In general, this method has yielded good results for a particular set of scaling factors. However, due to some of the constraint functions having too much weight placed on them, or due to uneven distribution of scaling factors, it happens that $P(x,Fs(i))$ has little effect on changing the

constraint value. Another weighting factor added to P(x,Fs(i)) is desirable in order to obtain better results.

There are no fixed rules for selecting the scaling factors. The scaling factors are selected arbitrarily to maintain a balance among all the constraint functions in the objective function.

5.4 Operation of The Optimisation Program

The optimisation program is added to the original design program. The optimisation consists of three subroutines namely, Pattern, Search and Function. Fig. 5.8 shows the flow diagram of the whole program.

The objective function and the constraint functions are in the Function subroutine. The Main subroutine is the original design program used in the previous design. The Search subroutine is used to determine the direction of the search. The Pattern subroutine determines the pattern of the search and controls the step size of the increment or decrement.

Initially, the Search subroutine finds the direction towards the minimum of the objective function at the first base point. If the search is sucessful, a pattern of searches is formed in the same direction. If the pattern

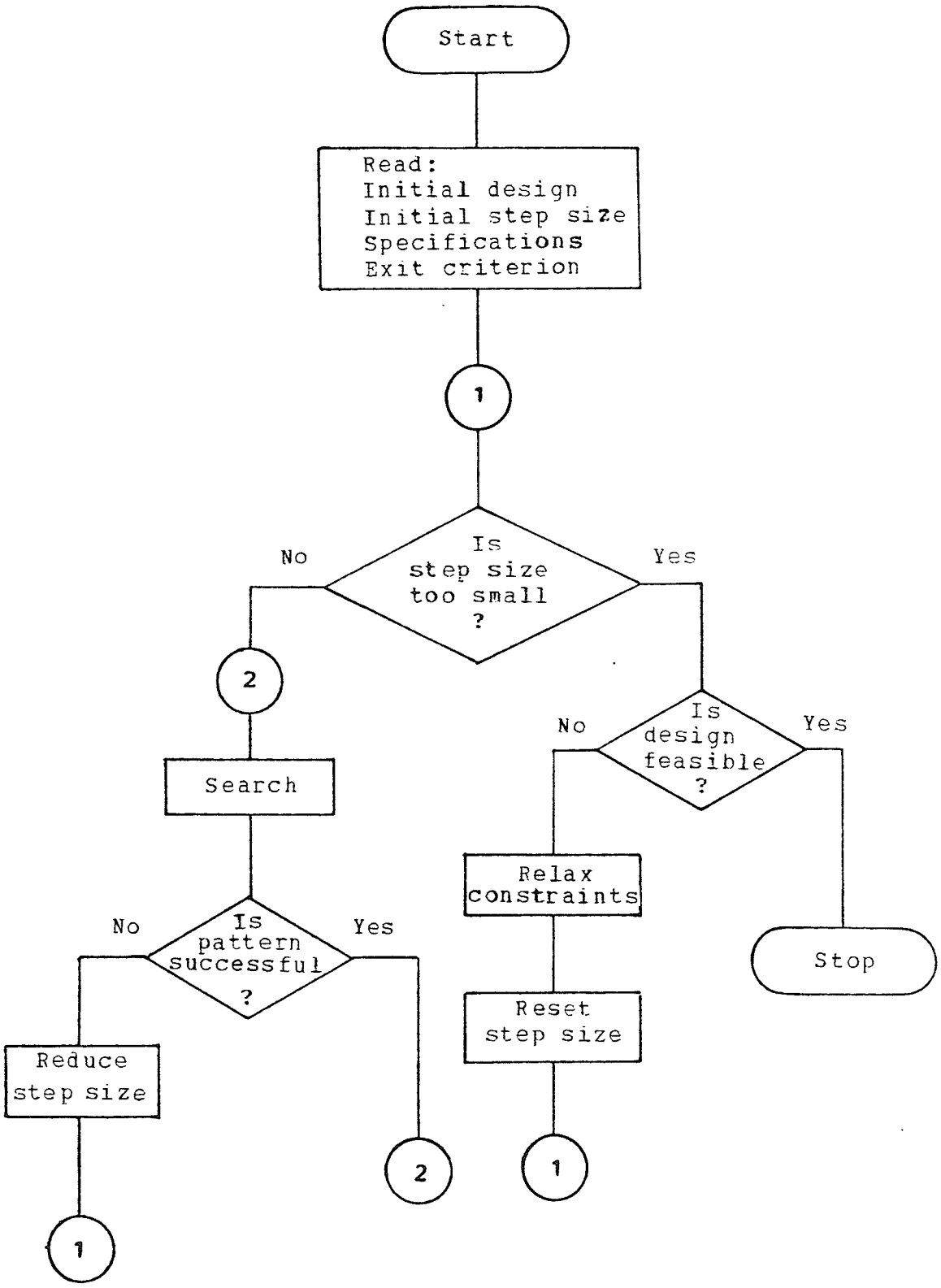


Figure 5.8: Flow diagram of the optimisation program

fails, a new direction has to be searched from the previous base point. If the search fails, the step size will be reduced and the search restarted. The process is repeated until the step size is reduced to the specified minimum value. If the specified minimum step size is reached but still some of the constraints are violated, the specification of the machine has to be changed.

5.5 Test Runs Results

The design in Table 5.1 was used as the start for the test runs. The first run is to obtain a feasible design with 75% efficiency at furling and threshold. In the second run, the specified efficiency is changed to compare with the first run. The third test run is to obtain a suitable range of rated output power for the machine.

Table 5.2 shows the results of optimal design of the first and second run. In order to obtain a feasible design with 75% efficiency, the minimum weight of the machine is increased to 1610 kg. For higher specified efficiency, the weight of the machine has also to increase. By reducing the specified efficiency to 60%, the weight is still very high. The field and stator current density have to keep very low to reduce the I^2R losses. The weight of the copper and the frame constitute a great part of the total weight. It is not economically to have a 1610 kg machine with 20 to 160W

TABLE 5.2

Results From The Test Runs

	Original design	First run	Second run
Core length (m)	0.3867	0.8853	0.0698
Stator bore diameter (m)	0.1969	0.211	0.2166
Stator outside diameter (m)	0.3662	0.6893	0.5028
Length of the frame (m)	1.178	1.477	0.8952
Thickness of the frame (m)	0.00733	0.00545	0.00493
Stator current density (A/m^2)	$1.5X10^6$	$1.69X10^6$	$2.2X10^6$
Field current density (A/m^2)	$7.5X10^5$	$4.6X10^4$	$1.26X10^5$
Threshold magnetic loading (T)	0.6	0.338	0.276
Total weight (Kg)	243.3	1607	460
Efficiency at furling (%)	70.63	75.4	65
Efficiency at threshold (%)	22.56	75	65.2

output. Thus, a suitable range of rated output power is sought.

Different specified rated power output of the machine were used in the third test run. Fig. 5.9 shows the minimum weight of the machine at different rated power output at 75% efficiency. It can be shown that the best range of operation is between 800W to 1500W rated output.

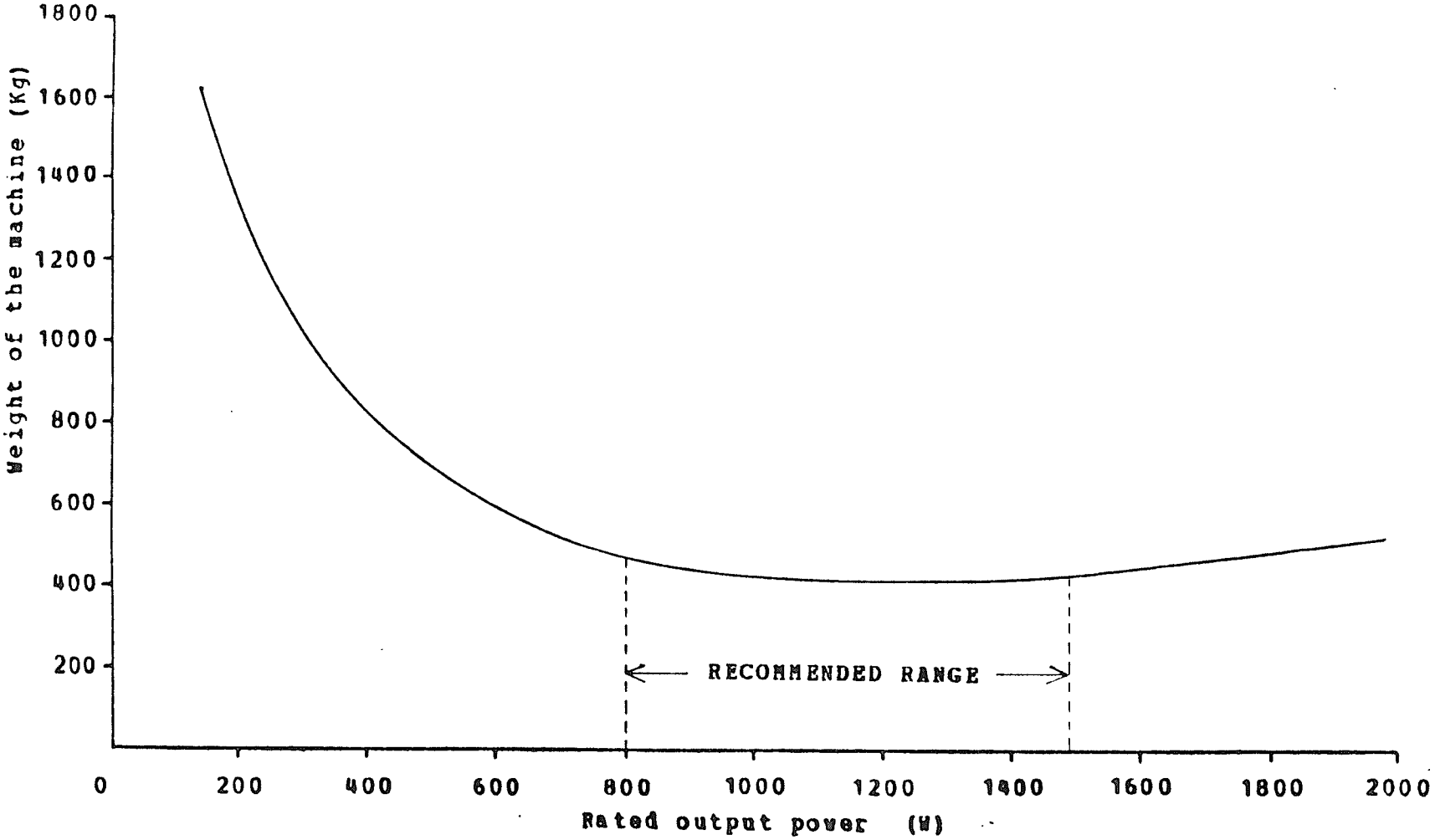


Figure 5.9: Weight of First Design Vs. Rated Power Outputs

Chapter VI

ALTERNATE DESIGNS

6.1 Introduction

In this section two alternate designs based on the same theory used in Chapter Two will be introduced. The two types of alternate designs are :

(1) Field coils under poles type,

(2) Inverted machine type.

These two types of design have two different field winding configurations. A theoretical sample design on Type 1 has been carried out, and since both designs are similar, Type 2 design will be discussed only briefly. The sensitivity of Type 1 is compared to the first design.

Type 1: Field coils under poles

The stator of this design is the same as that of first design, except that the field winding is placed inside the claw-poles. Fig. 6.1 shows the diagram of this design. The field coils are surrounding a stationary shaft. The stationary shaft is held at one end and supported by a bearing at the other end. The rotor is supported by three bearings such that it can rotate on the stationary shaft.

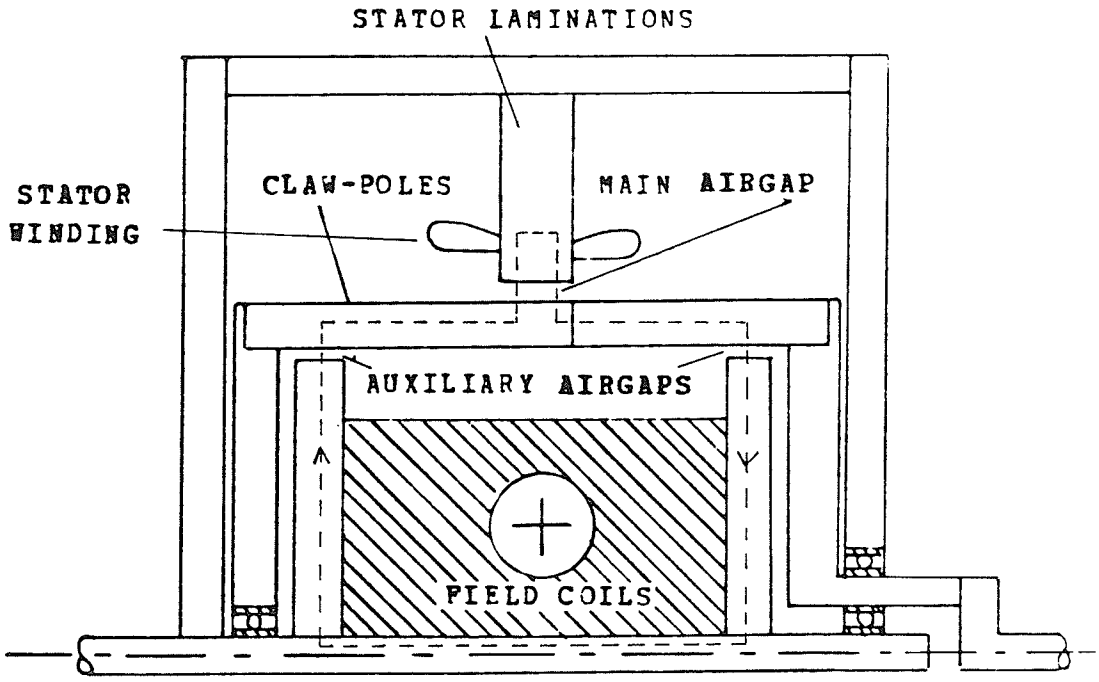


Figure 6.1: Type 1 Brushless Alternator

The broken line represent the magnetic path of this design. There are still four airgaps in the magnetic path as in the first design; however, the shorter mean turn of the field coil makes this type of design more efficient.

Type 2: Inverted Machine

This type is specially designed for the application of Darrius wind turbine. Fig. 6.2 shows the diagram of this design. The stator and the field windings are situated on the shaft which is stationary. The claw-poles ring is

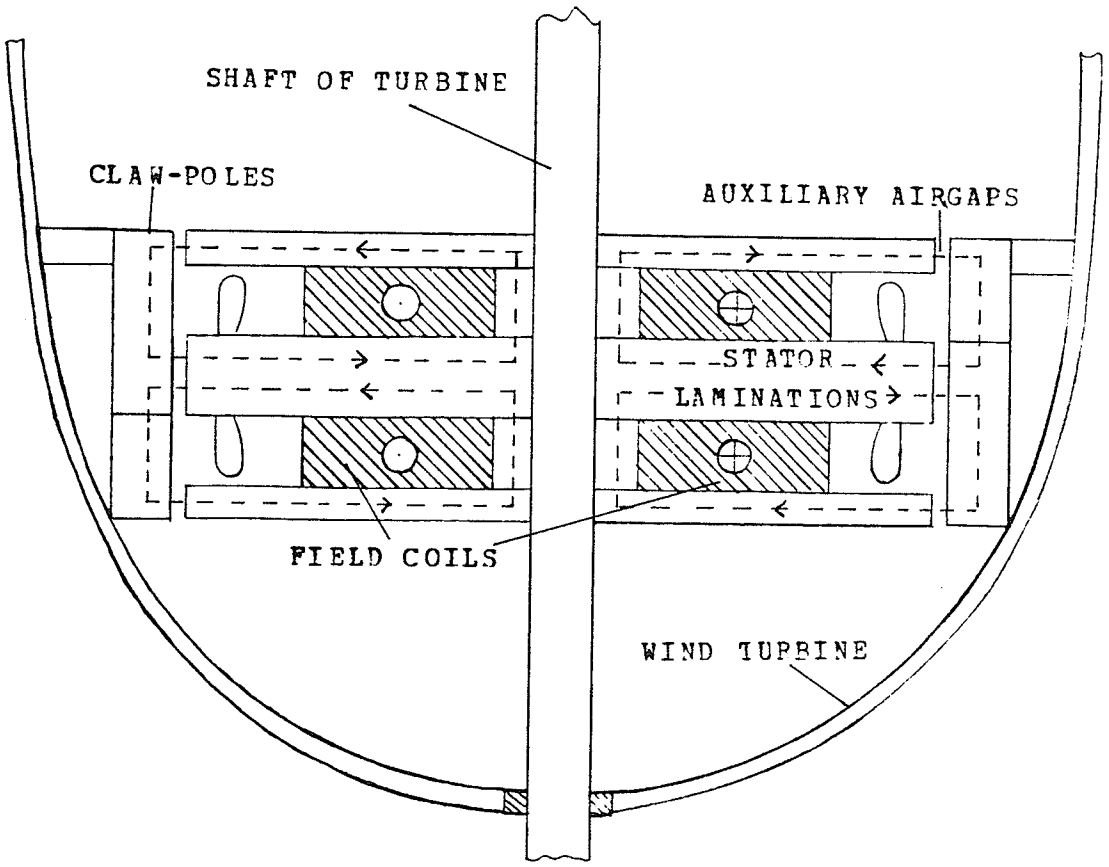


Figure 6.2: Type 2 Brushless Alternator

mounted on the blades of the turbine. When the blades are turning, only the claw-poles ring is moving. The field winding resided on both side of the stator core remains stationary. The broken lines show the magnetic paths of this machine. The main advantage of this design is the shorter field mean turn compared to the first design. In this design, no additional bearing is required other than that for the turbine. But the blades have to be rigid enough to support the poles ring and maintain the same airgap at all times. This is not easily achieved in practice and therefore may not be a practical alternative.

6.2 Sample Design On Type 1

Sample designs with the same specifications as the first design has been done with the simulation program. The optimal design of Type 1 is compared with the optimal design of the first design. A suitable range of operation is suggested.

Table 6.1 shows the comparison of two optimal designs with 75% specified efficiency. The weight of Type 1 design is lighter than the first design because the windings of Type 1 have shorter mean turn. The loss in the field is not as high as the first design, so a smaller conductor size can be used in the field to reduce the weight. The frame and the stator outside diameter are smaller than the first design because the field winding is situated under the pole instead of beside the stator back core.

Type 1 machine has a power output of 160W at furling but the weight is 120Kg, which is too high, only giving 1.3 W/Kg at furling. Fig. 6.3 shows the weight of the Type 1 machine with 75% efficiency varied as the rated output power at furling increased. In order to have a machine giving 3 W/Kg or more, the recommended range of operation is between 400W to 700W rated output power. For the rated power over 700W, the weight of the machine is increased faster, and the rated output current with 8V connection is too high. Therefore,

TABLE 6.1

Comparison of Two Designs

	First Design	Type 1
Core length (m)	0.0885	0.03
Stator bore diameter (m)	0.211	0.273
Stator outside diameter (m)	0.689	0.477
Length of the frame (m)	1.477	0.189
Thickness of the frame (m)	0.00545	0.0127
Stator current density (A/m^2)	$1.69X10^6$	$1.35X10^6$
Field current density (A/m^2)	$4.6X10^4$	$3.1X10^6$
Threshold magnetic loading (T)	0.338	0.322
Total weight (Kg)	1607	120
Efficiency at furling (%)	75.4	75
Efficiency at threshold (%)	75	75.2

it is not practical to go for higher power output unless the rated voltage of the machine is increased as well.

Although Type 1 is more complicated to fabricate, the weight is much lighter and the efficiency is higher. For low power output and low r.p.m., Type 1 design can achieve better performance than the first design. For higher rated power outputs, both designs will provide a lighter machine. So it is recommended that both designs should be applied for machines of higher ratings.

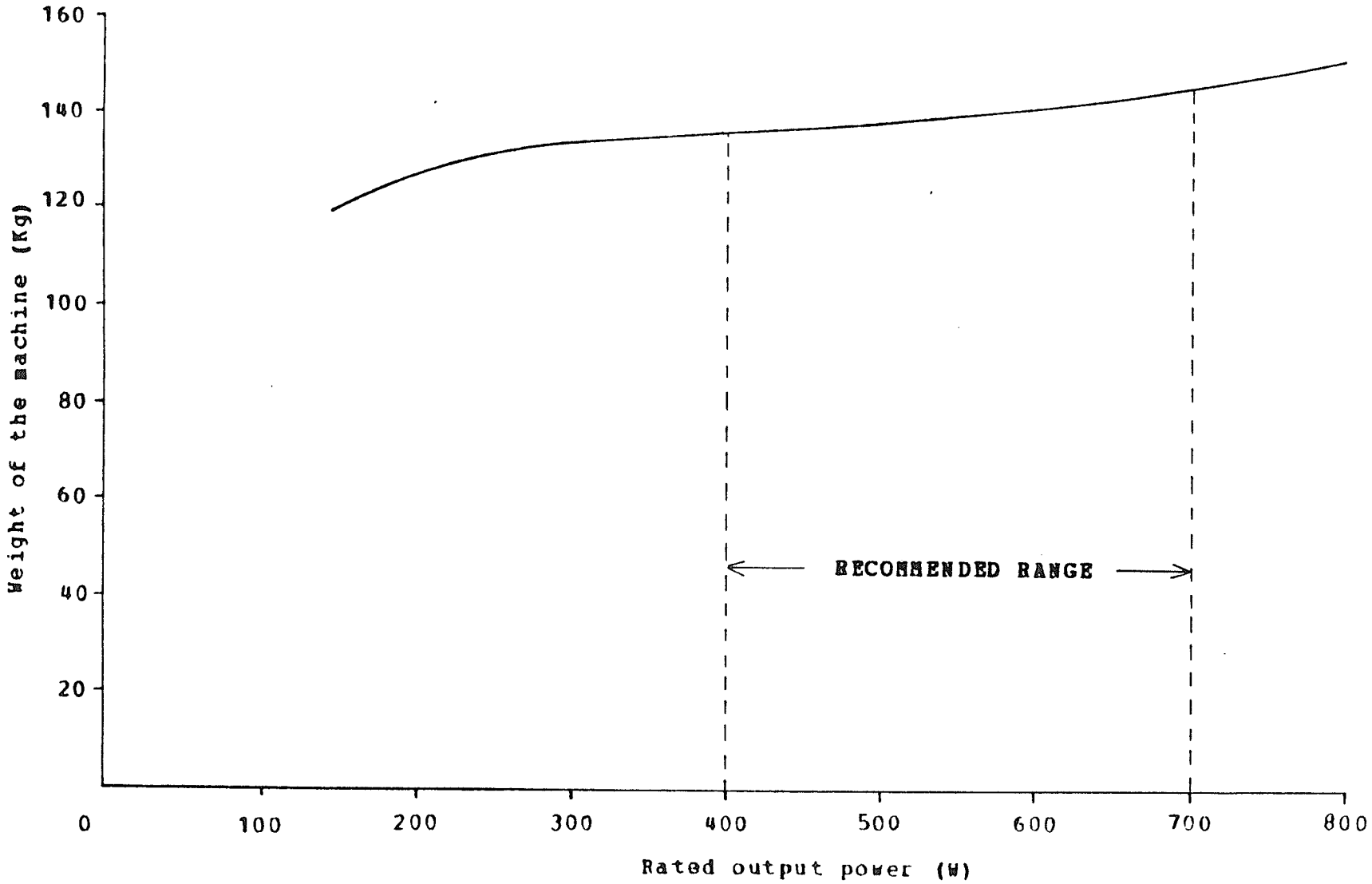


Figure 6.3: Weight of Type 1 Vs. Rated Power Outputs

Chapter VII

CONCLUSIONS

The following conclusions are drawn from the research work described in this thesis :

(1) The design concept and procedures for the design of a brushless alternator are practicable.

(2) The first design is not suitable for machines of low ratings.

(3) Type 1 design has potential to be a viable candidate for wind power generation.

(4) Both designs are suitable for operation at higher rated voltage and higher rated power.

(5) The least pth approximation method with a direct search technique was successfully applied to the brushless alternator design.

Suggestions for future work are :

(1) The first design has to be further developed to eliminate the high field loss.

(2) The brushless Lundell alternator design concept can be extended to areas other than windpower.

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Appendix I

Leakage Mutual Inductance of The Slot

The mutual inductance of the coil B due to the unit current in coil A is equal to the mutual inductance in coil A due to the unit current in coil B, i.e.

$$\lambda ab = \lambda ba \tag{1}$$

Since the currents in each coil are out of phase by an angle θ , assume the currents are given as

$$ia = Im.Sin\,\omega t \tag{2}$$

$$ib = Im.Sin(\omega t + \theta) \tag{3}$$

where Im is the magnitude of the currents.

The total flux linkage in coil A and coil B are

$$\Psi a = \lambda a.ia + \lambda ab.ib \tag{4}$$

$$\Psi b = \lambda ba.ia + \lambda b.ib \tag{5}$$

Substitute Eqns. (2) and (3) into (4), the total flux leakage in coil A becomes,

$$\Psi a = \lambda a.Im.Sin\,\omega t + \lambda ab.Im.Sin(\omega t + \theta) \qquad (6)$$

The voltage induced on coil A is

$$Va = \frac{d\Psi a}{dt}$$

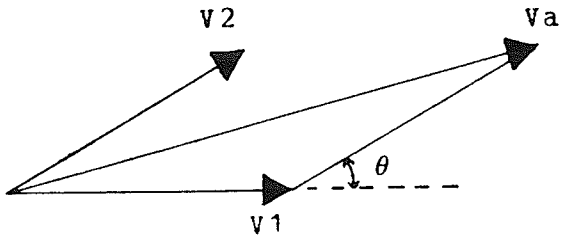
$$= \omega.Im.\lambda a.Cos\,\omega t + \omega.Im.\lambda ab.Cos(\omega t + \theta)$$

$$= V1.Cos\,\omega t + V2.Cos(\omega t + \theta) \qquad (7)$$

where $V1 = \omega.Im.\lambda a$

$V2 = \omega.Im.\lambda ab$

Va can be represented by the following phasor diagram



The magnitude of Va is

$$|Va| = (V1^2 + V2^2 + 2.V1.V2.Cos\,\theta)^{1/2} \qquad (8)$$

Since the inductance of the coil A is

$$La = \frac{|Va|}{Im.\omega}$$

$$= (\lambda a^2 + \lambda ab^2 + 2.\lambda a.\lambda ab.\cos\theta)^{1/2} \qquad (9)$$

Similarly, the inductance of coil B is

$$Lb = (\lambda b^2 + \lambda ab^2 + 2.\lambda ab.\lambda b.\cos\theta)^{1/2} \qquad (10)$$

APPENDIX II

Program Listing

```
      $JOB  WATFIV CHEUNG,NOEXT
      C
      C  DESIGN PROGRAM OF BRUSHLESS ALTERNATOR
      C
      C
      C  DESIGN=1 : FIRST DESIGN
      C  DESIGN=2 : TYPE ONE DESIGN
      C
      C
 1          REAL X(6)
 2          READ,LA,DESIGN
 3          READ,(X(K),K=1,LA)
 4          CALL MAIN(EFFF,EFFT,TOTWT,X(1),X(2),X(3),X(4),X(5),X(6),1,
           @DESIGN)
 5          STOP
 6          END
      C
      C
      C
      C  MAIN
      C

 7          SUBROUTINE MAIN(EFFF,EFFT,TOTWT,BAVT,DB,LENGG,JS,JF,BCA,KCON,
           @DESIGN)
 8          REAL NT,NF,LAMDA
 9          REAL IFB,IFC,ITB,ITC,IFFA,IFFB,IFFC,IRLT,IRLF
10          REAL LENGI,LENGG,IFL,IPP,LF,KO,NSP,LGE,JF
11          REAL LM,LH,LP,JS,KP,KD,LR
12          REAL KW,KDT,KDF,LGS,LPS,ITH,NP,NPB,NPC,NS
13          REAL LSF,LST,LFLUX,IF,IT,IFF,IAF,IBF,ICF
14          BF=0.75
15          BB=0.03807
16          COPS=2
17          DENC=8900
18          DENS=7700
19          FF=0.4
20          FFA=4
21          FFB=2
22          FFC=1
23          H3=0.002
24          H2=0.003
25          KO=0.65
26          KW=0.999
27          KD=0.966
28          KP=0.966
29          LGE=LGS=0.001
30          NC=72
31          NP=4
32          NPB=2
33          NPC=1
34          NS=72
35          POWT=20
36          POWF=160
37          PHASE=3
38          PF=0.6
39          PI=3.14159
40          POLES=24
41          RHO=2.1E-8
42          RPMF=174
43          RPMT=87
44          SF=0.4
45          S=0.002538
46          TPP=3
47          UO=PI*4.E-7
48          VPHA=8
49          VPHB=16
```

```
50          VPHC=32
      C
      C*****************************************************************
      C
      C CALCULATION OF ELECTRIC LOADING
      C
      C
51          VLINA=VPHA*(SQRT(3.0))
52          VLINB=VPHB*(SQRT(3.0))
53          VLINC=VPHC*(SQRT(3.0))
54          BAVP=BAVT/2
55          FT=POLES*RPMT/120
56          FF=POLES*RPMF/120
57          NF=RPMF/60
58          NT=RPMT/60
59          QF=POWF/PF
60          QT=POWT/PF
61          ACF=QF/(10.955*NF*BAVF*KW*LENGG*DB**2)
62          ACT=ACF/8
63          GT=10.955*ACT*BAVT*KW*1.0E-3
64          GF=10.955*ACF*BAVF*KW*1.0E-3
65          PST=PI*DB*NT
66          PSF=PI*DB*NF
67          LENGI=LENGG*0.9
68          PP=(PI*DB)/POLES
69          PHIP=BAVT*PP*LENGI
70          PHIPF=BAVF*PP*LENGI
71          PW=PP*0.7
      C
      C*****************************************************************
      C
      C  CALCULATION OF THE STATOR WINDING
      C
      C
      C
72          TPH=VPHA*1.05/(0.11624*RPMT*KW*BAVT*DB*LENGI)
73          TPHB=TPH*2
74          TPHC=TPH*4
75          IF=POWF/(3*PF*VPHA)
76          IT=POWT/(3*PF*VPHA)
77          IFB=POWF/(3*PF*VPHB)
78          ITB=POWT/(3*PF*VPHB)
79          IFC=POWF/(3*PF*VPHC)
80          ITC=POWT/(3*PF*VPHC)
      C
      C
      C
      C
81          G=NC/PHASE
82          GPC=G/POLES
83          IPP=IF/NP
84          COPP=G/NP
85          TPC=TPH/COPP
86          CPS=TPC*COPS
87          AC=CPS*IPP
88          NSP=NS/POLES
      C
      C
89          YS=PI*DB/NS
90          TW=YS*2/5
91          WO=YS-TW
      C
92          ASCS=IPP/JS
93          AS=ASCS*CPS/SF
94          HT=AS/WO
95          D=WO+S
```

```
 96          ALPHA=ARSIN(D/YS)
 97          CP=PI*(DB+HT)/POLES
 98          CC=CP/COS(ALPHA)
 99          LH=CC+BB+HT+LENGG
100          LM=2*LH
101          LP=COPP*TPC*LM
102          RP=RHO*LP/ASCS
103          RPH=RHO*LP/(4*ASCS)
104          RPHB=RP
105          RPHC=RP*4.
106          LST=3*RPH*IT**2
107          LSF=3*RPH*IF**2
     C
108          CALL EDDY(WO,ASCS,CPS,PI,UO,RHO,KDT,PT)
109          CALL EDDY(WC,ASCS,CPS,PI,UO,RHO,KDF,PF)
110          EDT=KDT*LST
111          EDF=KDF*LSF
112          STLT=(EDT+LST)*0.2
113          STLF=(EDF+LSF)*0.2
     C
114          H1=HT-H2-H3
115          CALL LEAK(PT,H1,H2,H3,WO,UC,TPC,PI,LENGI,DB,NS,POLES,XT,XOT)
116          CALL LEAK(PF,H1,H2,H3,WO,UC,TPC,PI,LENGI,DB,NS,POLES,XF,XOF)
117          XAT=(XT+XOT)/16
118          XAF=(XF+XOF)/16
119          XBT=(XT+XOT)/4
120          XBF=(XF+XOF)/4
121          XCT=XT+XOT
122          XCF=XF+XOF
     C
     C
123          HC=PHIP/(2*LENGI*BCA)
124          DOS=DB+(HT+HC+LGS)*2
125          FFLUX=BAVT*PI*DB*LENGI/2
126          AF=FFLUX/BF
127          CALL THICK(TF,DOS,AF,PI)
128          DO=DOS+TF*2
     C
129          IF(DESIGN.EQ.1) THEN DO
     C
     C  CALCULATION OF FIRST DESIGN FIELD WINDING
     C
130          LF=0.0001
131          CALL F1(ATFDP,ATFD,ATAR,ATART,YS,WO,NSP,LENGI,LENGG,PHIP,PHIPF,
            @LGS,LGE,POLES,DB,DO,DOS,TF,LF,PW,NS,HT,TPP,KW,TPH,IF,IT,UO,PI
            @,HC,BTA,BTAF,BCA,BCAF,TP,LPS,TE,1,BF1)
132          LL=1
133          WHILE(LL.LE.5)DO
134          CALL FRAME(LF,HC,LENGG,JF,ATFD)
135          CALL F1(ATFDP,ATFD,ATAR,ATART,YS,WO,NSP,LENGI,LENGG,PHIP,PHIPF,
            @LGS,LGE,POLES,DB,DO,DOS,TF,LF,PW,NS,HT,TPP,KW,TPH,IF,IT,UO,PI
            @,HC,BTA,BTAF,BCA,BCAF,TP,LPS,TE,1,BF1)
136          LL=LL+1
137          END WHILE
     C
138          ELSE DO
     C
     C  CALCULATION OF TYPE 1 FIELD WINDING
     C
139          LR=LENGG
140          IN=1
141          WHILE(IN.LE.5)DO
142          CALL F2(ATFDP,ATFD,LPS,TP,YS,WO,NSP,LENGI,LENGG,PHIP,PHIPF,
            @AGPP,LGS,LGE,PI,DB,PW,UO,HT,TPP,HC,POLES,IT,IF,TPH,KW,BTAF,
            @BTA,BCAF,BCA,LR,NS,DOS,DR,DS,ATAR,ATART,TR)
143          CALL LENG(LR,ATFD,JF,DR,DS,HRF,XH)
```

```
144          IN=IN+1
145          END WHILE
146          CALL F2(ATFDP,ATFD,LPS,TP,YS,WO,NSP,LENGI,LENGG,PHIP,PHIPF,
            @AGPP,LGS,LGE,PI,DB,PW,UO,HT,TPP,HC,POLES,IT,IF,TPH,KW,BTAF,
            @BTA,BCAF,BCA,LR,NS,DOS,DR,DS,ATAR,ATART,TR)
147          EC=0.01269
148          TF=0.01269
149          LF=LPS+0.02538
150          END IF
151          TWT=((((DB+2*HT)/2)**2-(DB/2)**2)*PI-NS*WO*HT)*LENGI*DENS
152          CWT=((DOS**2)-(DB**2))*PI*LENGI*DENS/4-TWT
153           CALL IRON(BTAF,FF,TWT,PTF)
154           CALL IRON(BTA,FT,TWT,PTT)
155           CALL IRON(BCAF,FF,CWT,PCF)
156           CALL IRON(BCA,FT,CWT,PCT)
157          IRLT=PCT+PTT
158          IRLF=PCF+PTF
      C
      C
      C
      C
      C*************************************************************************
      C
159          IF(DESIGN.EQ.1) THEN DO
160          CALL FW1(ASC,TPF,RF,IFF,PLF,ATFD,RHO,PI,JF,HC,DOS,DF)
161          CALL F1(ATFFP,ATFF,ATAR,ATART,YS,WO,NSP,LENGI,LENGG,PHIP,PHIPF,
            @LGS,LGE,POLES,DB,DO,DOS,TF,LF,PW,NS,HT,TPP,KW,TPH,IF,IT,UO,PI,
            @HC,BTA,BTAF,BCA,BCAF,TP,LPS,TE,2,BF2)
162          ICF=ATFF/(4.*TPF)
163          IAF=ICF*4.
164          IBF=ICF*2.
165          PLFF=4.*RF*ICF**2.
166          ELSE DO
167          CALL FW2(ASC,TPF,RF,IFF,PLF,ATFD,JF,LR,RHO,PI,DS,DF)
168          END IF
169          VOLF=(DO**2-DOS**2)*PI*LF/4
170          CALL STEEL(FRWT,VOLF)
171          STWT=TWT+CWT
172          VOLP=LPS*PW*TP*POLES
173          CALL STEEL(PPWT,VOLP)
174          VOLPS=((DB-2*(TP+LGS))**2)*PF*0.02538/4
175          CALL AL(PSWT,VOLPS)
176          SWT=12*LP*DENC*ASCS
177          FWT=4*TPF*PI*DF*DENC*ASC
178          IF(DESIGN.EQ.1) THEN DO
179          VOLER=(DOS**2)*PI*TE/4
180          CALL STEEL(ERWT,VOLER)
181          TOTWT=FRWT+PPWT+PSWT+FWT+SWT+ERWT+STWT
182          ELSE DO
183          VOLSD=(DR**2-DS**2)*PI*TR/2
184          CALL STEEL(SDWT,VOLSD)
185          VOLEC=(DO**2)*PI*0.02538/2
186          CALL AL(ECWT,VOLEC)
187          TOTWT=FRWT+PPWT+PSWT+FWT+SWT+SDWT+ECWT+STWT
188          END IF
189          RFA=RF/4
190          RFB=RF
191          RFC=RF*4
192          IFFA=IFF*4
193          IFFB=IFF*2
194          IFFC=IFF
      C
      C*************************************************************
      C
      C EFFICIENCY
      C
```

```
      C
195         TOLT=LST+EDT+STLT+PLF+IRLT
196         TOLF=LSF+EDF+STLF+PLFF+IRLF
197         EFFT=POWT*100./(POWT+TOLT)
198         EFFF=POWF*100./(POWF+TOLF)
199         OPF=(EFFF**30/TOTWT)*1.0E-60
      C
200         IF(DESIGN.EQ.1)THEN DO
201          SFO=LF*DO*PI
202          SERO=((DO**2.)-(DB**2.))*PI/2.
203          DI=DOS-2*0.6*HC
204          SFI=LF*DI*PI
205          SERI=PI*((DI**2.)-(DB**2.))
206          STA=SFO+SERO+SFI+SERI
207          CALL TEMP1(PHIT,TT,TOLT,STA)
208          CALL TEMP1(PHIF,TTF,TOLF,STA)
209         ELSE DO
210          SFO=LF*DO*PI
211          SERO=(DO**2.)*PI/2
212          CALL TEMP2(PHIT,TT,TOLT,SFO,SERO)
213          CALL TEMP2(PHIF,TTF,TOLF,SFO,SERO)
214         END IF
215         IF (KCON.EQ.1)THEN DO
      C
216         PRINT 100
217         PRINT 101
218         PRINT 102
219         PRINT 103
220         PRINT 10
221         PRINT 11
222         PRINT 12,QT,QF,QT,QF,QT,QF
223         PRINT 13,POWT,POWF,POWT,POWF,POWT,POWF
224         PRINT 14,VLINA,VLINA,VLINB,VLINB,VLINC,VLINC
225         PRINT 15,VPHA,VPHA,VPHB,VPHB,VPHC,VPHC
226         PRINT 104,IT,IF,ITB,IFB,ITC,IFC
227         PRINT 16,PF,PF,PF,PF,PF,PF
228         PRINT 17,FT,FF,FT,FF,FT,FF
229         PRINT 18,RPMT,RPMF,RPMT,RPMF,RPMT,RPMF
230         PRINT 19,POLES,POLES,POLES,POLES,POLES,POLES
231         PRINT 20
232         PRINT 21
233         PRINT 22,BAVT,BAVF,BAVT,BAVF,BAVT,BAVF
234         PRINT 23,ACT,ACF,ACT,ACF,ACT,ACF
235         PRINT 24,GT,GF,GT,GF,GT,GF
236         PRINT 25,DB,DB,DB,DB,DB,DB
237         PRINT 26,DOS,DOS,DOS,DOS,DOS,DOS
238         PRINT 27,LENGG,LENGG,LENGG,LENGG,LENGG,LENGG
239         PRINT 28,LENGI,LENGI,LENGI,LENGI,LENGI,LENGI
240         PRINT 29,PP,PP,PP,PP,PP,PP
241         PRINT 30,DO,DO,DO,DO,DO,DO
242         PRINT 31,TF,TF,TF,TF,TF,TF
243         PRINT 32,LF,LF,LF,LF,LF,LF
244         PRINT 33,DO,DO,DO,DO,DO,DO
245         PRINT 34,DB,DB,DB,DB,DB,DB
246         IF(DESIGN.EQ.1) THEN DO
247         PRINT 35,TE,TE,TE,TE,TE,TE
248         ELSE DO
249         PRINT 123,TR,TR,TR,TR,TR,TR
250         PRINT 124,EC,EC,EC,EC,EC,EC
251         END IF
252         PRINT 36
253         PRINT 37
254         PRINT 38
255         PRINT 39,NP,NP,NPE,NPB,NPC,NPC
256         PRINT 40,NS,NS,NS,NS,NS,NS
257         PRINT 41,GPC,GPC,GPC,GPC,GPC,GPC
```

```
258          PRINT 42,CPS,CPS,CPS,CPS,CPS,CPS
259          PRINT 43,TPH,TPH,TPHB,TPHB,TPHC,TPHC
260          PRINT 44,KP,KP,KP,KP,KP,KP
261          PRINT 45,KD,KD,KD,KD,KD,KD
262          PRINT 46,KW,KW,KW,KW,KW,KW
263          PRINT 47,ASCS,ASCS,ASCS,ASCS,ASCS,ASCS
264          PRINT 48,JS,JS,JS,JS,JS,JS
265          PRINT 49,YS,YS,YS,YS,YS,YS
266          PRINT 50,WO,WO,WO,WO,WO,WO
267          PRINT 51,HT,HT,HT,HT,HT,HT
268          PRINT 52,TW,TW,TW,TW,TW,TW
269          PRINT 53,RPH,RPH,RPHB,RPHB,RPHC,RPHC
270          PRINT 54,LST,LSF,LST,LSF,LST,LSF
271          PRINT 55,EDT,EDF,EDT,EDF,EDT,EDF
272          PRINT 56,STLT,STLF,STLT,STLF,STLT,STLF
273          PRINT 57,XAT,XAF,XBT,XBF,XCT,XCF
274          PRINT 58
275          PRINT 59
276          PRINT 60
277          PRINT 61,PW,PW,PW,PW,PW,PW
278          PRINT 62,TP,TP,TP,TP,TP,TP
279          PRINT 63,LPS,LPS,LPS,LPS,LPS,LPS
280          PRINT 64,TPF,TPF,TPF,TPF,TPF,TPF
281          PRINT 65,FPA,FPA,FPB,FPB,FPC,FPC
282          PRINT 66,ASC,ASC,ASC,ASC,ASC,ASC
283          PRINT 67,IFFA,IAF,IFFB,IBF,IFFC,ICF
284          PRINT 68,JF,JF,JF,JF,JF,JF
285          PRINT 69,RFA,RFA,RFB,RFB,RFC,RFC
286          PRINT 70,PLF,PLFF,PLF,PLFF,PLF,PLFF
287          PRINT 71,PST,PSF,PST,PSF,PST,PSF
288          PRINT 72
289          PRINT 73
290          PRINT 74,PHIP,PHIPF,PHIP,PHIPF,PHIP,PHIPF
291          PRINT 75,BCA,BCAF,BCA,BCAF,BCA,BCAF
292          PRINT 76,BTA,BTAF,BTA,BTAF,BTA,BTAF
293          PRINT 77,BF1,BF2,BF1,BF2,BF1,BF2
294          PRINT 78,LGS,LGS,LGS,LGS,LGS,LGS
295          PRINT 79,LGE,LGE,LGE,LGE,LGE,LGE
296          PRINT 80,ATFDP,ATFFP,ATFDP,ATFFP,ATFDP,ATFFP
297          PRINT 81,ATART,ATAR,ATART,ATAR,ATART,ATAR
298          PRINT 111
299          PRINT 112
300          PRINT 113,SWT,SWT,SWT,SWT,SWT,SWT
301          PRINT 114,FWT,FWT,FWT,FWT,FWT,FWT
302          PRINT 122,STWT,STWT,STWT,STWT,STWT,STWT
303          PRINT 115,FRWT,FRWT,FRWT,FRWT,FRWT,FRWT
304          PRINT 116,POWT,POWT,POWT,POWT,POWT,POWT
305          PRINT 117,PSWT,PSWT,PSWT,PSWT,PSWT,PSWT
306          IF(DESIGN.EQ.1)THEN DO
307          PRINT 118,ERWT,ERWT,ERWT,ERWT,ERWT,ERWT
308          ELSE DO
309          PRINT 119,SDWT,SDWT,SDWT,SDWT,SDWT,SDWT
310          PRINT 120,ECWT,ECWT,ECWT,ECWT,ECWT,ECWT
311          END IF
312          PRINT 121,TOTWT,TOTWT,TOTWT,TOTWT,TOTWT,TOTWT
313          PRINT 82
314          PRINT 83
315          PRINT 444,PHIT,PHIF,PHIT,PHIF,PHIT,PHIF
316          PRINT 445,TT,TTF,TT,TTF,TT,TTF
317          PRINT 84,IRLT,IRLF,IRLT,IRLF,IRLT,IRLF
318          PRINT 85,LST,LSF,LST,LSF,LST,LSF
319          PRINT 86,EDT,EDF,EDT,EDF,EDT,EDF
320          PRINT 87,STLT,STLF,STLT,STLF,STLT,STLF
321          PRINT 88,PLF,PLFF,PLF,PLFF,PLF,PLFF
322          PRINT 89,TOLT,TOLF,TOLT,TOLF,TOLT,TOLF
323          PRINT 90,EFFT,EFFF,EFFT,EFFF,EFFT,EFFF
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324     100  FORMAT('1',47X,'8 V. OUTPUT',21X,'16 V. OUTPUT',21X,'32 V. OUTPU
            @)
325     101  FORMAT(' ',47X,'-----------',21X,'------------',21X,'-----------
            @,/)
326     102  FORMAT('0',40X,' THRESHOLD ',5X,'FURLING',10X,' THRESHOLD ',5X,
            @'FURLING',10X,' THRESHOLD ',5X,'FURLING')
327     103  FORMAT(' ',40X,' --------- ',5X,'-------',10X,' --------- ',5X,
            @'-------',10X,' --------- ',5X,'-------')
328      10  FORMAT(' ','RATING')
329      11  FORMAT(' ','------',///)
330      12  FORMAT(' ','FULL LOAD (VA)                              : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
331      13  FORMAT(' ','FULL LOAD POWER (W)                         : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
332      14  FORMAT(' ','LINE VOLTAGE (V)                            : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
333      15  FORMAT(' ','PHASE VOLTAGE (V)                           : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
334     104  FORMAT(' ','CURRENT PER PHASE (A)                       : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
335      16  FORMAT(' ','POWER FACTOR                                : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
336      17  FORMAT(' ','FREQUENCY (HZ)                              : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
337      18  FORMAT(' ','SPEED (RPM)                                 : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
338      19  FORMAT(' ','NUMBER OF POLES                             : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
339      20  FORMAT('0','MAIN DIMENSIONS')
340      21  FORMAT(' ','---------------',///)
341      22  FORMAT(' ','MAGNETIC LOADING (T)                        : ',F10.5,4X,
            @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
342      23  FORMAT(' ','ELECTRIC LOADING (AC/M)                     : ',F10.3,4X,
            @F10.3,4X,'|',4X,F10.3,4X,F10.3,4X,'|',4X,F10.3,4X,F10.3)
343      24  FORMAT(' ','OUTPUT COEFFICIENT (KVA/RPS/M**3)           : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
344      25  FORMAT(' ','STATOR BORE DIAMETER (M)                    : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
345      26  FORMAT(' ','STSTOR OUTSIDE DIAMETER (M)                 : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
346      27  FORMAT(' ','GROSS CORE LENGTH (M)                       : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
347      28  FORMAT(' ','IRON LENGTH (M)                             : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
348      29  FORMAT(' ','POLE PITCH (M)                              : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
349      30  FORMAT(' ','FRAME OUTSIDE DIAMETER (M)                  : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
350      31  FORMAT(' ','THICKNESS OF THE FRAME (M)                  : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
351      32  FORMAT(' ','LENGTH OF THE FRAME (M)                     : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
352      33  FORMAT(' ','END-RING OUTSIDE DIAMETER (M)               : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
353      34  FORMAT(' ','END-RING INSIDE DIAMETER (M)                : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
354      35  FORMAT(' ','THICKNESS OF THE END-RING (M)               : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
355     123  FORMAT(' ','THICKNESS OF THE SHAFT DISC (M)             : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
356     124  FORMAT(' ','THICKNESS OF THE END CAP (M)                : ',E10.4,4X,
            @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
357      36  FORMAT('0','STATOR')
358      37  FORMAT(' ','------',///)
359      38  FORMAT(' ','WINDING                                     :  TWO LAYERS P
            @ SLOT ')
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360      39  FORMAT(' ','NUMBER OF PARALLEL CIRCUIT          : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
361      40  FORMAT(' ','NUMBER OF SLOTS                     : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
362      41  FORMAT(' ','SLOTS/POLE/PHASE                    : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
363      42  FORMAT(' ','CONDUCTORS/SLOT                     : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
364      43  FORMAT(' ','TURNS/PARALLEL CIRCUIT              : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
365      44  FORMAT(' ','PITCH FACTOR                        : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
366      45  FORMAT(' ','DISTRIBUTION FACTOR                 : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
         C
367      46  FORMAT(' ','WINDING FACTOR                      : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
368      47  FORMAT(' ','CONDUCTOR SIZE (M**2)               : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
369      48  FORMAT(' ','CURRENT DENSITY (A/M**2)            : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
370      49  FORMAT(' ','SLOT PITCH (M)                      : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
371      50  FORMAT(' ','SLOT WIDTH (M)                      : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
372      51  FORMAT(' ','SLOT DEPTH (M)                      : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
373      52  FORMAT(' ','TOOTH WIDTH (M)                     : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
374      53  FORMAT(' ','RESISTANCE/PHASE (OHM)              : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
375      54  FORMAT(' ','I**2R LOSS (W)                      : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
376      55  FORMAT(' ','EDDY CURRENT LOSS (W)               : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
377      56  FORMAT(' ','STRAY LOSS (W)                      : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
378      57  FORMAT(' ','LEAKAGE REACTANCE (OHM)             : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
379      58  FORMAT('0','ROTOR')
380      59  FORMAT(' ','-----',///)
381      60  FORMAT(' ','TYPE                                :LUNDELL TYPE')
382      61  FORMAT(' ','POLE ARC (M)                        : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
383      62  FORMAT(' ','THICKNESS OF THE POLE (M)           : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
384      63  FORMAT(' ','LENGTH OF POLE-SHOE (M)             : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
385      64  FORMAT(' ','FIELD TURNS                         : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
386      65  FORMAT(' ','NUMBER OF PARALLEL CIRCUIT          : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
387      66  FORMAT(' ','CONDUCTOR SIZE (M**2)               : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
388      67  FORMAT(' ','FIELD CURRENT (A)                   : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
389      68  FORMAT(' ','CURRENT DENSITY (A/M**2)            : ',E10.4,4X,
        @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
390      69  FORMAT(' ','RESISTANCE (OHM)                    : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
391      70  FORMAT(' ','I**2R LOSS (W)                      : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
392      71  FORMAT(' ','PERIPHERAL VELOCITY (M/S)           : ',F10.5,4X,
        @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
393      72  FORMAT('0','MAGNETIZATION')
394      73  FORMAT(' ','-------------',///)
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395      74  FORMAT(' ','FLUX/POLE (WB)                          :  ',E10.4,4X,
     @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
396      75  FORMAT(' ','CORE FLUX DENSITY (T)                   :  ',E10.4,4X,
     @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
397      76  FORMAT(' ','TOOTH FLUX DENSITY (T)                  :  ',E10.4,4X,
     @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
398      77  FORMAT(' ','FRAME FLUX DENSITY (T)                  :  ',E10.4,4X,
     @E10.4,4X,'|',4X,E10.4,4X,E10.4,4X,'|',4X,E10.4,4X,E10.4)
399      78  FORMAT(' ','GAP LENGTH AT STATOR (M)                :  ',F10.5,4X,
     @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
400      79  FORMAT(' ','GAP LENGTH AT END-RING (M)              :  ',F10.5,4X,
     @F10.5,4X,'|',4X,F10.5,4X,F10.5,4X,'|',4X,F10.5,4X,F10.5)
401      80  FORMAT(' ','FIELD A.T./POLE                         :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
402      81  FORMAT(' ','ARMATURE A.T./POLE                      :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
403     111  FORMAT('0','WEIGHT OF THE MACHINE')
404     112  FORMAT(' ','--------------------',///)
405     113  FORMAT(' ','WEIGHT OF STATOR WINDING                :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
406     114  FORMAT(' ','WEIGHT OF FIELD WINDING                 :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
407     122  FORMAT(' ','WEIGHT OF THE STATOR CORE               :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
408     115  FORMAT(' ','WEIGHT OF THE FRAME                     :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
409     116  FORMAT(' ','WEIGHT OF THE POLES                     :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
410     117  FORMAT(' ','WEIGHT OF THE POLE SUPPORT              :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
411     118  FORMAT(' ','WEIGHT OF THE END RING                  :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
412     119  FORMAT(' ','WEIGHT OF THE SHAFT DISC                :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
413     120  FORMAT(' ','WEIGHT OF THE END CAP                   :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
414     121  FORMAT(' ','TOTAL WEIGHT                            :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
415      82  FORMAT('0','EFFICIENCY')
416      83  FORMAT(' ','----------',///)
417      84  FORMAT(' ','IRON LOSS                               :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
418      85  FORMAT(' ','STATOR I**2R LOSS (W)                   :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
419      86  FORMAT(' ','EDDY CURRENT LOSS (W)                   :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
420      87  FORMAT(' ','STRAY LOSS (W)                          :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
421      88  FORMAT(' ','FIELD I**2R LOSS (W)                    :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
422      89  FORMAT(' ','TOTAL LOSS (W)                          :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
423      90  FORMAT(' ','EFFICIENCY (%)                          :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
424          PRINT 200
425     444  FORMAT(' ','TEMPERATURE RISE (C)                    :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
426     445  FORMAT(' ','TEMPERATURE INSIDE THE MACHINE  (C)     :  ',F10.4,4X,
     @F10.4,4X,'|',4X,F10.4,4X,F10.4,4X,'|',4X,F10.4,4X,F10.4)
427     200  FORMAT('1')
     C
428          END IF
     C
429          RETURN
430          END
     C
```

```
      C
      C
      C
      C

431         SUBROUTINE CURVE1(BX,HX)
      C
      C  MAGNETIC CURVE OF THE FRAME
      C
432         DIMENSION BS(16),HS(16)
433         DATA (BS(II),II=1,16,1)/.01,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1
           @,1.1,1.2,1.3,1.4,1.5/
434         DATA (HS(MM),MM=1,16,1)/0.,160.,170.,200.,220.,245.,275.,320.,350
           @,405.,475.,590.,720.,890.,1150.,1500./
435         L=1
436          WHILE(L.LE.16) DO
437           IF(BX.LE.BS(L))THEN DO
438            HX=HS(L-1)+(BX-BS(L-1))*(HS(L)-HS(L-1))/(BS(L)-BS(L-1))
439            L=17
440           ELSE DO
441            L=L+1
442           END IF
443          END WHILE
444         RETURN
445         END
      C
      C
      C

446         SUBROUTINE CURVE2(BY,HY)
      C
      C  MAGNETIC CURVE OF THE LAMINATIONS
      C
447         DIMENSION BB(28),HH(28)
448         DATA (BB(K),K=1,28,1)/.01,0.15,0.2,0.25,0.3,0.35,0.4,0.45,0.5,0.
           @,0.6,0.65,0.7,0.75,0.8,0.85,0.9,0.95,1.0,1.05,1.1,1.15,1.2,1.25,
           @1.3,1.35,1.4,1.5/
449         DATA (HH(KK),KK=1,28,1)/0.,100.,240.,300.,380.,440.,500.,550.,60
           @,650.,700.,750.,800.,850.,950.,1040.,1130.,1250.,1375.,1520.,
           @1780.,2100.,2500.,2865.,3370.,3800.,4150.,4700./
450         L=1
451          WHILE(L.LE.28) DO
452            IF(BY.LE.BB(L)) THEN DO
453              HY=HH(L-1)+(BY-BB(L-1))*(HH(L)-HH(L-1))/(BB(L)-BB(L-1))
454              L=30
455            ELSE DO
456              L=L+1
457            END IF
458          END WHILE
459         RETURN
460         END
      C
      C
      C

461         SUBROUTINE THICK(X,DOS,AF,PI)
      C
      C  CALCULATION OF THE THCIKNESS OF THE FRAME
      C
462         A=1
463         B=DOS
464         C=-AF/PI
465         TEST=B**2-4*A*C
466         IF(TEST.LT.0)THEN DO
467           PRINT,'****** ERROR ********'
468         ELSE DO
```

```
469           X=(-B+SQRT(B**2-4*A*C))/2*A
470         END IF
471         RETURN
472         END
      C
      C
      C

473         SUBROUTINE FRAME(LF,HC,LENGG,JF,ATF)
      C
      C  ESTIMATION OF THE FRAME SIZE
      C
474         REAL L,LF,LENGG,JF
475         SF=0.4
476         AF=ATF/(SF*JF)
477         HF=0.6*HC
478         L=AF/HF
479         LF=L+LENGG
480         RETURN
481         END
      C
      C
      C

482         SUBROUTINE IRON(B,F,WT,P)
      C
      C CALCULATION OF IRON LOSS
      C
483          REAL L,KE
484          KE=2.1335E-4
485          RHOS=2.2E-7
486          D=3.807E-4
487          L=(KE*(B*F*D)**2)/RHOS
488          P=WT*L
489          RETURN
490          END
      C
      C

491          SUBROUTINE LEAK(F,H1,H2,H3,WO,UO,TPC,PI,LENGI,DB,NS,POLES,X,XO)
      C
      C  CALCULATION OF LEAKAGE REACTANCE
      C
492          REAL LAMS,LAM1,LAM2,LAM12,L1,L2,LT,LENGI,NS
493          LAMS=(H3/WO+H2/(WO+H2)+H1/(3*WO))*4*UO*TPC**2
494          LAM1=(H3/WO+H2/(WO+H2)+H1/(6*WO))*UO*TPC**2
495          LAM2=(H3/WO+H2/(WO+H2)+2*H1/(3*WO))*UO*TPC**2
496          LAM12=(H3/WO+H2/(WO+H2)+H1/(4*WO))*UO*TPC**2
497          L1=SQRT(LAM1**2+LAM12**2+LAM1*LAM12)
498          L2=SQRT(LAM2**2+LAM12**2+LAM2*LAM12)
499          LT=L1+L2
500          XS=LAMS*48*PI*F*LENGI
501          XM=LT*16*PI*F*LENGI
      C
      C CALCULATION OF OVERHANG REACTANCE
      C
502          P=5./6.
503          XO=38.4*PI*F*UO*DB*NS*(TPC**2)*(3.0*P-1.0)/(POLES**2)
504          X=XS
505          RETURN
506          END
      C
      C
      C
      C
```

```
507           SUBROUTINE EDDY(WO,ASCS,CPS,PI,UO,RHO,KD,F)
      C
      C  EDDY CURRENT LOSS
      C
508           REAL N,M,KD
509           B=0.7*WO
510           D=SQRT(4.0*ASCS/PI)
511           N=B/D
512           M=CPS/N
513           A=SQRT(PI*F*UO*B/(RHO*WO))
514           KD=(M**2)*((A*D)**4)/9.0
515           RETURN
516           END
      C
      C
517           SUBROUTINE F1(ATFDP,ATFD,ATAR,ATART,YS,WO,NSP,LENGI,LENGG,PHIPT
             @,PHIPF,LGS,LGE,POLES,DB,DO,DOS,TF,LF,PW,NS,HT,TPP,KW,TPH,IF,IT,UO
             @PI,HC,BTA,BTAF,BCA,BCAF,TP,LPS,TE,L,BF)
      C
      C  FIRST DESIGN : MAGNETIC CIRCUIT
      C
518           REAL LENGI,LENGG,LGS,LF,KW,IF,IT,NS,KO,NSP,LGE,LPS
519           REAL PHIP(2),BCAX(2),BTAX(2)
520           PHIP(1)=PHIPT
521           PHIP(2)=PHIPF
      C
522           KO=0.65
523           BEI=0.6
524           BP=0.8
525           BPA=BP/2
      C
      C
      C  AMPERE-TURN FOR THE AIR GAP
      C
      C
526           YSE=YS-KO*WO
527           AGPP=YSE*NSP*LENGI
528           BGS=PHIP(L)/AGPP
529           HGS=BGS/UO
530           ATSGP=HGS*LGS
      C
      C  A.T. FOR THE END RING
      C
      C
      C
531           TE=PHIP(1)*POLES/(BEI*PI*DB*2)
532           BEO=PHIP(L)*POLES/(PI*2*TE*(DO-TF))
533           BEAV=(BEO+BEI)/2
534             CALL CURVE1(BEAV,HE)
535           ATER=HE*(DO-DB-TF)/2
      C
      C  A.T. FOR ROTOR POLE
      C
      C
536             CALL CURVE1(BPA,HPA)
537             CALL CURVE1(BP,HP)
538           LPS=(LF+LENGG)/2
539           TP=PHIP(1)/(2*BPA*PW)
540           ATRP=HPA*TE+LENGG*HPA+(LF-LENGG)*HP/2
      C
      C  A.T. FOR THE GAP AT END-RING
541           BGE=BEI
542           ATGE=LGE*BGE/UO
      C
      C  A.T. FOR THE FRAME
```

```
      C
      C
543         BF=PHIP(L)*POLES/(2*PI*(DO-TF)*TF)
544           CALL CURVE1(BF,HFA)
545         ATF=HFA*LF/2
      C
      C  A.T. FOR THE TEETH
      C
      C
546         BT=PI*(2*HT/3+2*LGS+DB)/NS-WO
547         BT=0.006
548         BTAX(L)=PHIP(L)/(TPP*BT*LENGI)
549         BTAX(2)=PHIP(2)/(TPP*BT*LENGI)
550           CALL CURVE2(BTAX(L),HTA)
      C
551         BTA=BTAX(1)
552         BTAF=BTAX(2)
      C
553         ATT=HT*HTA
      C
      C  A.T. FOR THE CORE
      C
      C
      C
554         DCM=(DOS-HC)
555         BCAX(L)=PHIP(L)/(HC*LENGI*2)
556         BCAX(2)=PHIP(2)/(HC*LENGI*2)
557           CALL CURVE2(BCAX(L),HCA)
558         ATC=PI*DCM*HCA/(POLES*2)
      C
559         BCA=BCAX(1)
560         BCAF=BCAX(2)
      C
      C
      C
      C  A.T. FOR ARMATURE REACTION
      C
      C
561         ATAR=1.35*KW*TPH*IF/POLES
562         ATART=1.35*KW*TPH*IT/POLES
      C
      C  TOTAL FIELD A.T.
      C
      C
      C
563         ATFDP=ATSGP+ATER+ATRP+ATGE+ATF+ATT+ATC+ATAR
564         ATFD=ATFDP*2
565         RETURN
566         END
      C
      C**********************************************************************
      C
      C
567         SUBROUTINE F2(ATFDP,ATFD,LPS,TP,YS,WO,NSP,LENGI,LENGG,PHIP
           @,PHIPP,AGPP,LGS,LGE,PI,DB,PW,UO,HT,TPP,HC,POLES,IT,IF,TPH,
           @KW,BTAF,BTA,BCAF,BCA,LR,NS,DOS,DR,DS,ATAR,ATART,TR)
      C
      C  TYPE 1 : MAGNETIC CIRCUIT
      C
568         REAL LPS,NSP,LENGI,LENGG,LGS,LGE,IF,IT,LR,KO,KW,NS
569         BP=0.8
570         BS=1.4
571         BPA=BP/2
572         BRI=1.2
573         KO=0.65
```

```
      C
      C   AMPERE-TURN FOR THE AIR GAP
      C
      C
574           YSE=YS-KO*WO
575           AGPP=YSE*NSP*LENGI
576           BGS=PHIP/AGPP
577           HGS=BGS/UO
578           ATSGP=HGS*LGS
      C
      C   A.T.FOR THE SHAFT
      C
579           DS=SQRT(2*PHIP*POLES/(PI*BS))
580           CALL CURVE1(BS,HS)
581           ATS=LR*HS/2
      C
      C   A.T. FOR THE SHAFT DISC
      C
      C
      C
582             CALL CURVE1(BPA,HPA)
583             CALL CURVE1(BP,HP)
584           TP=PHIP/(2*BPA*PW)
585           DR=DB-(TP+LGE+LGS)*2
586           TR=PHIP*POLES/(2*PI*DS*BRI)
587           BRO=PHIP*POLES/(2*PI*DR*TR)
588           BRAV=(BRI+BRO)/2
589           CALL CURVE1 (BRAV,HR)
590           ATR=HR*(DR-DS)/2
      C
      C
      C
      C   A.T. FOR THE ROTOR POLE
      C
591           LPS=TR+0.02538+(LR+LENGG)/2
592           ATRP=HPA*TR+LENGG*HPA+(LR-LENGG)*HP/2
      C
      C
      C   A.T. FOR THE GAP AT END-RING
593           BGE=BRO
594           ATGE=LGE*BGE/UO
      C
      C   A.T. FOR THE TEETH
      C
      C
595           BT=PI*(2*HT/3+2*LGS+DB)/NS-WO
596           BTA=PHIP/(TPP*BT*LENGI)
597           BTAF=PHIPF/(TPP*BT*LENGI)
598             CALL CURVE2(BTA,HTA)
599           ATT=HT*HTA
      C
      C
      C   A.T. FOR THE CORE
      C
      C
      C
600           DCM=(DOS-HC)
601           BCA=PHIP/(HC*LENGI*2)
602           BCAF=PHIPF/(HC*LENGI*2)
603             CALL CURVE2(BCA,HCA)
604           ATC=PI*DCM*HCA/(POLES*2)
      C
      C
      C   A.T. FOR ARMATURE REACTION
      C
      C
```

```
605           ATAR=1.35*KW*TPH*IF/POLES
606           ATART=1.35*KW*TPH*IT/POLES
      C
      C
      C  TOTAL FIELD A.T.
      C
      C
      C
607           ATFDP=ATSGP+ATR+ATRP+ATGE+ATS+ATT+ATC+ATAR
608           ATFD=ATFDP*2
609           RETURN
610           END
      C
      C
611           SUBROUTINE FW2(ASC,TPF,RF,IFF,PLF,ATFD,JF,LR,RHO,PI,DS,DF)
      C
      C  TYPE 1 : FIELD WINDING CALCULATION
      C
612           REAL IFF,LR,JF
      C
613           SF=0.4
614           PERCEN=0.6
615           EF=12
616           CACF=ATFD/(SF*JF)
617           HRF=CACF/LR
618           DF=HRF+DS
619           ASC=(ATFD*RHO*PI*DF)/(4*EF)
620           TPF=ATFD/(4*ASC*JF)
621           RF=RHO*PI*DF*TPF/ASC
622           IFF=EF/RF
623           PLF=RHO*PI*DF*ATFD*JF
624           RETURN
625           END
      C
626           SUBROUTINE FW1(ASC,TPF,RF,IFF,PLF,ATFD,RHO,PI,JF,HC,DOS,DF)
      C
      C  FIRST DESIGN :  FIELD WINDING CALCULATION
      C
627           REAL IFF,JF
628           SF=0.4
629           PERCEN=0.6
630           EF=12
631           HF=PERCEN*HC
632           DF=DOS-HF
633           ASC=(ATFD*RHO*PI*DF)/(4*EF)
634           TPF=ATFD/(4*ASC*JF)
635           RF=RHO*PI*DF*TPF/ASC
636           IFF=EF/RF
637           PLF=RHO*PI*DF*ATFD*JF
638           RETURN
639           END
      C
      C
640           SUBROUTINE LENG(LR,ATFD,JF,DR,DS,HRF,XH)
      C
      C  CALCULATION OF FRAME LENGTH
      C
641           REAL LR,JF
642           SF=0.4
643           CACF=ATFD/(SF*JF)
644           XH=(DR-DS)*0.8/2
645           HRF=XH
646           LR=CACF/XH
```

```
647         RETURN
648         END
      C
649         SUBROUTINE STEEL(WT,VOL)
      C
      C  WEIGHT OF IRON
      C
650         DENS=7700
651         WT=VOL*DENS
652         RETURN
653         END
      C
      C
654         SUBROUTINE AL(WT,VOL)
      C
      C  WEIGHT OF ALUMINUM
      C
655         DENAL=2700
656         WT=VOL*DENAL
657         RETURN
658         END
      C
659         SUBROUTINE TEMP1(PHI,TT,PL,STA)
      C
      C  FIRST DESIGN : CALCULATION OF TEMPERATURE
      C
660         I=1
661         WHILE(I.LE.150)DO
662          T=I+298
663          PHI=T-298
664          PC=30.*PHI
665          PV=2*PHI**(5./4.)
666          PR=(3.135E-8)*((T**4.)-(298.**4.))
667          PD=(PR+PV+PC)*STA
668          S=PD-PL
669          I=I+1
670          IF(S.GE.0)THEN DO
671           I=200
672          END IF
673         END WHILE
674         TT=T-273
675         RETURN
676         END
      C
      C
677         SUBROUTINE TEMP2(PHI,TT,PL,SFO,SERO)
      C
      C  TYPE 1 : CALCULATION OF TEMPERATURE
      C
678         I=1
679         WHILE(I.LE.100)DO
680          T=I+298
681          PHI=T-298
682          PC=30.*PHI
683          PV=2*PHI**(5./4.)
684          PR=(3.135E-8)*((T**4.)-(298.**4.))
685          P1=(PV+PC+PR)*SFO
686          PRA=(5.7E-8)*0.1*((T**4.)-(298.**4.))
687          PVA=2*PHI**(5./4.)
688          P2=(PRA+PC+PVA)*SERO
689          S=P1+P2-PL
690          I=I+1
```

```
691           IF(S.GE.0)THEN DO
692             I=200
693           END IF
694         END WHILE
695         TT=T-273
696         RETURN
697         END
      C

      $ENTRY
```