Chapter 1

Introduction

1.1 Background

The electric motor has been the horse power of the industrial world from the time it was commercialised almost a century ago to today. The design of the electric motor varies according to the need, however the most used electric motor is the induction motor and in particular the squirrel cage induction motor. This is because of its ruggedness in design and versatility in operation.

This project was focused on the retrofit design and local manufacture proposition of the electric motor-the squirrel cage induction motor. The motor derives its name from its rotor construction which appears like a squirrel cage set in an iron core. The cage is a cylindrical rung of bars shorted on either end. The type of motor considered in this work is the three phase type commonly referred to as polyphase. This type of motor has many uses ranging from domestic to industrial applications. Some of its uses are as a driving unit for pumps engaged in de-watering systems such as in underground mining or in domestic clean water supply; farming as in irrigation or in industrial machines like lathes and drilling machine, hammer mills or extruders.

Since its discovery around the 1800 the induction motor has been developed into a highly efficient machine which has seen a reduction in actual physical size and can be made to suit almost any application from the biggest in concentrator crushing units in the mines to small motors in toys. However even though the induction motor has seen great strides in its development more work is still being carried out to improve further it’s performance. This work is going on in the design of the rotor using copper and copper alloys or aluminium with the aim to reduce stator, rotor and frictional losses. With further improvement in performance still smaller motors of equal rating will be realised. This Thesis outlines the steps taken in coming up with a retrofit electric motor and its manufacturing possibility to equip the University of Zambia (UNZA) pump [1].

The UNZA pump is a centrifugal vertical submersible pump designed by Nyirenda in his Thesis “Redesign and Manufacture of the Centrifugal Pump [1]”. The overall objective was to come up with a centrifugal pump which can be manufactured locally. In line with this objective, there was need to design a retrofit electric motor drive the pump and manufactured in Zambia.
Chapter 2: The Polyphase Induction Motor Design

Nyirenda's work was centred on producing a vertical submersible pump with an open impeller. He came to this conclusion after an extensive market research into the sales of pumps from retailers in Zambia. He designed a simplified open impeller centrifugal pump using concurrent engineering and CAD-CAM software (Master Cam and Solid Works) by eliminating some components and yet also by merging some components. He also employed the Computer Numerical Control (CNC) technology to produce permanent moulds for casting the diffuser casings, impeller, and the bearing housing. As a result Nyirenda designed a pump with the following parameters:

1. Discharge $Q = 32 \text{ m}^3/\text{hr}$       (1-1)
2. Head $H = 40\text{m}$         (1-2)
3. Speed $n_r = 2890 \text{ rpm}$  (1-3)
4. Pump efficiency $\eta = 0.66$              (1-4)

Though Nyirenda did not physically produce the pump his objective to design a simplified version of the vertical submersible centrifugal pump was achieved.

Steman [2] on the other hand looked at the manufacturability and marketability of the pump designed by Nyirenda. He carried out an extended market survey on pumps imported into Zambia directly by the user. Steman came to the same conclusion as Nyirenda that the most commonly applied pump in the country was the Vertical Submersible Pump with an Open Impeller. Steman therefore looked at the Product Technology and Production Technology of this pump. He showed that capacity existed in Zambia for both Product Technology and Production Technology at the main Foundries in Zambia. He singled out Scaw Foundries Ltd in Kitwe and Zambia Railways workshops in Kabwe as some of the foundries that possessed enough know how and equipment to produce the pump parts like the impeller, vane diffuser, pump casing, bearing houses and end covers. He also identified machining workshops in Zambia to work the rotor shaft, bearing seats and overall diameters and mating faces of the cast parts of the pump and motor. He however stated that the simplified pump would be no match for the imported advanced pumps if the cost of production was high. Overall the retail price of a complete University of Zambia (UNZA) pump was priced at US $ 1680-1750 [2]. Out of which production costs were US$600-800. Therefore Steman concluded that the advantage of the UNZA pump should be the price, spares availability and good after sales service.
1.1.1 Centrifugal Pump History in Zambia

The two studies mentioned above are not the only studies carried out on the pump in Zambia. There is actually a history to the study of the centrifugal pump at the University of Zambia. Attempts at studying and working on the horizontal centrifugal pump had been carried out in the Department of Mechanical Engineering at the University of Zambia for years as final year projects.


However all the final year project work in 1, 2, and 3 above were on the horizontal centrifugal pump and not on the vertical submersible centrifugal pump as in the case of the studies carried out by Nyirenda [1] and Steman [2] in their master’s work. Also the works carried out in 1, 2, and 3 above were attempts at reproducing an existing pump and not reengineering of a pump as done in Nyirenda’s Master of Engineering work [1].

1.1.2 Problem Statement

Even though advanced works on the pump in Zambia had been achieved culminating into the redesign of the vertical submersible centrifugal pump by Nyirenda, no attempt at designing the drive unit, the electric motor, had been made. In all these attempts the electric motor, that is the stator and rotor, was considered as an item to be imported complete to fit into the pump [1, 2]. For example both Nyirenda [1] and Steman [2] considered the electric motor powering the Flygt B2102.041 pump [3] as suitable for the UNZA pump. The Flygt B2102.041 was an imported pump and therefore could not give the advantage required for a wholly locally produced pump.

This project therefore is the first attempt to look into the manufacture of the electric motor to retrofit the University of Zambia pump.

1.1.3 Polyphase Induction Motor

The pedestal polyphase induction motor is shown in Figure 1-1 showing part 29, the rotor and part 30, the stator which were the focus of this study.
Figure 1-1 Exploded View of the Pedestal Polyphase Induction Motor

Pump parts:


1.1.4 The Vertical Submersible Centrifugal Pump

The vertical submersible pump is shown in Figure 1-2. The rotor is mounted on the shaft labelled 5 and the stator is labelled 3. The pump in Figure 1-2 is the likeness of Nyirenda’s design. Nyirenda’s design provided most of the parts shown in Figure 1-2, except parts 3 the stator and the rotor which constitutes the induction motor within the submersible pump.
The induction motor is classified in four categories as NEMA class A, B, C, and D, of which NEMA class B is the most common and is found in general application. The other classes are designed for special application depending on need.

The real difference in the design of the different induction motors lies in the design of the rotor. Figure 1-3 shows the slot designs of an induction motor which distinguishes the various classes and therefore determines the important characteristics of a motor like starting torque, and other performance criteria.
1.1.5 Induction Motor Rotor Slot Designs

Laminations from typical cage induction motor, cross section of the rotor bars
(a) NEMA class A – large bars near the surface
(b) NEMA class B – large, deep rotor bars
(c) NEMA class C – double-cage rotor design
(d) NEMA class D – small bars near the surface

Figure 1-3. Rotor Slot Designs of the Induction Motor

Figure 1-4 Cut away View of the Squirrel-Cage Class B Rotor for Induction Motor showing imbedded Aluminium Rotor Segments (Courtesy of UTH maintenance workshop)
Chapter 2: The Polyphase Induction Motor Design

As can be seen from Figure 1-3 NEMA class B motor has a deep bar design allowing it to start direct on line which is one of the most desirable performance criteria of a submersible pump. Its other quality is a relatively high starting torque suitable for many applications.

1.1.6 Induction Motor Performance Curves

The performance curves shown in Figure 1-5 are for the rotor designs shown in Figure 1-3 above. The curves show that NEMA class B which corresponds to curve B is the most desired performance. It has good starting torque, good pullout torque, and good breakdown torque. It is therefore sufficient to drive a centrifugal load.

![Figure 1-5 Typical Torque-Speed Curves for Class A, B, C, and D Rotors](image)

1.1.7 Electric Motor Construction

The electric motor is divided in two major components, the stator made up of the copper winding embedded in an iron core, and in the case of the squirrel cage motor Aluminium or Copper bars cast or driven in an iron core. The stator and rotor are shown in Figures 1-6 and 1-7 respectively.
Figure 1-6 Stator Core (a) and Stator Winding (b)

Figure 1-7 Stator Core showing a typical Stator Slot (Courtesy of UTH Workshop)
The plant was designed after the process flow of the product [4, 5] shown in chapter 3 combining both cellular and process layouts [6]. This plant combines both the cellular and process layout. The financials of the plant were also done to show the viability of production of the electric motor and pump in Zambia. In designing this plant, the annual production was based on three scenarios of 105 pumps production, 500 pumps production and 3000 pumps production. The three considerations were necessary to determine the most optimal production quantities; the driver being the price of the product and the starting figure of 105 electric motors being the determined market of Zambia. The calculation of the plant viability at 500 electric motors and 3000 electric motors was to calculate the profitability of the plant seeing that at 105 units the plant was not viable. The figures of 500 units and 3000 units per annum were selected at random to see which production levels can produce an affordable electric motor. At 3000 units per annum the retail price of the electric motor was K1500000. The price was considered reasonable on the Zambian market for this size of motor.

In this work though the physical stator and rotor were not produced the main machinery to do so was identified (AppendixE) as listed below:

1. Manual Punching Machine for production of stator and rotor laminations,
2. Lamination Machine for stacking the laminations,

Figure 1.8 Sketch of Cage Rotor
3. Welding Machine for welding the laminations together,
4. Winding Machine for production of stator coils,
5. Bending Machine for rolling Motor casings (Motor casings may be cast [1, 2]),
6. Lathe Machine for production of motor shafts,
7. Vertical Drilling for general purposes,
8. Lamination Dies for production of stator and rotor laminations, and
9. A Foundry for casting rotor bars (Not included in Appendix E)

The pump casing, impeller, diffuser, end covers and bearing houses were to be cast and machined to finish on the lathe and other parts like seals and bearings were to be imported [1, 2].

In determining the profitability of the plant the income statement and the balance sheet were prepared using formats in International accounting standard 1[7]. The cash flow statement was prepared using basic format used in Finance and decision making [8, 9]. Further, Return on Investment [10], Payback period [11] and Internal Rate of Return [11] were calculated.

The benefits of the UNZA pump and electric motor in comparison to imported units are:

1. Shorter time to bring the product to market,
2. Smoother transition into market,
3. Fewer components in the final product,
4. Easier assembly,
5. Lower costs of production,
6. Higher product quality, and

1.2 Project Justification

Zambia needs to become a middle earning country by 2030. In its quest to achieve this position Zambia needs to industrialise. To do so deliberate programmes meant to drive the country towards industrialisation must be put in place. The University of Zambia, Department of Mechanical Engineering wanting to be part of this target put in place projects which can help elevate the country to the status of a middle earning country. The projects were “Redesign and Manufacturing of a Centrifugal Pump [1]”, and the “Electric Motor Retrofit design and Local Manufacture Proposition”, among others.
The University of Zambia pump when built and the electric motor retrofit when manufactured in Zambia will trigger many auxiliary industries which could start an industrial revolution in the country.

The simplified University of Zambia pump was designed to suit the pocket of the majority of Zambian peasant farmers so that they can be encouraged to embark on farming through irrigation and contribute to the food basket of the country throughout the year. In this way the food basket of the country will be enhanced and in turn help to eliminate poverty in Zambia.

It is clear therefore that the benefits of the two projects are immense and beneficial to Zambians and Zambia as a country.

In a questionnaire conducted as part of this work, it came out clearly that electric motor users in Zambia would be ready to purchase motors made in Zambia as long as the product was good. Therefore the market for the University of Zambia pump and the electric motor is guaranteed.

1.3 Research Objectives

The overall objective of the research was to design an electric motor retrofit for the UNZA pump that could be locally manufactured.

The specific objectives were to:

1.3.1 Design a retrofit induction motor for the UNZA pump.
1.3.2 Develop a manufacturing process plan for the designed retrofit induction motor.
1.3.3 Investigate the feasibility for local production and operations costs for local manufacture of the designed retrofit induction motor.
1.4 Methodology

The design of the electric motor was realized by the methodology flow chart shown in Figure 1-8.

Figure 1-9 Methodology Flow Chart
1.4.1. Validation of Electric Motor Retrofit Design

The Flygt B2102.041 pump characteristics [3] (see Appendix D) were used to validate the electric motor parameters of the developed electric motor (Table 2-3). The motor data of the Flygt pump B2102.041 were obtained from the internet. The interest in this motor was because it was the preferred drive for the UNZA pump. This motor was then used as the benchmark for the locally designed motor.

1.4.2. Literature review

An extensive search of published works and books was undertaken. The references are given in section 6.
Chapter 2

Electric Motor Design

2.1 Introduction

Development of any new three-phase motor design begins with selection of basic overall stator and rotor dimensions, then the number of stator slots, $N_1$ and rotor slots $N_2$ [12]. Together with the number of magnetic poles in the stator winding, the $N_1$ and $N_2$ values—what is called the “slot combination”—influence the winding alternatives. This chapter therefore deals with the electric motor design starting with the determination of the stator and rotor dimensions and then the slot dimensions and slot combination and lastly the winding from the given motor design specifications.

2.2 Design Specifications

The design specifications are from the UNZA pump parameters and approximate desired values.

- Rated Power $P_s = 5.28$ kW
- Speed $n_r = 2890$ rpm
- Synchronous speed $n_s = 3000$ rpm
- Line voltage $V_1 = 380$ V
- Supply frequency $f_1 = 50$ Hz
- Number of phases = 3
- Phase connections : star
- Targeted power factor = 0.85
- Targeted efficiency: $\eta_n = 0.85$
- Rated slip $S_n = 3.7\%$
- Number of poles $P = 2$
- Number of pole pair $P_1 = 1$
- Environment conditions: standard (no derating)
- Configuration (vertical or horizontal shaft etc.): Vertical shaft
- Service factor load: 1.0
- Insulation class: F; temperature rise; class B
- Motor casing dimensions $D_{out} = 180$ mm
- Rotor seat length $R_{SL} = 90$ mm
2.3 The Algorithm

The algorithm Figure 2.1 shows the main steps in designing the induction motor [13]. The process started with (1) the design specifications given in 2.1 and assigned values of flux densities and current densities and in (2) the stator bore diameter $D_{sbd}$, the stack length $L$, stator slots $N_1$, and stator outer diameter $D_{out}$, were calculated, after which the stator and rotor currents were found.

In step (3) all dimensions were adjusted to standardised values (stator outer diameter $D_{out}$, stator bore diameter $D_{sbd}$, etc.). Then in (4), the actual magnetic and electric loadings (current and flux densities) were verified. At this stage the results of the magnet saturation coefficient ($1 + K_{sc}$) of the stator and rotor tooth were compared to assigned values. This is a decision point upon which if the values differ then the whole process starting with (1) starts with adjusted values of tooth flux densities until convergence is obtained in $1 + K_{sc}$. When this condition was met steps (5) to (8) were followed calculating the magnetisation current $I_o$ (5); the equivalent circuit parameters in (6), losses, rated slip $S_n$, and efficiency in (7) and then power factor, locked rotor current and torque, breakdown torque, and temperature rise in (8).

In (9) all this performance was checked. This step was crucial because if the values are not satisfactory then the whole process is restarted at (1) with new values of flux densities and/or current densities and stack aspect ratio $\lambda = L/\tau$ ($L =$ length of stack, $\tau =$ pole pitch).

The stator winding design did not fall into this algorithm and was done independent of it. As such it is not cast in any of the steps outlined above.
Figure 2.1 Design Algorithm
Chapter 2: The Polyphase Induction Motor Design

Figure 2.1 Design Algorithm (cont’d)
2.4 Determination of Stator Core main Dimensions.

There are many ways of designing the induction motor stator and rotor dimensions. The most common being:

1. The $D_{sbd}^2L$ output constant concept and
2. The rotor tangential stress concept.

The $D_{sbd}^2L$ output constant concept is the most widely accepted method [13, 14] and was therefore used in this project. The rotor tangential concept is used for completely new designs [13], and was not therefore considered.

Based on the advanced reasons, the stator bore diameter $D_{sbd}$ [13] is given by

$$D_{sbd} = 3\sqrt{\left(\frac{2P_1 \times P_1 \times S_{gap}}{\pi \times \lambda \times f_1 \times C_o}\right)} \quad (2-1)$$

And from Equation (2-2) $K_E$ the ratio between the generated electromotiveforce (emf) $E_1$ and input voltage $V_{in}$ is given by

$$K_E = \frac{E_1}{V_{in}} = 0.98 - 0.005 \times P_1 \quad (2-2)$$

For $P_1 = 1$, $K_E = 0.975$

The air-gap apparent power $S_{gap}$ [13] is given as

$$S_{gap} = 3 \times E_1 \times I_{in} \quad (2-3)$$

The input apparent power $S_{in}$ [13] is given as

$$S_{in} = 3 \times V_{in} \times I_{in} = \frac{P_n}{\left(\eta_n \times \cos \Phi_{in}\right)} \quad (2-4)$$

And from Equation 2-1, 2-2, 2-3 and 2-4, the air-gap apparent power is given as

$$S_{gap} = \frac{K_E \times P_n}{\left(\eta_n \times \cos \Phi_{in}\right)} \quad (2-5)$$

The stack aspect ratio $\lambda$ [13] is given as
\[
\lambda = L \frac{(2 \times P_1}{\pi \times D_{sbd})} = L / \tau 
\] (2-6)

Past experience has shown that the stack aspect ratio \( \lambda \) fall in the range shown in table 2-1

<table>
<thead>
<tr>
<th>2P_1</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda )</td>
<td>0.6 – 1.0</td>
<td>1.2 – 1.8</td>
<td>1.6 – 2.2</td>
<td>2 - 3</td>
</tr>
</tbody>
</table>

From Equation 2-5, the apparent air-gap power \( S_{\text{gap}} \) is

\[
S_{\text{gap}} = \frac{(0.975 \times 5.28 \times 10^3)}{(0.85 \times 0.85)} = 7125.26 \text{ VA}
\]

Using the value of \( S_{\text{gap}} \) calculated, \( C_0 \) is obtained graphically [13], so for \( S_{\text{gap}} = 7125.26 \text{ VA} \), \( C_0 = 144.5 \times 10^3 \text{ J} / \text{m}^3 \). Since this is a 2 pole motor, \( P_1 = 1 \), and from Table 2-1, we select \( \lambda = 0.6 \), \( f_1 = 50 \text{ Hz} \), therefore the stator bore diameter \( D_{sbd} \) from Equation 2-1 is

\[
D_{sbd} = 3\sqrt{\frac{(2 \times 1 \times 7125.26)}{(\pi \times 0.6 \times 50 \times 144.5 \times 10^3)}} = 0.1015 \text{ m}
\]

From Equation 2-6 the stack length \( L \) is

\[
L = \frac{(0.6 \times \pi \times 0.1015)}{(2 \times 1)} = 0.0957 \text{ m}
\]

From Equation 2-6 the pole pitch \( \tau \) is

\[
\tau = \frac{(\pi \times D_{sbd})}{(2 \times P_1)} = \frac{(\pi \times 0.1015)}{(2 \times 1)} = 0.1594 \text{ m}
\]

The slot pitch \( \tau_s \) for \( q = 6 \) is

\[
\tau_s = \frac{\tau}{(3 \times q)} \quad (2-7)
\]

\[
= \frac{0.1594}{(3 \times 6)} = 0.008865 \text{ m}
\]

The guide as to the ratio of internal to external stator diameter \( D_{sbd} / D_{\text{out}} \) is given in table 2-2.
Chapter 2: The Polyphase Induction Motor Design

### Table 2-2 Ratio of Internal and External Stator Diameter

<table>
<thead>
<tr>
<th>$2 \times P_1$</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{sbd}/D_{out}$</td>
<td>0.54 – 0.58</td>
<td>0.61 – 0.63</td>
<td>0.68 – 0.71</td>
<td>0.72 – 0.74</td>
</tr>
</tbody>
</table>

For $2 \times P_1 = 2$, $D_{sbd}/D_{out} = K_{DD} = 0.56$ was selected, therefore

$$D_{out} = D_{sbd}/K_{DD}$$  \hspace{1cm} (2-8)

$$D_{out} = 0.1015 / 0.56 = 0.180 \text{ m}$$

The air-gap value $g$ [13] is given as

$$g = (0.1 + 0.02 \times \sqrt[3]{P_n}) \times 10^{-3} \text{ m for } 2P_1 = 2$$  \hspace{1cm} (2-9)

$$g = (0.1 + 0.012 \times \sqrt[3]{P_n}) \times 10^{-3} \text{ m for } 2P_1 \geq 2$$

For this design therefore $2P_1 = 2$ and $g$ was given as

$$g = (0.1 + 0.02 \times \sqrt[3]{5280}) \times 10^{-3} = 0.45 \times 10^{-4} \text{ m}$$

#### 2.5 The Stator Winding

The number of slots $N_1$ is given as

$$N_1 = 2 \times P_1 \times q \times m$$  \hspace{1cm} (2-10)

$$= 2 \times 1 \times 6 \times 3 = 36$$

In a two layer winding with chorded coils: $y / \tau = 0.8$, is chosen. Therefore the motor is of the fractional pitch of $10 / 12 = 0.833$. This pitch would reduce the effect of the 5th and 7th harmonics [15]. The 3rd harmonics are self eliminating by virtue of the three phase design of the stator [15].

The electrical angle between emfs in neighbouring slots $\alpha_{ea}$ is

$$\alpha_{ea} = (2 \times \pi \times P_1) / N_1$$  \hspace{1cm} (2-11)

$$= (2 \times \pi \times 1) / 36 = \pi / 18$$
The pitch factor $K_{P_1}$ [13] is

\[
K_{P_1} = \sin \left( \frac{P^*}{2} \right)
\]

\[
= \sin \left( \frac{150}{2} \right) = 0.924
\]

Where $P^*$ is the span of the coil in electrical degrees

The distribution factor $K_{d1}$ [13] is

\[
K_{d1} = \frac{\sin \left( q \times d^\prime / 2 \right)}{q \times \sin \left( d^\prime / 2 \right)}
\]

\[
= \frac{\sin \left( 6 \times 10 / 2 \right)}{(6 \times \sin (10 / 2))} = 0.956
\]

Where $d^\prime = \alpha_{ca}$

Therefore the stator winding factor $K_{W_1}$ [13] is

\[
K_{W_1} = K_{P_1} \times K_{d1} = 0.924 \times 0.956 = 0.907
\]

Now the number of turns per phase is determined on the value of the pole flux $\phi$, where flux $\phi$ is

\[
\phi = \alpha_1 \times \tau \times L \times B_g
\]

where $B_g$ is the air-gap flux density [13] and is specified in intervals as follows:

\[
B_g = (0.5 - 0.75)T \text{ for } 2 \times P_1 = 2
\]

\[
B_g = (0.65 - 0.78)T \text{ for } 2 \times P_1 = 4
\]

\[
B_g = (0.7 - 0.82)T \text{ for } 2 \times P_1 = 6
\]

\[
B_g = (0.75 - 0.85)T \text{ for } 2 \times P_1 = 8
\]

The spanning coefficient $\alpha_1$ [13] depends on the tooth saturation factor $1 + K_{sc}$. For $1 + K_{sc} = 1.4$, $\alpha_1 = 0.729$, $K_f = 1.085$, and for a 2 pole motor $B_g = 0.5T$.

Therefore $\phi = 0.729 \times 0.1594 \times 0.0957 \times 0.58 = 6.45 \times 10^{-3}$ Wb

The number of turns per phase $W_1$ [13] is

\[
W_1 = \frac{(K_E \times V_{1ph})}{(4 \times K_f \times K_{W1} \times f_1 \times \phi)}
\]
\[
W_1 = \frac{(0.975 \times 380 / \sqrt{3}) \times (4 \times 1.085 \times 0.907 \times 50 \times 6.45 \times 10^{-3})}{4 \times 1.085 \times 0.907\times 50 \times 6.45 \times 10^{-3}} = 168.641 \text{ turns/phase}
\]

Therefore the number of conductors per slot \(N_c\) is

\[
N_c = \frac{a_1 \times W_1}{P_1 \times q} \quad (2-17)
\]

\[
N_c = \frac{1 \times 168.641}{1 \times 6} = 28.107
\]

The number of conductors must be even, therefore \(N_c = 28\).

Hence the adjusted value of \(W_1 = W_{1A} = P_1 \times q \times N_c = 1 \times 6 \times 28 = 168\)

Therefore the actual flux density \(B_g = 0.5 \times \frac{W_1}{W_{1A}}\) \((2-18)\)

\[
B_g = 0.5 \times \frac{168.641}{168} = 0.58 \text{T}
\]

The rated current \(I_{1n}\) [13] is

\[
I_{1n} = \frac{P_n}{\eta_n \times \cos \phi_n \times \sqrt{3} \times V_1} \quad (2-19)
\]

Therefore \(I_{1n} = \frac{5280}{0.85 \times 0.85 \times \sqrt{3} \times 380} = 11.103 \text{ A}\)

The recommended current densities [13] are

\[
J_{\text{cos}} = (4 – 7) \text{ A/mm}^2 \text{ for } 2P_1 = 2, 4
\]

\[
J_{\text{cos}} = (5 – 8) \text{ A/mm}^2 \text{ for } 2P_1 = 6, 8
\]

For this design the value of current density \(J_{\text{cos}} = 7 \text{ A/mm}^2\) was chosen.

Now the magnetic wire cross section \(A_{Co}\) is

\[
A_{Co} = \frac{I_{1n}}{J_{\cos} \times a_1} \quad (2-21)
\]

Therefore \(A_{Co} = 11.103 / 7 = 1.586 \text{ mm}^2\)

From the conductor area \(A_{Co}\) the conductor diameter \(d_{Co}\) [13] is
\[ d_{Co} = \sqrt{4 \times A_{Co} / \pi} \]  
(2-22) 
\[ d_{Co} = \sqrt{4 \times 1.586 / 3.14} = 1.421 \text{ mm} \]  
Therefore \( d_{Co} \approx 1.3 \text{ mm} \)

In general if \( d_{Co} \geq 1.3 \text{ mm} \) in low power induction motors, a few conductors may be used in parallel [13] in which case \( a_1 \) becomes \( a_p > 1 \). Since \( d_{Co} = 1.4 \text{ mm} \) is approximately equal to \( d_{Co} = 1.3 \text{ mm} \), the conductor diameter of \( d_{Co} = 1.3 \text{ mm} \) was used to avoid designing a motor with conductors in parallel. With this reduction however, the conductor temperature was expected to be slightly higher than it would otherwise be and this turned out to be 4 degrees higher on maximum temperature. The design of the stator winding is shown in Figure 2-8.

### 2.6 Stator Slot Sizing

In calculating the slot sizing a factor known as slot fill \( K_{fill} \) with the known values of \( N_c \) and \( a_p \) were used. For round wire the slot fill, \( K_{fill} \approx 0.35 \) to 0.4 below 10 kW, and 0.4 to 0.5 above 10 kW [13]. Therefore the useful slot area \( A_{su} \) is

\[ A_{su} = (\pi \times d_{Co}^2 \times a_p \times N_c) / (4 \times K_{fill}) \]  
(2-23) 
Therefore for \( K_{fill} = 0.4 \), \( A_{su} \) is

\[ A_{su} = (3.14 \times 1.3^2 \times 1 \times 28) / (4 \times 0.4) = 111.03 \text{ mm}^2 \]  
\[ A_{su} = 111 \text{ mm}^2 \]

For this design a trapezoidal shape was used. For this type of shape the stator tooth is rectangular see Figure 2-2. In Figure 2-2 the variables \( b_{os}, h_{os}, h_w \) are assigned values from accepted practice as, \( b_{os} = 2 \) to 3 mm ≤ 8g, \( h_{os} = (0.5 \) to 1.0), wedge height \( h_w = 1 \) to 4 mm.

Now assuming that all the air-gap flux passes through the stator teeth, then

\[ B_g \times \tau_s \times L = B_{ts} \times b_{ts} \times L \times K_{Fe} \]  
(2-24) 
Where \( K_{Fe} \approx 0.96 \) for 0.5 mm thick lamination, and \( B_{ts} \) is given as

\[ B_{ts} = 1.5 - 1.65T. \]  
(2-25) 
Therefore \( B_{ts} = 1.6T \) was chosen.
From Equation 2-24 $b_{ts}$ is

$$b_{ts} = \frac{0.58 \times 8.8565 \times 10^{-3}}{1.6 \times 0.96} = 3.344 \times 10^{-3} \text{ m}$$

From acceptable practice the value of tooth width $b_{ts} > 3.5 \times 10^{-3} \text{ m}$ [13] therefore the value of $b_{ts} = 3.3 \times 10^{-3} \text{ m}$, being just below the lower limit is acceptable.

Now from the assigned value ranges of $b_{os}$, $h_{os}$ and $h_w$, the following values are assigned, $b_{os} = 2.4 \times 10^{-3} \text{ m}$, $h_{os} = 1.0 \times 10^{-3} \text{ m}$, $h_w = 1.5 \times 10^{-3} \text{ m}$, therefore the slot lower width $b_{s1}$ (Figure 2-2) is

$$b_{s1} = \pi \left( \frac{D_{sbd} + 2 \times h_{os} + 2 \times h_w}{N_1} \right) - b_{ts}$$

(2-26)

$$b_{s1} = 3.14 \left( \frac{0.1015 + 2 \times 1.0 \times 10^{-3} + 2 \times 1.5 \times 10^{-3}}{36} \right) - 3.344 \times 10^{-3}$$

$$= 5.95 \times 10^{-3} \text{ m}$$

The useful area of the slot $A_{su}$ (Figure 2-2) may be expressed as

$$A_{su} = h_s \left( b_{s1} + b_{s2} \right) / 2$$

(2-27)

And

$$b_{s2} \approx b_{s1} + 2 \times h_s \times \tan \left( \pi / N1 \right)$$

(2-28)

From Equation 2-27 and 2-28 the unknown values of $b_{s2}$ and $h_s$ were computed.

Therefore

$$b_{s2}^2 - b_{s1}^2 = 4 \times A_{su} \times \tan \left( \pi / N1 \right)$$

(2-29)
Therefore \( b_{s2} = \sqrt{(4 \times A_{su} \times \tan(\pi/N1)) + b_{s1}^2} \) \hspace{1cm} (2-30)

\[
b_{s2} = 10^{-3} \times \sqrt{(4 \times 111.03 \times \tan(3.14/36) + 5.95^2)} = 8.62 \times 10^{-3} \text{ m}
\]

And the slot useful height \( h_s \) is

\[
h_s = \frac{2 \times A_{su}}{(b_{s1} + b_{s2})} \hspace{1cm} (2-31)
\]

therefore \( h_s = \frac{2 \times 111}{5.95 + 8.62} = 15.24 \times 10^{-3} \text{ m} \)

\[
h_s = 15 \times 10^{-3} \text{ m}
\]

The teeth saturation factor \( 1 + K_{sc} \) was then calculated as follows,

\[
1 + K_{sc} = 1 + \frac{(F_{mts} + F_{mtr})}{F_{mg}} \hspace{1cm} (2-32)
\]

The airgap mmf \( F_{mg} \) is

\[
F_{mg} \approx 1.2 \times g \times B_g / \mu_0 \hspace{1cm} (2-33)
\]

For \( g = 0.45 \times 10^{-3} \text{ m} \) (Equation 2-9)

\[
F_{mg} = (1.2 \times 0.45 \times 10^{-3}) \times 0.58 / (1.256 \times 10^{-6}) = 249.349 \text{ Aturns}
\]

From Equation 2-25 \( B_{ts} = 1.6 \text{T} \), and from the magnetisation curve (Table A-4) \( H_{ts} = 2460 \text{ A/m} \).

Therefore the stator tooth mmf \( F_{mts} \) is

\[
F_{mts} = H_{ts} (h_s + h_{os} + h_w)
\]

Therefore \( F_{mts} = 2460 \times (15 + 1.0 + 1.5) \times 10^{-3} = 43.66 \text{ Aturns} \) \hspace{1cm} (2-34)

Now from Equation 2-32 and assuming \( 1 + K_{sc} = 1.4 \), rotor tooth mmf \( F_{mtr} \) was calculated.

\[
F_{mtr} = K_{sc} \times F_{mg} - F_{mts} \hspace{1cm} (2-35)
\]

\[
F_{mtr} = 0.4 \times 249.349 - 43.66 = 56.0796 \text{ Aturns}
\]

The value of \( F_{mtr} \) is approximately equal to that of \( F_{mts} \), therefore \( F_{mtr} \approx F_{mts} \), and this satisfies step 4 of the algorithm. Therefore no further iterations are necessary.

After closing step 4 in the flow chart (Figure 2-1) the stator back iron height \( h_{cs} \) (Figure 2-2) was calculated.
Chapter 2: The Polyphase Induction Motor Design

\[ h_{cs} = \frac{((D_{out} - ((D_{sbd} + 2(h_{os} + h_{w} + h_{s}))) / 2}{2} \]  \hspace{1cm} (2-36)

\[ h_{cs} = \frac{((180 - ((101.5 + 2(1 + 1.5 + 15.2))) / 2 = 21.5 \text{ mm} \]  Having calculated \( h_{cs} \), the back core flux density \( B_{cs} \) was verified using the calculated value of flux \( \phi = 5.5603 \times 10^{-3} \text{ Wb} \) (Equation 2-14).

\[ B_{cs} = \frac{\phi}{(2 \times L \times h_{cs})} \]  \hspace{1cm} (2-37)

\[ B_{cs} = \frac{6.45 \times 10^{-3}}{(2 \times (95.65 \times 21.5) \times 10^{-3})} = 1.6T \]  This value of \( B_{cs} \) is within the range for \( B_{cs} = 1.4 \) to \( 1.7T \). If this had not been the case it would have been necessary to adjust either of the following: increase the stator outside diameter \( D_{out} \), or use a bigger stack aspect ratio \( \lambda \) which would reduce the stator bore diameter \( D_{sbd} \), or increase the back iron height \( h_{cs} \), to lower \( B_{cs} \). The other alternative is to increase the current density which would result in the reduction of \( h_{s} \). In this work this did not apply since is within range, \( B_{cs} = 1.6T \). The developed stator design is shown in Figure 2-6.

2.7 Rotor Slot Sizing

The selection of the number of rotor slots \( N_{2} \) was based on theoretical analysis dating back as far as 1909 plus proven experience on the rules for slot combination of which the most prominent is that \( N_{2} \) should be either below or above \( N_{1} \) by 15 to 20\% of \( N_{1} \) [13]. In this particular design \( N_{2} \) was taken to be 15\% below \( N_{1} \), therefore,

\[ N_{2} = N_{1} - 0.15 \times N_{1} \]  \hspace{1cm} (2-38)

\[ N_{2} = 36 - 0.15 \times 36 = 30 \]  The other rule is that \( N_{2} \) must be an even number therefore \( N_{2} = 30 \) is acceptable.

Now the value of rated rotor bar current \( I_{b} \) [13] is

\[ I_{b} = K_{1} \times (2 \times m \times W_{1} \times K_{w1} / N2) \times I_{1n} \]  \hspace{1cm} (2-39)

When \( K_{1} = 1 \), the stator and rotor mmf's are equal and yet in reality the stator mmf is larger than the rotor mmf, therefore \( K_{1} \) is,

\[ K_{1} \approx 0.8 \cos \phi \ln + 0.2 \]  \hspace{1cm} (2-40)

Development of the electric motor
\[ K_1 = 0.8 \times 0.85 + 0.2 = 0.88 \]

Therefore the rotor bar current \( I_b \) (Equation 2-39) is

\[
I_b = 0.88 \times (2 \times 3 \times 168 \times 0.907 / 30) \times 11.103 = 298.78 \text{ A}
\]

For high efficiency, the current density in the rotor bar \( J_b = 3.42 \text{ A/mm}^2 \). The rotor slot area is

\[
A_b = \frac{I_b}{J_b} \quad (2-41)
A_b = \frac{298.78}{3.42} = 87.36 \times 10^{-6} \text{ m}^2
\]

The end ring current \( I_{er} \) is

\[
I_{er} = \frac{I_b}{(2 \times \sin(\pi \times P_1 / N_2))} \quad (2-42)
I_{er} = \frac{298.78}{(2 \times \sin (3.14 \times 1 / 30))} = 1429.903 \text{ A}
\]

The current density in the end ring \( J_{er} \) is

\[
J_{er} = (0.75 - 0.8) \times J_b \quad (2-43)
\]

Whereby the selection of \( J_{er} \) is

\[
J_{er} = 0.75 \times J_b = 0.75 \times 3.45 \times 10^6 = 2.57 \times 10^6 \text{ A/m}^2
\]

Therefore the end ring cross section \( A_{er} \) is

\[
A_{er} = \frac{I_{er}}{J_{er}} \quad (2-44)
A_{er} = \frac{1429.903}{(2.57 \times 10^6)} = 557.5 \times 10^{-6} \text{ m}^2
\]

Figure 2-3 below shows the variables of the rotor slot.
The rotor slot pitch is given by the Equation

$$\tau_r = \pi \left( D_{sbd} - 2g \right) / N_r$$ \hspace{1cm} (2-45)

Therefore

$$\tau_r = \pi \left( 0.1015 - 2 \times 0.45 \right) / 30 = 10.5 \times 10^{-3} \text{ m}$$

Now the tooth width is

$$b_{tr} \approx \left( B_g / K_{Fe} \times B_{tr} \right) \times \tau_r$$ \hspace{1cm} (2-46)

From Equation 2-25 $B_{tr} = 1.6T$, therefore

$$b_{tr} = \left( 0.58 / 0.96 \times 1.6 \right) \times 10.5 \times 10^{-3} = 3.99 \times 10^{-3} \text{ m}$$

To determined $d_1$ (the top rotor diameter) following the formula was used (Note $D_{re} = D_{sbd}$)

$$\pi \left( D_{sbd} - 2 \times h_{or} - d_1 \right) / N2 = d_1 + b_{tr}$$ \hspace{1cm} (2-47)
Therefore \(d_1\) is

\[
d_1 = \left( \frac{\pi (D_{re} - 2 \times h_{or}) - N2 \times b_{tr}}{\pi + N2} \right)
\]  

(2-48)

Therefore

\[
d_1 = \left( \frac{\pi (101.5 - 2 \times 0.5 - 0.9) - 30 \times 3.99}{3.14 + 30} \right) = 5.9 \times 10^{-3} \text{ m}
\]

to calculate the value of \(d_2\) and \(h_r\) the following formulas of the slot area were applied

\[
A_b = \frac{\pi}{8} (d_1^2 + d_2^2) + \frac{(d_1 + d_2) \times h_r}{2}
\]  

(2-49)

\[
d_1 - d_2 = 2 \times h_r \times \tan \left( \frac{\pi}{N2} \right)
\]  

(2-50)

Using Equation 2-49 and making \(h_r = 15.2 \times 10^{-3} \text{ m}\), same as \(h_s\)

\[
d_2 = 5.9 \times 10^{-3} - 2 \times 15.2 \times 10^{-3} \times \tan \left( \frac{3.14}{30} \right) = 2.7 \times 10^{-3} \text{ m}
\]

This value of \(d_2 = 2.7 \times 10^{-3} \text{ m}\) did not satisfy \(A_b\) (Equation 2-41) = 87.36 \times 10^{-6} \text{ m}^2, so a series of iterations were done using Equation 2-49 and 2-50 and at \(h_r = 19.4 \times 10^{-3} \text{ m}\), \(d_2 = 1.8 \times 10^{-3} \text{ m}\) and \(A_b = 87.54 \times 10^{-6} \text{ m}^2\), this was satisfactory.

Therefore the values of \(h_r\) and \(d_2\) are

\[
\begin{align*}
h_r & = 19.4 \text{ mm} \\
d_2 & = 1.8 \text{ mm}
\end{align*}
\]

At this value of \(h_r\), \(d_1\) and \(d_2\) the rotor tooth mmf \(F_{mtr}\) was calculated to see how it compares with the earlier calculated value of \(F_{mtr} = 56.09 \text{ Aturns}\). At \(B_{tr} = B_{ts} = 1.6 \text{T}\) (Table A-4), \(H_{tr} = 2460 \text{ Aturns}\) and \(F_{mtr}\) is

\[
F_{mtr} = H_{tr} \times (h_r + h_{or} + ((d_1 + d_2) / 2))
\]  

(2-51)

\[
= 2460 \times (19.4 + 0.5 + ((5.9 + 1.8) / 2)) \times 10^{-3} = 58.43 \text{ Aturns}
\]

This calculated value (Equation 2-51) of \(F_{mtr} = 58.43 \text{ Aturns}\) is very close to the earlier calculated value (Equation 2-35) of \(F_{mtr} = 56.09 \text{ Aturns}\). Therefore the design is acceptable.

The next parameter to calculate was the rotor back core height \(h_{cr}\). For this calculation a value of \(B_{cr} = 1.4\) was used since the range of \(B_{cr} = 1.4 - 1.7 \text{T}\). Therefore the \(h_{cr}\) is

\[\text{Development of the electric motor}\]
The maximum shaft diameter $D_{\text{shaft}}$ is

$$D_{\text{shaft}} \leq D_{\text{bd}} - 2 \times g - 2 \times (h_{or} + ((d_1 + d_2) / 2)) + h_r + h_{cr}$$

$$= 101.5 - 2 \times 4.5 \times 10^{-4} - 2 \times (0.5 + ((5.9 + 1.8) / 2)) + 19.4 + 20.4$$

$$= 12.0 \text{ mm}$$

The shaft diameter must correspond to the rated torque $T_{en}$ given by the tables and often by comparison from past designs. The rated torque is

$$T_{en} = \frac{P_n}{2 \times \pi \times \left(\frac{f_1}{P_1}\right) \times (1 - S_n)}$$

$$= 5280 \times (2 \times 3.14 \times (50 / 1) \times (1 - 0.05) = 17.7 \text{ Nm}$$

For this design the 14 mm left for shaft diameter suffices. However the shaft diameter of 22 mm given by Nyirenda [1] might be on the high side and therefore a shaft diameter of $D_{\text{shaft}} = 14 \text{ mm}$ is recommended. The developed rotor design is shown in Figure 2-7.

The end ring cross section is shown in Figure 2-4 below.

Figure 2-4 End Ring Cross-Section
In general $D_{sbld} - D_{cr} = (3 - 4) \times 10^{-3}$ and also

$$b = (1.0 - 1.2) \times ((h_r + h_or + (d_1 + d_2) / 2) \quad (2-55)$$

From Equation 2-56 b is

$$b = 1.0 \times (h_r + h_or + (d_1 + d_2) / 2) \quad (2-57)$$

$$b = 1.0 \times (19.4 + 0.5 + (5.9 + 1.8) / 2) = 23.9 \text{ mm}$$

the dimension $a$ is

$$a = \frac{A_{cr}}{b} \quad (2-58)$$

$$a = \frac{557.5 \times 10^{-6}}{23.9 \times 10^{-3}} = 23.3 \text{ mm}$$

The Magnetisation current $I_0$ is

$$I_0 = \frac{(\pi \times P1 \times (F_{1m} / 2)) / (3 \times \sqrt{2} \times W_1 \times K_{w1})}{(2-59)}$$

where $F_{1m}$ is

$$F_{1m} = 2 \times (K_c \times g \times b_g / \mu_o + F_{mts} + F_{mtr} + F_{mcs} + F_{mcr}) \quad (2-60)$$

And $K_c$, $F_{mcs}$ and $F_{mcr}$ are calculated as follows

$K_c$ is called Carter’s coefficient and is calculated as follows

$$\gamma_1 = \frac{b_{os}^2}{(5 \times g + b_{os})} \quad (2-61)$$

$$\gamma_1 = \frac{(2.2 \times 10^{-3})^2}{(5 \times 4.5 \times 10^{-4} + 2.2 \times 10^{-3})} = 1.09 \times 10^{-3} \text{ m}$$

$$\gamma_2 = \frac{b_{or}^2}{(5 \times g + b_{or})} \quad (2-62)$$

$$\gamma_2 = \frac{(1.5 \times 10^{-3})^2}{(5 \times 0.45 \times 10^{-3} + 1.5)} = 0.60 \times 10^{-3} \text{ m}$$

Where $K_{c1}$ and $K_{c2}$ are given by the formulas involving $\gamma_1$ and $\gamma_2$ as follows

$$K_{c1} = \frac{\tau_s}{(\tau_s - \gamma_1)} \quad (2-63)$$

$$K_{c1} = 8.865 \times 10^{-3} / (8.865 - 1.09) \times 10^{-3} = 1.14$$

$$K_{c2} = \frac{\tau_r}{(\tau_r - \gamma_2)} \quad (2-64)$$
\[ K_{c2} = 10.5 \times 10^{-3} / (10.5 - 0.6) \times 10^{-3} = 1.061 \]

Therefore \[ K_c = K_{c1} \times K_{c2} \]
\[ K_c = 1.14 \times 1.061 = 1.21 \] (2-65)

Now \( F_{mcs} \) and \( F_{mcr} \) are given by the following

\[ F_{mcs} = C_{cs} \times \pi \times \frac{(D_{out} - h_{cs})}{2 \times P_1} \times H_{cs}(B_{cs}) \] (2-66)

And

\[ F_{mcr} = C_{cr} \times \pi \times \frac{(D_{shaft} + h_{cr})}{2 \times P_1} \times H_{cr}(B_{cr}) \] (2-67)

Where

\[ C_{cs} = C_{cr} \approx 0.88 \times e^{-0.4xBcs,r²} \] (2-68)

And for \( B_{cs} = 1.5T, H_{cs} = 1340 \text{ A/m}, B_{cr} = 1.65T, H_{cr} = 3460 \text{ A/m} \) (2-69)

Therefore from Equation 2-66 \( F_{mcs} \) is

\[ F_{mcs} = 0.88 \times e^{-0.4 \times 1.5²} \times 3.14 \times ((180 - 21.5) / 2 \times 1) \times 1340 = 119.32 \text{ Aturms} \]

\[ F_{mcr} = 0.88 \times e^{-0.4 \times 1.65²} \times ((12 + 20.4) / 2 \times 1) \times 3460 = 57.45 \text{ Aturms} \]

Therefore from Equation 2-60 \( F_{1m} \) is

\[ F_{1m} = 2 \times ((1.21 \times 0.45 \times 10^{-3} \times 6.45 \times 10^{-3} / 1.3 \times 10^{-6}) + 43.66 + 56.08 + 119.32 + 57.45) \]
\[ F_{1m} = 1055.60 \text{ Aturms} \]

The total saturation factor \( K_s \) is

\[ K_s = \frac{F_{1m}}{(2 \times F_{mg})} - 1 \] (2-70)

\[ K_s = (1055.60 / (2 \times 249.349)) - 1 = 1.1167 \]

From Equation 2-59 the magnetisation current \( I_o \) is

\[ I_o = (3.14 \times 1 \times (1055.60 / 2)) / 3 \times \sqrt{2} \times 168 \times 0.907 = 2.55 \text{ A} \]

And the unit per unit value \( i_o \) is

\[ i_o = I_o / I_{in} \] (2-71)
\[ i_o = 2.55 / 11.103 = 0.23 \]
2.8 Resistances and Inductances

Resistances and inductances are shown in Figure 2-5 below.

\[ I_s \quad R_s \quad jw_1L_{s1} \quad I_f \quad jw_1L_{r1} \]

\[ V_s \]

\[ I_o \quad jw_1L_m \quad R_o/S \]

Figure 2-5 The Equivalent Circuit of an Induction Motor (Core Losses ignored)

The stator phasor resistance \( R_s \) is

\[ R_s = \rho_{co} x (I_c x W_1) / A_{co} x a_1 \]  \hspace{1cm} (2-72)

Where \( I_c \) is

\[ I_c = 2 x (L + I_{end}) \]  \hspace{1cm} (2-73)

The coil end connection depends on the coil span \( y \). Number of poles \( P \), shape of coils, and number of layers in the winding.

Therefore \( I_{end} = 2 x y - 0.04 \text{ m} \) for \( 2 \times P_1 = 2 \) \hspace{1cm} (2-74)

And the ratio \( y / \tau = \beta \) called the chording factor = 15 / 18 \hspace{1cm} (2-75)

Where the acceptable values of \( \beta \) are \( 2 / 3 \leq \beta \leq 1 \) \hspace{1cm} (2-76)

Therefore \( \beta = 15 / 18 = 0.833 \) is acceptable and therefore
\[
y = \beta \times \tau \tag{2-77}
\]
\[
y = 0.83333 \times 0.1594 = 0.13285 \text{ m}
\]

and from Equation 2-74 \( I_{\text{end}} \) is
\[
I_{\text{end}} = 2 \times 0.13285 - 0.04 = 0.2457 \text{ m}
\]

And from Equation 2-73 \( I_c \) is
\[
I_c = 2 \times (0.0957 + 0.2457) = 0.6828 \text{ m}
\]

Now induction motor of high efficiency are desired and in designing for this requirement the winding temperature is regard important and must not be large even if the insulation class is F. In this design therefore similar caution was observed. To achieve this the motor was designed for copper resistivity \((\rho_{Co})_{80^\circ C} \) at 80°C. Now for copper resistivity at 20°C, \((\rho_{Co})_{20^\circ C} = 1.78 \times 10^{-8} \Omega \text{ m} \).

And at 115°C, \((\rho_{Co})_{115^\circ C} = 1.37 \times (\rho_{Co})_{20^\circ C} \).

Therefore at copper resistivity = 80°C, \((\rho_{Co})_{80^\circ C} \) is
\[
(\rho_{Co})_{80^\circ C} = (\rho_{Co})_{20^\circ C} \times (1 + (1 / 273) \times (80 - 20)) \tag{2-78}
\]

\[
(\rho_{Co})_{80^\circ C} = 1.78 \times 10^{-8} \times (1 + (1 / 273) \times (80 - 20)) = 2.171 \times 10^{-8} \Omega \text{ m}
\]

Therefore the stator phasor resistance \( R_s \) (Equation 2-72) is
\[
R_s = 2.171 \times 10^{-8} \times ((0.6828 \times 168) / (1.586 \times 10^{-6} \times 1)) = 1.570 \Omega
\]

And the rotor bar-end ring equivalent resistance \( R_{be} \) is
\[
R_{be} = \rho_{A1} \times ((L / A_b) \times K_R + (\tau_{er} / (2 \times A_{er} \times \sin^2(\pi \times P_1 / 2)))) \tag{2-79}
\]

Where \( \rho_{A1} \) is the cast aluminium resistivity and at 20°C \((\rho_{A1})_{20^\circ C} = 3.1 \times 10^{-8} \Omega \text{ m} \) (2-80)

The end-ring length \( \tau_{\text{end}} = \pi \times (D_{er} - b) / N_2 \) (2-81)

Now from Equation 2-55 \( D_{er} = D_{sbd} - 2 \times g - 2 \times 3 \times 10^{-3} \text{ m} \) (2-82)
\[
D_{er} = 94.64 \times 10^{-3} \text{ m}
\]
And from Equation 2-81 the end-ring length $t_{\text{end}}$ is

$$t_{\text{end}} = 3.14 \times (94.64 - 23.9) / 30 = 7.36 \text{ mm}$$

In Equation 2-79, $K_R$ is the approximate skin effect resistance coefficient, for a rectangular slot, and is

$$K_R = \xi \times (\sinh(2 \times \xi) + \sin(2 \times \xi)) / (\cosh(2 \times \xi) - \cos(2 \times \xi)) \approx \xi$$  \hspace{1cm} (2-83)

And

$$\xi = \beta_s \times h_s \times \sqrt{S}, \text{ where } S = 1$$  \hspace{1cm} (2-84)

And

$$\beta_s = \sqrt{\left(\frac{\omega_1 \times \mu_0}{2 \times \rho A_1}\right)}$$  \hspace{1cm} (2-85)

$$\beta_s = \sqrt{\left(\frac{314 \times 1.3 \times 10^{-6}}{2 \times 3.1 \times 10^{-8}}\right)} = 80 \text{ (m)}^{-1}$$

And from Equation 2-83

$$\xi = 80 \times 19.4 \times 10^{-3} \times \sqrt{1} = 1.56$$

From Equation 2-83

$$K_R = \xi = 1.56$$  \hspace{1cm} (2-86)

Now from Equation 2-79, $R_{be80^\circ C}^{S=1}$ is

$$(R_{be80^\circ C})^{S=1} = 3.1 \times 10^{-8} \times (1+1/273 \times (80-20)) \times \left((95.7 \times 10^{-3}) / 87.36 \times 10^{-6}\right) \times 1.56 + (7.36 \times 10^{-3} / 2 \times 557.5 \times 10^{-6} \times \sin(3.14 \times 1/30))$$

$$(R_{be80^\circ C})^{S=1} = 6.612 \times 10^{-5} \text{ Ω}$$

The rotor cage resistance reduced to the stator $R'_r$ is

$$(R'_r)_{S=1} = ((4 \times m) / N2) \times (W_1 \times K_{W1})^2 \times R_{be80^\circ C}$$  \hspace{1cm} (2-87)

$$= ((4 \times 3) / 30) \times (168 \times 0.907)^2 \times 6.612 \times 10^{-5} = 0.614 \text{ Ω}$$

The stator phase leakage reactance $X_{s1}$ is

$$X_{s1} = 2 \times \mu_0 \times \omega_1 \times L \times (W_1^2 / (P_1 \times q)) \times (\lambda_s + \lambda_{ds} + \lambda_{ec})$$  \hspace{1cm} (2-88)

Where $\lambda_s$, $\lambda_{ds}$, $\lambda_{ec}$ are the slot differential and end ring connection coefficients:
And \[
\lambda_s = (((2 / 3) x (h_s / (b_{s1} + b_{s2})) + ((2 x h_u) / (b_{os} + b_{s1})) + (h_{os} / b_{os})) x \\
((1 + 3 x \beta) / 4) \] (2-89)

\[
\lambda_s = (((2/3)x(15 x 10^{-3} / (5.95 + 8.62) x 10^{-3}) + ((2 x 1.5 x 10^{-3}/(1.5 + 5.95)x10^{-3}) + \\
(1 / 1.5)) x ((1 + 3 x (15 / 18)) / 4) = 1.331
\]

And \[
\lambda_{ds} = (0.9 x \tau_s x q^2 x K_{w1}^2 x C_s x \gamma_{ds}) / (K_c x g x (1 + K_{st})) \] (2-90)

Where \[
C_s = 1 - 0.033 x (b_{os}^2 / (g x \tau_s)) \] (2-91)

\[
= 1 - 0.033 x ((1.5 x 10^{-3})^2 / (0.45 x 10^{-4} x 8.865 x 10^{-3}) = 0.960
\]

And \[
\gamma_{ds} = (0.11 x \sin(\phi_1 + 0.41) x 10^{-2}; \text{ for } q = 6 \] (2-92)

Where \[
\phi_1 = \pi x (6 x \beta - 5.5) \] (2-93)

From Equation 2-93 \[
\phi_1 = 3.14 x (6 x 0.8333 - 5.5) = -1.57
\]

From Equation 2-92 \[
\gamma_{ds} = (0.11 x \sin(-1.57) + 0.41) x 10^{-2} = 3 x 10^{-3}
\]

From Equation 2-90 \[
\lambda_{ds} = (0.9 \times 8.865 \times 10^{-3} \times 6^2 \times 0.907^2 \times 0.96 \times 3 \times 10^{-3} / (1.21 \times 0.45 \times 10^{-4} \times 1.4) = 0.8948
\]

This design being a two layer winding, the end connection specific geometric permeance coefficient \(\lambda_{ec}\) is

\[
\lambda_{ec} = 0.34 x (q / L) x (I_{end} - 0.64 x \beta x \tau) \] (2-94)

\[
= 0.34 x (6 / (95.7 \times 10^{-3})) x (245.7 \times 10^{-3} - 0.64 x 0.8333 x 159.4 \times 10^{-3})
\]

\[
= 3.427
\]

From Equation 2-88 \[
X_{s1} = 2 \times 1.3 \times 10^{-6} \times 139 \times 95.7 \times 10^{-3} \times (1682 / (1 \times 6)) + 1.331 + 0.8948 + 3.427
\]

\[
X_{s1} = 2.021 \Omega
\]

The equivalent rotor bar leakage reactance \(X_{be}\) is

\[
X_{be} = 2 x \pi x f_1 x \mu_o x L x (\lambda_r x K_x + \lambda_{dr} + \lambda_{er}) \] (2-95)

Where \(\lambda_r, \lambda_{dr}, \lambda_{er}\) are the rotor slot differential and end ring permeance coefficient,
\[
\lambda_r = 0.66 + (2 \times h_r / (3 \times (d_1 + d_2))) + h_{or} / b_{or} \quad (2-96)
\]

\[
\lambda_r = 0.66 + (2 \times 19.4 \times 10^{-3} / (3 \times (5.9 + 1.8))) + 0.5 / 1.5 = 2.679
\]

And the differential coefficient \(\lambda_{dr}\) is

\[
\lambda_{dr} = ((0.9 \times \tau_r \times \gamma_{dr}) / (K_c \times g)) \times (N_r / (6 \times P_1))^2 \quad (2-97)
\]

and

\[
\gamma_{dr} = 9 \times (6 \times P^1 / N^2)^2 \times 10^{-2} \quad (2-98)
\]

Therefore

\[
\gamma_{dr} = 9 \times (6 \times 1 / 30)^2 \times 10^{-2} = 0.36 \times 10^{-2}
\]

From Equation 2-97

\[
\lambda_{dr} = ((9 \times 10.5 \times 10^{-3} \times 0.36 \times 10^{-2}) / (1.21 \times 0.45 \times 10^{-4})) \times (30 / (6 \times 1))^2
\]

\[
= 1.574
\]

And the end-ring coefficient \(\lambda_{er}\) is

\[
\lambda_{er} = ((2.3 \times (D_{er} - b)) / N^2 \times L \times 4 \times \sin^2(\pi x P_1 / N^2)) \times \log((4.7 \times (D_{er} - b)) / (b + 2 x a)) \quad (2-99)
\]

\[
= ((2.3 \times (94.64 - 23.9) \times 10^{-3}) / 30 \times 95.7 \times 10^{-3} \times 4 \times \sin^2(3.14 \times 1 / 30)) \times \log((4.7 \times (94.64 - 23.90 \times 10^{-3}) / (23.9+2x23.3) \times 10^{-3}) = 0.8691
\]

The skin coefficient for the leakage reactance \(K_x (\xi = 1.56)\) is

\[
K_x = (3/(2 \times \xi)) \times ((\sinh(2 x \xi) - \sin(2 x \xi)) / (\cosh(2 x \xi) - \cos(2 x \xi))) = 3 / (2 x \xi) \quad (2-100)
\]

\[
K_x = (3 / (2 \times 1.56)) = 0.964
\]

From Equation 2-95 \(X_{be}\) is

\[
X_{be} = 2 \times 3.14 \times 50 \times 1.3 \times 10^{-6} \times 95.7 \times 10^{-3} \times (2.679 \times 0.964 + 1.574 + 0.8691)
\]

\[
= 1.9 \times 10^{-4} \Omega
\]

The rotor leakage reactance \(X_{r1}\) is a function of \(X_{be}\) and is given as

\[
X_{r1} = 4 \times m_1 \times ((W_1 \times K_{er})^2 / N^2) \times X_{be} \quad (2-101)
\]

\[
X_{r1} = 4 \times 3 \times ((168 \times 0.907)^2 / 30) \times 1.9 \times 10^{-4} = 1.7597 \Omega
\]
At standstill \( S = 1 \), both stator and rotor leakage reactance are reduced due to leakage flux path saturation. For power levels in semi-closed stator and rotor slots, therefore

\[
(X_{s1})^{S=1}_{\text{sat}} = X_{s1} \times (0.7 - 0.8) \approx X_{s1} \times 0.75 \quad (2-102)
\]

\[
= 2.021 \times 0.75 = 1.516 \Omega
\]

\[
(X_{r1})^{S=1}_{\text{sat}} = X_{r1} \times (0.6 - 0.7) \approx X_{r1} \times 0.65 \quad (2-103)
\]

\[
= 1.7597 \times 0.65 = 1.144 \Omega
\]

For rated slip (speed), both skin and leakage saturation effects are undesirable and must be eliminated by making \( K_R = K_s = 1 \)

Therefore from Equation 2-79 \((R_{be80°C})_{Sn}\) is

\[
(R_{be80°C})_{Sn} = 3.1 \times 10^{-8} \times (1 + (1/273) \times (80-20)) \times ((95.7 \times 10^{-3}/8.736 \times 10^{-5}) \times 1 + \\
7.4 \times 10^{-3}/(2 \times 557.5 \times 10^{-6} \times \sin^2(3.14 \times 1/30)) = 6.43 \times 10^{-5} \Omega
\]

The rotor resistance \((R_r')_{Sn}\) is

\[
(R_r')_{Sn} = (R_r')^{S=1}_{Sn} \times R_{be80°C}^{S=Sn} / R_{be80°C}^{S=1} \quad (2-104)
\]

\[
(R_r')^{S=1}_{Sn} = 0.614 \times 6.44 \times 10^{-5} / 6.612 \times 10^{-5} = 0.598 \Omega
\]

The magnetisation \(X_m\) is

\[
X_m = \sqrt{(V_{ph} / I_0)^2 - R_s^2} - X_{s1} \quad (2-105)
\]

\[
= \sqrt{(219.393 / 2.55)^2 - 1.57^2} - 2.021 = 84 \Omega
\]

The skewing effect on reactances

In most designs rotor slots are skewed. The topic of skewing is however not the subject of this design. Nevertheless it is sufficient to know that a skewing factor \( C \) of one stator slot pitch \( \tau_s \) is typical \( C = \tau_s \)

The effect of skewing on \(X_m\) is

\[
(X_m)_{skew} = X_m \times K_{skew} \quad (2-106)
\]
And \( K_{\text{skew}} = \sin(\pi / 2 x C / \tau) / (\pi / 2 x C / \tau) = \sin(\pi / 2 x \tau_s / \tau) / (\pi / 2 x \tau_s / \tau) \)

Therefore \( K_{\text{skew}} = \sin(3.14 / 2 x 8.865 x 10^{-3} / 159.4 x 10^{-3}) = 0.9987 \)

Therefore from Equation 2-106 \((X_m)_{\text{skew}}\) is

\[(X_m)_{\text{skew}} = 84 \times 0.9987 = 83.73 \Omega\]

The rotor leakage inductance is augmented by a new term \(X'_{r1\text{skew}}\) equal to

\[X'_{r1\text{skew}} = X_{mskew} \times (1 - K_{\text{skew}}^2) \quad \text{(2-107)}\]

\[= 83.73 \times (1 - 0.9987^2) = 0.2121 \Omega\]

The final values of rotor reactance at \( S=1 \) and \( S = S_n \) respectively are

\[\begin{align*}
(X_{r1})_{\text{skew}}^{S=1} &= (X_{r1})_{\text{sat}}^{S=1} + X'_{r1\text{skew}} \\
&= 1.144 + 0.2121 = 1.356 \Omega
\end{align*}\]

\[\begin{align*}
(X_{r1})_{\text{skew}}^{S=S_n} &= X_{r1} + X'_{r1\text{skew}} \\
&= 1.7597 + 0.2121 = 1.972 \Omega
\end{align*}\]

### 2.9 Losses and Efficiency

Efficiency \( \eta \) is defined as the output divided by the input power and is given by the expression,

\[\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{P_{\text{out}}}{P_{\text{in}} + \sum \text{losses}} \quad \text{(2-110)}\]

The loss components are

\[\sum \text{losses} = P_{\text{Co}} + P_{\text{A1}} + P_{\text{iron}} + P_{\text{mv}} + P_{\text{stray}} \quad \text{(2-111)}\]

Where \( P_{\text{Co}} \) is the stator winding losses and is equal to

\[P_{\text{Co}} = 3 \times R_s \times I_{in}^2 \quad \text{(2-112)}\]

\[= 3 \times 1.575 \times 11.103^2 = 580.642 \text{ W}\]

And \( P_{\text{A1}} \) is the rotor cage losses, therefore

\[\]
\[ P_{A1} = 3 \times (R_r)_{Sh} \times I_{in}^2 = 3 \times R_r \times K_1^2 \times I_{1n}^2 \]  
\[ = 3 \times 0.598 \times 0.88^2 \times 11.103^2 = 170.826 \text{ W} \]

The mechanical/ventilation losses \( P_{mv} = 0.03 \times P_n \)  
\[ (2-115) \]

Therefore for \( P_1 = 1 \),  
\[ P_{mv} = 0.03 \times 5280 = 158.4 \text{ W} \]

The stray losses \( P_{stray} = 0.01 \times P_n \)  
\[ (2-114) \]

Therefore  
\[ P_{stray} = 0.01 \times 5280 = 52.8 \text{ W} \]

The iron core losses are complicated and are composed of the fundamental \( P_{i,iron}^1 \) and additional \( P_{i,iron}^h \) (harmonics) loss. The fundamental core losses occur only in the teeth and back iron (\( P_{t1}, P_{y1} \)) of the stator as the rotor (slip) frequency is low (\( f_2 < (3 - 4) \text{ Hz}) \).  
\[ (2-115) \]

Therefore  
\[ P_{t1} = K_t \times P_{10} \times (f_1 / 50)^{1.3} \times B_{ts}^{1.7} \times G_{t1} \]  
\[ (2-116) \]

Where \( P_{10} \) is the specific losses in W / Kg at 1.0 Tesla and 50 Hz (\( P_{10} = (2-3) \) W / Kg) , \( \gamma_{iron} = 7800 \) and \( K_t = (1.6 - 1.8) \) is the core loss augmentation for mechanical working.  
\[ (2-117) \]

The stator tooth weight \( G_{t1} \) is  
\[ G_{t1} = \gamma_{iron} \times N_s \times b_{ts} \times (h_s + h_w + h_{os}) \times L \times K_{Fe} \]  
\[ (2-118) \]

\[ = 7800 \times 36 \times 3.344 \times 10^{-3} \times (15 + 1.5 + 1) \times 10^{-3} \times 95.7 \times 10^{-3} \times 0.96 \]

\[ = 1.5304 \text{ Kg} \]

From Equation 2-116 \( P_{t1} \) is  
\[ P_{t1} = 1.7 \times 2 \times (50 / 50)^{1.3} \times 1.6^{1.7} \times 1.5304 = 11.569 \text{ W} \]

Similarly the stator back iron (yoke) fundamental losses \( P_{y1} \) is  
\[ P_{y1} = K_y \times P_{10} \times (f_1 / 50)^{1.3} \times B_{cs}^{1.7} \times G_{y1} \]  
\[ (2-119) \]

Where \( K_y = 1.6 - 1.9 \) takes care of the influence of mechanical machining. Let \( K_y = 1.6 \). And \( G_{y1} \) is
\[ Gy_1 = \gamma_{\text{iron}} \times (\pi / 4) \times (D_{\text{out}}^2 - (D_{\text{out}} - 2 \times h_{\text{cs}})^2) \times L \times K_{\text{Fe}} \] (2-120)

\[ = 7800 \times (3.14 / 4) \times (180^2 - ((180 - 2 \times 20.4) \times 10^{-3})^2) \times 95.7 \times 10^{-3} \times 0.96 \]

\[ = 7.658 \text{ Kg} \]

Now from Equation 2-119 \( P_{y1} \) is

\[ P_{y1} = 1.6 \times 2 \times (50 / 50)1.3 \times 1.51.7 \times 7.658 = 45.515 \text{ W} \]

Therefore the fundamental iron losses \( P_{1_{\text{iron}}} \) is

\[ P_{1_{\text{iron}}} = P_{t1} + P_{y1} \] (2-121)

\[ = 11.569 + 45.515 = 53.084 \text{ W} \]

The stray losses \( P_{S_{\text{iron}}} \) are made up of the tooth flux pulsation losses, therefore \( P_{S_{\text{iron}}} \) is

\[ P_{S_{\text{iron}}} = 0.5 \times 10^{-4} \times ((N2 \times (f_1 / P_1) \times K_{ps} \times B_{ps})^2 \times G_{ts} + (N_s \times (f_1 / P_1) \times K_{pr} \times B_{pr})^2 \times G_{tr}) \] (2-122)

Where the quantities \( K_{ps}, B_{ps}, G_{ts}, K_{pr}, B_{pr} \) and \( G_{tr} \) are as follows,

\[ K_{ps} = 1 / (2.2 - B_{ts}) \] (2-123)

Therefore \( K_{ps} = 1 / (2.2 - 1.6) = 1.667 \)

\[ B_{ps} = (Kc2 - 1) / B_g \] (2-124)

\[ B_{ps} = (1.061 - 1) / 0.58 = 0.0353 \text{ T} \]

And \( K_{pr} = 1 / (2.2 - B_{tr}) \) (2-125)

\[ K_{pr} = 1 / (2.2 - 1.6) = 1.667 \]

\[ B_{pr} = (Kc1 - 1) / B_g \] (2-126)

\[ B_{pr} = (1.140 - 1) / 0.58 = 0.0817 \text{ T} \]

The rotor teeth \( G_{tr} \) is

\[ G_{tr} = \gamma_{\text{iron}} \times L \times K_{\text{Fe}} \times N2 \times (h_{t} + ((d_1 + d_2) / 2)) \times b_{tr} \] (2-127)
\[ G_{tr} = 7800 \times 95.7 \times 10^{-3} \times 0.96 \times 30 \times (19.4 + ((5.9 + 1.8)/2) \times 10^{-3} \times 3.99 \times 10^{-3} \]

\[ G_{tr} = 2.043 \text{ Kg} \]

And \[ G_{ts} = G_{t1} = 1.530 \text{ Kg} \]

Therefore from Equation 2-122 \( P_{iron}^s \) is

\[ P_{iron}^s = 0.5 \times 10^{-4} \times ((30 \times (50/1) \times 1.667 \times 0.0353)^2 \times 1.53 + (36 \times (50/1) \times 1.667 \times 0.0817)^2 \times 2.043 \]

\[ P_{iron}^s = 6.7 \text{ W} \]

Therefore the total core loss \( P_{iron} \) is

\[ P_{iron} = P_{iron}^l + P_{iron}^s \]

\[ P_{iron} = 53.084 + 6.7 = 59.8 \text{ W} \]

And from Equation 2-111 the summation of all losses \( \sum \text{ losses} \) is

\[ \sum \text{ losses} = 580.642 + 170.826 + 158.4 + 52.8 = 1022.480 \text{ W} \]

From Equation 2-110 the efficiency \( \eta \) is

\[ \eta = 5280 / (5280 + 1022.480) = 0.84 \]

The efficiency \( \eta_n \) used in the design of the motor was \( \eta_n = 0.85 \) which is very close to the calculated efficiency \( \eta = 0.84 \), therefore the design is acceptable. However it should be noted that if the calculated efficiency \( \eta \) had been much smaller than the design efficiency \( \eta_n \) then the design would not have been accepted and design calculations would have started right from step one of the algorithm.

### 2.10 Operation Characteristics

Operating characteristics were calculated to see if the design power factor \( \cos \phi_{1n} \) was achieved.

The operation characteristics are the active no load current \( I_{0a} \), rated slip \( S_n \), rated torque \( T_n \), breakdown slip and torque \( S_k, T_{bk} \), current \( I_s \) and power factor versus slip, starting current, and torque \( I_{LR}, T_{LR} \).

The no load current \( I_{0a} \) is given by the no load losses as follows;
I_{0a} = (P_{iron} + P_{mv} + (3 \times I_{0}^2 \times R_s)) / (3 \times V_{ph}) \quad (2-129)

I_{0a} = (59.8 + 158.4 + (3 \times 2.55 \times 1.57)) / (3 \times 219.393) = 0.350 \, A

The rated slip $S_n$ is

$$S = \frac{P_A}{P_n + P_A + P_{mv} + P_{stray}}$$ \quad (2-130)

$$S = \frac{170.826}{5280 + 170.826 + 158.4 + 52.8} = 0.03$$

The value of the design slip is $S_n = 0.05$, therefore the design is acceptable since the calculated value $S < 0.05$.

The rated shaft torque $T_n$ is

$$T_n = \frac{P_n}{2 \times \pi \times (f_1 \times P_1) \times (1 - S)} \quad (2-131)$$

$$T_n = \frac{5280}{2 \times 3.14 \times (50 / 1) \times (1 - 0.03)} = 17.34 \, Nm.$$

The torque versus slip expression is given by the equation,

$$T_c = \frac{(3 \times P_1 / \omega_1) \times (((V_{ph}^2 \times (R_r / S))) / ((R_s + C_m \times (R_r / S))^2 + (Xs_1 + C_m \times Xr_1)^2) \quad (2-132)$$

Where

$$C_m = 1 + X_{s1} / X_m$$ \quad (2-133)

$$C_m = 1 + 2.021 / 84 = 1.0241$$

Therefore from (2-132) the breakdown torque $T_{bk}$ is

$$T_{bk} = \frac{(3 \times P_1 / 2 \times \omega_1) x ((V_{ph}^2) / (\sqrt{R_s^2 + (X_{s1} + C_1 \times Xr_1)^2}) \quad (2-134)$$

And $C_1 = 1.1658 \times C_m$ \quad (2-135)

$$C_1 = 1.1658 \times 1.0241 = 1.1939$$

From Equation 2-134 $T_{bk}$ is

$$T_{bk} = \frac{(3 \times 1 / (2 \times 314)) \times ((219.393)2 / (\sqrt{1.5702 + (2.021 + 1.1939 \times 1.7597)2})$$

$$T_{bk} = 38.74 \, Nm$$

The starting current $I_{LR}$ is
The starting torque $T_{LR}$ is

$$T_{LR} = ((3 \times R_{r}^{S=1} \times I_{LR}^2) / \omega 1) \times P1$$  \hspace{1cm} (2-137)$$

$$T_{LR} = ((3 \times 0.614 \times 63.75^2 / 314) \times 1) = 23.83 \text{Nm}$$

The rated power factor $\cos \phi_{1n}$ is

$$\cos \phi_{1n} = P_n / (3 \times V_{ph} \times I_{n} \times \eta)$$  \hspace{1cm} (2-138)$$

$$\cos \phi_{1n} = 5280 / (3 \times 219.393 \times 11.103 \times 0.84) = 0.86$$

The calculated power factor $\cos \phi_{1n} = 0.86$ is above the design value of $\cos \phi_{1n} = 0.85$. Therefore the design is acceptable.

The other quantities of interest are the ratios of breakdown torque to rated torque $t_{bk}$, the starting torque to the rated torque $t_{LR}$ and the starting current to the input current $i_{LR}$, therefore,

$$t_{bk} = T_{bk} / T_{n}$$  \hspace{1cm} (2-139)$$

$$t_{bk} = 38.74 / 17.34 = 2.2$$

$$t_{LR} = T_{LR} / T_{n}$$  \hspace{1cm} (2-140)$$

$$t_{LR} = 23.89 / 17.34 = 1.4$$

$$i_{LR} = I_{LR} / I_{in}$$  \hspace{1cm} (2-141)$$

$$i_{LR} = 63.75 / 11.103 = 5.7$$

2.11 Temperature Rise

The temperature rise of the induction motor in operation was very important and it was calculated to prove that it was below that of insulation class F, even though the motor was designed for class F
insulation. The temperature rise must not exceed the design class for the design to be thermally valid.

To start with the temperature differential between the conductors in slots and the slot wall $\Delta \theta_{co}$ was calculated as follows;

$$\Delta \theta_{co} = \frac{P_{co}}{(\alpha_{cond} \times A_{1s})} \quad (2-142)$$

The frame temperature rise $\Delta \theta_{frame}$ with respect to ambient air was determined as follows;

$$\Delta \theta_{frame} = \frac{\sum \text{losses}}{(\alpha_{cond} \times A_{frame})} \quad (2-143)$$

Where

$$\alpha_{cond} = \frac{\lambda_{ins}}{h_{ins}} \quad (2-144)$$

And $\lambda_{ins} = 0.25$ is the insulation thermal conductivity in (W / m$^2$ x K) \quad (2-145)

$h_{ins} = 3 \times 10^{-4}$ is the total insulation thickness from the slot middle to the teeth of the wall \quad (2-144)

and $\alpha_{cond}$ is the slot insulation conductivity plus its thickness lumped together.

Therefore from (2-144) $\alpha_{cond}$ is

$$\alpha_{cond} = 0.25 / 3 \times 10^{-4} = 833 \text{ W} / \text{m}^2 \text{K}$$

The stator slot lateral area $A_{1s}$ is

$$A_{1s} = (2 \times h_{s} + b_{s2}) \times L \times N1 \quad (2-146)$$

$$A_{1s} = (2 \times 15.2 + 8.62) \times 10^{-3} \times 95.7 \times 10^{-3} \times 36 = 134.7 \times 10^{-3} \text{ m}^2$$

The frame area $A_{frame}$ is

$$A_{frame} = \pi \times D_{out} \times (L + \tau) \times K_{fin} \quad (2-147)$$

Where $K_{fin} = 2.0$, is the frame area multiplied by number of fins.

Therefore from Equation 2-147 $A_{frame}$ is

$$A_{frame} = 3.14 \times 180 \times 10^{-3} \times (95.7 + 159.4) \times 10^{-3} \times 2 = 432.5 \times 10^{-3} \text{ m}^2$$

From Equation 2-112, 2-144 and 2-146 $\Delta \theta_{co}$ is
Δθ_{co} = \frac{580.642}{(833 \times 134.7 \times 10^{-3})} = 5.17°C

From Equation 2-142, \( α_{\text{cond}} = \frac{P_{co}}{60 \times (2P1=2) \times Δθ_{\text{frame}} \times Δθ_{\text{frame}} \text{ is}} \)

\[ Δθ_{\text{frame}} = \frac{1022.480}{(60 \times 432.5 \times 10^{-3})} = 39°C \]

Now if ambient temperature \( θ_{\text{amb}} = 40°C \), then \( θ_{co} \) is

\[ θ_{co} = θ_{\text{amb}} + Δθ_{co} + Δθ_{\text{frame}} \] (2-148)

Therefore

\[ θ_{co} = 40 + 5.17 + 39 = 84.17°C > 80°C \]

The conductor temperature \( θ_{co} = 84.17°C \) is above class F insulation by 4.17°C, which is acceptable and therefore the design is acceptance. In most instances the desire is to design for a conductor temperature less than the insulation allowable temperature. In this design too this can be achieved by reducing the ambient temperature or increasing the area of cooling.

### 2.12 Shaft Power and Input Power calculations

The pump driving power \( P \) is the energy \( E \) imparted on the fluid equal to the flow rate \( Q \) multiplied by the pressure difference \( H \) [16]. Therefore energy \( E \) is

\[ E = \rho \times g \times H \times Q \] (2-149)

Now

\[ E = P = 0.163 \times s \times H \times Q \] (2-150)

\( g = 9.8, s \) is the specific gravity, \( H = 40 \) m (1-2), \( Q = 32 \) m\(^3\)/hr (1-1)

Therefore

\[ P = 0.163 \times 1 \times 40 \times 32 / 60 = 3.48 \) kW

Now the shaft power \( P_s = P / \) Pump efficiency, pump efficiency = 0.66 (Equation 1-4) (2-151)

Therefore

\[ P_s = \frac{3.48}{0.66} = 5.272 \) kW

The motor capacity \( P_m \) [16] is equal to the input power \( P_{1n} \). Therefore \( P_m (=P_{1n}) \) is

\[ P_m = (1 + d) \times P_s \] [16] (2-152)

Where \( d = 0.25 \) [16], therefore \( P_{1n} \) is

\[ P_{1n} = (1 + 0.25) \times 5272 = 6.6 \) kW
Chapter 2: The Polyphase Induction Motor Design

2.13 Motor Speed

The motor speed \( n \) is

\[
    n = n_s \times (1 - 0.06) \quad \text{for a type 6 motor} \quad (2-153)
\]

Where \( n_s \) is synchronous speed and is equal to

\[
    n_s = \frac{120 \times f_1}{2} \quad (2-154)
\]

Therefore \( n_s = 120 \times 50 / 2 = 3000 \text{ rpm} \)

Therefore \( n = 3000 \times (1 - 0.06) = 2820 \text{ rpm} \)

2.14 Rotor Inertia

Rotor inertia is made up the shaft and rotor core components;

The shaft dimensions are

Diameter = 22 mm \quad (2-155)

Length = 244.3 mm \quad (2-156)

Therefore \( \text{Weight} = 0.7287 \text{ Kg} \quad [10] \)

Now center of gyration \( = (\text{Radius})^2 = \left(\frac{22}{2} \times 10^{-3}\right)^2 \)

Moment of Inertia \( I_s = \text{Weight} \times (\text{Radius})^2 \)

Therefore \( I_s = 0.7287 \times (11 \times 10^{-3})^2 = 0.00008817 \text{ Kg} \cdot \text{m}^2 \)

The core dimensions are

Diameter = 101.5 mm \quad (2-159)

Length = 95.7 mm \quad (2-160)

Therefore \( \text{Weight} = 6 \text{ Kg} \)

And center of gyration \( = (\text{Radius})^2 \quad (2-161) \)

Then \( I_c = 6 \times (50.75 \times 10^{-3})^2 = 0.01545337 \text{ Kg} \cdot \text{m}^2 \)

(Development of the electric motor)
The value of the core inertia $I_{nc} = 0.0155 \text{K}\text{gm}^2$ is with the assumption that the whole rotor core is made of steel, but this is not so. Almost half of the core will be made of aluminium which is much lighter than steel. Therefore if the weight of aluminium is considered insignificant compared to steel then the rotor inertial is only half the calculated value therefore $I_{nc} = 0.00775 \text{K}\text{gm}^2$

Therefore the rotor inertia $I_{nr} = I_{nc} + I_{ns}$

$$I_{nr} = 0.00775 + 0.00008817 = 0.007838 \text{K}\text{gm}^2$$

### 2.15 Induction Motor Design Validation

The motor parameters calculated in this design were compared to that of the electric motor of Flygt 2102.041 pump (Appendix D). Below is the comparison.

<table>
<thead>
<tr>
<th>Electric Motor Parameters</th>
<th>Flygt 2102.041</th>
<th>UNZA Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Frequency</td>
<td>Hz</td>
<td>50</td>
</tr>
<tr>
<td>2 Poles</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>3 Number of phases</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>4 Rated speed</td>
<td>rpm</td>
<td>2810</td>
</tr>
<tr>
<td>5 Rated voltage</td>
<td>Volts</td>
<td>400</td>
</tr>
<tr>
<td>6 Rated current</td>
<td>A</td>
<td>10.0</td>
</tr>
<tr>
<td>7 Rated output power</td>
<td>kW</td>
<td>5.2</td>
</tr>
<tr>
<td>8 Rated input power</td>
<td>kW</td>
<td>6.7</td>
</tr>
<tr>
<td>The values are valid at 75°C</td>
<td></td>
<td>Flygt 2102.041</td>
</tr>
<tr>
<td>1 Output power</td>
<td>kW</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>---</td>
<td>------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>2</td>
<td>Input power</td>
<td>kW</td>
</tr>
<tr>
<td>3</td>
<td>Efficiency</td>
<td>%</td>
</tr>
<tr>
<td>4</td>
<td>Current</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>Power factor</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Torque</td>
<td>Nm</td>
</tr>
<tr>
<td>7</td>
<td>Speed</td>
<td>rpm</td>
</tr>
<tr>
<td>8</td>
<td>No load current</td>
<td>A</td>
</tr>
<tr>
<td>9</td>
<td>Power factor at no load</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Break away starting current</td>
<td>A</td>
</tr>
<tr>
<td>11</td>
<td>Starting torque</td>
<td>Nm</td>
</tr>
<tr>
<td>12</td>
<td>Max: torque / Rated torque</td>
<td>Nm</td>
</tr>
<tr>
<td>13</td>
<td>Speed at max torque</td>
<td>rpm</td>
</tr>
<tr>
<td>14</td>
<td>Rotor inertial</td>
<td>Kgm2</td>
</tr>
<tr>
<td>15</td>
<td>Iron losses</td>
<td>W</td>
</tr>
<tr>
<td>16</td>
<td>Friction losses</td>
<td>W</td>
</tr>
<tr>
<td>17</td>
<td>Max: torque / Rated torque $t_{bk}$</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Starting torque / Rated torque $t_{LR}$</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Starting current / Rated current $i_{LR}$</td>
<td></td>
</tr>
</tbody>
</table>
The objective of this Master’s work which was to design a motor with a rated power of 5280 W, rated speed of 2890 and rated slip of 3.6% was met. However a few assumptions were made in the process for example the requirement to have the teeth width greater than 3.5 mm fell short and the actual achievable value of 3.3 mm was acceptable being very close to 3.5 mm.

The conductor temperature exceeded the limit value by 4°C which is not desirable, but acceptable since this is a very small rise in temperature and it is in very rare times that the motor will be expected to operate at maximum temperatures.

In table 2-3 it is clear that the UNZA pump motor is very close to the Flygt pump B2102.041 motor. The Flygt pump B2102.041 motor was recommended by both Nyirenda [1] and Steman [2] to retrofit the UNZA pump. The electric motor designed in this Master’s work therefore meets the expectations and should be developed into a physical motor by later studies.
Figure 2-6 Stator Lamination

Development of the electric motor
Chapter 2: Induction Motor Drawings

Development of the electric motor

Figure 2-7 Rotor Lamination
2.17 The Wiring Diagram

The wiring diagram of the motor was designed with a pitch factor of 15/18 [15]. This was to reduce significantly the 5\textsuperscript{th} and 7\textsuperscript{th} harmonics of the motor to such a level that they have negligible effect on the generated voltage. The pitch factor of 15/18 also made the span of the coils equal to 15 instead of 18 slots. This design is called fractional pitch and is preferred over the full pitch because the generated waveform closely approximates the sinusoidal waveform.

In designing the wiring of the induction motor, the following steps were followed:

1. The number of slots was determined, as explained in the design of the stator lamination.

2. A whole-coiled lap winding configuration was used. In this winding there are as many coils as there are slots.

3. The coil span was determined by using a pitch factor of 15/18 as explained above.

4. The number of coils per phase which is the same as the slots per phase was determined.

5. The number of coils in each pole group per phase equals to slots/(poles x phases) was determined.

6. The motor was designed for a star connection so as to automatically eliminate third harmonics and all its multiples.

7. This electric motor being designed for a two pole machine, the coils were connected for simplex lap winding.

The wiring diagram for this motor is shown in Figure 2-8.
Figure 2-8 Wiring Diagram of the Stator Winding
The wiring diagram in Figure 2-8 above is for the 5.28 kW 2 pole 380 volts 50 hertz 2820 rpm electric motor design for the UNZA pump. The diagram also shows the simplex lap connections of the coils and the three phase star connection.

The diameter of the stator in Figure 2-6 is bigger than the allowed space in the design of the pump by Nyirenda [1]. It was therefore necessary to redesign the outer cover, motor casing, the bottom bearing housing section and the shaft, see Figures 2-9, 2-10, 2-11, 2-12, and 2-13.

1. Figure 2-9 gives the original dimensions of the electric motor casing design [1].
2. Figure 2-10 gives the original pump-motor unit casing assembly and dimensions for the UNZA pump [1].
3. Figure 2-11 gives the modified dimensions of the electric motor casing.
4. Figure 2-12 gives the modified pump-motor unit casing assembly and dimensions for the UNZA pump unit.
5. Figure 2-13 gives the modified centrifugal pump casing.
Figure 2-9 Original Electric Motor Casing

Development of the electric motor
Figure 2-10 Pump and Motor Casing Dimensions
Figure 2-11 Modified Electric Motor Casing to suit the New Stator Dimensions Requirements
Figure 2-12 Modified Pump-Motor Casing for the New Stator Dimension Requirements
Figure 2-13 Modified Centrifugal Pump Casing
Chapter 3
Electric Motor Manufacture Proposition

3.1 Introduction

This chapter deals with the set up and operation of the electric motor manufacturing plant. It shows in detail the plant set up and personnel requirements. It also shows the expected cash flow for the plant.

It is important to note that a factory of this kind operates well as a hybrid layout combining cellular and process layouts.

In the beginning, the factory will produce squirrel cage electric motors by manufacturing in house, motor shafts, winding wire coils, and rotor and stator laminations from imported round bar steel stock, magnet wire and steel sheet respectively. Other items to be imported are the bearings. End covers, fans and fan covers will be outsourced from the foundries within Zambia.

The rotor will be made of a copper bar cage or an aluminium bar cage. In Zambia, therefore, with abundant copper, it is obvious that a copper bar cage rotor will be the most preferred but this is not so because aluminium carries a big advantage of weight and therefore is the front runner in rotor design. This design therefore will concentrate on production of aluminium squirrel cage rotors. The production of the aluminium cage rotors will require setting up a die casting foundry.

Later, the production of motor casings will entail putting up a foundry unit to cast motor casings and end covers [2].

The production of rotor and stator laminations will require the purchase of a laminate puncher. This is a press that carries a design die according to the laminate design and punches out laminates of rotor and stator design simultaneously from a roll of steel sheet.

The stator core windings will be formed on wire winders. These are machines which will carry a former according to the required coil pitch upon which the windings will be formed from a drum of magnet wire.
Chapter 3: Manufacturing plant of the Induction Motor

The factory will also have a machine shop with lathes, boring machines, electric power saws for cutting steel, arc and gas welding machines and vertical drilling machines for the manufacture of motor shafts and machining of motor casings and end covers.

The raw materials for the manufacture of the electric motor are:
1) sheet steel rolls,
2) magnet wire (winding wire),
3) aluminium bars,
4) copper bars,
5) round steel bar stock.
6) Varnish.

The outsourced components are:
1) bearings,
2) end covers,
3) motor casings and
4) end fans.

The basic processes involved in the manufacture of the electric motor are:

1) form coils from the magnet wire,
2) make rotor and stator perforated laminations from the sheet steel strip and
3) make shafts from the steel round bar stock.

The primary processes involve:

1) stacking the laminations into rotor and stator cores and welding the same,
2) winding the stator core using the preformed magnet wire coils,
3) place copper bars in the rotor slots, or cast aluminium in the rotor slots,
4) machine rotor to the right diameter,
5) shrink fit rotor on to the shaft.
Chapter 3: Manufacturing plant of the Induction Motor

The secondary processes involve:

1) placing the stator into the motor casing,
2) fitting the bearings on the shaft,
3) placing the rotor in the stator,
4) putting both end covers on the shaft and bolting it to the motor casing,
5) placing the end fan on to the shaft,
6) fixing the fan cover onto the shaft.

The final process involves:

1) meggering to ensure that the insulation on the wires has not been damaged,
2) connecting the three phase power supply to the motor terminals to check the performance by measuring load current and speed.
3.2 Work Flow Diagram

The work flow diagram in Fig. 3-1, gives the actual flow of raw materials and work in progress in the whole factory [4]. A loop for rework is provided in the rotor path at die-casting stage. This is
because poor casts are sometimes made and therefore a rework is ordered. To avoid poor casts however, the aluminium bar stock must be kept clean in storage and handling.

In house produced parts are:

1. Stator core made of steel laminates
2. Rotor core made of steel laminates
3. Rotor shaft made of EN8 steel
4. Stator winding coils made from magnet wire
5. Aluminium bars cast or forced into the rotor

Parts ordered from other sources are:

1. Motor housing
2. Bearing housing
3. End covers
4. Bearings
3.2.1 Stator and Rotor Core Process Flow

![Diagram of Stator and Rotor Core Process Flow]

- Storage in warehouse of stock sheet steel material
- Transfer to stamping machine
- Stamp both Stator and Rotor laminations
- Convey to Stator assembly line and rotor assembly line
- Conduct quality control checks on stator laminations and rotor laminations
- Stack and rivet/weld laminations
- Conduct quality control checks on stator laminations and rotor laminations
- Slot stator winding coils
- Cast/drive aluminium bars/end ring
- Stator core with coils
- Rotor core with aluminium/copper bars
- Vanish stator, dry and scrap off excess
- Transfer to final assembly point
- Assemble stator with rotor, bearings, end covers
- Machine rotor bars and end ring
- Transfer to final assembly point
- Assemble rotor with shaft to stator
- Assembled electric motor

Figure 3-2 Stator and Rotor Process Flow
3.2.2 Rotor Shaft Process Flow

Storage in warehouse stock of round steel

Shaft steel in stock

Transfer to cutting point from storage

Turning operations (Secondary process)

Conduct quality checks

Convey to component assembly location

Assemble shaft and rotor core

Transfer to final assembly point

Assemble rotor shaft with rotor core to the stator core, bearings, end covers

Assembled electric motor

Figure 3-3 Rotor Shaft Process Line to Final Assembly Stage
3.2.3 Magnet Wire Coil Forming

Storage in warehouse of Magnet wire stock material

Transfer to wire winder for coil forming

Coil forming

Conduct quality inspections

Transfer to stator assembly line

Slot preformed coils into the stator core slots

Transfer to varnishing point

Varnish stator core, oven dry and scrap off excess varnish

Transfer to final assembly

Assemble stator and rotor with shaft, bearings and end covers

Assembled electric motor

Figure 3-4 Magnetic Wire Coil Forming Process Flow to the Final Product
3.3 The Plant.

The Plant is a place where manufacturing takes place. A combination of cellular and process layout of the plant to be constructed for the manufacture of the squirrel cage induction motor in Zambia is as below.

3.3.1 The Combined Cellular and Process Plant Layout.

![Diagram of Plant Cellular and Process Layout]

The combined plant layout as shown in Figure 3-5 is the best set up in an electric motor manufacturing plant of this kind. This is because semi-finished products flow downstream for assembly and are checked for compliance and quality [5, 6].
3.4 The Organization

The company is organized in two sections, the administration and the plant.

3.4.1 The Administration.

The administration makes up the core management team of the company. It is the amalgamation of all the functions of the company at the top level and it is made up of the following officers:

1. The Chief Executive Officer

   The Chief Executive officer is the highest ranking corporate officer of the company and is responsible for its operations. The Chief Executive Officer oversees all the functions of the company especially Manufacturing, Finance, Marketing, Procurement and Human Resources.

2. The Plant Manager

   The Plant Manager reports to the Chief Executive Officer and is responsible for manufacturing. The Plant Manager oversees the departments of Production, Production Planning and Materials Control, Engineering and Quality Control.

3. The Chief Accountant

   The Chief Accountant reports to the Chief Executive Officer and is responsible for finances of the company.

4. The Marketing Manager

   The Marketing Manager reports to the Chief Executive Officer and is responsible for the marketing functions of the company. The Marketing Manager oversees the functions of sales, product promotion and customer relations.
5. The Purchasing Manager

The Purchasing Manager reports to the Chief Executive Officer and is responsible for all procurements of the company.

6. The Personnel Manager

The Personnel Manager reports to the Chief Executive Officer and is responsible for recruitments and public relations of the company.

3.4.2 The Plant Manning.

The Plant is the manufacturing arm of the company. It is headed by the Plant Manager who reports directly to the Chief Executive Officer. The Plant Manager is the Plant main representative in management. The Plant management is made up of the following managers:

1. The Plant Manager

As explained in 2 above.

2. The Engineering Manager

The Engineering Manager reports to the Plant Manager and is responsible for plant maintenance of machinery and buildings.

3. The Quality Control Manager

The Quality control Manager reports to the Plant Manager and is responsible for product quality control.

4. The Production Manager

The Production Manager reports to the Plant Manager and is responsible for production of electric motors.
5. The Production Planning and Materials Control Manager

The Production Planning and Materials Control Manager reports to the Plant Manager and is responsible for planning of plant operations and ordering of all raw materials and outsourced components.

6. Cost Accountant

The Cost Accountant reports to the Chief Accountant and is responsible for costing of the production of the electric motor.

In addition to the above mentioned officers, the Plant also employs all the direct labour and most of the indirect labour. These are the operators, various technicians and workmen.
Chapter 3: Manufacturing plant of the Induction Motor

3.5 The Organisation Chart

Key: A x B, A is the number of people. B is the number of shifts.

Figure 3-6 Company Organisation Chart
3.6 The Product

The product is a 5.28 kilo watt (kW) squirrel cage electric motor, but the factory can also be set up to manufacture other sizes when required, since the process is the same for all squirrel cage induction motors.

As per design, the squirrel cage electric motor is made up of a squirrel cage rotor and a wound stator. The squirrel cage rotor winding is made up of either copper bars driven into the rotor slots or aluminium bars cast into the rotor slots. On the other hand the stator is made up of formed enamelled wire slotted into the stator slots.

The squirrel cage electric motor is designed to operate on 380 volts, at 50 hertz frequency.

The work station manning in the diagram in Figure 3-1 is as follows:

<table>
<thead>
<tr>
<th>Station</th>
<th>Personnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw/Finished Material Stores:</td>
<td>9</td>
</tr>
<tr>
<td>Machine shop</td>
<td>2</td>
</tr>
<tr>
<td>Punch Press</td>
<td>2</td>
</tr>
<tr>
<td>Winding Machine</td>
<td>2</td>
</tr>
<tr>
<td>Die casting</td>
<td>2</td>
</tr>
<tr>
<td>Rotor assembly</td>
<td>7</td>
</tr>
<tr>
<td>Stator assembly</td>
<td>5</td>
</tr>
<tr>
<td>Motor assembly</td>
<td>4</td>
</tr>
<tr>
<td>Testing</td>
<td>2</td>
</tr>
</tbody>
</table>

3.7 Production Processes

There are five major production processes in the manufacture of the polyphase induction motor. These are: coil forming, steel punching, stator assembly, rotor assembly and final assembly [4].
3.7.1 The Steel Punching Assembly

This is a process consisting of a steel punching machine for rotor and stator punching. The steel punching for both rotor and stator are then insulated, stacked and pressed to make the stator or rotor core. The stator core is welded to keep the punching (laminations) in place and compressed.
Input material: Silicon steel sheet rolls.

3.7.2 Coil Forming

The magnet wire (enamel insulated copper wire) is preformed into a coil that fits the stator slot span. This step is done by using two winding machines. The set up for the coils is eight hours per set up. Since this factory is set up to produce one type of motor only, the set up is done once a week. The only other time a set up is done or checked is when a departure in coil size is noticed or suspected. Each machine is manned by one operator and the coils are tagged as per the machine that produced it. This is to ensure easy traceability of a problem on the coil.

3.7.3 Stator Assembly

The slots of the welded stator core are insulated with Mylar and paper insulation and pre-formed copper coils are slotted in them. The entire assembly is then immersed in vanish and oven dried.
Input material: Stator core
  Preformed magnet wire coils
  Mylar insulation
  Paper insulation
  Mica strips
  Mica sheets

3.7.4 Rotor Assembly

The stacked rotor punching is compressed and taken to the foundry for die-casting if the rotor is of aluminium bar cage. The molten aluminium is poured into the slots to form the bars and end rings. The cast rotor is then checked for defects and sent for further processing.
Input material: Rotor core
  Aluminium bar stock or copper bars
  Shaft
3.7.5 Final Assembly

The stator is pressed into the housing; the rotor on the shaft is assembled into the stator. The end covers carrying bearing are then bolted to the stator housing. The bearing in the end covers provides the seat for the rotor shaft.

Input components:  
- Stator assembly
- Rotor assembly
- Stator housing
- End covers
- Bearings
- Miscellaneous parts

3.8 Accounting Information

All costs and wages are expressed in Kwacha, at the exchange rate of US $1 = K3, 500.

3.8.1 Plant wages-Direct Staff

Direct staff comprises of what is known as direct labour force. Direct labour force is the personnel described as directly linked to the manufacture of the product. This group of labour is mainly made up of operators but the group can be enlarged to include other related personnel like store men.

Table 3-1 Monthly Plant Wages for direct labour staff showing the Cost of One Unit

<table>
<thead>
<tr>
<th>Station</th>
<th>Number of staff</th>
<th>Basic pay/month</th>
<th>Total/month</th>
<th>Total/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supervisor</td>
<td>1</td>
<td>2,500,000</td>
<td>2500000</td>
<td>30000000</td>
</tr>
<tr>
<td>Work men</td>
<td>2</td>
<td>800,000</td>
<td>1600000</td>
<td>19200000</td>
</tr>
<tr>
<td>Assistant Storemen</td>
<td>2</td>
<td>700,000</td>
<td>1400000</td>
<td>16800000</td>
</tr>
<tr>
<td>Punch Press</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operator</td>
<td>2</td>
<td>1,500,000</td>
<td>3000000</td>
<td>36000000</td>
</tr>
</tbody>
</table>

Machine shop

Development of the electric motor
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machinists</strong></td>
<td>8</td>
<td>1,500,000</td>
<td>12000000</td>
<td>144000000</td>
</tr>
<tr>
<td><strong>Winding Machines</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operators</td>
<td>2</td>
<td>900,000</td>
<td>1800000</td>
<td>21600000</td>
</tr>
<tr>
<td><strong>Diecasting</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operator</td>
<td>2</td>
<td>1,500,000</td>
<td>3000000</td>
<td>36000000</td>
</tr>
<tr>
<td><strong>Rotor assembly</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stackers</td>
<td>2</td>
<td>1,200,000</td>
<td>2400000</td>
<td>28800000</td>
</tr>
<tr>
<td>Loaders</td>
<td>1</td>
<td>900,000</td>
<td>900000</td>
<td>10800000</td>
</tr>
<tr>
<td>Assemblers/Balancers</td>
<td>4</td>
<td>1,300,000</td>
<td>5200000</td>
<td>62400000</td>
</tr>
<tr>
<td><strong>Stator assembly</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welders</td>
<td>1</td>
<td>1,500,000</td>
<td>1500000</td>
<td>18000000</td>
</tr>
<tr>
<td>Insulation</td>
<td>2</td>
<td>900,000</td>
<td>1800000</td>
<td>21600000</td>
</tr>
<tr>
<td>Assemblers/Testing</td>
<td>2</td>
<td>1,200,000</td>
<td>2400000</td>
<td>28800000</td>
</tr>
<tr>
<td><strong>Final assembly</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assemblers/Testing</td>
<td>4</td>
<td>2,500,000</td>
<td>10000000</td>
<td>120000000</td>
</tr>
<tr>
<td><strong>Finished product</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Store men</td>
<td>2</td>
<td>800,000</td>
<td>1600000</td>
<td>19200000</td>
</tr>
<tr>
<td>Assistant Storemen</td>
<td>2</td>
<td>700,000</td>
<td>1400000</td>
<td>16800000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>39</td>
<td>20,400,000</td>
<td>52500000</td>
<td>630,000,000</td>
</tr>
</tbody>
</table>

Cost of 1 unit: **6000000**
Motor production/year: **105**

The wages shown in Table 3-1 above include all allowances. This is a normal week operation of 5 days 8 hours a day and therefore does not attract overtime.

Table 3-1 gives the cost of direct labour contribution to the cost of production. It is seen that for 105 units the cost of direct labour is ZK 6,000,000 per unit.
3.8.2 Plant Wages - Indirect Staff

Indirect labour is the group of employees who are not very closely linked to the product but work to assist the direct labour continue with manufacturing with minimum interruption. Indirect labour staff can do many other jobs not related to the product.

Table 3-2 Indirect Staff

<table>
<thead>
<tr>
<th>Station</th>
<th>Number of staff</th>
<th>Basic pay/month</th>
<th>Total/month</th>
<th>Total/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supervisor</td>
<td>1</td>
<td>1500000</td>
<td>1500000</td>
<td>18000000</td>
</tr>
<tr>
<td>Mechanics</td>
<td>2</td>
<td>900000</td>
<td>1800000</td>
<td>21600000</td>
</tr>
<tr>
<td>Electricians</td>
<td>2</td>
<td>900000</td>
<td>1800000</td>
<td>21600000</td>
</tr>
<tr>
<td>Assistant Electricians</td>
<td>4</td>
<td>750000</td>
<td>3000000</td>
<td>36000000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9</strong></td>
<td><strong>4050000</strong></td>
<td><strong>8100000</strong></td>
<td><strong>97,200,000</strong></td>
</tr>
</tbody>
</table>

Cost per unit: $925714.28$

Number of units: 105

Table 3-2 gives the cost contribution of indirect labour towards production. It is seen that the cost contribution of indirect labour is ZK 925,714 per unit.

3.8.3 Administration

Administration is another group of indirect labour. This group of people is detached from the direct manufacture of the product and does not need to be near the plant. And yet this is the group that carries out all the planning of the entire factory and also work hard towards the success of the factory. Though this group looks far from the product and yet they are very near to ensure its success in the plant and its success in the market.

Table 3-3 Administration Costs (Source: Teamskill [4])

<table>
<thead>
<tr>
<th>Station</th>
<th>Number of staff</th>
<th>Basic pay/month</th>
<th>Total/month</th>
<th>Total/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chief Executive</td>
<td>1</td>
<td>1500000</td>
<td>1500000</td>
<td>18000000</td>
</tr>
<tr>
<td>Plant Manager</td>
<td>1</td>
<td>1000000</td>
<td>1000000</td>
<td>12000000</td>
</tr>
<tr>
<td>Financial Accountant</td>
<td>1</td>
<td>1000000</td>
<td>1000000</td>
<td>12000000</td>
</tr>
<tr>
<td>Marketing Manager</td>
<td>1</td>
<td>800000</td>
<td>800000</td>
<td>96000000</td>
</tr>
<tr>
<td>Purchasing Manager</td>
<td>1</td>
<td>600000</td>
<td>600000</td>
<td>72000000</td>
</tr>
<tr>
<td>Personnel Manager</td>
<td>1</td>
<td>500000</td>
<td>500000</td>
<td>60000000</td>
</tr>
<tr>
<td>Technical Manager</td>
<td>1</td>
<td>500000</td>
<td>500000</td>
<td>60000000</td>
</tr>
</tbody>
</table>

Development of the electric motor
3.8.4 Material Costs.

Table 3-4 Material Costs, Landed (source of information: LME, Steman [2])

<table>
<thead>
<tr>
<th>Material</th>
<th>K/Kg</th>
<th>Quantity</th>
<th>Total per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>23800</td>
<td>630</td>
<td>14994000</td>
</tr>
<tr>
<td>Aluminum</td>
<td>8655.5</td>
<td>157.5</td>
<td>1363241.25</td>
</tr>
<tr>
<td>Mylar insulation</td>
<td>1000</td>
<td>52.5</td>
<td>52500</td>
</tr>
<tr>
<td>Paper Insulation</td>
<td>1000</td>
<td>52.5</td>
<td>52500</td>
</tr>
<tr>
<td>Stator housing cast</td>
<td>3500</td>
<td>966</td>
<td>3381000</td>
</tr>
<tr>
<td>End cover</td>
<td>3500</td>
<td>63</td>
<td>220500</td>
</tr>
<tr>
<td>Bearings</td>
<td>102725</td>
<td>105</td>
<td>10786125</td>
</tr>
<tr>
<td>Silicon sheet steel</td>
<td>3500</td>
<td>1050</td>
<td>3675000</td>
</tr>
<tr>
<td>Shaft</td>
<td>3500</td>
<td>95</td>
<td>330750</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td><strong>34,855,616</strong></td>
</tr>
</tbody>
</table>

Cost per unit **331958.25**
Number of units 105

From table 3-3 the cost contribution of administration cost is ZK 10,548,571 per unit. This is the biggest component of labour costs.
Table 3-4 gives the cost contribution of raw materials to the product. The material requirement was worked over the production of 105 electric motors, but as seen in appendix C the material requirements is the same per unit no matter the number of motors produced. The cost of materials is ZK 331,958 per unit.

Table 3-5 Standard Cost of the Electric Motor Per Unit.

<table>
<thead>
<tr>
<th>Year</th>
<th>Plant wages</th>
<th>Indirect staff</th>
<th>Administration</th>
<th>Material</th>
<th>Other Fixed Costs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6000000</td>
<td>925714.2857</td>
<td>10548571.43</td>
<td>331958.25</td>
<td>1571428.571</td>
<td>19377672.54</td>
</tr>
</tbody>
</table>

Table 3-5 summarises the cost of production of 105 motors at ZK 19,377,672.54. And at a profit mark up of 15% the sales price of the electric motor is ZK 22,284,323.42. This cost is without the other costs like land and equipment. These have been dealt with in Appendix C, where the entire cost and values of Return on Investment, Payback period and Internal Rate of Return (IRR) are dealt with.

3.8.5 Equipment Cost, Landed

Table 3-6 Equipment Cost (Source: infoprod@direct-industry.com.)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Cost (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broomfield winding machine</td>
<td>45,000,000</td>
</tr>
<tr>
<td>Broomfield winding machine</td>
<td>45,000,000</td>
</tr>
<tr>
<td>Punch Press stamping machine</td>
<td>250,000,000</td>
</tr>
<tr>
<td>Megger</td>
<td>5,000,000</td>
</tr>
<tr>
<td>Arc welding machine</td>
<td>10,000,000</td>
</tr>
<tr>
<td>Caterpillar Folk truck</td>
<td>60,000,000</td>
</tr>
<tr>
<td>Lathe machine</td>
<td>50,000,000</td>
</tr>
<tr>
<td>Lathe machine</td>
<td>50,000,000</td>
</tr>
<tr>
<td>Riveting machine</td>
<td>5,000,000</td>
</tr>
<tr>
<td>Tachometer</td>
<td>2,000,000</td>
</tr>
<tr>
<td>Multimeter</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Multimeter</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Multimeter</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Multimeter</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Steel cutter</td>
<td>5,000,000</td>
</tr>
<tr>
<td>Trolley</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Trolley</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Wire cutter</td>
<td>200,000</td>
</tr>
<tr>
<td>Wire cutter</td>
<td>200,000</td>
</tr>
<tr>
<td>Wire cutter</td>
<td>200,000</td>
</tr>
<tr>
<td>Wire cutter</td>
<td>200,000</td>
</tr>
</tbody>
</table>
The equipment in Table 3-6 is the barest requirement for the factory to produce laminations and stator coils. The Megger and the Multimeter are for the quality certification of the coils and the motor after assembly.

3.9 After Sales Maintenance

After sales maintenance is cardinal for the UNZA pump. Availability of spares is very critical, shops for spares must be located in all important towns close to the users. This is the only way the pump can have an advantage over imported pumps like the Flygt pump B2102.041 and others as noted by Steman [2].

3.10 Plant Finances

Appendix C provides the calculation scenario for three levels of production of 105, 500 and 3000 electric motors per year. From Table 3-7 it is clear that the plant can break even at any level of production, but the differentiating factor is the cost of the unit. The cost of the unit is seen to be very high with lower production than with higher production. The reason is because the fixed costs are very high at low production as compared to when production is very high. It is therefore clear that for this plant to be competitive production should be above 2000 units per year at which level the price of the motor is K 2,000,000. Table 3-7 also shows that the payback period for all the levels of production is the same, 2.4 years, but this is so because of varying prices of the motor at different production levels. In reality the cost of a motor at K 29,000,000 per unit as is the case in the 105 units is unrealistic and cannot be sold. Therefore this plant was designed for 3000 electric motors production per year at which the price of a 5.28 kW electric motor is K 1,497,837. At this price the motor is definitely affordable.

Table 3-7 Table of Comparison for Different Production Units

<table>
<thead>
<tr>
<th>Number</th>
<th>Production / year</th>
<th>ROI %</th>
<th>IRR %</th>
<th>PBP (Yr)</th>
<th>BEP (Units)</th>
<th>Price / Unit (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>105</td>
<td>5</td>
<td>11.6</td>
<td>2.4</td>
<td>60</td>
<td>29,066,509</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>5</td>
<td>18</td>
<td>2.4</td>
<td>279</td>
<td>6,497,337</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>8</td>
<td>32</td>
<td>2.4</td>
<td>1,014</td>
<td>1,997,787</td>
</tr>
<tr>
<td>4</td>
<td>3000</td>
<td>8</td>
<td>37.6</td>
<td>2.4</td>
<td>1,433</td>
<td>1,497,837</td>
</tr>
</tbody>
</table>

In Table 3-7:  ROI = Return On Investment  
IRR = Internal Rate of Return
Chapter 3 proves the fact that manufacturing of the polyphase 5.28 kW induction motor in Zambia is feasible. The financial figures in Appendix C and Table 3-7 show that and give a good performance of the plant by posting a good return on investment and a reasonable breakeven point for higher production of electric motors than low production. However, major observations must be noted and these are that the production of 3000 units per year will require an aggressive marketing and sales division. This is due to the fact that by the market survey conducted by both Nyirenda [1] and Steman [2], the Zambia market is very small. It is only capable of absorbing about 4 percent of the annual production of 3000, meaning that the remainder of the production will have to be marketed outside Zambia. This being the case the pump and motor will have to compete with other imported units in these countries and this could prove difficult as the manufacturers of the other brands already on the market will try to close out the UNZA pump unit. However, the design of the UNZA pump unit is such that it will be the cheapest pump unit on the market as it contains fewer parts and will be easier to maintain compared to the European and Asian pumps. The cost component therefore will be the strength of the UNZA pump to market it within the region.
Chapter 4
Results and Discussion

4.1 Introduction
The development of the electric motor to drive the University of Zambia pump became a necessity upon Nyirenda [1] development of the pump. The objective of this study therefore was to come up with a retrofit electric motor which would be lifted off the shelf and fitted into the pump or develop a motor suitable to the pump. Both objectives were met.

4.2 Results
The study to develop an electric motor suitable for the University of Zambia pump achieved its objectives. The main parts of the motor like the stator and rotor laminations were designed and the physical size of the motor was determined by specifying the diameters of stator and rotor and by determining the number and size of laminations for both stator and rotor by determining the lengths of both the stator and rotor and also by determining the thickness of the laminations.

It was shown that the Flygt pump B2102.041 could retrofit the University of Zambia pump as the parameters of the Flygt B2102.041 pump motor [17] matched well with the parameters of the motor calculated using the University of Zambia pump characteristics (see Table 2-3). Indeed any electric motor that would match these parameters other than the Flygt B2102.041 pump motor would equally suit.

4.3 Discussion
The problem faced in this design was one of the diameters allotted in the University of Zambia pump. The diameter of 120 mm provided [1] for the stator was too small and resulted in an otherwise long stator and rotor which is undesirable due to magnet problems of the motor and would result in unnecessary vibration of the motor in operation. The diameter requirement for this kind of motor is in the range of 170 mm to 200 mm. Therefore the diameter of 120 mm as provided by Nyirenda [1] was not sufficient and was enlarged to accommodate a stator of 180 mm diameter and 95.7 mm long.

To accommodate a stator of 180 mm the casing of the motor was redesigned (see Figure 2-11, 2-12, 2-13). The new design however did not change the volume requirements of the water passage from the empeller to the outlet pipe as designed by Nyirenda [1].
The electric motor developed for the University of Zambia pump will go a long in re-vitalising the collapsed industry of this country. With the local production of the electric motor and pump a breath of life will be given to a lot of other economic sectors like agriculture and water and sewerage services.

The electric motor development is good progress for Zambia. There is need for Zambia to embark on import substitution industries like the pump but also must develop industries targeting the abundant export market within the region.
Chapter 5
Conclusion and Recommendations

5.1 Conclusion

The development of the electric motor involved the design of the stator and rotor laminations. This was successfully achieved as evidenced by the drawings of stator and rotor laminations in Figures 2-6, 2-7, 2-8, 2-11, 2-12 and 2-13. The study also determined the diameters and the lengths for both stator and rotor cores.

This study though carried out to develop the electric motor for the University of Zambia pump applies to any three phase squirrel cage electric motor. Therefore pedestal motors, or flange mounted motors will be manufactured from the same parameters used in designing the electric motor for the University of Zambia pump, the only difference therefore appearing in the mode of base mounting and hence a different motor casing design.

The selection of the type of factory and machinery is very important in this case. And for this factory a hybrid plant layout of process and cellular layouts was recommended.

5.2 Recommendations

This study on the development of a three phase induction motor is the first carried out on the manufacture of an electric motor in Zambia. It was conducted purely on the premise of equipping the University of Zambia pump. It is therefore important to extend it to other useful forms of electric motors like the single phase electric motor which is generally used for domestic purposes.

The issue of the motor casing size also needs to be seriously re-looked into. The provision in Nyirenda [1] study is not enough and if used will cause motors to rattle and heat up resulting into premature failure.
Chapter 6

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Chapter 1: Introduction

Chapter 1: Introduction

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Development of the electric motor
Appendix A

The Electric Motor Design

A-0 Introduction

Development of any new three-phase motor design begins with selection of basic overall stator and rotor dimensions, then the number of stator slots, $N_1$ and rotor slots $N_2$. Together with the number of magnetic poles in the stator winding, the $N_1$ and $N_2$ values—what is called the “slot combination” influence the winding alternatives [12]. This chapter therefore deals with the electric motor design starting with the determination of the stator and rotor dimensions and then the slot dimensions and slot combination and lastly the winding from the given motor design specifications.

A-1 Determination of Stator Core Main Dimensions.

There are many ways of designing the induction motor stator and rotor dimensions. The most common being:

1. The $D_{sbd}^2L$ output constant concept and
2. The rotor tangential stress concept.

The $D_{sbd}^2L$ output concept is the most widely accepted method and was therefore used in this project [13, 14]. The rotor tangential concept is used for completely new designs [13], and was not therefore considered.

Based on the above advanced reasons, the stator bore diameter $D_{sbd}$ is given by

$$D_{sbd} = 3\sqrt{\left(\frac{2P_1 \times P_1 \times S_{gap}}{\pi \times \lambda \times f_1 \times C_0}\right)} \quad (A-1)$$

Where $P_1 =$ the number of pole pairs

$S_{gap} =$ the apparent power in the air gap

$\lambda =$ the stack aspect ratio

$C_0 =$ Esson’s constant

$f_1 =$ supply’s frequency

$K_E$ is the ratio between the generated electromotiveforce (emf) $E_1$ and input voltage $V_{in}$ and is given by

$$K_E = \frac{E_1}{V_{in}} = 0.98 - (0.005 \times P_1) \quad (A-2)$$
The air-gap apparent power $S_{\text{gap}}$ is given as

$$S_{\text{gap}} = 3 \times E_1 \times I_{1n}$$  \hspace{1cm} (A-3)

Where $E_1$ = generated emf

$I_{1n}$ = input current

The input apparent power $S_{1n}$ is given as

$$S_{1n} = 3 \times V_{1n} \times I_{1n} = P_n / (\eta_n \times \cos \phi_{1n})$$  \hspace{1cm} (A-4)

Where $V_{1n}$ = input voltage

$I_{1n}$ = input current

$P_n$ = the shaft power

$\eta_n$ = the assigned design efficiency

$\cos \phi_{1n}$ = the assigned design power factor

And from Equation 2-1, 2-2, 2-3 and 2-4, the air-gap apparent power $S_{\text{gap}}$ is given as

$$S_{\text{gap}} = \left( K_E \times P_n \right) / (\eta_n \times \cos \phi_{1n})$$  \hspace{1cm} (A-5)

The stack aspect ratio $\lambda$ is given as

$$\lambda = L \times \left( (2 \times P_1 / \pi \times D_{sbd}) \right) = L / \tau$$  \hspace{1cm} (A-6)

where $L$ = length of stator core

$\tau$ = pole pitch

Past experience has shown that the stack aspect ratio $\lambda$ falls in the range shown in Table A-1

<table>
<thead>
<tr>
<th>$2P_1$</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>0.6 – 1.0</td>
<td>1.2 – 1.8</td>
<td>1.6 – 2.2</td>
<td>2 – 3</td>
</tr>
</tbody>
</table>

Table A-1 Stack Aspect Ratio $\lambda$
Using Equation A-5 to calculate the value of $S_{\text{gap}}$, $C_0$ is then obtained from Figure A-1.

![Figure A-1 Esson’s “Constant” $C_0$ versus $S_{\text{gap}}$ (Air-Gap Apparent Power)](image)

From A-6 the pole pitch $\tau$ is

$$\tau = (\pi \times D_{\text{sbd}}) / (2 \times P_1) \quad \text{(A-7)}$$

And the slot pitch $\tau_s$ is

$$\tau_s = \tau / (3 \times q) \quad \text{(A-8)}$$

Where $q$ = the number of slots per pole per phase.

The guide to the ratio of internal to external stator diameters $D_{\text{sbd}} / D_{\text{out}}$ is given in Table A-2.

<table>
<thead>
<tr>
<th>$2 \times P_1$</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{sbd}} / D_{\text{out}}$</td>
<td>0.54 – 0.58</td>
<td>0.61 – 0.63</td>
<td>0.68 – 0.71</td>
<td>0.72 – 0.74</td>
</tr>
</tbody>
</table>

Table A-2 Ratio of Internal and External Stator Diameter

And the ratio of internal to external diameters $K_{DD} = D_{\text{sbd}} / D_{\text{out}}$, therefore output diameter $D_{\text{out}}$ is

$$D_{\text{out}} = D_{\text{sbd}} / K_{DD} \quad \text{(A-9)}$$
The air-gap value $g$ is given by the following equations and depending on the number of pole pairs $2 \times P_1$ [13].

$$g = (0.1 + 0.02 \times \sqrt[3]{P_n}) \times 10^{-3} \text{ m for } 2 \times P_1 = 2$$

$$g = (0.1 + 0.012 \times \sqrt[3]{P_n}) \times 10^{-3} \text{ m for } 2 \times P_1 \geq 2$$

**A-2 Stator Winding**

The number of stator slots $N_1$ is

$$N_1 = 2 \times P_1 \times q \times m_1$$

(A-11)

Where $m_1 = \text{number of phases}$

In a two layer winding with chorded coils: $y / \tau = 0.8$, is chosen. This pitch reduces the unwanted $5^{th}$ and $7^{th}$ harmonics [15]. The $3^{rd}$ harmonics are automatically removed by a balanced circuit or a star connected circuit.

The electrical angle between emfs in neighbouring slots $\alpha_{ea}$ is

$$\alpha_{ea} = (2 \times \pi \times P_1) / N_1$$

(A-12)

The pitch factor $K_{P_1}$ is

$$K_{P_1} = \sin (P_1 / 2)$$

(A-13)

Where $P_1 = \text{the span of the coil in electrical degrees}$

The distribution factor $K_{d_1}$ is

$$K_{d_1} = \sin (q \times d^\prime / 2) / q \times \sin (d^\prime / 2)$$

(A-14)

Where $d^\prime = \alpha_{ea}$ (Equation A-12)

Therefore the stator winding factor $K_{W_1}$ is

$$K_{W_1} = K_{P_1} \times K_{d_1}$$

(A-15)

Now the number of turns per phase is determined on the value of the pole flux $\phi$, where flux $\phi$ is

$$\phi = \alpha_1 \times \tau \times L \times B_g$$

(A-16)

Where $B_g$ is the air-gap flux density [13] and is specified in intervals as follows

$$B_g = (0.5 - 0.75)T \text{ for } 2 \times P_1 = 2$$

$$B_g = (0.65 - 0.78)T \text{ for } 2 \times P_1 = 4$$

(A-17)
\[ B_g = (0.7 - 0.82)T \text{ for } 2 \times P_1 = 6 \]
\[ B_g = (0.75 - 0.85)T \text{ for } 2 \times P_1 = 8 \]

As for the spanning coefficient \( \alpha_1 \), this is obtained from Figure A-2 and depends on the tooth saturation factor \( 1 + K_{sc} \).

The number of turns per phase \( W_1 \) is given as

\[ W_1 = \left( K_E \times V_{1ph} \right) / \left( 4 \times K_f \times K_w \times f_1 \times \varphi \right) \quad \text{(A-18)} \]

Therefore the number of conductors per phase \( N_c \) is

\[ N_c = \left( a_1 \times W_1 \right) / \left( P_1 \times q \right) \quad \text{(A-19)} \]

\( N_c \) must be made an even number if it is not. Hence the adjusted value of \( W_1 \) becomes

\[ W_1 = W_{1A} = P_1 \times q \times N_c \quad \text{(A-20)} \]

Therefore the actual flux density \( B_g = 0.5 \times \left( W_1 / W_{1A} \right) \)

\[ \text{(A-21)} \]

The rated current \( I_{1n} \) is

\[ I_{1n} = \left( P_n / (\eta_n \times \cos \phi_n \times \sqrt{3} \times V_1) \right) \quad \text{(A-22)} \]

Figure A-2 Form Factor \( K_f \) and Flux Density Shape Factor \( \alpha_1 \) versus Teeth Saturation

Development of the electric motor
The recommended current densities [13] are

\[ J_{\cos} = (4 - 7) \, \text{A} / \text{mm}^2 \text{ for } 2P_1 = 2, 4 \]  
\[ J_{\cos} = (5 - 8) \, \text{A} / \text{mm}^2 \text{ for } 2P_1 = 6, 8 \]  
(A-23)

Now the magnetic wire cross section \( A_{Co} \) is

\[ A_{Co} = I_{1n} / (J_{\cos} \times a_1) \]  
(A-24)

Where \( a_1 = 1 \)

From the conductor area \( A_{Co} \) (Equation A-24) the conductor diameter \( d_{Co} \) is

\[ d_{Co} = \sqrt{4 \times A_{Co} / \pi} \]  
(A-25)

The values of standardised diameter sizes are given in Table A-3.

<table>
<thead>
<tr>
<th>Rated diameter [mm]</th>
<th>Insulated diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.327</td>
</tr>
<tr>
<td>0.32</td>
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Table A-3 Standardised Diameter Sizes.

In general if \( d_{Co} \geq 1.3 \, \text{mm} \) in low power induction motors, a few conductors may be used in parallel in which case \( a_1 \) becomes \( a_P > 1 \)[13].
A-3 Stator Slot Sizing
In calculating the slot sizing a factor known as slot fill $K_{fill}$ is used in a formula of values of $N_c$ and $a_p$. For round wire the slot fill, $K_{fill} \approx 0.35$ to 0.4 below 10 kW, and 0.4 to 0.5 above 10 kW [13]. Therefore the useful slot area $A_{su}$ is

$$A_{su} = \frac{\pi \times d_{CoP}^2 \times a_p \times N_c}{4 \times K_{fill}}$$  \hspace{1cm} (A-26)

There are main types of shapes of slots but in general a trapezoidal shape design is used for motors < 10 kW as shown in Figure A-3.

![Figure A-3 Recommended Stator Slots](image)

The slot shown in Figure A-3a is further detailed in Figure A-4. For this kind of slot the shape of the stator tooth is rectangular. In Figure A-4 the variables $b_{os}, h_{os}, h_w$ are assigned values from accepted practice as, $b_{os} = 2$ to 3 mm $\leq 8g$, $h_{os} = (0.5$ to $1.0)$, wedge height $h_w = 1$ to 4 mm [13].
Now assuming that all the air-gap flux passes through the stator teeth, then

$$B_g \times \tau_s \times L = B_{ts} \times b_{ts} \times L \times K_{Fe}$$  \hspace{1cm} (A-27)

Where $K_{Fe} \approx 0.96$ for 0.5 mm thick lamination, constitutes the influence of lamination insulation thickness and $B_{ts}$ is given as

$$B_{ts} = 1.5 - 1.65T.$$  \hspace{1cm} (A-28)

From Equation A-27 $b_{ts}$ is

$$b_{ts} = (B_g \times \tau_s) / (B_{ts} \times K_{Fe})$$  \hspace{1cm} (A-29)

From acceptable practice the value of tooth width $b_{ts} > 3.5 \times 10^{-3}$ m is acceptable.

From Figure A-4 the slot lower width $b_{s1}$ is

$$b_{s1} = \pi ((D_{abd} + 2 \times h_{os} + 2 \times h_w) / N1) - b_{ts}$$  \hspace{1cm} (A-30)

The useful area of the slot $A_{su}$ (Figure A-4) may be expressed as

$$A_{su} = h_s (b_{s1} + b_{s2}) / 2$$  \hspace{1cm} (A-31)

And

$$b_{s2} \approx b_{s1} + 2 \times h_s \times \tan (\pi / N1)$$  \hspace{1cm} (A-32)

From Equation A-31 and A-32, the unknown values of $b_{s2}$ and $h_s$ are computed.
Therefore \( b_{s2}^2 - b_{s1}^2 = 4 \times A_{su} \times \tan (\pi / N1) \) \hfill (A-33)
Therefore \( b_{s2} = \sqrt{((4 \times A_{su} \times \tan (\pi / N1) + b_{s1})^2)} \) \hfill (A-34)

And the slot useful height \( h_s \) is
\[
  h_s = (2 \times A_{su}) / (b_{s1} + b_{s2})
\] \hfill (A-35)

The teeth saturation factor \( 1 + K_{sc} \) is calculated as follows,
\[
  1 + K_{sc} = 1 + (F_{mts} + F_{mtr}) / F_{mg}
\] \hfill (A-36)

The airgap mmf \( F_{mg} \) is
\[
  F_{mg} \approx 1.2 \times g \times B_g / \mu_0
\] \hfill (A-37)

The stator tooth mmf \( F_{mts} \) is
\[
  F_{mts} = H_{ts} (h_s + h_{os} + h_w)
\] \hfill (A-38)

And from (A-36) \( F_{mtr} \) is
\[
  F_{mtr} = K_{sc} \times F_{mg} - F_{mts}
\] \hfill (A-39)

At this point the value of \( F_{mtr} \) must equal that of \( F_{mts} \). If this requirement is not met then the calculation must start again right from the beginning. But if \( F_{mtr} \approx F_{mts} \), then the design is acceptable and no further iterations are necessary.

The next step is to calculate the stator back iron height \( h_{cs} \) (Figure A-4).
\[
  h_{cs} = (((D_{out} - ((D_{sbd} + 2(h_{os} + h_w + h_s))) / 2
\] \hfill (A-40)

Having calculated \( h_{cs} \), the back core flux density \( B_{cs} \) must be verified using the calculated value of flux \( \phi \) from Equation A-16. Therefore \( B_{cs} \) is
\[
  B_{cs} = \phi / (2 \times L \times h_{cs})
\] \hfill (A-41)

\( B_{cs} \) must be within the range 1.4 to 1.7T. If \( B_{cs} \) is outside this range then it is necessary to adjust either of the following; increase the stator outside diameter \( D_{out} \), until \( B_{cs} \) gets into range. Or use a bigger stack aspect ratio \( \lambda \) which would reduce the stator bore diameter \( D_{sbd} \). Or increase the back iron height \( h_{cs} \), to lower \( B_{cs} \). The other alternative is to increase the current density which would
result in the reduction of $h_s$ but this compromises efficiency. All these measures would lead to bringing $B_{cs}$ within the range.

**A-4 Rotor Slot Sizing**

The selection of the number of rotor slots $N_2$ was based on theoretical analysis dating back as far as 1909 plus proven experience on the rules for slot combination of which the most prominent is that $N_2$ should be either below or above $N_1$ by 15 to 20% of $N_1[12]$. In this particular design $N_2$ was taken to be 15% below $N_1$.  

\[(A-42)\]

Now the value of rated rotor bar current $I_b$ is

\[I_b = K_1 \times (2 \times m \times W_1 \times K_{w1} / N_2) \times I_{1n}\]  

\[(A-43)\]

When $K_1 = 1$, the stator and rotor mmfs are equal and yet in reality the stator mmf is larger than the rotor mmf, therefore $K_1$ is

\[K_1 \approx 0.8 \cos \phi_{1n} + 0.2\]  

\[(A-44)\]

For high efficiency, the current density in the rotor bar $J_b = 3.42$ A / mm$^2$. The rotor slot area is

\[A_b = I_b / J_b\]  

\[(A-45)\]

The end ring current $I_{er}$ is

\[I_{er} = I_b / (2 \times \sin(\pi \times P_1 / N2))\]  

\[(A-46)\]

The current density in the end ring $J_{er}$ is

\[J_{er} = (0.75 - 0.8) \times J_b\]  

\[(A-47)\]

Therefore the end ring cross section $A_{er}$ is

\[A_{er} = I_{er} / J_{er}\]  

\[(A-48)\]
A-5 Rotor Slot Sizing

Figure A-5 below shows the variables of the rotor slot.

![Rotor Slot Geometry](image)

Figure A-5 Rotor Slot Geometry

The rotor slot pitch $\tau_r$ is given by the Equation

$$\tau_r = \pi \left( D_{sbd} - 2g \right) / N_r$$  \hspace{1cm} (A-49)

Now $b_{tr}$ the tooth width is

$$b_{tr} \approx \left( \frac{B_g}{K_{Fe} \times B_{tr}} \right) \times \tau_r$$  \hspace{1cm} (A-50)

To determine $d_1$ the top rotor slot diameter ($D_{re} = D_{sbd}$)

$$\pi \left( D_{sbd} - 2 \times h_{or} - d_1 \right) / N2 = d_1 + b_{tr}$$  \hspace{1cm} (A-51)

Therefore $d_1$ is

$$d_1 = \left( \pi \left( D_{re} - 2 \times h_{or} \right) - N2 \times b_{tr} \right) / (\pi + N2)$$  \hspace{1cm} (A-52)

To calculate the value of $d_2$ and $h_t$ the following formulas apply

$$A_{tr} = \pi / 8 \left( d_1^2 + d_2^2 \right) + \left( (d_1 + d_2) \times h_t \right) / 2$$  \hspace{1cm} (A-53)

$$d_1 - d_2 = 2 \times h_t \times \tan \left( \pi / N2 \right)$$  \hspace{1cm} (A-54)

At this point the rotor tooth mmf $F_{mtr}$ is calculated using the values of $h_t$, $d_1$ and $d_2$ and compared to the earlier calculated value of $F_{mtr}$ (Equation A-39), therefore $F_{mtr}$ is
\[ F_{\text{mtr}} = H_{tr} \times (h_r + h_{or} + ((d_1 + d_2) / 2)) \]  

(A-55)

The values of \( H_{tr} \) depends on the values of \( B_{tr} \) as shown in Lamination magnetisation curve of Table A-4

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Table A-4 Lamination Magnetisation Curve \( B_{tr} \) (\( H_{tr} \))

At this point if \( F_{\text{mtr}} \) (Equation A-39) \( \approx \) \( F_{\text{mtr}} \) (Equation A-55), then the design is acceptable.

The next parameter to calculate is the rotor back core height \( h_{cr} \).

\[ h_{cr} = \phi / (2 \times L \times B_{cr}) \]  

(A-56)

The maximum shaft diameter \( D_{\text{shaft}} \) required is

\[ D_{\text{shaft}} \leq D_{\text{sbld}} - 2 \times g - 2 \times (h_{or} + ((d_1 + d_2) / 2)) + h_r + h_{cr} \]  

(A-57)

The shaft diameter must correspond to the rated torque \( T_{en} \) given by the tables and often by comparison from past designs. The rated torque is

\[ T_{en} = P_n / (2 \times \pi \times (f_1 / P_1) \times (1-S_n)) \]  

(A-58)
The end ring cross section is shown in Figure A-6 below.

\[ h_{or} + h_r + (d_1 + d_2)/2 \]

![End Ring Cross-Section Diagram](image)

Figure A-6 End Ring Cross-Section

In general \( D_{sbd} - D_{er} = (3 - 4) \times 10^{-3} \) and also

\[ b = (1.0 - 1.2) \times ((h_r + h_{or} + (d_1 + d_2) / 2) \]

From Equation A-60 \( b \) is

\[ b = 1.0 \times (h_r + h_{or} + (d_1 + d_2) / 2) \]

the dimension \( a \) is

\[ a = A_{er} / b \]

The Magnetisation current \( I_o \) is

\[ I_o = (\pi \times P1 \times (F_{1m} / 2)) / (3 \times \sqrt{2} \times W_1 \times K_{w1}) \]

where \( F_{1m} \) is

\[ F_{1m} = 2 \times (K_c \times g \times B_g / \mu_o + F_{mts} + F_{mtr} + F_{mcs} + F_{mcr}) \]

And \( K_c, F_{mcs} \) and \( F_{mcr} \) are calculated as follows

\( K_c \) is called Carter’s coefficient and is calculated as follows

\[ \gamma_1 = b_{os}^2 / (5 \times g + b_{os}) \]
\[ \gamma_2 = \frac{b_{or}^2}{5 \cdot g + b_{or}} \]  
\hfill (A-66)

Where \( K_{c1} \) and \( K_{c2} \) are given by the formulas involving \( \gamma_1 \) and \( \gamma_2 \) as follows
\[ K_{c1} = \frac{\tau_s}{(\tau_s - \gamma_1)} \]  
\hfill (A-67)
\[ K_{c2} = \frac{\tau_r}{(\tau_r - \gamma_2)} \]  
\hfill (A-68)

Therefore
\[ K_c = K_{c1} \times k_{c2} \]  
\hfill (A-69)

Now \( F_{mcs} \) and \( F_{mcr} \) are given by the following
\[ F_{mcs} = C_{cs} \times \pi \times ((D_{out} - h_{cs}) / 2 \times P_1) \times H_{cs}(B_{cs}) \]  
\hfill (A-70)
And
\[ F_{mcr} = C_{cr} \times \pi \times ((D_{shaft} + h_{cr}) / 2 \times P_1) \times H_{cr}(B_{cr}) \]  
\hfill (A-71)

Where
\[ C_{cs} = C_{cr} \approx 0.88 \times e^{-0.4 x B_{cs} \gamma_2} \]  
\hfill (A-72)

The total saturation factor \( K_s \) is
\[ K_s = \frac{F_{1m}}{(2 \times F_{mg})} - 1 \]  
\hfill (A-73)

And the unit per unit value \( i_0 \) is
\[ i_0 = \frac{I_o}{I_{1n}} \]  
\hfill (A-74)
A-6 Resistances and Inductances

Resistances and inductances are shown in Figure A-7.

![Figure A-7 Equivalent Circuit of an Induction Motor (Core Losses ignored)](image)

The stator phasor resistance $R_s$ is

$$R_s = \rho_{Co} x \left( (I_c x W_1) / A_{Co} x a_1 \right) \quad (A-75)$$

Where $I_c$ is

$$I_c = 2 x (L + I_{end}) \quad (A-76)$$

The coil end connection depends on the coil span $y$. Number of poles $P$, shape of coils, and number of layers in the winding.

From common practice the following empirical formulas are used in determining $I_{end}$ [13].

- $I_{end} = 2 x y - 0.04 \text{ m for } 2 \times P_1 = 2 \quad (A-77)$
- $I_{end} = 2 x y - 0.02 \text{ m for } 2 \times P_1 = 4$
- $I_{end} = \pi / 2 x y + 0.018 \text{ m for } 2 \times P_1 = 6$
- $I_{end} = 2.2 x y - 0.012 \text{ m for } 2 \times P_1 = 8$

And the ratio $y / \tau = \beta$ called the chording factor usually equal to 0.8. \quad (A-78)

Where the acceptable values of $\beta$ is $2 / 3 \leq \beta \leq 1$ \quad (A-79)
From Equation A-77 the coil span $y$ is

$$y = \beta x \tau$$  \hspace{1cm} (A-80)

Now in designing an induction motor of high efficiency the winding temperature is regarded important and must not be large even if the insulation class is F. In any design therefore caution must be observed to design a motor below the maximum insulation temperature. To achieve this the motor is designed for copper resistivity $(\rho_{Co})_{80^\circ C}$ at $80^\circ C$. Now for copper resistivity at $20^\circ C$, $(\rho_{Co})_{20^\circ C} = 1.78 \times 10^{-8} \text{ \Omega m}$. And at $115^\circ C$, $(\rho_{Co})_{115^\circ C} = 1.37 \times (\rho_{Co})_{20^\circ C}$.

Therefore at copper resistivity = $80^\circ C$, $(\rho_{Co})_{80^\circ C}$ is

$$(\rho_{Co})_{80^\circ C} = (\rho_{Co})_{20^\circ C} \times (1+(1/273) \times (80-20))$$  \hspace{1cm} (A-81)

And the rotor bar-end ring equivalent resistance $R_{be}$ is

$$R_{be} = \rho_{A1} \times ((L / A_b) \times K_R + (\iota_{er} / (2 \times A_{er} \times \sin^2(\pi \times P_1 / 2))))$$  \hspace{1cm} (A-82)

Where $\rho_{A1}$ is the cast aluminium resistivity and at $20^\circ C$ $(\rho_{A1})_{20^\circ C} = 3.1 \times 10^{-8} \text{ \Omega m}$  \hspace{1cm} (A-83)

The end-ring length $\iota_{end} = \pi \times (D_{er} - b) / N2$  \hspace{1cm} (A-84)

Now from Equation 2-57 $D_{er} = D_{sbd} - 2 \times g - 2 \times 3 \times 10^{-3} \text{ m}$  \hspace{1cm} (A-85)

In Equation A-82, $K_R$ is the approximate skin effect resistance coefficient, for a rectangular slot, and is

$$K_R = \xi \times (\sinh(2 \times \xi) + \sin(2 \times \xi)) / (\cosh(2 \times \xi) - \cos(2 \times \xi)) \approx \xi$$  \hspace{1cm} (A-86)

And

$$\xi = \beta_s \times h_s \times \sqrt{S}$$, where $S = 1$  \hspace{1cm} (A-87)

And

$$\beta_s = \sqrt{(\omega_i \times \mu_0) / (2 \times \rho_{A1})}$$  \hspace{1cm} (A-88)

From Equation A-85

$$K_R = \xi$$  \hspace{1cm} (A-89)
The rotor cage resistance reduced to the stator $R_{r'}$ is

$$R_{r'}_{st} = \frac{(4 x m) / N2 x (W_1 x K_{W1})^2 x R_{be80°C}}{(R_{r'})_{st}}$$  (A-90)

The stator phase leakage reactance $X_{s1}$ is

$$X_{s1} = 2 x \mu_o x \omega_1 x L x \left(\frac{W_1^2}{(P1 x q)} x (\lambda_s + \lambda_{ds} + \lambda_{ec})\right)$$  (A-91)

Where $\lambda_s$, $\lambda_{ds}$, $\lambda_{ec}$ are the slot differential and end ring connection coefficients.

And

$$\lambda_s = (((2 / 3) x (h_s / (b_{s1} + b_{s2}))) + ((2 x h_w) / (b_{os} + b_{s1})) + (h_{os} / b_{os})) x ((1 + 3 x \beta) / 4)$$  (A-92)

And

$$\lambda_{ds} = (0.9 x \tau_s x q^2 x K_{W1}^2 x C_s x \gamma_{ds}) / (K_c x g x (1 + K_{st}))$$  (A-93)

Where

$$C_s = 1 - 0.033 x \left(\frac{b_{os}^2}{(g x \tau_s)}\right)$$  (A-94)

And

$$\gamma_{ds} = (0.11 x \sin\phi_1 + 0.28) x 10^{-2}; \text{for } q = 8$$
$$\gamma_{ds} = (0.11 x \sin\phi_1 + 0.41) x 10^{-2}; \text{for } q = 6$$
$$\gamma_{ds} = (0.14 x \sin\phi_1 + 0.76) x 10^{-2}; \text{for } q = 4$$
$$\gamma_{ds} = (0.18 x \sin\phi_1 + 1.24) x 10^{-2}; \text{for } q = 3$$
$$\gamma_{ds} = (0.25 x \sin\phi_1 + 2.6) x 10^{-2}; \text{for } q = 2$$

Where

$$\phi_1 = \pi x (6 x \beta - 5.5)$$  (A-96)

For a two layer winding, the end connection specific geometric permeance coefficient $\lambda_{ec}$ is

$$\lambda_{ec} = 0.34 x \left(\frac{q}{L}\right) x (I_{end} - 0.64 x \beta x \tau)$$  (A-97)

The equivalent rotor bar leakage reactance $X_{be}$ is

$$X_{be} = 2 x \pi x f_1 x \mu_o x L x (\lambda_r x K_x + \lambda_{dr} + \lambda_{er})$$  (A-98)

Where $\lambda_r$, $\lambda_{dr}$, $\lambda_{er}$ are the rotor slot differential and end ring permeance coefficient.

$$\lambda_r = 0.66 + (2 x h_i / (3 x (d_1 + d_2))) + h_{oi} / b_{oi}$$  (A-99)
And the differential coefficient $\lambda_{dr}$ is

$$\lambda_{dr} = ((0.9 \times \tau \times \gamma_{dr}) / (K_c \times g)) \times (N_r / (6 \times P_1))^2$$  \hspace{1cm} (A-100)

and

$$\gamma_{dr} = 9 \times (6 \times P^1 / N2)^2 \times 10^{-2}$$  \hspace{1cm} (A-101)

And the end-ring coefficient $\lambda_{er}$ is

$$\lambda_{er} = ((2.3x(D_{er} – b)) / N2 \times L \times 4 \times \text{SIN}^2(\pi \times P_1/N2)) \times \log((4.7 \times (D_{er} – b)) / (b +2 \times a))$$  \hspace{1cm} (A-102)

The skin coefficient for the leakage reactance $K_x$ is

$$K_x = (3/(2 \times \xi)) \times ((\text{SINH}(2 \times \xi) – \text{SIN}(2 \times \xi) / (\text{COSH}(2 \times \xi) – \text{COS}(2 \times \xi))) = 3 / (2 \times \xi)$$  \hspace{1cm} (A-103)

The rotor leakage reactance $X_{r1}$ is a function of $X_{be}$ and is given as

$$X_{r1} = 4 \times m_1 \times ((W_1 \times K_{w1})^2 / N2) \times X_{be}$$  \hspace{1cm} (A-104)

At standstill $S = 1$, both stator and rotor leakage reactance are reduced due to leakage flux path saturation. For power levels in semi-closed stator and rotor slots, therefore

$$(X_{s1})_{S=1}^{sat} = X_{s1} \times (0.7 – 0.8) \approx X_{s1} \times 0.75$$  \hspace{1cm} (A-105)

$$(X_{r1})_{S=1}^{sat} = X_{r1} \times (0.6 – 0.7) \approx X_{r1} \times 0.65$$  \hspace{1cm} (A-106)

For rated slip(speed), both skin and leakage saturation effects are undesirable and must be eliminated by making $K_R = K_x = 1$. This condition then gives the rotor bar end resistance $(R_{be80°C})_{S_n}$ at rated slip (A-81).

The rotor resistance $(R_{r})_{S_n}$ is

$$(R_{r})_{S_n} = (R_{r})_{S=1} \times R_{be80°C}^{S=Sn} / R_{be80°C}^{S=1}$$  \hspace{1cm} (A-107)

The magnetisation reactance $X_m$ is

$$X_m = \sqrt{(V_{ph} / I_0)^2 - R_{r}^2} - X_{s1}$$  \hspace{1cm} (A-108)
A-7 The Skewing Effect on Reactances

In most designs rotor slots are skewed. The topic of skewing is however not the subject of this design. Nevertheless it is sufficient to know that a skewing factor $C$ of one stator slot pitch $\tau_s$ is typical ($C = \tau_s$).

The effect of skewing on $X_m$ is

$$(X_m)_{skew} = X_m \times K_{skew}$$

(A-109)

And $K_{skew} = \sin(\pi / 2 \times C / \tau) / (\pi / 2 \times \tau / \tau) = \sin(\pi / 2 \times \tau_s / \tau) / (\pi / 2 \times \tau_s / \tau)(2-108)$

The rotor leakage inductance is augmented by a new term $X'_{r1skew}$ equal to

$$X'_{r1skew} = X_{mskew} \times (1 - K_{skew}^2)$$

(A-110)

The final values of rotor reactance at $S=1$ and $S = S_n$ respectively are

$$(X_{r1})_{skew}^{S=1} = (X_{r1})_{sat}^{S=1} + X'_{r1skew}$$

(A-111)

$$(X_{r1})_{skew}^{S=S_n} = X_{r1} + X'_{r1skew}$$

(A-112)

A-8 Losses and Efficiency

Efficiency $\eta$ is defined as the output divided by the input power and is given by the expression,

$$\eta = P_{out} / P_{in} = P_{out} / (P_{in} + \sum \text{losses})$$

(A-113)

The loss components are

$$\sum \text{losses} = P_{Co} + P_{Al} + P_{iron} + P_{mv} + P_{stray}$$

(A-114)

Where $P_{Co}$ is the stator winding losses and is equal to

$$P_{Co} = 3 \times R_s \times I_{in}^2$$

(A-115)

And $P_{Al}$ is the rotor cage losses, therefore

$$P_{Al} = 3 \times (R_n)_{Sn} \times I_{m}^2 = 3 \times R_r \times K_1^2 \times I_{1n}^2$$

(A-116)
The mechanical/ventilation losses $P_{mv} = 0.03 \times P_n$ \hfill (A-117)

The stray losses $P_{stray} = 0.01 \times P_n$ \hfill (A-118)

The iron core losses are complicated and are composed of the fundamental $P_{1, iron}$ and addition (harmonics) $P_{h, iron}$ loss. The fundamental core losses occur only in the teeth and back iron ($P_{t1}, P_{y1}$) of the stator as the rotor (slip) frequency is low ($f_2 < (3 – 4) \text{ Hz}$). \hfill (A-119)

Therefore $P_{t1} = K_t \times P_{10} \times (f_1 / 50)^{1.3} \times B_{ts}^{1.7} \times G_{t1}$ \hfill (A-120)

Where $P_{10}$ is the specific losses in W / Kg at 1.0 Tesla and 50 Hz ($P_{10}=(2-3)$) W / Kg, $\gamma_{iron} =$ 7800 and $K_t = (1.6 – 1.8)$ is the core loss augmentation for mechanical working. \hfill (A-121)

The stator tooth weight $G_{t1}$ is

$$G_{t1} = \gamma_{iron} \times N_1 \times b_{ts} \times (h_s + h_w + h_{oa}) \times L \times K_{Fe}$$ \hfill (A-122)

Similarly the stator back iron (yoke) fundamental losses $P_{y1}$ is

$$P_{y1} = K_y \times P_{10} \times (f_1 / 50)^{1.3} \times B_{cs}^{1.7} \times G_{y1}$$ \hfill (A-123)

Where $K_y = 1.6 -1.9$ takes care of the influence of mechanical machining.

$$G_{y1} = \gamma_{iron} \times (\pi / 4) \times (D_{out}^2 - (D_{out} - 2 \times h_{cs})^2) \times L \times K_{Fe}$$ \hfill (A-124)

Therefore the fundamental iron losses $P_{1, iron}$ is

$$P_{1, iron} = P_{t1} + P_{y1}$$ \hfill (A-125)

The stray losses $P_{S, iron}$ are made up of the tooth flux pulsation losses, therefore $P_{S, iron}$ is

$$P_{S, iron} = 0.5 \times 10^{-4} \times ((N2 \times (f_1/P_1) \times K_{ps} \times B_{ps})^2 \times G_{ts} + (N_1 \times (f_1/P_1) \times K_{pr} \times B_{pr})^2 \times G_{tr})$$ \hfill (A-126)

Where the quantities $K_{ps}$, $B_{ps}$, $G_{ts}$, $K_{pr}$, $B_{pr}$ and $G_{tr}$ are as follows

$$K_{ps} = 1 / (2.2 - B_{ts})$$ \hfill (A-127)

$$B_{ps} = (K_{c2} -1) / B_g$$ \hfill (A-128)

And

$$K_{pr} = K_{ps} = 1 / (2.2 - B_{tr})$$ \hfill (A-129)
\[ B_{pr} = \frac{(K_c - 1)}{B_g} \]  \hspace{1cm} (A-130)

The rotor teeth weight \( G_{tr} \) is

\[ G_{tr} = \gamma_{iron} \times L \times K_{Fe} \times N2 \times (h_r + \frac{(d_1 + d_2)}{2}) \times b_{tr} \]  \hspace{1cm} (A-131)

And

\[ G_{ts} = G_{t1} \]  \hspace{1cm} (A-132)

Therefore the total core loss \( P_{iron} \) is

\[ P_{iron} = P_{iron}^1 + P_{iron}^S \]  \hspace{1cm} (A-133)

**A-9 Operation Characteristics**

Operating characteristics are calculated to see if the design power factor \( \cos \phi_{1n} \) is achieved.

The operation characteristics are the active no load current \( I_{0a} \), rated slip \( S_n \), rated torque \( T_n \), breakdown slip and torque \( S_k \), \( T_{bk} \), current \( I_s \) and power factor versus slip, starting current, and torque \( I_{LR} \), \( T_{LR} \).

The no load current \( I_{0a} \) is given by the no load losses as follows

\[ I_{0a} = \frac{(P_{iron} + P_{mv} + (3 \times I_0^2 \times R_s))}{(3 \times V_{ph})} \]  \hspace{1cm} (A-134)

The rated slip \( S_n \) is

\[ S_n = \frac{P_{A1}}{P_n + P_{A1} + P_{mv} + P_{stray}} \]  \hspace{1cm} (A-135)

The value of the design slip \( S_n \) used in the initial stages of the design must be equal or more than the rated slip \( S_n \) calculated in Equation A-135 for the design to be acceptable.

The rated shaft torque \( T_n \) is

\[ T_n = \frac{P_n}{2 \times \pi \times (f_1 / P_1) \times (1 - S)} \]  \hspace{1cm} (A-136)

The torque versus slip expression is given by the equation

\[ T_e = \frac{(3 \times P_1 / \omega_1) \times ((V_{ph}^2 \times (R_r / S)) / ((R_s + C_m \times (R_r / S))^2 + (X_{s1} + C_m \times X_{r1})^2)} \]  \hspace{1cm} (A-137)
Where \[ C_m = 1 + \frac{X_{s1}}{X_m} \]  

(A-137)

Therefore from Equation A-137 the breakdown torque \( T_{bk} \) is

\[ T_{bk} = \left(3 \times \frac{P_1}{2 \times \omega_1}\right) \times \left(\frac{V_{ph}^2}{\sqrt{\left(R_s^2 + (X_{s1} + C_1 \times X_{r1})^2\right)}}\right) \]  

(A-138)

And \( C_1 = 1.1658 \times C_m \)  

(A-139)

The starting current \( I_{LR} \) is

\[ I_{LR} = \frac{V_{ph}}{\sqrt{\left(R_s^2 + \left(R_{r1}^{S=1}\right)^2 \times X_{s1}^{S=1} + X_{r1}^{S=1}\right)^2}}} \]  

(A-140)

The starting torque \( T_{LR} \) is

\[ T_{LR} = \left(3 \times \frac{R_{r1}^{S=1} \times I_{LR}^2}{\omega_1}\right) \times P_1 \]  

(A-141)

The rated power factor \( \cos \varphi_{1n} \) is

\[ \cos \varphi_{1n} = \frac{P_n}{3 \times V_{ph} \times I_n \times \eta} \]  

(A-142)

The calculated power factor \( \cos \varphi_{1n} \) must be bigger or equal to the initial assumed value of \( \cos \varphi_{1n} \) used in the design for the design to be acceptable.

The other quantities of interest are the ratios of breakdown torque to rated torque \( t_{bk} \), the starting torque to the rated torque \( t_{LR} \) and the starting current to the input current \( i_{LR} \), therefore

\[ t_{bk} = \frac{T_{bk}}{T_n} \]  

(A-143)

\[ t_{LR} = \frac{T_{LR}}{T_n} \]  

(A-144)

\[ i_{LR} = \frac{I_{LR}}{I_n} \]  

(A-145)

A-10 Temperature Rise

The temperature rise of the induction motor in operation was is very important and it was calculated to prove that it was below that of insulation class F, even though the motor was designed for class F insulation. The temperature rise must not exceed the design class for the design to be thermally valid.
To start with the temperature differential between the conductors in slots and the slot wall $\Delta \theta_{co}$ was calculated as follows

$$\Delta \theta_{co} = \frac{P_{co}}{(\alpha_{cond} \times A_{1s})}$$  \hspace{1cm} (A-146)

The frame temperature rise $\Delta \theta_{frame}$ with respect to ambient air was determined as follows

$$\Delta \theta_{frame} = \sum \text{losses} / (\alpha_{cond} \times A_{frame})$$  \hspace{1cm} (A-147)

Where

$$\alpha_{cond} = \frac{\lambda_{ins}}{h_{ins}}$$  \hspace{1cm} (A-148)

And $\lambda_{ins} = 0.25$ is the insulation thermal conductivity in $(W / m^2 \times K)$  \hspace{1cm} (A-149)

$h_{ins} = 3 \times 10^{-4}$ is the total insulation thickness from the slot middle to the teeth of the wall  \hspace{1cm} (A-150)

and $\alpha_{cond}$ is the slot insulation conductivity plus its thickness lumped together.

The stator slot lateral area $A_{1s}$ is

$$A_{1s} = (2 \times h_{s} + b_{s2}) \times L \times N1$$  \hspace{1cm} (A-151)

The frame area $A_{frame}$ is

$$A_{frame} = \pi \times D_{out} \times (L + \tau) \times K_{fin}$$  \hspace{1cm} (A-152)

Where $K_{fin} > 1.0$ is the frame cooling constant and expresses the cooling effect of the number of fins on the motor casing.  \hspace{1cm} (A-153)

Now if ambient temperature $\theta_{amb} = 40^\circ C$, then $\theta_{co}$ is

$$\theta_{co} = \theta_{amb} + \Delta \theta_{co} + \Delta \theta_{frame}$$  \hspace{1cm} (A-154)

The conductor temperature $\theta_{co}$ must fall below that of class F insulation.

### A-11 Construction and Armature Windings

A motor or generator is divided into two parts namely, the stator and the rotor. The stationary part of the motor is called the stator, while the rotating part is called the rotor. Both the stator and the
rotor are built up of laminated steel cores and windings. The stator core usually carries the field winding while the rotor core carries the armature windings. The windings on both the stator and the rotor are similar.

A-12 Types of Armature Windings

There are generally two types of windings, the lap-winding and the wave-winding [15, 18]. These are classified as simplex or multiplex depending on the end connection sequence.

A-13 Lap-Winding and Wave winding

Figure A-8 Lap and Wave Coils
A-14 Simplex Lap-Winding

In this winding the coil ends are connected to the adjacent coil ends in case of an ac machine and to the adjacent segments in case of a dc machine.

This winding was used for the development of the University of Zambia electric motor.

A-15 Coil Span and the Coil Pitch

The coil span \( Y_s \) is often referred to as the coil pitch [15] and is expressed as,

\[
Y_s = S - K \quad \frac{P}{P}
\]

(A-155)

Where \( Y_s \) = coil pitch, in slots

\( S \) = total number of slots

\( P \) = number of poles

\( K \) = any fraction remainder of \( S/K \) that is subtracted to make \( Y_s \) an integer.

When a coil spans exactly 180 electrical degrees, the coil pitch is called full pitch. If the coil spans less than 180 electrical degrees, the coil pitch is called a fractional pitch. The ratio of the voltage generated in a fractional pitch coil to that generated in the full pitch coil is called the pitch factor.

A-16 Pitch Factor

\[
K_{pl} = \sin \frac{P^o}{2}
\]

(A-156)
where \( k_p \) = pitch factor (always a decimal for a fractional-pitch winding) [13]

\( p^\circ \) = span of the coil in electrical degrees.

**A-17 Distribution Factor**

When coils are connected in series their resultant voltage is not equal to the voltage of individual coils (not connected) added together. The factor used to multiply to the voltage from the series connection to equal that of the sum of the unconnected coils is called the distribution factor and is expressed as,

\[
K_{d1} = \frac{\sin(n \times d^\circ / 2)}{n \times \sin(d^\circ / 2)}
\]  \hspace{1cm} (A-157)

where \( K_{d1} \) = distribution factor

\( n \) = number of slots per phase per pole

\( d^\circ \) = number of electrical degrees between adjacent slots
## Induction Motor Design Formulae

**Motor Parameters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
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</tr>
<tr>
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</tr>
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<tr>
<td>$K_{Fe}$</td>
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<tr>
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</tr>
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<tr>
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<td>$h_{os}$</td>
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<tr>
<td>$b_{os}$</td>
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<tr>
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<tr>
<td>$\eta_n$</td>
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<tr>
<td>$h_{w}$</td>
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<tr>
<td>$K_{fin}$</td>
<td>3</td>
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<tr>
<td>$V_1$</td>
<td>380 V</td>
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<tr>
<td>$V_{ph}$</td>
<td>219.39 V</td>
</tr>
<tr>
<td>$J_b$</td>
<td>3E+06 A/m²</td>
</tr>
<tr>
<td>$h_{os}$</td>
<td>0.0005 m</td>
</tr>
<tr>
<td>$h_{cr}$</td>
<td>3460 A/m</td>
</tr>
</tbody>
</table>

The airgap apparent power $S_{gap}$ is

$$S_{gap} = (K_E x P_n)/(\eta_n x Cos\phi_1n) = 7125.3 \text{ VA (B-1)}$$

For $S_{gap} = 7125.3 \text{ VA}$, $C_o = 144500 \text{ J / m}^3$ obtained from Figure A-1.

The stator bore diameter $D_{sbd}$ is

$$D_{sbd} = \sqrt[3]{((2xP_1 x S_{gap})/(\pi x \lambda_x f_1 x C_o))} = 0.10154 \text{ m (B-2)}$$

Pole pitch $\tau$ is

$$\tau = (\pi x D_{sbd})/(2xP_1) = 0.15942 \text{ m (B-3)}$$

The length of the stator core $L$ is

$$L = (\lambda x \pi x D_{sbd})/(2xP_1) = 0.09565 \text{ m (B-4)}$$
APPENDIX B Motor Design Calculations

The stator slot pitch is

\[ \tau_s = \tau / (3 \times q) = 0.00886 \text{ m} \quad (B-5) \]

From Appendix A (Table A-2) \( K_{DD} \) is

\[ K_{DD} = D_{shd} / D_{out}, \quad (B-6) \]

The stator out diameter \( D_{out} \) is

\[ D_{out} = D_{shd} / K_{DD} = 0.181 \text{ m} \quad (B-7) \]

Therefore \( D_{out} = 0.18 \text{ m} = 180 \text{ mm} \)

The air-gap \( g \) is

\[ g = (0.1 + 0.02 \times \sqrt[3]{P_n}) \times 10^{-3} \text{ m}, \quad \text{for } 2 \times P_1 = 2(\text{i.e. 2 pole motors}) \quad (B-8) \]

\[ g = 0.0004 \text{ m} \quad = \quad 4.50E-04 \text{ m} \]

**Stator Winding Electrical Calculations**

The number of primary winding \( N_1 \) is

\[ N_1 = 2 \times P_1 \times q \times m = 36 \quad (B-9) \]

The stator electric angle \( \alpha_{ea} \) is

\[ \alpha_{ea} = (2 \times \pi \times P_1) / N_1 = 0.174 \quad \text{or} \quad \pi / 18 \quad (B-10) \]

The pitch factor \( K_{p1} \) is

\[ K_{p1} = \sin(P'/2) = 0.948 \quad (B-11) \]
The distribution factor $K_{d1}$ is

$$K_{d1} = \frac{\sin(qx'd'/2)}{qx\sin(d'/2)} = 0.956$$  \hspace{1cm} (B-12)

Therefore the stator winding factor $K_{w1}$ is

$$K_{w1} = K_{p1}xK_{d1} = 0.907$$  \hspace{1cm} (B-13)

Flux per pole $\phi$ is

$$\phi = \alpha_1 x T x B_g = 0.00645 \text{ Wb}$$  \hspace{1cm} (B-14)

The range of $B_g$ for a 2xP1=2 motor is

$$B_g = (0.5 - 0.75)T, \text{ therefore } B_g = 0.58 \text{ T}$$  \hspace{1cm} (B-15)

From Appendix A (Figure A-2) the tooth saturation coefficient $1+K_{st}$ is

$$1+K_{st} = 1+0.4$$  \hspace{1cm} From which graph $\alpha_1 = 0.729$  \hspace{1cm} (B-16)

and $K_t = 1.085$

The number of turns per phase $W_1$ is

$$W_1 = \frac{K_E x V_{ph}}{4 x K_t x K_{w1} x f_1 x \phi} = 168.641$$  \hspace{1cm} (B-17)

The number of conductors per slot $N_c$ is

$$N_c = \frac{(a_1 x W_1)}{(P_1 x q)} = 28.107$$  \hspace{1cm} (B-18)

But $N_c$ must be an even number, since the slot accommodates two distinct coils in a double layer winding.

Therefore $N_c = 28$

Therefore the number of turns per phase as to be corrected as $W_{c1}$ and is

\textit{Development of the electric motor}
$$W_{c1} = P_1 x q x N_c = 168 \quad \text{(B-19)}$$

Therefore the actual flux density $B_{ag}$ is

$$B_{ag} = B_g x (W_1/W_{c1}) = 0.58 \text{ T} \quad \text{(B-20)}$$

The input current $I_{in}$ is

$$I_{in} = P_n/(\eta_n x Cos \phi_{1n} x \sqrt{3} x V_1) = 11.103 \text{ A} \quad \text{(B-21)}$$

Current density range $J_{cos}$ is

$$J_{cos} = (4 - 7) \text{ A/mm}^2 \text{ for } 2 \times P1 = 2,4, \text{ i.e. 2 pole, 4 pole motor} \quad \text{(B-22)}$$

Therefore $J_{cos} = 7 \text{ A/mm}^2$ was selected.

The conductor cross section area $A_{co}$ is

$$A_{co} = I_{in}/J_{cos} = 1.586 \text{ mm}^2 \quad \text{(B-23)}$$

Therefore the conductor diameter $d_{co}$ is

$$d_{co} = \sqrt{4 \times A_{co}/\pi} = 1.421 \text{ mm} \quad \text{(B-24)}$$

In general, if $d_{co} > 1.3 \text{ mm}$ in low power induction motors, a few conductors may be used in parallel. But in this design $d_{co} = 1.4 \text{ mm}$ is close to the maximum range = 1.3 mm therefore

$$d_{co} = \sqrt{4 \times A_{co}/(\pi a_1)} = 1.421 \text{ mm}$$

**Stator Slot sizing**

The stator slot area $A_{sa}$ is
\[
A_{su} = \frac{\pi x d_{oc}^2 x a_1 x N_c}{(4 x K_{fill})} = 111.03 \text{ mm}^2 \quad (B-25)
\]

Assuming that all the airgap flux passes through the stator teeth, then,

\[
B_{g x t_s x L} \approx B_{ts} x b_{ts} x L x K_{Fe}, \quad \text{where } b_{ts} \text{ is the tooth width and expressed as } \quad (B-26)
\]

\[
b_{ts} = \frac{(B_{g x t_s x L})/(B_{ts} x K_{Fe})}{(B-27)} = 0.00334 \text{ m}
\]

For technological reasons \(b_{ts}\) must not be below \(3.5 \times 10^{-3} \text{ m}\). But the calculated value of \(3.3 \times 10^{-3} \text{ m}\) is acceptable as it is just below the limit.

The slot front width \(b_{s1}\) is

\[
b_{s1} = \frac{((\pi (D_{sd} + 2x h_{sw} + 2x h_w))/N_1)-b_{ts}}{b_{ts}} = 0.00595 \text{ m} \quad (B-28)
\]

The useful area of the slot may be expressed as

\[
A_{su} = h_s x (b_{s1}+b_{s2})/2, \quad \text{also} \quad (B-29)
\]

\[
b_{s2} = b_{s1} + 2x h_s x \tan(\pi/N_1) \quad (B-30)
\]

From the two equations the values of \(b_{s2}\) and \(h_s\) may be found as follows:

\[
b_{s2}^2-b_{s1}^2 = 4x A_{su} x \tan(\pi/N_1), \quad \text{therefore} \quad (B-31)
\]

\[
b_{s2} = \sqrt{((4x A_{su} x \tan(\pi/N_1))+b_{s1}^2)} = 0.00862 \text{ m} \quad (B-32)
\]

Therefore the slot useful height \(h_s\) is

\[
h_s = 2x A_{su}/(b_{s1}+b_{s2}) = 0.0152 \text{ m} \quad (B-33)
\]

We then must compute the teeth saturation factor \(1+K_{st}\) by assuming that stator and rotor
produce the same effects in this regard. Therefore the teeth saturation factor is

\[ 1 + K_{st} = 1 + \left( \frac{F_{mts} + F_{mtr}}{F_{mg}} \right), \]  
where the airgap \( F_{mg} \) is

\[ F_{mg} = 1.2xgxB/\mu_o = 249.349 \text{ Aturns} \]  

(B-34)

For \( B_{ts} = 1.6 \text{ T} \) \( H_{ts} = 2460 \text{ A/m} \) (B-36)

Therefore \( F_{mts} \) is

\[ F_{mts} = H_{ts}(h_s + h_{sw} + h_w) = 43.660 \text{ Aturns} \]  

(B-37)

And \( F_{mtr} \) is

\[ F_{mtr} = K_{st}xF_{mg} - F_{mts} = 56.079 \text{ Aturns} \]  

(B-38)

This value of the rotor tooth \( F_{mtr} \) is only slightly more than that of the stator tooth saturation \( F_{mts} \) therefore the design is acceptable.

The stator back iron height \( h_{cs} \) is given by the equation,

\[ h_{cs} = (D_{out} - (D_{shd} + 2x(h_{os} + h_w + h_s)))/2 = 0.0215 \text{ m} \]  

(B-39)

The back core diameter \( B_{cs} \) with \( h_{cs} = 0.0215 \text{ m} \) is,

\[ B_{cs} = \phi/(2xLxh_{cs}) = 1.569 \text{ T} \]  

(B-40)

The acceptable value of \( B_{cs} \) is 1.4 to 1.7T, therefore the calculated value of \( B_{cs} = 1.569 \text{T} \) is acceptable.
**Rotor Slot Calculations**

In selecting the number of rotor slots care must be exercised to avoid electromagnetic noise, vibration and anomalies in the speed-torque curve. Manufacturing cost, losses, and heating are affected.

Based on past experience one general rule often used is that the number of stator slots N2 must be either below or above N1 by 15 to 20(some say 25)% of N1. Therefore in this design N2 is,

\[ N2 = N1 - 0.15xN1 = 30.6 \]  \hspace{1cm} (B-41)

Therefore \( N2 = 30 \)

The value of the rated rotor bar current \( I_b \) is,

\[ I_b = K_I x (2xmxW_1xK_w_1)xI_1n/N2 = 298.78 \text{ A} \]  \hspace{1cm} (B-42)

Where \( K_I = 0.8 \cos \phi_1n + 0.2 = 0.88 \)  \hspace{1cm} (B-43)

If \( K_I = 1 \), the rotor and stator mmf are equal but in reality stator mmf is slightly larger.

For high efficiency, the current density in the rotor bar is \( J_b = 3.45 \text{ A/mm}^2 \). The rotor slot area is,

\[ A_b = I_b/J_b = 8.7 \times 10^{-5} \text{ m}^2 \]  \hspace{1cm} (B-44)

The end ring current \( I_{er} \) is,

\[ I_{er} = I_b/(2 \times \sin(\pi P_1/N2)) = 1429.9 \text{ A} \]  \hspace{1cm} (B-45)

The current density in the end ring \( J_{er} = (0.75-0.8)J_b \). Selecting \( J_{er} = 0.75J_b \),

\[ J_{er} = 3 \times 10^6 \text{ A/m}^2 \]

Therefore the end ring cross section \( A_{er} \) is

\[ A_{er} = I_{er}/J_{er} = 0.00056 \text{ m}^2 \]  \hspace{1cm} (B-47)
Rotor Slot Sizing

The rotor slot pitch $\tau_r$ is

$$\tau_r = \frac{\pi(D_{sbd}-2xg)}{N_2} = 0.0105 \text{ m}$$

(B-48)

With the rotor tooth flux density $B_{tr} = 1.6T$, the tooth width $b_{tr}$ is,

$$b_{tr} = \frac{B_g x \tau_r}{(K_{Fe} x B_{tr})} = 0.00399 \text{ m}$$

(B-49)

The diameter $d_1$ is obtained from the following equation,

$$\frac{\pi(D_{sbd}-2xh_{se}-d_1)}{N_2} = d_1 + b_{tr}$$

(B-50)

Therefore

$$d_1 = \frac{\pi(D_{sbd}-2xh_{se}-N_2xb_{tr})}{(\pi+N_2)} = 0.0059 \text{ m}$$

(B-51)

To complete the slot dimensions we apply the following slot area equations

$$A_b = \frac{\pi}{8}(d_1^2-d_2^2)+(d_1+d_2)h_r/2 \text{ and}$$

$$d_1-d_2 = 2xh_r x \tan(\pi/N_2)$$

(B-52)

(B-53)

Starting with $h_r = h_s = 0.152m$, $d_2$ is

$$d_2 = d_1-2xh_r x \tan(\pi/N_2)= 0.0027 \text{ m}$$

(B-54)

<table>
<thead>
<tr>
<th>$h_r$ (m)</th>
<th>$d_2$ (m)</th>
<th>$A_b$ (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0152</td>
<td>0.0027</td>
<td>7.7E-05</td>
</tr>
<tr>
<td>0.0194</td>
<td>0.0018</td>
<td>8.8E-05</td>
</tr>
</tbody>
</table>

With $h_r = 0.0194m$, $A_b = 8.754E-05m^2$. This value of $A_b$ is almost equal to the earlier calculated value of $A_b=8.74E-05m^2$. Therefore the values of $h_r$ and $d_2$ are,
At this point the value of the rotor tooth mmf \( F_{\text{mtr}} \) was calculated to see how it compares to the earlier value of \( F_{\text{mtr}} = 56.09 \) Aturns calculated. Therefore for \( B_{tr} = B_{ts} = 1.6 \) T, \( H_{tr} = 2460 \) Aturns, \( F_{\text{mtr}} \) is given by the following equation

\[
F_{\text{mtr}} = H_{tr}(h_r+h_{sr}+((d_1+d_2)/2)) = 58.69 \text{ Aturns.} \tag{B-55}
\]

The value of \( F_{\text{mtr}} = 58.69 \) Aturns is very close to the earlier calculated value of \( F_{\text{mtr}} = 56.09 \) Aturns, therefore the design is acceptable.

The rotor back core height \( h_{cr} \) is calculated for rotor core flux density \( B_{cr} = 1.6 \) T, since acceptable \( B_{cr} = 1.4 \) to \( 1.7 \) T. Therefore \( h_{cr} \) is,

\[
h_{cr} = \phi/(2\pi L B_{cr}) = 0.0204 \text{ m} \tag{B-56}
\]

The maximum shaft diameter \( D_{\text{shaft}} \) is,

\[
D_{\text{shaft}} \leq D_{sbd}-2xg-2x(h_{or}+((d_1+d_2)/2)+h_r+h_{cr}) = 0.012 \text{ m} \tag{B-57}
\]

The shaft diameter must correspond to the rated torque given by the mechanical design \( D_{\text{shaft, mec}} = 22 \) mm [1] and often from past designs. The rated torque \( T_{en} \) is,

\[
T_{en} = P_{e}/(2\pi x(f_{1}/P_{1})x(1-S_{n}) = 17.7 \text{ Nm} \tag{B-58}
\]

In this design 22 mm given as the shaft diameter by Nyirenda[1] suffices.

The dimensions \( a \) and \( b \) of the end ring cross section area were calculated from figure B-3 as follows.
Figure B-1 End Ring Cross-Section

In general $D_{sbd} - D_{er} = (3 \text{ to } 4) \times 10^{-3}$m. Also

$$b = (1.0 - 1.2) \times ((h_r + h_{or} + (d_1 + d_2)/2) \text{ from which } b \text{ is}$$

$$b = 1.0x((h_r + h_{or} + (d_1 + d_2)/2)) = 0.0239 \text{ m}$$  \hfill (B-60)

and $a$ is

$$a = A_{er}/b = 0.0234 \text{ m}$$  \hfill (B-61)

The Magnetisation current $I_o$

The magnetisation mmf $F_{1m}$ is

$$F_{1m} = 2x(K_c \times g \times B_g/\mu_o + F_{mts} + F_{mtr} + F_{mcs} + F_{mcr})$$  \hfill (B-62)

Where $K_c$, $F_{mcs}$ and $F_{mcr}$ are calculated as follows,
K_c is called Carter's coefficient and is calculated as follows,

\[ \gamma_1 = \frac{b_{os}}{2/(5 \times g + b_{os})} = 0.00109 \text{ m} \tag{B-63} \]

\[ \gamma_2 = \frac{b_{or}}{2/(5 \times g + b_{or})} = 0.00060 \text{ m} \tag{B-64} \]

Where K_{1c} and K_{2c} are

\[ K_{1c} = \frac{\tau_s}{(\tau_s - \gamma_1)} = 1.140 \tag{B-65} \]

\[ K_{2c} = \frac{\tau_r}{(\tau_r - \gamma_2)} = 1.061 \tag{B-66} \]

Therefore K_c = K_{1c} x K_{2c} = 1.21

Now F_{mcs} = C_{cs} \times \pi \times ((D_{out} - h_{cs})/2P1) \times H_{cs}(B_{cs}) \tag{B-67}

Where B_{cs} = 1.456T and C_{cs} \approx 0.88 \times e^{-0.4 B_{cs, r}^2}

Therefore F_{mcs} = 119.32 \text{ Aturns} \quad C_{cr} = 0.296

and F_{mcr} = C_{cr} \times (\pi \times (D_{shaft} + h_{cr})/2P1) \times H_{cr} \tag{B-68}

Therefore F_{mcr} = 52.30 \text{ Aturns}

Therefore F_{1m} = 1045.29

And the total saturation factor K_s is

\[ K_s = \left( \frac{F_{1m}}{2 \times F_{mg}} \right) - 1 = 1.0960 \tag{B-69} \]

The magnetisation current I_o is

\[ I_o = \frac{\pi P_1 \times (F_{1m}/2)}{(3 \times \sqrt{2} \times W_1 \times K_{w1})} = 2.53 \text{ A} \tag{B-70} \]

And the relative per unit value i_o is
\[ i_0 = I_o/I_{1n} = 0.228 \quad 23\% \]  

\[ (B-71) \]

**Resistances and Inductances**

Resistances and reactances are as shown in figure B-2 below.

\[ \begin{align*}
I_s & \quad R_s & \quad jw1Ls1 & \quad I_r & \quad jw1Lr1 \\
V_s & \quad jw1L_m & \quad I_o & \quad R_s/S
\end{align*} \]

Figure B-2 Equivalent Circuit of an Induction Motor (Core Losses ignored)

The stator phasor resistance is given as

\[ R_s = \rho_{Co}x((I_c x W_1)/A_{co} x a_1) \]

\[ (B-72) \]

where \( I_c = 2x(L+I_{end}) \)

\[ (B-73) \]

The coil end connection depends on the coil span \( y \), number of poles, shape of coils, and number of layers in the winding.

and \( I_{end} = 2y - 0.04 \text{ m} \) for \( 2P1 = 2 \)

\[ (B-74) \]

Also the ratio \( y/\tau = 15/18 = \beta \), is called the chording factor.

\[ (B-75) \]

and the acceptable value of \( \beta \) is the range \( 2/3 \leq \beta \leq 1 \)

\[ (B-76) \]

Therefore \( y = (15/18) \times \tau = 0.13285 \text{ m} \)

\[ \beta = 0.8333 \]

Development of the electric motor
Therefore $I_{\text{end}} = 2xy - 0.02 = 0.24570$ m \hspace{1cm} (B-78)

$I_c = 0.6827$ m

In all designs high efficiency is desired and in achieving this the winding temperature must not be large even if the insulation class if F. In this design therefore similar caution was taken. Now the copper resistivity at $20^\circ C$ is $(\rho_{Co})_{20^\circ C} = 1.78 \times 10^{-8} \text{\Omega m}$ and $(\rho_{Co})_{115^\circ C} = 1.37 \times (\rho_{Co})_{20^\circ C}$. \hspace{1cm} (B-79)

Therefore at copper resistivity $= 80^\circ C$, $\rho_{Co}$ is

$$(\rho_{Co})_{80^\circ C} = (\rho_{Co})_{20^\circ C} x ((1+(1/273)) x (80-20)) = 2.171E-08 \text{\Omega m} \hspace{1cm} (B-80)$$

Therefore from (B-70) $R_s = (\rho_{Co})_{80^\circ C} x ((I_c x W_1)/(A_{Co} x a_1)) = 1.570 \text{\Omega}$ \hspace{1cm} (B-81)

And the rotor bar-end ring equivalent resistance $R_{be}$ is

$$R_{be} = \rho_{A1} x ((L/A_b) x K_R + (\tau_{er}/(2A_{er} x \sin^2(\pi x P_1/N_2))) = \hspace{1cm} (B-82)$$

The cast aluminium resistivity at $20^\circ C$ $(\rho_{A1})_{20^\circ C} = 3.1 \times 10^{-8} \text{\Omega m}$. Therefore $(\rho_{A1})_{20^\circ C} = 3.1E-08 \text{\Omega m} \hspace{1cm} (B-83)$

The end ring length $\tau_{er}$ is

$$\tau_{er} = \pi(D_{er} - b)/N_2 \hspace{1cm} (B-84)$$

From (B-57) $D_{er} = D_{shd} - 2 x g - 2 x 3 \times 10^{-3}$ m $0.09464$ m

From (B80) $\tau_{er} = 0.00741$ m

In (B-79) $K_R$ is the approximate skin effect resistance coefficient (and for a rectangular) is

$$K_R = \xi x ((\sinh(2 x \xi) + \sin(2 x \xi))/(\cosh(2 x \xi) - \cos(2 x \xi)) \approx \xi \hspace{1cm} (B-84)$$
APPENDIX B Motor Design Calculations

And \( \xi = \beta_s \times h_s \times \sqrt{S} \) \hspace{1cm} \text{where} \ S = 1 \hspace{1cm} \text{(B-85)}

And \( \beta_s = \sqrt{((\omega_1 \times \mu_0)/(2 \times \rho_{A1}))} \hspace{1cm} 80 \ (\text{m})^{-1} \hspace{1cm} \text{(B-86)} \)

From (B-82) \( \xi = 1.56 \) \hspace{1cm} \text{From (B-81) } K_R \approx \xi \approx 1.56 \hspace{1cm} \text{(B-87)}

Now from (B-79) \( R_{be}^{s=1, 80^\circ C} = 6.6 \times 10^{-5} \ \Omega \hspace{1cm} \text{(B-88)} \)

The rotor cage resistance reduced to the stator \( R_r' \) is

\[
(R_r')_{s=1} = ((4 \times m)/N2) \times (W_1 \times Kw_1)^2R_{be80^\circ} \hspace{1cm} 0.614 \ \Omega \hspace{1cm} \text{(B-89)}
\]

The stator phase leakage reactance \( X_{s1} \) is

\[
X_{s1} = 2 \times \mu_0 \times \omega_1 \times L \times (W_1^2/(P_1 \times q)) \times (\lambda_s + \lambda_{ds} + \lambda_{ec}) \hspace{1cm} \text{(B-90)}
\]

where \( \lambda_s, \lambda_{ds}, \lambda_{ec} \) are the slot differential and end ring connection coefficients:

and \( \lambda_s = ((2/3) \times (h_s/(b_{s1} + b_{s2})) + ((2 \times h_w)/(b_{os} + b_{s1})) + (h_{os}/b_{os})) \times ((1 + 3 \times \beta)/4) \hspace{1cm} \text{(B-91)} \)

Therefore \( \lambda_s = 1.331 \hspace{1cm} \text{(B-92)} \)

And \( \lambda_{ds} \approx (0.9 \times \tau_s \times q^2 \times Kw_1^2 \times C_s \times \gamma_{ds})/(K_c \times g \times (1 + K_{st}) \hspace{1cm} \text{(B-93)} \)

Where \( C_s = 1 - 0.033(b_{os}^2/(g \times \tau_s)) \hspace{1cm} 0.960 \hspace{1cm} \text{(B-94)} \)

For \( \beta = 15/18 \) and \( q = 6, \gamma_{ds} \) is

\[
\gamma_{ds} = (0.11 \times \text{SIN} \varphi_1 + 0.41) \times 10^{-2} \hspace{1cm} \text{(B-95)}
\]

where \( \varphi_1 = \pi \times (6 \times \beta - 5.5) = -1.57 \hspace{1cm} \text{(B-96)} \)

From (B-90) \( \gamma_{ds} = 0.003 \hspace{1cm} \text{(B-97)} \)

Therefore from (B-88) \( \lambda_{ds} = 0.89481 \hspace{1cm} \text{(B-98)} \)
This design being a two layer winding, the end connection specific geometric permeance coefficient \( \lambda_{ec} \) is

\[
\lambda_{ec} = 0.34 \times (q / L) \times (I_{end} - 0.64 \times \beta \times \tau) = 3.426781 \quad \text{(B-92)}
\]

From (B-86) the stator phase reactance \( X_{s1} \) is

\[
X_{s1} = 2.02131
\]

The equivalent rotor bar leakage reactance \( X_{be} \) is

\[
X_{be} = 2 \times \pi \times f_1 \times \mu_0 \times L \times (\lambda_r \times K_x + \lambda_{dr} + \lambda_{er}) \quad \text{(B-93)}
\]

where \( \lambda_r, \lambda_{dr}, \lambda_{er} \) are the rotor slot, differential and end ring permeance coefficient.

For this design \( \lambda_r \) is

\[
\lambda_r = 0.66 + (2 \times h_r/(3 \times (d_1 + d_2))) + h_{or}/b_{or} = 2.679 \quad \text{(B-94)}
\]

And the differential coefficient \( \lambda_{dr} \) is

\[
\lambda_{dr} = ((0.9 \times \tau_r \times \gamma_{dr})/(K_c \times g)) \times (N_2/(6 \times P_1))^2 \quad \text{(B-95)}
\]

and \( \gamma_{dr} = 9 \times (6 \times P_1/N_2)^2 \times 10^{-2} = 0.0036 \)

From (B-95) \( \lambda_{dr} = 1.574 \)

And the end ring coefficient \( \lambda_{er} \) is

\[
\lambda_{er} = ((2.3 \times (D_{er}-b))/(N_2 \times L \times 4 \times \sin^2(\pi \times P_1/N_2)) \times \log((4.7 \times (D_{er}-b))/(b+2 \times a)) \quad \text{(B-96)}
\]

Therefore \( \lambda_{er} = 0.8750 \)

The skin effect coefficient for the leakage reactance \( K_x \) is, for \( \zeta = 1.56 \)
\[ K_x = \frac{3}{2 \times \xi} \times \frac{(\text{SINH}(2 \times \xi) - \text{SIN}(2 \times \xi))/(\text{COSH}(2 \times \xi) - \text{COS}(2 \times \xi))}{3/(2 \times \xi)} \]  

(B-97)

Therefore \( K_x = \frac{3}{2 \times \xi} = 0.964 \)  

(B-98)

From (B-93) \( X_{be} = 0.00019 \ \Omega \)

The rotor leakage reactance \( X_{r1} \) is a function of \( X_{be} \) and is given as

\[ X_{r1} = 4 \times m_1 \times \frac{(W_1 \times K_{w1})^2/N2 \times X_{be}}{} \]  

(B-99)

Therefore \( X_{r1} = 1.7618 \ \Omega \)

At stand still \( S=1 \), both stator and rotor leakage reactances are reduced due to leakage flux path saturation. For power levels in semi-closed stator and rotor slots, therefore,

\[ (X_{s1})_{S=1}^{\text{sat}} = X_{s1} \times (0.7 - 0.8) \approx X_{s1} \times 0.75 = 1.516 \ \Omega \]  

(B-100)

\[ (X_{r1})_{S=1}^{\text{sat}} = X_{r1} \times (0.6 - 0.7) \approx X_{r1} \times 0.65 = 1.145 \ \Omega \]  

(B-101)

For rated slip (speed), both skin and leakage saturation effects are undesirable and must be eliminated by making \( K_R = K_x = 1 \)

Therefore from (B-80) \( R_{be80^\circ} \) is

\[ (R_{be80^\circ})_{Sn} = 6.4E-05 \ \Omega \]

The rotor resistance \( (R_r')_{Sn} \) is

\[ (R_r')_{Sn} = (R_r')_{s=1} \times \frac{R_{be80^\circ}^{Sn/Sn}/R_{be80^\circ}^{S=1}}{} = 0.598 \ \Omega \]  

(B-101)

The magnetization \( X_m \) is

\[ X_m = \sqrt{((V_{ph}/I_0)^2 \times R_s^2) - X_{s1}^2} = 84.68 \ \Omega \]  

(B-102)
The skewing effect on reactances

In most designs rotor slots are skewed. The topic of skewing is however not the subject for this design. Nevertheless it is sufficient to know that a skewing $C$ of one stator slot pitch $\tau_s$ is typical ($C = \tau_s$)

The effect of skewing on $X_m$ is

$$X_m = X_m \times K_{skew} \quad \text{(B-103)}$$

And $K_{skew} = \frac{\sin(\pi/2 \times C/\tau)}{\pi/2 \times C/\tau} = 0.9987 \quad \text{(B-104)}$

Therefore from (B-103) $X_m$ is

$$X_m = 84.58 \ \Omega$$

The rotor leakage inductance is augmented by a new term $X_{r1skew}$

$$X'_{r1skew} = X_m(1-K_{skew}^2) = 0.2143 \ \Omega \quad \text{(B-105)}$$

The final values of rotor reactances at $S=1$ and $S=Sn$ respectively are,

$$\begin{align*}
(X_{r1})_{skew}^{S=1} &= (X_{r1})_{sat}^{S=1} + X_{r1skew} = 1.359 \ \Omega \\
(X_{r1})_{skew}^{S=Sn} &= X_{r1} + X_{r1skew} = 1.976 \ \Omega
\end{align*} \quad \text{(B-106)}$$

**Losses and Efficiency**

Efficiency $\eta$ is defined as output divided by the input power

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{in} + \sum \text{losses}} \quad \text{(B-108)}$$

The loss components are

$$\sum \text{losses} = P_{co} + P_{A1} + P_{iron} + P_{mv} + P_{stray} \quad \text{(B-109)}$$

where $P_{co}$ is the stator winding losses, $P_{A1}$ is the rotor cage losses.

Therefore $P_{co} = 3 \times R_s \times I_{in}^2 = 580.642 \ \text{W} \quad \text{(B-110)}$
And $P_{A1} = 3 \times (R_{s} \times I_{m}^2 = 3 \times R_{r} \times K_{t}^2 \times I_{in}^2 = 171.218 \text{ W}$ (B-111)

The mechanical/ventilation losses $P_{mv} = 0.03P_{n}$ for $P_{1} = 1$ (B-112)

Therefore $P_{mv} = 158.4 \text{ W}$

The stray losses $P_{stray} = 0.01P_{n}$ is considered standard estimation (B-113)

Therefore $P_{stray} = 52.8 \text{ W}$

The iron core losses are complicated and are composed of the fundamental $P_{iron}^l$ and addition (harmonics) $P_{iron}^h$ loss.

The fundamental core losses occur only in the teeth and back iron ($P_{t1}, P_{y1}$) of the stator as the rotor (slip) frequency is low ($f_{2} < (3 - 4) \text{ Hz}$). (B-114)

Therefore $P_{t1} = K_{t} \times P_{10} \times (f_{1}/50)^{1.3} \times B_{ts}^{1.7} \times G_{t1}$ (B-116)

where $P_{10}$ is the specific losses in W/Kg at 1.0 Tesla and 50 Hz ($P_{10} = (2 - 3)$ W/Kg and $K_{t} = (1.6 - 1.8)$ is the core loss augmentation for mechanical working. (B-117)

$G_{t1}$ is the stator tooth weight and is

$G_{t1} = \gamma_{iron} \times N_{s} \times b_{ts} \times (h_{a} + h_{w} + h_{os}) \times L \times K_{Fe} = 1.5304 \text{ Kg}$ (B-118)

From (B-116) $P_{t1}$ is

$P_{t1} = 11.5689 \text{ W}$

Similarly the stator back iron (yoke) fundamental losses $P_{y1}$ is

$P_{y1} = K_{y} \times P_{10} \times (f_{1}/50)^{1.3} \times B_{cs}^{1.7} \times G_{y1}$ (B-119)

where $K_{y} = 1.6 - 1.9$ takes care of the influence of mechanical machining. Let $K_{y} = 1.6$ (B-120)

And $G_{y1} = \gamma_{iron} \times (\pi/4) \times (D_{out}^2 - (D_{out} - 2 \times h_{cs})^2) \times L \times K_{Fe} = 7.6583 \text{ Kg}$ (B-121)

Therefore from (B-119) $P_{y1} = 41.5148 \text{ W}$
Therefore the fundamental iron losses $P_{\text{iron}}^1$ is

$$P_{\text{iron}}^1 = P_{t1} + P_{y1} = 53.0838 \text{ W} \quad (B-122)$$

The tooth flux pulsation core losses makes up the main components of stray losses $P_{\text{iron}}^s$.

Therefore $P_{\text{iron}}^s = 0.5 \times 10^{-4} \times ((N2 \times (f_1/P_1) \times K_{ps} \times B_{ps})^2 \times G_{ts} + (N_s \times (f_1/P_1) \times K_{pr} \times B_{pr})^2 \times G_{tr}) \quad (B-123)$

where $K_{ps} = 1 / (2.2 - B_{ts}) = 1.6667 \quad (B-124)$

and $K_{pr} = 1 / (2.2 - B_{tr}) = 1.6667 \quad (B-125)$

$B_{ps} = (K_{c2} - 1) \times B_g = 0.0353 \text{ T} \quad (B-126)$

$B_{pr} = (K_{c1} - 1) \times B_g = 0.0817 \text{ T} \quad (B-127)$

And the rotor teeth weight $G_{tr}$ is

$$G_{tr} = \gamma_{\text{iron}} \times L \times K_{Fe} \times N2 \times (h_r + ((d_1 + d_2)/2) \times b_{tr} = 2.0428 \text{ Kg} \quad (B-128)$$

Now from (B-203), $P_{\text{iron}}^s$ is

$$P_{\text{iron}}^s = 6.7 \text{ W}$$

Therefore the total core loss $P_{\text{iron}}$ is

$$P_{\text{iron}} = P_{\text{iron}}^1 + P_{\text{iron}}^s = 59.8 \text{ W} \quad (B-129)$$

The summation of losses from (B-109) $\sum$ losses is

$$\sum \text{ losses} = 1022.872 \text{ W}$$

Having calculated the total losses the efficiency $\eta$ from (B-108) is

$$\eta = 0.84$$

The targetted efficiency used in this design was $\eta_n = 0.85$. The calculated value of efficiency $\eta = 0.84$ is very close to the targetted efficiency $\eta_n$ and therefore the design is acceptable.
Operation Characteristics

Operation characteristics were calculated to see from another targetted value of \( \cos \phi_{1n} = 0.85 \) if the design is acceptable.

The operation characteristics are the active no load current \( I_{0a} \), rated slip \( S_n \), rated torque \( T_n \), breakdown slip and torque \( S_k \), \( T_{bk} \), current \( I_s \) and power factor versus slip, starting current, and torque \( I_{LR}, T_{LR} \).

The no load current is given by the no load losses as follows:

\[
I_{0a} = \left( P_{iron} + P_{mv} + (3 \times I_{02} \times R_s) \right) / (3 \times V_{ph}) = 0.350 \text{ A} \tag{B-130}
\]

The rated slip \( S_n \) is

\[
S_n = P_{A1} / (P_n + P_{A1} + P_{mv} + P_{stray}) = 0.030 \tag{B-131}
\]

The rated shaft torque \( T_n \) is

\[
T_n = P_n / (2 \times \pi \times (f_1 / P_1) \times (1 - S_n)) = 17.34 \text{ Nm} \tag{B-132}
\]

The approximate expressions of torque versus slip are

\[
T_e = ((3 \times P_1) / \omega_1) \times ((V_{ph}^2 \times (R_s / S)) / (R_s + C_m \times (R_s / S))^2 + (X_{s1} + C_m \times X_{r1})^2) \tag{B-133}
\]

where \( C_m = 1 + X_{s1} / X_m = 1.0239 \tag{B-134} \)

From (B-210) the breakdown torque \( T_{bk} \) is

\[
T_{bk} = ((3 \times P_1) / 2 \times \omega_1) \times (V_{ph2} / (R_s + \sqrt{(R_s^2 + (X_{s1} + C_1 \times X_{r1})^2)})) = 38.73 \text{ Nm} \tag{B-135}
\]

The starting current \( I_{LR} \) is

\[
I_{LR} = (V_{ph} / \sqrt{(R_s + R_{s1}^S)^2 + (X_{s1} + X_{r1}^S)^2}) \tag{B-136}
\]

The starting torque \( T_{LR} \) is

\[
T_{LR} = ((3 \times R_s^S \times I_{LR})^2 / \omega_1) \times P_1 = 23.81 \text{ Nm} \tag{B-137}
\]

The rated power factor \( \cos \phi_{1n} \) is
\[ \cos \phi_1n = \frac{P_n}{(3 \times V_{ph} \times I_n \times \eta)} = \quad 0.86 \quad \text{(B-138)} \]

The calculated value of \( \cos \phi_1n = 0.86 \) is close to the rated value of \( \cos \phi_1n = 0.85 \). Therefore the design is acceptable and does not need any further iterations.

The other values of interest are

\[ t_{bk} = \frac{T_{bk}}{T_n} = \quad 2.2 \quad \text{(B-139)} \]
\[ t_{LR} = \frac{T_{LR}}{T_n} = \quad 1.4 \quad \text{(B-140)} \]
\[ i_{LR} = \frac{I_{LR}}{I_{1n}} = \quad 5.7 \quad \text{(B-141)} \]

**Temperature Rise**

The temperature rise of the induction motor in operation was very important to prove and compared to the design insulation class F, for the design to be thermally valid.

To start with the temperature differential between the conductors in slots and the slot wall \( \Delta \theta_{co} \) was calculated as follows:

\[ \Delta \theta_{co} = \frac{P_{co}}{(a_{cond} \times A_{1s})} \quad \text{(B-142)} \]

And the frame temperature rise \( \Delta \theta_{frame} \) with respect to the ambient air was determined.

\[ \Delta \theta_{frame} = \sum \text{losses} / (a_{cond} \times A_{frame}) \quad \text{(B-143)} \]

Where \( a_{cond} = \frac{\lambda_{ins}}{h_{ins}} = 833 \quad \text{W} / \text{m}^2 \text{K} \quad \text{(B-144)} \)

Where \( a_{cond} \) is the slot insulation conductivity plus its thickness lumped together and \( \lambda_{ins} = 0.25 \) and \( h_{ins} = 3 \times 10^{-4} \) are the insulation thermal conductivity in \( \text{(W} / \text{m}^2 \text{K}) \) and the total insulation thickness from the slot middle to the teeth wall respectively.

The stator slot lateral area \( A_{1s} \) is

\[ A_{1s} = (2 \times h + b_{s2}) \times L \times N1 = \quad 0.1347 \quad \text{m}^2 \quad \text{(B-145)} \]

and the frame area \( A_{frame} \) is

\[ A_{frame} = \pi \times D_{out} \times (L + \tau) \times K_{fin} = \quad 0.4325 \quad \text{m}^2 \quad \text{(B-146)} \]
where $K_{\text{fin}} = 2.0$, is the frame area multiplied by fins, provided to maximise heat transfer.

Now from (B-219),(B-110),(B-221),(B-222)

$$\Delta \theta_{\text{co}} = 5.17 \, ^\circ\text{C}$$

And from (B-220), and for $\alpha_{\text{cond}} = 60$, for $2P_1 = 2$

$$\Delta \theta_{\text{frame}} = 39 \, ^\circ\text{C}$$

Therefore if ambient temperature $\Delta \theta_{\text{amb}} = 40^\circ\text{C}$, then the conductor temperature $\theta_{\text{cond}}$ is

$$\theta_{\text{cond}} = \theta_{\text{amb}} + \Delta \theta_{\text{co}} + \Delta \theta_{\text{frame}} = 85 \, ^\circ\text{C} > 80^\circ\text{C}$$

The conductor temperature $\theta_{\text{cond}} = 85^\circ\text{C} < 80^\circ\text{C}$, which is $5^\circ\text{C}$ more than the maximum. However it must be appreciated that the change in ambient temperature can quickly change the conductor temperature accordingly. And in this case if the ambient temperature $\theta_{\text{amb}} = 30^\circ\text{C}$, $\theta_{\text{cond}} = 75^\circ\text{C}$. Another way to improve the conductor temperature is by increasing the surface area of the motor casing by increasing the number of fins.
Appendix C Financial Statements

C-1 Financial Statements for Production of 105 Electric Motors.

Income Statement

<table>
<thead>
<tr>
<th>Year</th>
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Table C-1.1 Income Statement for 105 Units
Balance Sheet

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Table C-1.2 Balance Sheet for 105 Units
# Cash Flow

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Discounting Factor: 26.3%<br>Present Value: (837717) (378832) (16407) 124014 432447 232191 200905<br>Net Present Value: (243399)

Table C-1.3 Cash Flow for 105 Units
## C-1.4 Breakeven Point, Internal Rate of Return (IRR), Payback

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Discount Factor 26.5%

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1st Discount factor 1.263
2nd Discount factor 1.265
10% interest rate 26.3
X interest rate 26.5

IRR 26.47829708 %

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<th>PVI of inflows</th>
<th>Cumulative inflows</th>
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Payback 2 years 4 months
Discounted payback 3 years 4 months

Develoment of the electric motor
## C-1.5 Inflation

### Raw material

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<tr>
<th>Plant Wages</th>
<th>Indirect Staff</th>
<th>Administration</th>
<th>Material Costs</th>
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<tr>
<td>Year 1</td>
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<td>Year 3</td>
<td>Year 4</td>
</tr>
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<tr>
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<td>1,000,000</td>
<td>1,000,000</td>
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### Punch Press

| Station | Number of staff | Basic pay/month | Total/month | Year 2 inflated | Year 3 inflated | Year 4 inflated | Year 5 inflated | Year 6 inflated | Year 7 inflated |
|---------|----------------|-----------------|-------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Operator | 2              | 1,500,000       | 3600000     | 4356000        | 4791600        | 52707600       | 57978360       | 63776196       |                 |

### Machine shop

<table>
<thead>
<tr>
<th>Station</th>
<th>Number of staff</th>
<th>Basic pay/month</th>
<th>Total/month</th>
<th>Year 2 inflated</th>
<th>Year 3 inflated</th>
<th>Year 4 inflated</th>
<th>Year 5 inflated</th>
<th>Year 6 inflated</th>
<th>Year 7 inflated</th>
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### Winding Machines

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<th>Total/month</th>
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<th>Year 3 inflated</th>
<th>Year 4 inflated</th>
<th>Year 5 inflated</th>
<th>Year 6 inflated</th>
<th>Year 7 inflated</th>
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<tbody>
<tr>
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### Diecasting

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<th>Year 3 inflated</th>
<th>Year 4 inflated</th>
<th>Year 5 inflated</th>
<th>Year 6 inflated</th>
<th>Year 7 inflated</th>
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### Rotor assembly

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<th>Total/month</th>
<th>Year 2 inflated</th>
<th>Year 3 inflated</th>
<th>Year 4 inflated</th>
<th>Year 5 inflated</th>
<th>Year 6 inflated</th>
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</thead>
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### Stator assembly

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<th>Total/month</th>
<th>Year 2 inflated</th>
<th>Year 3 inflated</th>
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### Final assembly

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<th>Total/month</th>
<th>Year 2 inflated</th>
<th>Year 3 inflated</th>
<th>Year 4 inflated</th>
<th>Year 5 inflated</th>
<th>Year 6 inflated</th>
<th>Year 7 inflated</th>
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</thead>
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<th>Year 3 inflated</th>
<th>Year 4 inflated</th>
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<th>Year 7 inflated</th>
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### Total

| Total | 39          | 20,400,000     | 630,000,000 | 693000000     | 762300000     | 838530000     | 922383000     | 1014621300     | 1116834300     |

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<td>105</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>105</td>
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<td>Motor production/month</td>
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<td>9</td>
<td>9</td>
<td>9</td>
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### APPENDIX C Financial Statements

#### Development of the electric motor

#### C-1.7 Plant Wages, Indirect Staff

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<tr>
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<th>Total/month</th>
<th>Total/year</th>
<th>Year 2(inflated)</th>
<th>Year 3(inflated)</th>
<th>Year 4(inflated)</th>
<th>Year 5(inflated)</th>
<th>Year 6(inflated)</th>
<th>Year 7(inflated)</th>
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<td>Electricians</td>
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Total: 9 4050000 8100000 97,200,000 106920000 117612000 129373200 142310520 156541572 172195729.2

Cost per unit: 925714.2857 1018285.714 1120114.286 1232125.714 1355338.286 1490872.114 1639959.326

Number of units: 105 105 105 105 105 105 105

#### C-1.8 Administration

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<th>Year 5(inflated)</th>
<th>Year 6(inflated)</th>
<th>Year 7(inflated)</th>
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</table>

Total: 22 80400000 92300000 1,107,600,000 121836000 134019800 1474215600 1621637160 1763080876 1962180961

Cost per unit: 10548571.43 11603428.57 12757771.43 14040184.57 15444103.43 16886779.77 18687437.75

Number of units: 105 105 105 105 105 105 105

---

[Development of the electric motor]
### C-1.9 Equipment Cost

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<td>Arc Welding Machine</td>
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<td>Caterpillar Folk Truck</td>
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<td>Lathe Machine</td>
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### C-1.10 Material Cost

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<th>Year 3(inflated)</th>
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<th>Year 5(inflated)</th>
<th>Year 6(inflated)</th>
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<tbody>
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## C-1.12 Land, Buildings and Services

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## C-1.13 Non Current Asset Schedule

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### C-1.15 Statement of Changes in Equity

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### C-2 Financial Statements for Production of 500 Electric Motors.

#### Income Statement

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<td>K '000</td>
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Table C-2.1 Income Statement for 500 Units
## Balance Sheet

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Table C-2.2 Balance Sheet for 500 Units
### Table C-2.3 Cash Flow for 500 Units

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| Discounting Factor | 26.3% | 0.7918 | 0.6269 | 0.4964 | 0.3930 | 0.3112 | 0.2464 | 0.1951 |
| Present Value | **(837717)** | **(378832)** | **(16407)** | **124014** | **432447** | **232191** | **200905** |
| Net Present Value | **(243399)** | | | | | | |

Table C-2.3 Cash Flow for 500 Units
### C-2.4 Breakeven Point, Internal Rate of Return, Payback

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<th>DCH</th>
<th>Inflows</th>
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**Payback** 2 years 4 months

**Discounted payback** 3 years 4 months
C-2.5 Inflation

### PLANT WAGES

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### Punch Press

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### Total

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### Cost per unit

- 19400 21380 23522 25836 28462 31383 34439 38545

### Number of units

- 50 50 50 50 50 50 50 50

C-2.6 Plant Wages, Direct Staff

### Cost of 1 unit

- 1260000 1386000 1524600 1677060 1844766

### Motor production/year

- 500 500 500 500 500

### Motor production/month

- 42 42 42 42 42

C-2.7 Plant Wages, Indirect Staff

### Total

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### Cost per unit

- 19400 21380 23522 25836 28462 31383 34439 38545

### Number of units

- 50 50 50 50 50 50 50 50

### Development of the electric motor
### C-2.8 Administration

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Cost per unit: 2215200

Number of units: 500

### C-2.9 Material Cost

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<th>Year 3(inflated)</th>
<th>Year 4(inflated)</th>
<th>Year 5(inflated)</th>
<th>Year 6(inflated)</th>
<th>Year 7(inflated)</th>
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Cost per unit: 331958.25

Number of units: 500
### C-2.10 Product Cost and Contribution

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<th>Year</th>
<th>Plant wages</th>
<th>Indirect staff</th>
<th>Administration</th>
<th>Material</th>
<th>Other Fixed Costs</th>
<th>Total</th>
<th>Unit Wellness</th>
<th>Sale/unit</th>
<th>Contribution/unit</th>
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### C-2.11 Equipment Cost

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Total Equipment cost: **1,685,800,000**

### C-2.12 Land, Buildings and Other Fixed Costs

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<th>Administration</th>
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*Development of the electric motor*
## C-2.13 Non Current Asset Value

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## C-2.14 Cost of Sales

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## C-2.15 Statement of Change in Equity

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C-3 Financial Statements for Production of 3000 Electric Motors.

Income Statement

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Table C-3.1 Income Statement for 3000 Units
## Balance Sheet

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Table C-3.2 Balance Sheet for 3000 Units

*Development of the electric motor*
## Cash Flow

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Table C-3.3 Cash Flow
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# Development of the electric motor
C-3.5 Inflation

### PLANT WAGES

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<th>Year 5 (inflated)</th>
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C-3.6 Plant Wages, Direct Staff

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C-3.7 Plant Wages, Indirect Staff

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Development of the electric motor
### C-3.7 Administration

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#### C-3.8 Material Cost

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#### C-3.9 Product Cost and Contribution

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### C-3.10 Equipment Cost

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Total Equipment cost: 1,685,800,000

### C-3.11 Land, Buildings, Other Fixed Costs

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Development of the electric motor
### C-3.12 Non Current Asset Schedule

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### C-3.13 Cost of Sales

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### C-3.14 Statement of Changes in Equity

<table>
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<tr>
<th>Year</th>
<th>Share Capital (ZMK)</th>
<th>Retained Earnings (ZMK)</th>
</tr>
</thead>
<tbody>
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<td>-1108500875</td>
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<tr>
<td>2</td>
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<td>-1642302319</td>
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<td>3</td>
<td>10000000000</td>
<td>-1483182636</td>
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<tr>
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<tr>
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<td>2047255057</td>
</tr>
</tbody>
</table>

`Development of the electric motor`
## FLYGT PUMP 2102.041

**MOTOR CHART**

<table>
<thead>
<tr>
<th>MOTOR NO.</th>
<th>ISSUE</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-09-2AA</td>
<td>11</td>
<td>85 02 08</td>
</tr>
</tbody>
</table>

### NOMINAL VALUES:
- **VOLTAGE:** 3 * 400 V
- **FREQUENCY:** 50 Hz
- **POLES:** 2
- **STATOR:** 44 D
- **CURRENT:** 10 A
- **SPEED:** 2810 RPM

### TORQUE (NM / QUOTIENT COMPARED TO TORQUE AT NOMINAL SPEED)
- **START:** 26 / 1.6
- **PULL-UP:** 21 / 1.2
- **BREAK-DOWN:** 40 / 2.3

### MOMENT OF INERTIA:
- 0.8077 kgm²

### LOAD
- 1/1
- 3/4
- 1/2

### BREAKAWAY STARTING CURRENT (LOCKED ROTOR CURRENT ACC. TO NEMA)
- 66

### BREAKAWAY STARTING POWER FACTOR
- 0.74

### NO LOAD CURRENT
- 2.0

### NO LOAD POWER FACTOR
- 0.28

### EFFICIENCY %
- 77.0
- 80.0
- 80.5

### CURRENT A
- 10
- 7.6
- 5.2

### INSULATION
- CLASS H

---

**Figure D-1 Flygt Pump 2102-041 Motor Chart**
Figure D-2 Torque-Current-Speed-Chart
## Various Load Table

<table>
<thead>
<tr>
<th>Motor No.</th>
<th>19-09-2AA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Frequency | 50 Hz |
| Poles     | 2      |
| Number of phases | 3      |
| Rated speed | 2810 Rpm |
| Rated voltage | 400 V |
| Rated current | 10 A |
| Rated output power | 5.2 kW |
| Rated input power | 6.7 kW |
| Stator variant | 44 D |

The values are valid at 75 deg. C

<table>
<thead>
<tr>
<th></th>
<th>120%</th>
<th>110%</th>
<th>100%</th>
<th>90%</th>
<th>75%</th>
<th>50%</th>
<th>25%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>kW</td>
<td>8.5</td>
<td>6.7</td>
<td>5.2</td>
<td>4.7</td>
<td>3.9</td>
<td>2.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Input power</td>
<td>kW</td>
<td>9.9</td>
<td>7.8</td>
<td>6.7</td>
<td>6.0</td>
<td>4.9</td>
<td>3.2</td>
<td>1.7</td>
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<tr>
<td>Efficiency</td>
<td>%</td>
<td>72.5</td>
<td>75.5</td>
<td>77.0</td>
<td>78.5</td>
<td>80.9</td>
<td>82.6</td>
<td>84.0</td>
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<tr>
<td>Current A</td>
<td></td>
<td>14.0</td>
<td>12.0</td>
<td>10.0</td>
<td>9.3</td>
<td>7.6</td>
<td>5.2</td>
<td>3.3</td>
</tr>
<tr>
<td>Power factor</td>
<td></td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
<td>0.92</td>
<td>0.89</td>
<td>0.78</td>
</tr>
<tr>
<td>Torque Nm</td>
<td>23.0</td>
<td>20.0</td>
<td>16.0</td>
<td>15.0</td>
<td>13.0</td>
<td>8.5</td>
<td>4.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Speed Rpm</td>
<td>2740</td>
<td>2705</td>
<td>2610</td>
<td>2535</td>
<td>2470</td>
<td>2415</td>
<td>2360</td>
<td>2300</td>
</tr>
</tbody>
</table>

No load current | 2.0 A |
Power factor at no load | 0.28 |
Breakaway starting current | 6.6 A |
Breakaway start. power factor | 0.74 |
Starting torque | 28 Nm |
Max. torque/Rated torque | 40 Nm |
Speed at max. torque | 2900 |
Rotor inertia | 0.0077 kgm² |
Iron losses | 132. W |
Friction losses | 75.0 W |
Pull up torque | 21 Nm |

(4 at synchronous speed)

---

Figure D-3 Various Load Table

** Development of the electric motor **
The HEI Superior range of Hand Lamination Machines are fast and easy to use.

On the smaller models, they use a clutch system that prevents the operator from inadvertently over process and damage the laminations.

These machines are available in all the sizes below and specials are available on request.

Full spares and service are also provided by Series 4.

<table>
<thead>
<tr>
<th>Model</th>
<th>Metric</th>
<th>Lamination Size</th>
<th>Imperial</th>
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<tbody>
<tr>
<td></td>
<td>X (mm)</td>
<td>Y (mm)</td>
<td>Model</td>
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<tr>
<td>HEI-28</td>
<td>28</td>
<td>25</td>
<td>HEI-42,88</td>
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<tr>
<td>HEI-30</td>
<td>30</td>
<td>*</td>
<td>HEI-52,99</td>
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<tr>
<td>HEI-35</td>
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<td>HEI-57,15</td>
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<tr>
<td>HEI-38</td>
<td>38</td>
<td>*</td>
<td>HEI-66,98</td>
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<td>HEI-41</td>
<td>41</td>
<td>33</td>
<td>HEI-76,20</td>
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<tr>
<td>HEI-48</td>
<td>48</td>
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<td>HEI-86,73</td>
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<td>HEI-54</td>
<td>51</td>
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<td>HEI-95,25</td>
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<td>HEI-114,30</td>
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<td>HEI-133,36</td>
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<tr>
<td>HEI-60</td>
<td>66</td>
<td>55</td>
<td>HEI-161,93</td>
</tr>
</tbody>
</table>

HEI-96 PRICE
NEW: 945.00 GBP

www.series4.co.uk

Figure E-1 Lamination Machine
**COIL WINDING**

**Bench Type**

**Model No. 74**

**Automatic Stop**

A Bi-Directional single level preset counter counts from 1 to 999,999 turn counts. Registers turn count whether adding or subtracting turns. The counter displays the turn count and tachometer reading. It stops the winder at the preset number. The stopping position can be advanced up to one full turn to compensate for inertia over-ride under various loads and speeds.

**Light Duty Winder**

Constant torque winding machine. A permanent magnet DC motor drives a gear reducer. Engineered for those who require a coil winder with limited pulling power, and a wide infinitely variable speed range.

**Permanent Magnet DC Motor Drive**

Gives you soft, smooth starting and stopping. Controlled acceleration and deceleration from zero to full speed prevents shock loads, which could break the wire. The drive is reversible and can operate continuously at rated torque throughout the specified speed range.

**SPEED CONTROL**

Speed is controlled by the foot pedal. The operator has full control of acceleration and deceleration of the entire speed range by use of the remote foot pedal. The winder will accelerate to the same speed every time the foot pedal is depressed.

**Safety Feature**

The operator may stop the machine instantly at any desired turn count by removing pressure from the foot pedal. Starting and stopping remains in control of the foot pedal.

**Coil Weight Capacity**

Loads up to 240 Lbs. when used with an outboard support.

---

Medium Duty Model 3-VAS Automatic Stop
Price USD 17,010.00

Figure E-2 Coil Winding Machine
Figure E-3 Welding Machine

Development of the electric motor
For Purchase Information  
Price: $1100.00

Go To Our
ORDER MACHINES Page!

Specifications:
- Swing over Bed: 9"
- Swing over Cross Slide: 5 7/8"
- Distance between centers: 30"
- Carriage Travel: 22"
- Spindle speeds: 6
  (125, 210, 450, 620, 1000, 2000 rpm)
- Longitudinal Feeds: 2 (0.025, 0.10)
- Metric Threads: 12 (4 - 40TPI)
- Cross Slide Travel: 4 1/2"
- Compound Travel: 2 5/16"
- Tailstock Spindle Travel: 2 3/4"
- Tailstock Taper: MT2
- Spindle Bore: 20mm (3/4"
- Spindle Taper: MT3
- Motor: 3/4 HP, 110V/60Hz
- Machine Size: 58"x19"x18 1/2"
- Machine weight: 332lbs.
- Shipping weight: 350lbs.

STANDARD ACCESSORIES INCLUDED:
- 5" - 3 JAW CHUCK
- 5" - 4 JAW CHUCK
- FACEPLATE
- 4 WAY TOOLPOST
- MT2 DEAD CENTER
- WRENCH SET
- MT3 DEAD CENTER
- THREADING DIAL
- INCH CHANGE GEARS
- METRIC CHANGE GEARS
- STEADY REST
- FOLLOW REST
- FEED REVERSE GEAR

FEATURES:
The LatheMaster 9 x 30" Lathe is the highest quality lathe in its size and price range. Unlike some on the market today, this is a true, ready to machine, no need to assemble lathe. It is a solid machine (332lbs.) with induction hardened, precision ground bed ways and a sturdy reinforced frame. The spindle is constructed with quality tapered bearings. Spindle speeds up to 2000 RPM for turning small parts.
Feed ratio and thread selection are a simple task of changing a few easily removed gears.

Figure E-4 Lathe Machine

Development of the electric motor