DESIGN AND OPTIMIZATION OF THREE PHASE SQUIRREL CAGE INDUCTION MOTOR USED FOR GENERAL PURPOSE APPLICATION

GOSA FEYISSA DEGEFA

A Thesis Submitted To

Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfilment of the Requirement for the Degree in Power Electronics

Office of Graduate Studies

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Adama, Ethiopia

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Approval of Board of Examiners

We, the undersigned, members of the Board of Examiners of the final open defence by Gosa Feyissa Degefa have read and evaluated his thesis entitled "Design and Optimization of Three Phase Squirrel Cage Induction Motor used for General Application Purpose" and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfilment of the requirement of the Degree of Master's in Power Electronics.

Dr. _Ing. Getachew Biru	____________________	____________________
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Department Chair	Signature	Date
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Internal Examiner	Signature	Date
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External Examiner	Signature	Date

Declaration

I hereby declare that this MSc Thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

Name: Gosa Feyissa Degefa

Signature: ________________________

This MSc Thesis has been submitted for examination with my approval as thesis advisor

Name: Dr. _Ing. Getachew Biru

Signature: ________________________

Date of submission ________________________

Advisor's Approval Sheet

To: Electrical Power and Control Engineering Department

Subject: Thesis Submission

This is to certify that the thesis entitled "Design and Optimization of Three Phase Squirrel Cage Induction Motor used for General Application Purpose" submitted in partial fulfilment of the requirements for the Degree of Master's in Power Electronics, the Graduate program of the department of power and control engineering and has been carried out by Gosa Feyissa Degefa Id.No GSR/0050/09 under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence here by he can submit the thesis to the department.

Dr -Ing. Getachew Biru		15.09.2018
Name of Advisor	Signature	Date

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However, it would now not have been viable for me to finish this work without the inspiration, encouragement, and guide from many people.

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NOMENCLATURE

A

A_s	Stator slot area
A_b	Area of rotor bar
A_e	Area of end ring
A_{tr}	Area of the rotor tooth
AT	Total magnetising magneto motive force
AT_{st}	Ampere turns per meter in stator teeth corresponding to flux density in stator teeth
AT_{sc}	Ampere turns per meter in stator core corresponding to flux density in stator core
AT_{rt}	Ampere turns per meter in rotor teeth corresponding to flux density in rotor teeth
AT_{rc}	Ampere turns per meter in rotor core corresponding to flux density in rotor core
A_{st}	Area of stator teeth per pole
a_s	Area of wire

B

B_{av}	Specific magnetic loading
B_{tr}	Flux density in rotor tooth
B_g	Air gap flux density

C

C_o	Output coefficient
C_s	Coil span
$\cos\emptyset$	Power factor

D

D	Stator bore diameter
D_0	Stator outer diameter
D^2L	Volume of the motor
D_r	Outer diameter of rotor
D_{me}	Mean diameter of end ring
D_{ir}	Inner rotor diameter
d_{rs}	Rotor slot depth
d_{rc}	Rotor core depth
d_{ss}	Depth of stator slot
d_{sr}	Rotor slot depth

E

E_{ph} Induced voltage per phase

F

f_s Supply frequency to the stator

f_r Rotor frequency

I

I_{ph} Stator phase current

I_b Rotor bar current

I_e End ring current

I_m Magnetising current

I_c Core loss current due to hysteresis and eddy current

I_0 No load current

K

K_w Winding factor

k_{css} Carter's coefficient for stator slot opening

k_{gss} Gap construction factor due to stator slots

k_{csr} Carter's coefficient for rotor slot opening

k_{gsr} Gap construction factor due to rotor slot

k_{gs} Gap construction factor due to slot

k_{ds} Gap construction factor due to ducts

k_g Over all gap construction factor

L

L Stator core length

L_i Net iron length

l_g Air gap length between stator and rotor

l_{ge} Effective air gap length

l_b Rotor bar length

l_{me} Mean length of current path

l_{sc} Length of magnetic path through stator core

l_{rc} Length of magnetic path through rotor core

M

m Number of phase

mmf_{st}	Magneto motive force in stator teeth
mmf_{sc}	Magneto motive force in stator core
mmf_{rt}	Magneto motive force in rotor teeth
mmf_{rc}	Magneto motive force in rotor core

N

N_s	Synchronous speed in revolution per minute
n_s	Synchronous speed in revolution per second

P

P	Number of pole
P_{in}	Input power
pf	Power factor
pf_{nl}	No load power factor
P_{lst}	Iron loss in stator teeth
P_{lsc}	Iron loss in stator core
P_{culoss}	Copper loss in stator winding
$P_{barloss}$	Rotor bar loss
$P_{ringloss}$	End ring loss

Q

Q	Apparent power input to the motor
q_s	Number of slot per pole per phase
q	Specific electric loading

R

R_b	Rotor bar resistance
R_e	Resistance of end ring
R_s	Resistance of stator winding

S

s	Slot dimension
S_r	Number of rotor slots
S_s	Number of stator slot
S	Slip

T

T_{ph}	Number of turns per phase

$6T_{ph}I_{ph}$ Total electric loading

V

V_{ph} Supply phase voltage

V_{st} Volume of stator teeth

V_{sc} Volume of stator core

W

w_{tr} Width of rotor teeth

W_{st} Weight of stator teeth

W_{sc} Weight of stator core

Z

Z_{ph} Number of conductor per phase

Z Total number of conductor in stator winding

Z_s Number of conductor per slot

n_m Mechanical speed of the rotor in revolution per second

GREEK SYMBOLS

Φ Flux per pole

ΦP Total magnetic loading

τ_s Stator slot pitch

δ_s Current density in stator winding

δ_b Current density of rotor bar

ρ_b Resistivity of the bar conductor

δ_e Current density in end ring

μ_0 Permeability in air

ρ_s Resistivity of the stator conductor used for winding

τ_{sh} Shaft torque

η Efficiency

ABSTRACT

Interest in potential of optimization of electric powered motor design is excessive due to the truth of extended price of electrical power and pressures for its conservation, plus the accelerated competition in world markets. The goal of the optimization technique is normally to decrease the price of the machine or to maximize the efficiency of the machine. This thesis present an optimum design of three phase squirrel cage induction motor which is help for the producing of this machine in Ethiopia. First mathematical modelling used to be performed with the aid of calculating all the stationary and rotating phase of the motor. During the modelling the design parameters had been determine which is confined primarily based on the advantage and disadvantage of increasing and lowering of specific electric and magnetic loading. After the modelling was carried out with the aid of the assist of Rotational machine Expert (RMxprt) software from ANSYS cooperation was applied for simulation. The simulation result and manual design used to be in contrast which have very minimal deviation between the two results. By optimizing the dimension and shape of stator and rotor slots the efficient motor was designed. The result of simulation show that the starting torque, breakdown torque and efficiency of this design had been improved compared with the existing 11kW squirrel cage induction motor. According to International Electrician Commission (IEC) standard this existing motor operate with starting torque of 157.52Nm, break down torque of 214.8Nm and rating efficiency of 89.8%. The result of simulation indicated that the starting torque is increased to 161.281Nm, the break down torque additionally elevated to223.287Nm and the rating efficiency improved to 92.4%. Therefore due to enhancement of its efficiency the modelled motor have a long existence time and minimal operating cost when evaluate with the current one. Finally two dimensional (Maxwell 2D) used to be applied for evaluation of the magnetic field and flux density has been performed for the designed model.

***Keywords**: Three phase induction motor, ANSYS, design optimization, slots, RMxprt*

CHAPTER ONE

1. INTRODUCTION

Three phase induction motors are the most broadly used in domestic, commercial and a number of industrial applications. Particularly, the squirrel cage type is characterised by way of its simplicity, robustness and low cost, which has always made it very attractive, and captured the leading area in industrial sectors. Now a day almost 90% of the industry uses three phase induction motor. As a result of its sizable use in the industry, induction motors consume a significant percentage of the average produced electrical power. Therefore, the minimization of electrical power consumption through a better motor design becomes a principal concern. The interest of optimization of electric machine design is high because of extended value of electrical energy and pressures for its conservation, plus the increased competition in world markets. In the design of induction motors, as in all layout problems, the engineer is faced with making a selection in the face of competing objectives. The design trouble is considered as an optimization technique by using which the designer seeks the pleasant design. The optimization is executed via applying the ideas of nonlinear programming. In declaring a nonlinear programming problem, the fundamental variables are to be described and an objective characteristic was once minimized or maximized subjected to non violated constraints. In the applications of nonlinear programming techniques, to optimize the design of induction motor the objective feature have been the material cost, the power factor, efficiency, starting torque etc. In such cases, the designer deals with the goal characteristic in a scalar form. In fact, the designer of an induction motor, as in all design problems, is interested in accomplishing extra than one goal. In such case the goal characteristic is defined as a vector function consisting of factors each one representing a goal. The goals were given equal or exclusive weights according to the design requirements.

In this thesis, design and optimization of three phase squirrel cage induction motor was modelled and simulated by Rotational Machine Expert (RMxprt), an interactive software package from ANSYS Corporation. Using of this software for design has an advantage of saving our time consume for design, reduce theoretical hand calculation, minimized the error occurred during hand calculation and increase accuracy of the result. The optimized design was obtained by optimized the dimension of stator and rotor slot with suitable shape for the objective function of improving the starting torque and efficiency compared with the existing International Electrician Commission (IEC) standard motor.

1.2 Statement of the Problem

In Ethiopia, there is no any industry which designs and implements induction motors. These necessary machines are thoroughly imported by hard currency from foreign countries. This is why initiating the idea of local design and manufacturing of induction machines becomes very important. Therefore, this thesis focuses on designing an induction motor with improved operating efficiency and less production and operational cost, with the aim of producing the machines locally in the country.

1.3 Objective

1.3.1 General Objective

The general objective of this thesis is to design an optimized three phase squirrel cage induction motor.

1.3.2 Specific Objective

The specific objectives of the thesis are

- Design an optimized induction motor for local production.
- Model and simulate the designed induction motor.
- Draw relevant conclusion and recommendations for the local production of the machine.

1.4 Scope of study

The scope of this thesis includes mathematical modelling, design, simulation and performance evaluation of three phase squirrel cage induction motor.

1.5 Significant of study

All of the motors used for various purposes in Ethiopia are imported from Europe, Asia and other countries. Among those motors three phase squirrel cage induction motors have very wide application in the country. Therefore, this study is performing an optimized design of this important motor to initiate the local production of the motor.

1.6 Methodology

The approaches or procedure applied for the design of three phase induction motor in this thesis is as follows. On the first step, in order to identify the widely used induction motor and their rating, data collection was performed by visiting some industries around Adama, Ethiopia. Then the design was done by modelling the active internal and external part of the motor. Finally simulation of the model was performed by using rotational machine expert software and the simulation result and the result of manual design was compared. Based on the two results, the relevant conclusion was drawn. At the end, recommendation concerning the design and manufacturing of three phase induction motor is made.

CHAPTER TWO

2. THEORETICAL BACKGROUND AND REVIEW OF LITERATURE

2.1 Theoretical Background

Three phase induction motor is an alternate current motor in which currents in the stator winding is connected to the supply units make up a flux which motives currents to be brought in the rotor winding; these currents have interaction with the flux to produce rotation. The rotor receives electrical energy in precisely the identical way as the secondary of a two winding transformer receiving its energy from primary. That is why an induction motor can be referred to as rotating transformer in which primary winding is stationary but the secondary is free to rotate.

Based on their rotor types three phase induction motors are categorized into two:-

1. Squirrel cage induction motor: The rotor of this motor is very handy and consists of bars of aluminium (copper) with shorting rings at the end.
2. Wound rotor induction motor: The rotor of this motor consist a three section windings which is star connected with terminals brought out to slip rings for external connections.

From this two types, squirrel cage induction motor is more generally used in industry due to:

- Robust: No brushes and no contacts on rotor shaft
- Easy to manufacture
- Maintenance free besides for bearing and stator winding
- The copper loss is low and the efficiency of the motor is high due to the rotor has very low resistance.

Therefore, the motor manufacturing industry such as ABB (Asea Brown Boveri) and SIEMENS company focus on implementing of the squirrel cage induction motor in wide range because of the customer preferred this type of motor due to its advantages indicated above.

2.1.1 Three Phase Induction Motor (Squirrel Cage Type)

An AC induction motor consists of two electromagnetic parts

- Stationary section referred to as the stator and
- Rotating part referred to as the rotor

These two components are made up of

- An electric powered circuit: made of insulated copper conductor for stator winding and aluminium conductor for rotor bar winding, to carry current and
- A magnetic circuit: made up of laminated silicon steel, to carry magnetic flux

Let as explain the two components (stator and rotor) of squirrel cage induction motor one by one as follows to understand all the internal and external part of the motor.

2.1.2 Stator

The stator is the outer stationary section of an induction motor, which consists of

- The outer cylindrical body of the motor called yoke**,** which is made from welded sheet steel
- The magnetic path**,** which comprises a set of slotted steel laminations referred to as stator core pressed into the cylindrical space interior the outer frame
- A set of insulated electrical windings**,** which are placed into the slots of the laminated stator

2.1.3 Rotor

Rotor is the rotating section of an induction motor which consists of a set of slotted silicon steel laminated pressed together to structure a cylindrical magnetic and electrical circuit. Squirrel cage rotor consists of a set of aluminium or copper bars set up into the slots, which are linked to an end-ring at each end of the rotor.

The other components, which are required to complete the layout important points of an induction motors are:

- Two end-flanges to support the two bearings, one at the driving-end and the other at the non driving-end, where the driving gives up will have the shaft extension.
- Two units of bearings to help the rotating shaft,
- Steel shaft for transmitting the mechanical power to the load
- Cooling fan positioned at the non driving end to furnish pressured cooling for the stator and rotor
- Terminal box on top of the yoke or on side to receive the external electrical connections

The essential reason of designing an induction motor is to gain the complete physical dimensions of all the parts of the motor to satisfy the customer specifications. The following are the design important points which are required

A. The main dimensions of the motor

B. Stator windings

C. Design of rotor and its windings

D. Performance characteristics

In order to get the above design details the designer needs the customer specifications such as Rated output power, efficiency, power factor, rated voltage, quantity of phases, number of poles, magnetic loading, electric powered loading, rotor speed, supply frequency, connection of stator winding, kind of rotor winding, working conditions, shaft extension details etc. In addition to this specification the designer should have the important points related to design equations based totally on which the layout method is initiated, facts regarding the a number of preference of various parameters, information regarding the availability of specific substances and the limiting values of more than a few performance parameters such as iron and copper losses, no load current, energy factor, temperature upward jostle and efficiency. Let as define the parameters that show the hall bodily dimensions of the motor which is considering for the duration of design. Those dimensions are the main dimension of the motor, stator dimension and the rotor dimension.

Before starting to determine the value of the dimensions of the motor, the specification of the motor is selected. The standards to pick out the specification of the motor are as follows.

Criteria for Choice of power factor and efficiency

The criteria for the choice of power factor and efficiency under full load conditions is depend on the rating of the motor. As the machine rating enlarges the power issue and effectively of the machine also increases. This is take place because if the rating of the machine will increase Percentage magnetizing current and losses turn out to be lower. To determine the extent of the motor, the unique magnetic and electric loading values are required.

Choice of Specific Magnetic loading or Air gap flux density (B_{av})

The air gap flux density is one of the foremost factors for determining core loss. There is additionally every other limitation for deciding on of specific magnetic loading amongst them the flux density in tooth is much less than 1.8 Tesla and flux density in the core is between 1.3-1.5 Tesla. Within this limitation, selection of specific magnetic loading of higher value has some advantages:

- Motor size is reduced
- Cost of the motor decreases
- Overload capacity increases

For 50 Hz motor, 0.35 – 0.6 Tesla is selected.

Choice of Specific Electric loading (q)

The specific electric loading indicates the complete stator ampere conductor over the periphery. The selection of high fee of specific electric loading has the following blessings and disadvantages

The advantages are:

- Reduce size of motor and
- Reduce the cost

The disadvantages are:

- Lower overload capacity
- Higher amount of conductor required
- Copper losses is high
- Increased temperature rise

Normal range is 10000 ac/m – 450000 ac/m.

After proper defining of specific magnetic and electric loading then by using the output equation the volume or the product of D^2L of motor is determined. Then the main dimension of the motor is determined based on the criteria of the separation of stator bore diameter and gross core length.

2.1.4 The Main Dimension of Induction Motor

The main dimensions of induction motor include the stator core diameter (D) and core length of stator (L) as shown in the figure 2.1.

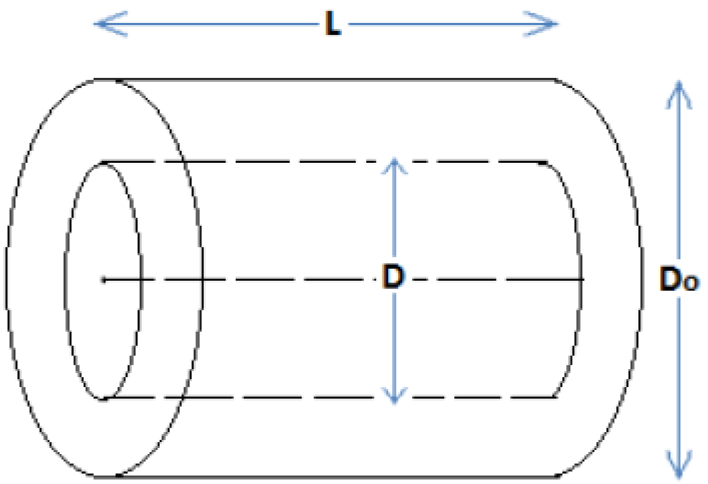


Figure 2. 1 main dimension of induction motor D and L

Where

D is stator bore diameter

L is stator core length

D_0 is stator outer diameter

2.1.5 Separation of D and L

To separate D and L there are a number of design concerns primarily based on which a suitable ratio between stator core size and pole pitch can be assumed. The separation standards are summarized in Table 2.1 below.

Table 2. 1: Separation criteria of outer diameter and length of stator core

Separation criteria	**Value of gross core length per pole pitch**
To obtain good power factor	1 to 1.3
To obtain good efficiency	1.4 to 1.6
To obtain minimum overall cost	1.5 to 2
To obtain good overall design	1 to 1.1

As power factor is improved by power factor correction technique a good efficiency design plays a very important role on the performance of induction motors specially to minimize losses and temperature rise in the motor .Therefore it is advisable to design an induction motor for best efficiency unless specified.

Using the standards in Table 2.1 D and L can be separated from D^2 L product. However the obtained values of D and L have to satisfy the condition imposed on the value of peripheral speed. For the everyday plan of an induction motors, the calculated diameter of the motor need to be such that the peripheral speed should be below 30 m/s. But in case of specifically designed rotor the peripheral speed can be improved until 60 m/s. After separating and finding out the values of the important dimensions of the motor, the internal parameters of the stator are determined.

2.1.6 Stator Parameters

The stator part of an induction motor consists of stator core and stator slots. There are different sorts of stator slots which are employed in induction motor. Because of the operating overall performance of the induction motors; efficiency, power factor and starting torque highly depends upon the shape of the slots. Therefore it is important to select suitable slot for the stator. The three types of stator slots are:

Semi closed slots

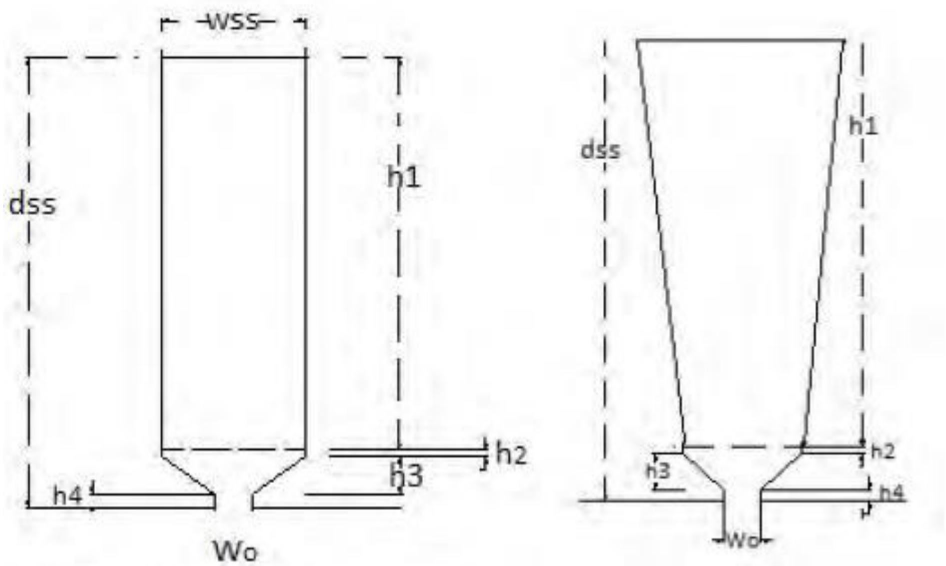
In this kind of slots, slot opening is a good deal smaller than the width of the slot. Hence in this type of slots assembly of windings is extra difficult and takes greater time compared to open slots and for this reason it is costlier. However the air gap traits are better compared to open kind slots.

Tapered slots

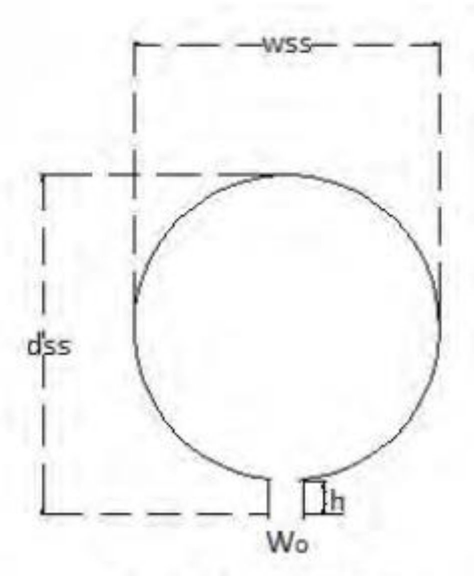
In this type of slots also, opening will be a whole lot smaller than the slot width. However the slot width will be various from top of the slot to backside of the slot with minimal width at the bottom.

Circular slot

The circular slot is not used most of the time due to difficulty for construction. The three types of stator slots are shown in Figure 2.2.



a. Semiclosed slot b. Tapered slot



C . Circular slot

Figure 2. 2 Types of stator slot

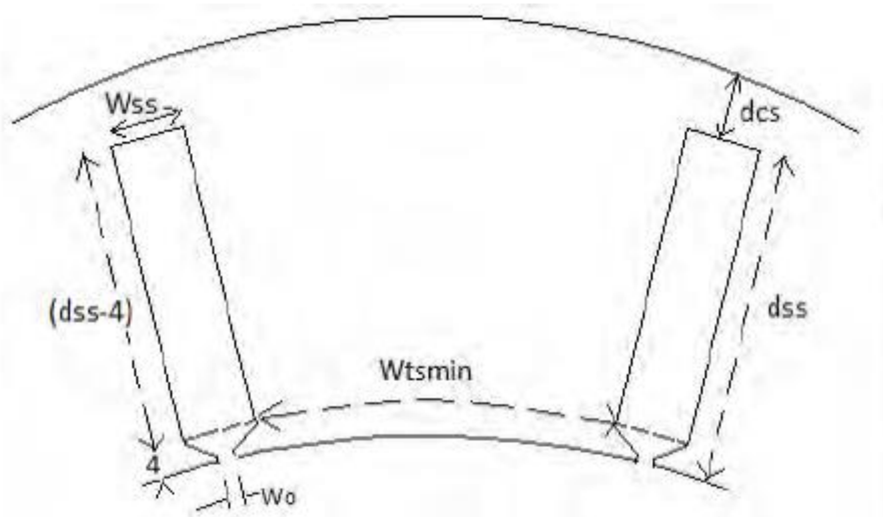


Figure 2. 3 Slot with stator teeth

Selection of number of stator slots

During the design stage, number of stator slots must be exact selected as such this number affects the cost, weight and operating characteristics of the motor. But there are no regulations for choosing the number of stator slots thinking about the blessings and dangers of deciding on higher wide variety slots. We have the following advantages and disadvantages of deciding on higher quantity of stator slots.

The advantages are

- Reduce tooth pulsation losses
- Reduce leakage reactance
- Higher over load capacity

The disadvantages are

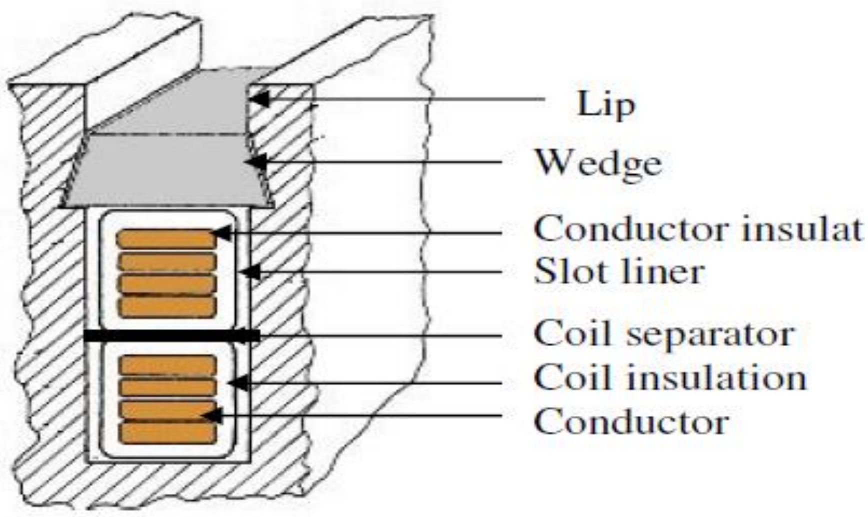
- Increase weight
- Increase cost
- Increase magnetizing current
- Increase iron losses
- Poor cooling
- Increased temperature rise
- Reduction in efficiency

Based on the above factors, the number of slots/pole/phase is selected as optimum value. Within consideration of the above factors, the selected number of slot should satisfy the consideration of stator slot pitch at the air gap surface, which should be between 1.5 to 2.5 cm.

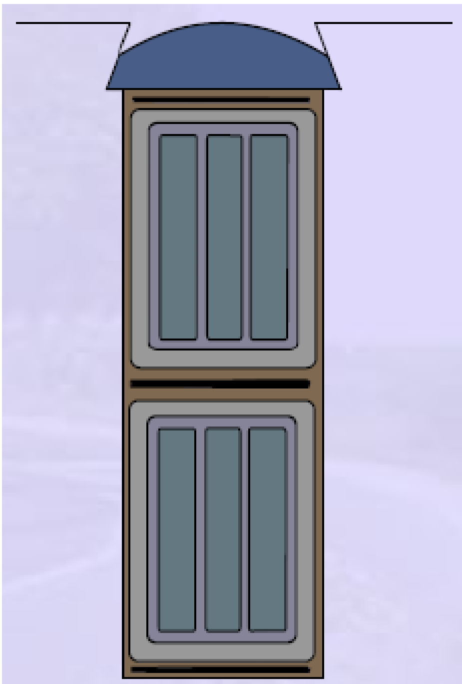
Slot size

As indicated above, in Figure (2.3) there are three kinds of slots which are employed for carrying stator windings or conductors of induction motors. These conductors are suitably organized alongside the depth and width of the winding. Stator slots must now not be too wide, main to thin enamel width, which makes the teeth robotically susceptible and maximum flux density may exceed the permissible limit. Therefore slot width ought to be selected such that the flux density in tooth should be below permissible limit.

Also the slots must not be too deep in any other case the leakage reactance increases. Proper slot insulation as per the voltage ranking of the machine has to be supplied before inserting the insulated coil in the slots which is known as the slot liner inside a thickness of 0.5mm to 0.7mm. Suitable thickness of insulation called coil separator separates the two layers of coils which have a thickness comparable to slot liner. Wedge is positioned at the top of the slot to hold the coils in position within a thickness of 3.5mm to 5mm. Lip of the slot are taken 1.0 to 2.0 mm. Slot within conductor and insulation details are shown in Figure 2.4



a. section of slot with conductor and insulation



b. model of slot cover by insulation and conductor

Figure 2. 4 Slot insulation details with conductor

2.1.7 Stator winding

Windings have been widely studied for three-phase machines in the past; the essential goal was to achieve sinusoidal magneto motive forces. This property implies correct traits for machines supplied without delay by way of three-phase voltages. With the creation of advanced contemporary controls, the necessity of this winding constraint for the dressmaker
Can be re-examined. When each aspect of a coil occupies a slot definitely barring any different coil mendacity on pinnacle of it and the range of coils equals half of the range of slots, the winding is acknowledged as single layer winding. Concentric winding or chain winding types are frequent and in this type of winding, short-pitched coils can't be used. The laying of concentrated winding relies upon on the coil span and the number of slots per pole per phase. The concentric winding can be in structure of unbifurcated (half-coiled) or bifurcated (whole-coiled) type. In unbifurcated concentric windings, the coils comprising a pair of pole phase groups beneath adjacent poles are concentric.

The overhangs of these windings are typically arranged in two or three separate tiers or planes. This arrangement is furnished in order to avoid the crossing of two coils under one section group. In bifurcated concentric windings, every pole phase group is split up in to two units of concentric coils and every set sharing its return coil facets with these of another pole segment crew in the same phase. Single layer winding is common in small ac machines of power rating below 15hp, though this by and large depends on the manufacturer. And such machines have large quantity of conductors per slot. The single layer fractional slot winding is common in brushless dc machines and permanent magnet synchronous machines (PMSM). Single layer windings have greater effectivity and quieter operations due to the openings of their narrow slots. Single layer windings are especially insulated because of the end connections that are separated by means of large air spaces which make them suitable for high voltages. The absence of inter layer separator is due to greater space factor. Mesh winding is relevant in alternating present day stator winding and the coil span is odd. It consists of lengthy and quick conductors and the range relies upon on the variety of slots per pole per phase. The longer conductors occupy odd slots while the short conductors occupy even slots. The long and quick conductors are connected. Winding diagram strategies have been a challenge of lookup for many years of the previous century. Many methods have been developed, each one characterized with the aid of some blessings and drawbacks. Nowadays, the star of slots is the most vast plan device for electrical machine windings. The star slots approach was once primarily based on Winding Distribution Table (WDT), allows the layout of all m-phase single or double-layer windings (including overlapping and non-overlapping ones), providing fast and automated winding designs. The winding distribution method is primarily based on the construction of a Winding Distribution Table (WDT), which permits the project of a unique stator slot to a winding phase section. WDT is a winding diagram illustration in table shape that can be used in a design tool. In this table every row corresponds to a phase (m) and number of columns equals to slots per phase (S_s/m). The definition of the WDT begins with the aid of assigning the slot number 1 to the first cell of table (row 1, column 1) .Then, the slot number 2 is assigned to the cell whose distance is equal to pole pair cells from the first one, the slot number three to the cell whose distance is equal to pole pair cells from the 2d one, following the orientation of the innovative numbering of the cells of table. After stator slot over pole pair assignments, the process continues by imagining that the last cell of the table is ideally consecutive to the first: therefore, once the S_s-th table factor is counted, the counting continues restarting from the first cell of the table. If the remember ends in a filled cell, the adjacent empty cell will be crammed with the counted slot. The manner continues until the table is definitely stuffed by using the slot numbers. The parameters of the stator had been described above now the rotor parameters are described as follows.

2.1.8 Rotor Parameters

Rotor is the rotating section of induction motor. There are two kinds of rotor construction. One is the squirrel cage rotor and the other is the slip ring rotor. Based on the kind of its rotor induction motors are named as squirrel cage or slip (wound) ring motor. Most of the induction motor are squirrel cage type. These are due to the fact of squirrel cage rotor kind having the benefit of rugged and simple in construction and comparatively cheaper. This paper centre of attention on the building of squirrel cage rotor type which consists bars of aluminium accommodated in rotor slots which are shorted at give up ring. Before beginning describing the parameters of the rotor let as define the air gap between stator and rotor. There is some hole between stator and rotor which is called an air gap size and a very essential part. The overall performance parameters of the motor like power factor, magnetizing current, over load capacity, cooling and noise are affected by size of this air gap. Therefore size of the air hole is chosen thinking about the advantages and risks of larger air hole length Advantages

- Unbalanced magnetic pull is reduced
- Tooth pulsation is minimized

- Reduced noise
- Increased cooling
- Overload capacity is increased

Disadvantages

- The power factor reduced and
- Magnetising current increased

Because of magnetising current and power factor being very important parameters in deciding the performance of induction motors, the induction motors are designed for optimum value of air gap or minimum air gap possible.

Number of Rotor Slots

Numbers of rotor slots are selected proper in relation to number of stator slots in any other case undesirable consequences will be determined at the starting of the motor. Crawling and Cogging are the two phenomena which are observed due to incorrect combination of variety of rotor and stator slots. In addition, induction motor develops unpredictable hooks and cusps in torque speed characteristics or the motor run with lot of noise.

Shape and Size of the Rotor slots

In general semi closed with very narrow openings is employed for the rotor slots. In case of fully closed slots the rotor bars are force suit into the slots from the facets of the rotor. The rotors with closed slots are giving better performance to the motor in the following manner.

- As the rotor is closed the rotor surface is smooth at the air gap and subsequently the motor draws lower magnetizing current.
- Reduced noise as the air gap characteristics are better decreased starting current.

From this two points, it can be concluded that semi closed slots are greater appropriate and as a result they are employed in rotors.

2.2 REVIEW OF LITERATURE

Three phase induction motors are extensively used for a number industrial and domestic applications such as pump drives, variable speed drives etc. Most of the massive sized three-phase induction motors function with low effectivity [2, 3] and low energy element [4], which are the most vital motives of terrible electricity issue in industrial installations.

Therefore ,in the three-phase induction motor design optimization with accelerated power effectivity and energy issue are the key problems of the day. For the design optimization of induction motors, the most frequently used objective features are the motor efficiency. The information related to motor circuit parameters is very necessary for design, overall performance evaluation, and feasibility of the manipulate techniques. Several methods have been used to resolve the plan problems. The conventional methods for estimating the induction motor parameters are primarily based on the locked-rotor and the no load tests. However, these techniques cannot be applied easily. The foremost drawback of these strategies is that the motor has to be locked mechanically. In the locked-rotor condition, the frequency of the rotor is equal to the provide frequency, however under operating condition, the rotor frequency is about 1/3Hz. This wrong rotor frequency will motive horrific outcomes for the locked-rotor test. Besides, in the motors with high power, this test is impractical. These troubles have influenced the researchers to look into alternative strategies for parameter estimation. The problem of induction motor parameter estimation has been addressed extensively by means of many researchers in the past. Deep bar motors had been considered in [5] and parameter estimation used to be carried out with emphasis on leakage reactance in [6]. The technique of finite issue evaluation was once employed in [7]. Also, parameter estimation of an induction motor using some evolutionary algorithms is presented in [8–11]. Evolutionary algorithms such as genetic algorithm (GA) and particle swarm optimization (PSO) seem to be a promising choice to standard techniques.

2.1 Genetic Algorithm (GA)

The GA is a search algorithm based on the mechanics of natural decision and natural genetics. This method is a computational model and evolutionary procedure which solves optimization issues applied for induction motor design by using imitating the behaviour of populations in the course of generations and based totally on the concept of evolution. It mimics organic evolution by using the usage of genetic operators [9]. It assumes that the solution of a trouble is an character and can be represented through a set of parameters. GA investigates the search space from the points it has to bias the search in the direction of the first-rate point. This algorithm is a stochastic search approach and has proven that the reply is gorgeous for problems where there are many global minimums or search house is extensive. A effective value, generally called health value, is used to measure the degree of “goodness” of the chromosome for fixing the problem, and this fee is carefully dependent on its objective value.

The goal function of a hassle is an essential supply offering the mechanism for evaluating the status of each chromosome. It takes the chromosome as input and produces a number or list of numbers such as goal fee as a measure to the chromosome's performance. This is a fundamental hyperlink between the algorithm and the system [10].

2.2 Particle Swarm Optimization (PSO)

The PSO is a stochastic optimization method, which uses swarming behaviours discovered in flock of birds. In fact, the PSO was once stimulated by the sociological behaviour related with swarms. The PSO used to be developed by using Kennedy and Eberhart in 1995 as a new heuristic approach [11]. Each particle in the PSO algorithm is a possible solution for the optimization problem and keeps track of its coordinates in the problem area and tries to search the high-quality position via flying in a multidimensional space, which are associated with the high-quality answer (called pleasant fitness) it has carried out so some distance called "Pbest." Another "best" cost known as "Gbest" that is tracked via the international model of the particle swarm optimizer is the standard fantastic value and its region is acquired so some distance via each particle in the swarm. Each particle is decided by way of two vectors in$N$-dimensional search space: the role vector and the velocity vector [12]. Each particle investigates its search house through previous experience, its existing velocity, and the journey of the neighbouring particles. The PSO idea is the alternate in the pace of each particle toward its Pbest and Gbest positions in each iteration. In the PSO, acceleration of every particle is weighted through a random time period [13]. The PSO is a history-based algorithm such that, in every iteration, particles use their very own behaviour related with the preceding iterations.

All of the above techniques are based on nonlinear equation solving problem for parameter estimation. These techniques focus on solving of the given problem only rather than field analysis in the motor. This thesis was applied a software called Rotational Machine Expert (RMxprt) and Maxwell two dimensional (Maxwell 2D) used for finite element analysis (FEA) for analysing of field in the stator, air gap and rotor. All the magnetic and electric parameters are analgised. The design was optimized by optimizing the dimension and shape of the slots of stator and rotor.

CHAPTER THREE

3. DESIGN OF INDUCTION MOTOR

Design is a work process which has a user perspective and drives improvement based totally on your unique customer's needs. Designing often necessitates thinking about the aesthetic, functional, financial and socio-political dimensions of each the sketch object and sketch process. It may contain great research, thought, modelling, interactive adjustment, and re-design.

The principal motive of designing of an induction motor is to reap the complete bodily dimensions of all the components of the motor to satisfy the client specifications. Those bodily dimensions are first modelled by means of the usage of the standard mathematical formula. The formulas required to mannequin an induction motor are beginning with the output equation.

3.1 Output Equation

Output equation is the mathematical expression which offers the relation between the variety of physical and electrical parameters of the electrical machine. In a three phase induction motor the output equation determine the enter apparent power (Q) in KVA which is given by means of eqn (1) below as

$$Q = \frac{\text{output power in kW}}{\text{efficiency x power factor}} \tag{1}$$

This input apparent power to the three phases motor is given in other way as

$$Q = 3 \text{ x } V_{ph} \text{ x } I_{ph} \text{ x } 10^{-3} \text{ KVA} \tag{2}$$

The voltage induced in the stator winding due to flux induced in the stator is given as

$$E_m = \frac{dT_{ph}\Phi}{dt} = \frac{dT_{ph}K_w\Phi_m \sin\varpi}{dt} = T_{ph}K_w\Phi_m\varpi\cos\varpi \tag{3}$$

The induced voltage determine in eqn (3) is its maximum or peak value whose rms value is given as

$$E_{ph} = E_{rms} = \frac{T_{phK_w}\Phi_m 2\pi f_s}{\sqrt{2}} = 4.44T_{ph}\Phi_m f_s\, K_w \tag{4}$$

Eqn (5) below indicate the relationship between supply frequency, pole of the motor and synchronous speed (magnetic field speed).

$$f_s = \frac{PN_s}{120} = \frac{Pn_s}{2} \tag{5}$$

The total magnetic loading in the motor is the product of the flux induced per pole and the total number of pole which is determine as

$$\Phi P = B_{av}\pi DL \tag{6}$$

The flux produced per pole is the ratio of total magnetic loading to number of pole

$$\Phi = \frac{B_{av}\pi DL}{P} \tag{7}$$

By rewriting eqn (6) the specific magnetic loading is given as

$$B_{av} = \frac{\Phi P}{\pi DL} \tag{8}$$

The total electric loading in the motor is determine by using eqn (9)

$$3 \text{ x } 2 \text{ x } T_{ph} \text{ x } I_{ph} = q\pi D \tag{9}$$

$$T_{ph}I_{ph} = \frac{q\pi D}{6} \tag{10}$$

By rewriting eqn (10) the specific electric loading is determine as

$$q = \frac{6 \text{ x } T_{ph} \text{ x } I_{ph}}{\pi D} \tag{11}$$

Assuming that the per phase induced voltage (E_{ph}) = supply voltage (V_{ph}) therefore substitute equation (4) into equation (2), the result is

$$Q = 3\left(4.44T_{ph}\Phi f_s K_w\right)I_{ph} \text{ x } 10^{-3} \tag{12}$$

Again substitute equation (5), (7) and (10) simultaneously to equation (12) the input apparent power to the three phase induction motor become

$$Q = 11K_w(B_{av}q)(D^2L)n_s \text{ x } 10^{-3} \quad \text{kVA} \tag{13}$$

From eqn (13) substitute the constant value by (C_o)

$$\text{Substitute that } C_o = 11K_wB_{av}q \text{ x } 10^{-3} \tag{14}$$

The final simplified or deduced equation represent the input apparent power is

$$Q = C_o D^2 L\, n_s \;\; KVA \tag{15}$$

Where

Q = the apparent power input to the motor

V_{ph} = supply phase voltage

I_{ph} = stator phase current

E_{ph} = induced voltage per phase

f_s = supply frequency to the stator

P = number of pole

N_s= synchronous speed in rpm

n_s =synchronous speed in rps

D= stator bore diameter

L= gross core length

T_{ph} = number of turns per phase

K_w = winding factor

Φ = flux per pole

ΦP=total magnetic loading

B_{av} = specific magnetic loading

$6T_{ph}I_{ph}$ = total electric loading

q = specific electric loading

C_o = output coefficient

D^2L = volume of the motor

Now the volume of the motor is determine from output equation as follow

$$D^2L = \frac{Q}{C_o n_s} \tag{16}$$

After determining the volume of the motor by using eqn (16) to calculate the main dimensions of the motor; stator core diameter (D) and stator core length (L) must be separated from D^2L product.

Separation of D and L

To separate D and L there are various design considerations primarily based on which a appropriate ratio between stator core length and pole pitch can be assumed. Those numbers of format issues are obtaining of right power factor, obtaining of desirable efficiency and minimizing of the typical cost. Among these considerations obtaining of precise efficiency has a major aspect on the existence of the motor and the ratio of the core size to the pole pitch for this design consideration is 1.5. The pole pitch is given by

$$\text{Pole pitch}(\tau_p) = \frac{\pi D}{P} \tag{17}$$

By using eqn (17) and ratio of the core length to pole pitch the main dimensions of the motor is determine. After separating and determine the main dimensions of the motor the next step is modelling of the stator.

3.2 Modelling of stator

Stator is the stationary part of an induction motor which consists core and stator slots which is ready for inserting stator winding. To model the stator part of this motor determines all parameters of the stator. The parameters are number of slot, number of turns per phase, stator phase current, number of conductor consumed per phase, conductor cross sectional area, area of stator slot, mean turn length, width of stator teeth, flux density in stator teeth, stator core depth and outer diameter of stator.

Number of stator slots

During the design stage number of stator slots must be properly selected as such this number affects the cost, weight and operating characteristics of the motor. The selected number of slot should satisfy the consideration of stator slot pitch at the air gap surface, which should be between1.5 to 2.5 cm. Where the stator slot pitch is given by

$$\text{stator slot pitch}(\text{Ʈ}_{ss}) = \frac{\pi D}{S_s} \tag{18}$$

Where S_s= number of stator slot

Turns per phase

To determine number of turns per phase of stator winding first determine the induced voltage which is equal to the applied phase voltage

$$E_{ph} = 4.44 f_s \Phi T_{ph} K_w \tag{19}$$

From equation (19) number of turns per phase is determine as

$$T_{ph} = \frac{E_{ph}}{4.44 f_s \Phi K_w} \tag{20}$$

Number of conductor per phase

After determining number turns per phase the number of conductor per phase in stator winding is determine as

$$Z_{ph} = 2 \text{ x } T_{ph} \tag{21}$$

The total number of conductor in three phase induction motor is determine as

$$Z = 3 \text{ x } 2 \text{ x } T_{ph} = 6 \text{ x } T_{ph} \tag{22}$$

Number of conductor per slot is

$$Z_s = \frac{6T_{ph}}{S_s} = \frac{Z}{S_s} \tag{23}$$

Where

Z_{ph}=number of conductor per phase

Z=total number of conductor in stator winding

Z_s=number of conductor per slot

Conductor cross sectional area

The cross sectional area of stator conductors is determine from the stator current per phase and suitably selected value of current density for the stator windings. The area of the stator conductor is given as

$$a_s = \frac{I_s}{\delta_s} \tag{24}$$

When the stator current per phase is given as

$$I_s = \frac{Q}{3V_{ph}\cos\emptyset} \tag{25}$$

Where

δ_s = current density in stator winding

I_s = stator current per phase

$\cos\emptyset$ = power factor

A suitable value of current density has to be selected considering its advantages and disadvantages.

Advantages of higher value of current density

- reduction in cross section
- reduction in weight
- reduction in cost

Disadvantages of higher value of current density

- increase in resistance
- increase in copper loss
- increase in temperature rise
- reduction in efficiency

Shape and size of the conductor can be decided based on the conductor cross sectional area.

Area of stator slot

Slot is occupied by the conductors and the insulation. Almost 25% of the stator area is employed by insulation. Once the number of conductors per slot and cross sectional area of the conductor is decided slot dimension is determine as

$$s = Z_s \text{ x } a_s \tag{26}$$

Then the stator slot area is

$$A_s = \frac{s}{\text{space factor}} = \frac{Z_s \text{ x } a_s}{\text{space factor}} \tag{27}$$

Where

s=slot dimension

A_s=stator slot area

Space factor=constant number indicate the space of slot occupied by insulation which is vary between 0.25 and 0.4

After decided the lip, wedge and height of slot the depth of stator slot is given as

$$d_{ss} = \text{lip} + \text{wedge} + \text{height} \tag{28}$$

Mean Turn Length (l_{mt})

Mean turn Length is calculated using an empirical formula

$$l_{mt} = 2L + 2.3\tau_p + 0.24 \tag{29}$$

Width of stator teeth

The width of stator teeth is the difference between slot pitch and slot width which is given as

$$w_{st} = \tau_s - w_s = \frac{\Phi}{\frac{S_{ss}}{P} L_i B_{st}} \tag{30}$$

Flux density in stator tooth

After knowing the dimensions of stator slot pitch, width of the slot and width of the stator tooth flux density in the stator tooth can be calculated as

$$B_{st} = \frac{\Phi}{S_{ss}/_P \, w_{st} L_i} \tag{31}$$

Where

L_i=net iron length=L+ stacking factor

Stacking factor is assumed as 0.95 which is standard for induction motor design

Stator core depth

There is a certain solid portion above the slots in the stator which is called the depth of the stator core. This depth of the stator core can be calculated by selecting suitable value for the flux density in the stator core (B_c). Generally the flux density in the stator core varying between 1.2 to 1.4 Tesla. Depth of the stator core can be calculated as follows

Flux in the stator core section (Φ_c)

Flux in the stator core is half of the flux per pole in the motor

$$\Phi_c = \Phi/_2 \tag{32}$$

Area of stator core (A_c)

After determining the flux in stator core and select the suitable of flux density in the core area of stator core is determine as

$$A_c = \frac{\Phi_c}{B_c} = \frac{\Phi}{2B_c} = L_i x d_{cs} \tag{33}$$

Then the stator core depth (d_{cs}) is calculated by

$$d_{cs} = \frac{A_c}{L_I} \tag{34}$$

The outer diameter of the stator core (D_o) is calculated as

$$D_o = D + 2d_{ss} + 2d_{cs} \tag{35}$$

After modelling all parameters of the outer or stationary part of the motor now the next step is modelling of the internal rotating part of the motor.

3.3 Rotor modelling

Rotor is the rotating part of induction motor. To model the squirrel cage rotor type formulates all the parameters in this rotor. Those parameters are outer diameter of rotor, number of rotor slot, length of rotor bar, rotor bar resistance, end ring current, area of end ring, resistance of the two end ring, flux density in rotor teeth and rotor core depth.

Before start to modelling the rotor part first determine the air gap length between stator and rotor which is given by empirical formula in eqn (36) as

$$l_g = 0.2 + 2\sqrt{DL}\ \text{(mm)} \tag{36}$$

Where

l_g= air gap length between stator and rotor

Outer diameter of rotor

After determine the air gap length the outer diameter of the rotor is determine as

$$D_r = D - 2l_g \tag{37}$$

Where

D_r=outer diameter of rotor

Number of rotor slots

Numbers of rotor slots are selected properly in relation to number of stator slots otherwise undesirable effects will be found at the starting of the motor. Those undesirable effects are cogging and crawling torque, synchronous hooks and noisy. Therefore when selecting the number of rotor slot we must avoid those problems by selecting in the following way.

To avoid crawling and cogging torque:

$S_s \neq S_r$, $S_s - S_r \neq \pm 3P$

To avoid synchronous hooks and cusps in torque speed characteristics:

$S_s - S_r \neq \pm P, \pm 2P, \pm 5P$

To avoid noisy operation:

$S_s - S_r \neq \pm 1, \pm 2, (\pm P \pm 1), (\pm P \pm 2)$

Where

S_r = number of rotor slot

P= number of poles

Rotor bar current

Current in the rotor bar of a squirrel cage induction motor is determined by

$$I_b = \frac{6\, I_s\, T_{ph}\, K_w\, pf}{S_r} \tag{38}$$

Where

I_b=rotor bar current

pf =power factor

Cross sectional area of rotor bar

The cross sectional area of the rotor bar can be calculated by rotor bar current and assumed value of current density for rotor bars. As cooling conditions are better for the rotor than the stator therefore higher current density can be assumed which is lead to reduce sectional area and hence increased resistance, rotor conductor losses and reduced efficiency. In other word with increased rotor resistance starting torque will be increased. Based on this merit and demerit the value of rotor bar current density can be assumed between 4 to 7 ($\frac{Amp}{mm^2}$). After assuming current density the sectional area of the rotor bars can be calculated by using eqn (39)

$$A_b = \frac{I_b}{\delta_b} \tag{39}$$

Where

A_b=area of rotor bar

δ_b=current density of rotor bar

Once the cross sectional area is known the size of the conductor can be selected from standard.

Shape and size of rotor slots

In general semi closed or closed slots with very small or narrow openings are employed for the rotor slots. In case of fully closed slots the rotor bars are force fit into the slots from the sides of the rotor. The rotors with closed slots are giving better performance to the motor in the following manner.

- As the rotor is closed the rotor surface is smooth at the air gap and hence the motor draws lower magnetizing current.
- Reduced noise as the air gap characteristics are better reduced starting current.

From this two point it can be concluded that semi closed slots are more suitable and hence are employed in rotors.

Length of rotor bar

The length of rotor bar is the sum of the stator core length and allowance length for skewing. The skewing factor is about 20% of the core length.

$$l_b = L + \text{allowance for skewing} \tag{40}$$

Where

l_b= Length of rotor bar

Rotor bar resistance

The resistivity of the conductor is selected from type of conductor used and after knowing the length of the rotor bars the resistance of the rotor bars can be calculated as

$$R_b = \frac{\rho_b l_b \, S_r}{A_b} \tag{41}$$

Where

l_b = rotor bar length

R_b= rotor bar resistance

ρ_b= resistivity of the bar conductor

End ring current (I_e)

All the rotor bars are short circuited by connecting them to the end rings at both the end of rotor. The rotating magnetic field produced induce an emf in the rotor bars which will be sinusoidal over one pole pitch. As the rotor is a short circuited body, there is a current flow because of this emf induced. These current is determine as

$$I_e = \frac{I_b \, S_r}{\pi \, P} \tag{42}$$

Area of end ring (A_e)

After knowing the end ring current and assuming suitable value for the current density in the end rings cross section area of the end ring can be determine as

$$A_e = \frac{I_e}{\delta_e} \tag{43}$$

Resistance of the two end ring

To determine the resistance of the end ring first mean length of the current path (l_{me}) in end ring can be calculated. It's calculated as

$$l_{me} = \pi D_{me} \tag{44}$$

When D_{me} is the mean diameter of end ring assumed as 4 to 6cm less than that of rotor inner diameter. Then the two end ring resistance is determine as

$$R_e = \frac{2\rho l_{me}}{A_e} = \frac{2\rho\pi D_{me}}{A_e} \tag{45}$$

Where

I_e=end ring current

δ_e=current density in end ring

A_e=area of end ring

l_{me} =mean length of current path

D_{me}=mean diameter of end ring

R_e=resistance of end ring

Flux density in rotor tooth

Flux density in rotor tooth is determined after the area of the tooth is calculated. This area is calculated as

$$A_{tr} = \frac{w_{tr} L_i S_r}{P} \tag{46}$$

Then the flux density in rotor tooth is determine as

$$B_{tr} = \frac{\Phi}{A_{tr}} = \frac{\Phi}{\frac{S_r}{P} L_i w_{rt}} \tag{47}$$

Where

A_{tr}= area of the rotor tooth

w_{tr}= width of rotor teeth

L_i= net iron length

B_{tr}= flux density in rotor tooth

The value of area and width of teeth is determined in suitable value to get the value of flux density which is less than 1.8 Tesla.

Assuming that during design depth of the rotor core is equal to depth of stator core because the same material is used for both parts which have the same flux per pole and flux density.

Rotor core depth (d_{rc})

The rotor core depth is the length of the rotor core excluding the depth of the rotor slot. This depth is determine as

$$d_{rc} = \frac{\Phi_c}{L_i B_{rt}} = \frac{\frac{\Phi}{2}}{L_i B_{rc}} \tag{48}$$

Finally the inner diameter of rotor is given as

$$D_{ir} = D_r - 2d_{rs} - 2d_{rc} \tag{49}$$

Where

D_{ir}=inner rotor diameter

d_{rs}=rotor slot depth

d_{rc}=rotor core depth

This is all about the modelling of the two main part of the motor; stator and rotor. Now based on those models the performances of the motor is evaluated.

3.4 Performance of motor

The performance of the induction motor can be evaluated based on the design data of the stator and rotor. The parameters for performance evaluations are no load current, no load losses, conductor losses (load losses), no load power factor, full load power factor, full load efficiency, full load slip and shaft torque. Based on these performances value the design parameter values of stator and rotor can be justified.

No-load current

The no load current of induction motor is the sum of magnetizing current and core loss current. Those current are determining as follows.

Magnetising current per phase (I_m)

$$I_m = \frac{\pi\, P\, AT}{6 T_{ph} K_w} \tag{50}$$

Where

AT= total magnetising magneto motive force (mmf)

AT= Magnetising mmf for air gap + Magnetising mmf for stator core +Magnetising mmf for stator teeth + Magnetising mmf for rotor teeth + Magnetising mmf for rotor core

Magnetising mmf is calculated by the help of magnetising (BH) curve and physical dimensions of stator teeth, stator core, rotor teeth and rotor core.

Mmf in air gap (mmf_g)

To determine the mmf in air gap first calculate the effective air gap length which is affected by stator and rotor slot opening and ducts on the air gap. These slots opening and ducts are made some gap factor whish determine as follows.

The gap construction factor made by the stator slot opening is determine by eqn (51) as

$$k_{gss} = \frac{y_{ss}}{y_{ss} - k_{css} B_{s0}} \tag{51}$$

The gap construction factor made by rotor slot opening is determine as

$$k_{gsr} = \frac{y_{sr}}{y_{sr} - k_{csr} B_{r0}} \tag{52}$$

The gap construction factor made by both stator and rotor slot opening is determine as

$$k_{gs} = k_{gss} k_{gsr} \tag{53}$$

The overall gap construction factor made by the slot opening and ducts is determine as

$$k_g = k_{gs} k_{ds} \tag{54}$$

Now the effective air gap between stator and rotor is determine multiplying the air gap length by the overall gap construction factor.

$$l_{ge} = l_g k_g \tag{55}$$

Where

k_{css}=carter's coefficient for stator slot opening

k_{gss}=gap construction factor due to stator slots

k_{csr}=carter's coefficient for rotor slot opening

k_{gsr}=gap construction factor due to rotor slot

k_{gs}=gap construction factor due to slot

k_{ds}=gap construction factor due to ducts=1

k_g=over all gap construction factor

l_{ge}=effective air gap length

After determining the effective air gap length the mmf required in air gap is given as

$$mmf_g = \frac{B_g l_{ge} \text{ x } 10^{-3}}{2\mu_0} \tag{56}$$

Where

B_g=air gap flux density =$1.36B_{av}$ Tesla

μ_0=permeability in air =$4\pi \times 10^{-7}$

Mmf in stator teeth (mmf_{st})

After determine flux density in stator teeth then corresponding to this flux density the ampere turns per meter required are read from BH curve of the material that the stator core made from. Then mmf in stator teeth is given as

$$mmf_{st} = AT_{st} d_{ss} \times 10^{-3} \quad (57)$$

Where

AT_{st}=ampere turns per meter in stator teeth corresponding to flux density in stator teeth

d_{ss}=depth of stator slot

Mmf in stator core (mmf_{sc})

Flux density in stator core is assumed then corresponding to this value ampere turn per meter is read from BH curve of the steel used for stator core. Then mmf in stator core is given as

$$mmf_{sc} = AT_{sc} l_{sc} \quad (58)$$

The length of magnetic path through stator core is determine as

$$l_{sc} = \frac{\pi(D + 2d_{ss} \times 10^{-3} + d_{cs} \times 10^{-3})}{3p} \quad (59)$$

Where

AT_{sc}= ampere turns per meter in stator core corresponding to flux density in stator core

l_{sc}=length of magnetic path through stator core

Mmf in rotor teeth (mmf_{rt})

Flux density in rotor teeth is assign and corresponding to this flux density ampere turn per meter is read from BH curve of the steel used for rotor construction. Then mmf in rotor teeth is given as

$$mmf_{rt} = AT_{rt} d_{sr} 10^{-3} \quad (60)$$

Where

AT_{rt}=ampere turns per meter in rotor teeth corresponding to flux density in rotor teeth

d_{sr}= rotor slot depth

Mmf in rotor core (mmf_{rc})

After flux density is determined in rotor core then corresponding to this flux density value ampere turns per meter required in rotor core is read from BH curve. Then mmf in rotor core is given as

$$mmf_{rc} = AT_{rc} l_{rc} \quad (61)$$

Length of the magnetic path through rotor core is determine as

$$l_{rc} = \frac{\pi D_i \text{ x } 10^{-3}}{3p} \quad (62)$$

Where

AT_{rc}=ampere turns per meter in rotor core corresponding to flux density in rotor core

l_{rc}= length of magnetic path through rotor core

The total ampere turn in the motor is the sum of ampere turn in air gap, stator and rotor core and stator and rotor teeth.

$$AT = AT_g + mmf_{st} + mmf_{sc} + mmf_{rt} + mmf_{rc} \quad (63)$$

Where

AT = total mmf required

No load losses

No load losses are the constant losses in induction motor which includes iron loss in stator core, iron loss in stator teeth, stray loss, friction and windage losses.

Iron loss in stator teeth

To determine iron loss in stator teeth weight of the steel in stator teeth is first determine as follows.

First determine volume of the teeth as

$$V_{st} = A_{st} \text{ p } d_{ss} \text{ x } 10^{-3} \text{ m}^3 \quad (64)$$

Then weight of the teeth is determined by multiplying the volume of teeth by density of the core made from.

$$W_{st} = V_{st} \text{ x density of material} \quad (65)$$

Finally the iron loss in stator teeth is the product of the specific iron loss for the material the core made from and weight of the teeth.

$$P_{lst} = \text{specific iron loss x } W_{st} \quad (66)$$

Where

V_{st}=volume of stator teeth

A_{st}=area of stator teeth per pole

W_{st}=weight of stator teeth

P_{lst}=iron loss in stator teeth

Iron loss in stator core

To get iron loss in stator core the volume and weight of iron in stator core is first determine. The volume of stator core is determined using eqn (67) below

$$V_{sc} = (D + 2d_{ss} \times 10^{-3})(\pi L d_{cs} \times 10^{-3}\ m^3) \tag{67}$$

Then weight of the core is given as

$$W_{sc} = V_{sc} \times \text{ density of iron core} \tag{68}$$

Iron loss in stator core is finally determine as

$$P_{lsc} = \text{specific iron loss } \times W_{sc} \tag{69}$$

Where

V_{sc} =Volume of stator core

W_{sc}=weight of stator core

P_{lsc}=iron loss in stator core

Total iron loss (P_{il})

Total iron loss is the sum of the loss in stator teeth and core.

P_{il} = Iron loss in stator teeth + Iron loss in stator core

No load loss is the sum of the total iron loss in stator, stray loss, friction and windage loss

No load loss = Total iron loss + Friction and windage loss + stray loss

Note that iron loss in rotor is negligible because of low frequency when compare with stator supply frequency.

Loss component current per phase (I_c)

The loss component current per phase at no load is the ratio of the total no load loss to the supply phase voltage which is given as

$$I_c = \frac{\text{Total no load loss}}{3\ V_{ph}} \tag{70}$$

After determine the magnetising and core loss component current the no load current (I_0) is given as

$$I_0 = \sqrt{{I_m}^2 + {I_c}^2} \quad (71)$$

No load power factor

No load power factor is the ratio of core loss current to no load current which is given as

$$pf_{nl} = \frac{I_c}{I_0} \quad (72)$$

Where

I_m=magnetising current

I_c=core loss current due to hysteresis and eddy current

pf_{nl}=no load power factor

Load loss

Load loss is the power loss in stator winding and power loss in rotor bar and end ring when the shaft of the motor is rotating with rating values.

Load loss= stator conductor loss + rotor conductor loss

Stator conductor loss

The power loss due to stator conductor is calculated by determine first the resistance of winding is calculating by using eqn (73). The resistivity of the conductor is read from the wire used for winding.

$$R_s = \frac{\rho_s T_{ph}\, l_{mts}}{a_s} \quad (73)$$

Then the power loss in stator conductor is determine as

$$P_{culoss} = I_s^2\, R_s \quad (74)$$

Where

R_s=resistance of stator winding

ρ_s =resistivity of the stator conductor used for winding

a_s=area of wire

P_{culoss}=copper loss in stator winding

Rotor conductor loss

Power losses in rotor conductor are the sum of Power loss in rotor bar and end ring.

Power loss in rotor bar ($P_{barloss}$)

The total power loss in rotor bar is determine as

$$P_{barloss} = \mathrm{s_r I_b^2 r_b} \tag{75}$$

Power loss in end ring ($P_{ringloss}$)

The power loss at the two end rings is determine as

$$\mathrm{P_{ringloss}} = 2\mathrm{I_{er}^2 r_e} \tag{76}$$

Total conductor loss in rotor of squirrel cage induction motor is the sum of the loss in the bar and the two end ring.

$$\mathrm{Rotor_{totalohmloss}} = P_{barloss} + \mathrm{P_{ringloss}} \tag{77}$$

Total loss of motor

Total power loss in induction motor is the sum of no load power loss and load power loss.

$$\mathrm{P_{totalloss}} = \text{noload loss} + \text{load loss} \tag{78}$$

Slip (S)

Induction motor is always rotate by speed less than the rotation of magnetic field which is called synchronous speed. The difference between the rotation of rotor of induction motor and the rotation of magnetic field in the motor is called slip. The full load slip is given as

$$\mathrm{S} = \frac{\mathrm{Rotor_{totalohmloss}}}{\mathrm{Rotor_{totalohmloss}} + \text{output power}} \tag{79}$$

Or

$$\mathrm{S} = \frac{\mathrm{n_s - n_m}}{\mathrm{n_s}} \tag{80}$$

Where

n_s=synchronous speed in revolution per second

n_m=mechanical speed of the rotor in revolution per second

Output torque

The output torque convert electrical power to mechanical power is given as

$$\tau_{sh} = \frac{\text{output power}}{\text{angular speed of shaft}} = \frac{\mathrm{P_{output}}}{\omega_m} \tag{81}$$

Where

τ_{sh}=shaft torque

Efficiency

Efficiency indicates how much persent of the electrical power convert to mechanical power which is determine as

$$\eta = \frac{\text{output power}}{\text{output power} + \text{no load loss} + \text{load loss}} \quad (82)$$

3.5 Design

As per the survey conducted in factories; adama agricultural and machinery industry and adama fettle factory around adama, almost all the motors deployed to drive machines are three phase squirrel cage motor. Those motors are available with different rating varying from 3kW to 20kW. A leading number of the motor have a rating between 8kw to 15kW. On the basis of this study, for the sample design, an 11 kW rated motor is selected with the following parameters as given in Table 3.1.

Table 3. 1: Design specification of induction motor

General data	
Type of motor	3 phase squirrel cage induction motor
rating or output power	11kW
Rated voltage	380V
frequency	50Hz
Winding connection	Delta
Number of pole	4
Reference speed	1450 rpm
Stray loss	0.1% of output power
Frictional and windage loss	1.5% of output power
Power factor	0.84
Efficiency	89%

Now, based on the design specification given in the Table 3.1 and the equations described in section 3.4, the motor important dimensions are calculated.

From the output equation, the input apparent power (Q) in kVA is determined as follows.

$$Q = \frac{\text{output power}}{\text{efficiency x power factor}} = \frac{11\text{KW}}{0.89\text{x}0.84} = 14.714 \text{ kVA} \quad (83)$$

To determine the output coefficient (C_0), eqn (84) below are used. It consists of constant value of specific magnetic loading (B_{av}) and electric loading (q) and winding factor (k_w).

$$C_0 = 11 \text{ x } k_w \text{x } B_{av} \text{ x } q \text{ x} 10^{-3} \quad (84)$$

The specific magnetic loading is one of the major factors for determining core loss. There is also another limitation for choosing of specific magnetic loading among them the flux density in teeth has to be less than 1.8 Tesla and flux density in the core is has to be between 1.3-1.5 Tesla. Based on this limit for specific magnetic loading and the advantage and disadvantage for selection of higher value of specific electric loading listed previously their values are choice as

B_{av}=0.55 Tesla

q=25000 amper.conductor /m

Kw=0.955

Substitute the value of B_{av}, q and Kw to eqn (84) the output coefficient is determined

$$C_0 = 11 \text{ x } 0.955 \text{ x } 0.5 \text{ x } 22000 \text{ x } 10^{-3} = 115$$

The synchronous speed (N_s) of the motor in revolution per minute is calculated as

$$N_s = \frac{120 \text{ x f}}{P} = \frac{120 \text{ x } 50}{4} = 1500 \text{ rpm} \quad (85)$$

The synchronous speed in revolution per second is determined using eqn (86) as follows.

$$n_s = \frac{2f}{P} = \frac{2 \text{ x } 50}{4} \text{ or } \frac{N_s}{60} = \frac{1500}{60} = 25\text{rps} \quad (86)$$

Then, using the value of (Q), (C_0) and (n_s), determined in eqn (83), (84) and (86) respectively, the volume of the motor (D^2L) is calculated as follows.

$$D^2L = \frac{Q}{C_0 n_s} = \frac{14.714}{115 \text{ x } 25} = 0.00512\text{m}^3 \quad (87)$$

To separate the stator core length (L) and stator bore diameter (D) from eqn (87) use the maximum efficiency criterion. This criterion stated that core length per pole pitch is equal to 1.5 which is given as

$$\frac{L}{\tau_p} = \frac{L}{\frac{\pi D}{P}} = 1.5 \quad (88)$$

From eqn (88) put stator core length in terms of bore diameter as below

$$L = \frac{1.5\pi D}{P} = \frac{1.5 \text{ x } 3.14 \text{ x } D}{4} = 1.18D \quad (89)$$

Now substitute eqn (89) into eqn (87) to determine the value of stator bore diameter

$$D^2(1.1775D) = 0.00512m^3 \quad (90)$$

$$D^3 = \frac{0.00512m^3}{1.18} = 4.34 \text{ x } 10^{-3} \text{ m}^3 \quad (91)$$

$$D = \sqrt[3]{4.34 \text{ x } 10^{-3} \text{ m}^3} = 0.163 \text{ m} = 163 \text{ mm} \sim 170\text{mm} \quad (92)$$

The bore diameter is determined in eqn (92) now the core length is calculated by substituting eqn (92) into eqn (89)

$$L = 1.18D = 1.18 \text{ x } 0.170 \text{ m} = 0.2 \text{ m} = 200 \text{ mm} \quad (93)$$

Maximum peripheral speed (V_m) is given as

$$V_m = \pi \text{ D } n_s = 3.14 \text{ x } 0.170 \text{ x}25 = 13.345\text{m/s} \quad (94)$$

3.5.1 Stator Design

The design of stator is started from the selection of number of stator slots (S_s). A criterion for selection of the number of stator slots should satisfy the consideration of stator slot pitch at the air gap surface, which should be between 1.5 to 2.5 cm. Take the number of slots per phase per pole ($q_s = 3$) to fulfil this criteria. Therefore, number of stator slot is given as

$$S_s = \text{m x p x } q_s = 3 \text{ x } 4 \text{ x } 3 = 36 \quad (95)$$

Where

m=number of phase

P=number of pole

q_s=number of slot per pole per phase

Stator slot pitch (τ_s) at the air gap surface is

$$\tau_s = \frac{\pi D}{S_{ss}} = \frac{3.14 \text{ x } 17.0 \text{ cm}}{36} = 1.5 \text{ cm} \quad (96)$$

Flux per pole (Φ)

The flux per pole of the motor is calculated by using eqn (97) below.

$$\Phi = \frac{B_{av}\, \pi\, D\, L}{P} = \frac{0.5 \text{ x } 3.14 \text{ x } 0.170 \text{ x } 0.200}{4} = 0.013345 \text{ weber} \qquad (97)$$

Turns per phase (T_{ph})

To determine number of turns per phase assume that the induced voltage (E_{ph}) is equal to the supplied phase voltage (V_{ph}).

$$T_{ph} = \frac{E_{ph}}{4.44\Phi f k_w} = \frac{V_{ph}}{4.44\Phi f k_w} = \frac{380}{4.44 \text{ x } 0.013345 \text{ x}50\text{x}0.955} = 134 \text{ turns} \qquad (98)$$

Number of conductor per phase (Z_{ph})

Number of conductor per phase indicates the amount of copper use in one phase out of three phases which calculated in eqn (99).

$$Z_{ph} = 2 \text{ x } T_{ph} = 2 \text{ x } 134 = 268 \text{ conductor per phase is required} \qquad (99)$$

Number of total stator conductor (Z)

The total stator copper use in the stator winding is calculated as

$$Z = m \text{ x } 2 \text{ x } T_{ph} = m \text{ x } Z_{ph} = 3 \text{ x } 268 \qquad (100)$$

$$= 804 \text{ conductor required for stator winding}$$

Number of conductor per slot (Z_s)

The number of conductor per slot indicates the amount of copper inserted in one slot which is calculated as

$$Z_s = \frac{Z}{S_s} = \frac{804}{36} = 22 \qquad (101)$$

Stator current per phase (I_s)

Stator current per phase determine from input power and supply voltage which is given by eqn (102) below

$$I_s = \frac{Q}{3V_{ph}\cos\emptyset} = \frac{14.714 \text{ x } 10^3}{3 \text{ x } 380 \text{ x } 0.84} = 15.369 \text{ A} \qquad (102)$$

Conductor cross sectional area (a_s)

The conductor cross sectional area of stator winding is calculated after determine of stator phase current and select a suitable value of stator winding current density which is taken by considering the advantages and disadvantages of higher value of stator winding current density. The advantages are reduction in cross, reduction in weight and reduction in cost section of conductor and the disadvantages are increase in resistance, increase in copper loss and reduction in efficiency. Therefore suitable value of current density for stator windings for this design is taken as ($\delta_s = 1.5A/mm^2$). By using stator phase current calculated in eqn (102) and the selected value of stator winding current density the conductor cross sectional area is calculated as

$$a_s = \frac{I_s}{\delta_s} = \frac{15.369}{1.5} = 10\ mm^2 \qquad (103)$$

Based on the sectional area; shape and size of the conductor can be decided. If the sectional area of the conductors is below $5mm^2$ then usually circular conductors are employed. If it is above $5mm^2$ then rectangular conductors will be employed.

Area of stator slot

Area of stator slot is determine from number of conductor consumed in slot multiply by cross sectional area of the conductor dived by space factor which is given in eqn (104) below.

$$A_s = \frac{Z_s \text{ x } a_s}{\text{space factor}} = \frac{22 \text{ x } 8.6\ mm^2}{0.4} = 473mm^2 \qquad (104)$$

Where the space factor is assumed as 0.4. This indicates the space covered by insulator in the slot.

Size of stator slot

The size of stator slot indicates the depth and width of the slot. Its shape is indicating on figure 3.5 which is narrowed on the opening to minimize the non uniformity of the air gap between stator and rotor. Among the three type of stator slot; circular, tapered and parallel a tapered slot type is applied for this design which have a lowest air gap factor on the opening and easiest for manufacturing. The dimensions of the slot were selected based on the limit value and for this design each top and bottom width is selected with optimized value as suitable for a good design with good performance.

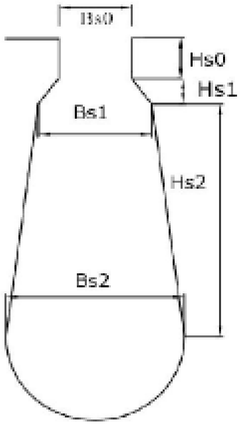


Figure 3. 1Tapered stator slot type with dimension

Where

B_{s0} = slot opening width with a limit value between 0.35mm to 1.5mm

B_{s1} = upper side slot width with limit value of 7mm to 10mm

B_{s2} = bottom side slot width with limit value of 11mm to 13mm

H_{s0} = slot opening height (lip) with limit value of 1mm to 2mm

H_{s1}=height of slot wedge with limit value of 1mm to 5mm

H_{s2}=bottom side height with limit value of 15mm to 22mm

For these design the input of the above parameters are taken as

B_{s0} = 1mm

B_{s1} =10mm

B_{s2} =11mm

H_{s0} =1.5mm

H_{s1}=1.5mm

H_{s2}= 17mm

Stator slot depth (d_{ss})

Stator slot depth is the summation of the slot opening height, slot wedge height and bottom side height which is calculated as

$$d_{ss} = H_{s0} + H_{s1} + H_{s2} = (1 + 1 + 20)mm = 22\ mm \quad (105)$$

Stator slot pitch (y_{ss})

Stator slot pitch is the distance between the successive slots which is help full to know the width of the teeth is within limit value. It is calculated as:

$$y_{ss} = \frac{\pi D}{S_s} = \frac{3.14 \text{ x } 170\text{mm}}{36} = 15\text{mm} \quad (106)$$

Length of the mean Turn (l_{mts})

The mean turn length is the length of the coil inside the slot without including the outer coil around the opening of the slot. This length is called active length which is determined as

$$l_{mts} = 2L + 2.3\tau_p + 0.24 = 2L + 2.3\left(\frac{\pi D}{P}\right) + 0.24 \quad (107)$$

$$= 2 \text{ x } 0.2\text{m} + \frac{2.3 \text{ x } 3.14 \text{ x } 0.17}{4} + 0.24$$

=0.95m=950mm

Coil span (C_s)

Coil span is helpful during inserting a conductor in the slot. After entering the incoming coil into the first slot the outgoing coil is inserted into the slot whose distance is equal to coil span for single layer winding.(This has to be calculated above

$$C_s = \frac{S_s}{P} = \frac{36}{4} = 9 \quad (108)$$

Stator Winding

Stator winding is the way of inserting conductor coil into stator slots. After calculating the major parameters required for winding such as number of stator slot, number of pole, number of phase, number of slot per pole per phase, pole pitch and coil span; the conductor coil is insert into stator slot by using winding distribution table (WDT). In this table number of row equals to phase number and number of columns equals to slots per phase (S_s/m). As calculated previously number of stator slot ($S_s = 36$), number of phase (m=3), slot per pole per phase ($q_s = 3$), coil span ($C_s = 9$) and pole (P = 4, where pole pair is 2). The Table is filled in pole pair = 2 filling cycles, each one corresponding to S_s/pole pair = 36/2=18 assignments. By starting from placing slot number 1 in the first cell (row 1, col. 1), the slot number 2 is placed after pole pairs = 2 cells (row 1, col. 3), till slot number 18 is assigned to the 35-th cell (row 3, col. 11), which corresponds to the $S_s/\text{pole pair}$ assignment and the first filling cycle is completed. The second cycle starts by counting pole pair elements from cell number 35, which corresponds to element number 37. However, due to the periodicity of this winding configuration (S_s=36), the element number 37 corresponds to the first element. Therefore, the slot number 19 will be placed in the adjacent empty second cell (row 1, col. 2).

This configuration is shown in the table 3.2. The vertical double bar in the table separates the active conductors with positive EMF from those with negative EMF.

Table 3. 2: Winding distribution table for 36 stator slot

1	**19**	**2**	**20**	**3**	**21**	**4**	**22**	**5**	**23**	**6**	**24**
7	**25**	**8**	**26**	**9**	**27**	**10**	**28**	**11**	**29**	**12**	**30**
13	**31**	**14**	**32**	**15**	**33**	**16**	**34**	**17**	**35**	**18**	**36**

(phase 1: red, phase 2: green, phase 3: blue).

The WDT facilitates the practical arrangement for assembling the coils and form the final winding configuration. Indeed, the WDT contains information about which of the slots belong to each phase section. In fact, once the WDT has been created and the phases are defined for each slot, the end winding can be chosen in order to reduce the connections length between positive and negative slots (coil sides) of the same phase. For this purpose, WDT can be directly used to represent in plane the active coil sides and to identify their phase by simply following the WDT rows, where every slot is already characterized by its EMF phase colour and by its sign, a positive in column one or a negative in column two, depending on the sign of each WDT element.

Flux density in stator tooth (B_{st})

After knowing flux per pole, coil span, width of stator teeth and net iron length the stator flux density is calculated.

Net core length (L_i)

Net core length is the pure length of the laminated steel without its stacking length. To get this length the stator core length is multiplied by its stacking factor.

$$L_i = L \text{ x stacking factor} = 0.200 \text{ x } 0.9 = 0.180 \text{ m} \qquad (109)$$

Where stacking factor is 0.9

Stator tooth width (W_{ts})

The width of stator tooth defines in suitable way which indicates the strength of the steel between the slots. To maximum this width has a positive effect on its strength but has a negative effect on the core loss. Therefore during design consider the width of the tooth is fulfilling these two factors. In addition to these factors the flux density in the teeth is less than 1.7 Tesla. It's calculated as

$$W_{ts} = \frac{\Phi}{1.7\frac{S_s}{P}L_i} = \frac{\Phi}{1.7C_sL_i} = \frac{0.013345}{1.7 \text{ x } 9 \text{ x } 0.18} = 4.85 \text{ mm} \tag{110}$$

Since the calculated value of stator tooth width is to small take the value of 6mm for stator tooth width to get appropriate design. Therefore use ($W_{ts} = 6\text{mm}$) for calculation of flux density in stator tooth.

Then flux density in stator tooth is

$$B_{st} = \frac{\Phi}{C_sW_{ts}L_i} = \frac{0.013345}{9 \text{ x } 0.006\text{x}0.18} = 1.4 \text{ Tesla(T)} \tag{111}$$

Depth of stator core (d_{sc})

Depth of the stator core can be calculated by assuming suitable value for the flux density in the stator core. Generally the flux density in the stator core is varying between 1.2 to 1.6 Tesla. Then depth of the stator core can be calculated as follows.

Flux in the stator core (Φ_c)

Flux in stator core is half of flux produced per pole which is given as

$$\Phi_c = \frac{\Phi}{2} = \frac{0.013345}{2} = 0.0067 \text{ weber (wb)} \tag{112}$$

Area of stator core (A_{cs})

The area of stator core is calculated by dividing flux in stator core to flux density in the core.

$$A_{cs} = \frac{\Phi_c}{B_c} = \frac{0.0067\text{wb}}{1.35 \text{ T}} = 0.00496 \text{ m}^2 = 4.96\text{x}10^3 \text{ mm}^2 \tag{113}$$

Where

B_c = flux density in stator core assume as 1.35T

In other form area of stator core is given as

$$A_{cs} = L_i\text{x}d_{sc} \tag{114}$$

By using eqn (109) and (113) the depth of the stator core is calculated as

$$d_{sc} = \frac{A_{cs}}{L_i} = \frac{0.00496\text{m}^2}{0.18\text{m}} = 0.0275 \text{ m} = 27 \text{ mm} \tag{115}$$

Stator outer diameter (D_0)

$$D_0 = D + 2d_{ss} + 2d_{sc} = (0.170 + 2 \text{ x } 0.022 + 2 \text{ x } 0.025)\text{m} = 0.264 \text{ m} = 264\text{mm} \quad (116)$$

3.5.2 Rotor Design

Before starting rotor design, the air gap between stator and rotor is determined first.

Air gap length (l_g)

An air gap between stator and rotor is a very important parameter because the magnetic field, flux density and induced current in the stator are flow to the rotor by induction through air gap. The higher value of this gap has a disadvantage of reduced power factor and increased magnetizing current. Therefore a suitable value of the air gap between stator and rotor is calculated to get a good performance of the motor. Its limit value is 0.7mm. By using the empirical formula on eqn (117) its value is calculated as

$$l_g = \left(0.2 + 2\sqrt{DL}\right)\text{mm} = \left(0.2 + 2\sqrt{0.17\text{m x } 0.2\text{m}}\right)\text{mm} = 0.56 \text{ mm} \quad (117)$$

Rotor outer diameter (D_r)

The outer diameter of the rotor is the distance between the centres of the shaft and the air gap which is calculated as

$$D_r = D - 2l_g = 170\text{mm} - 2\text{x}0.56\text{mm} = 169\text{mm} \quad (118)$$

Number of rotor slots (S_r)

The numbers of rotor slots are to be selected compared with stator slot to avoid cogging, crawling, unpredictable hooks and rating speed minimize. Therefore for this design the number of rotor slot is selected as

$S_r = 28$

Rotor slot type and dimension

Rotor slot is used by inserting the casting aluminium bar. Due to its advantage mention on stator slot above tapered type of rotor slot with the following dimension is used for this design.

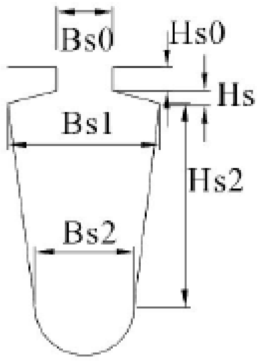


Figure 3. 2 rotor slot with dimension

The slot dimensions are determined as follows. The dimensions are taken many times by considering the motor performance such as efficiency power factor and magnetizing current and finally these values of rotor slot dimensions are selected to get the desired motor performance.

B_{so} =1mm	H_{so}=1mm
B_{s1} = 9mm	H_{so1}=1mm
B_{s2} =11mm	H_{s1}=2mm
	H_{s2}=18mm

Rotor slot depth (d_{sr})

Rotor slot depth indicates the total height of the slot which includes the active height cover by rotor bar and the height covered by insulator and the opening height. It is calculated by summing up those heights.

$$d_{sr} = H_{so} + H_{so1} + H_{s1} + H_{s2} = (1 + 1 + 2 + 18)mm = 22mm \quad (119)$$

Rotor bar current (I_b)

Rotor bar current is the current produced in the rotor bar due to the voltage induced in the bar as shorted by the end ring. This current is calculated by using eqn. (118).

$$I_b = \frac{2 \text{ x } 3 \text{ x } T_{ph} \text{ x } K_w \text{ x } I_s \text{x pf}}{S_r} = \frac{2 \text{ x } 3 \text{ x}134 \text{ x } 0.955 \text{ x } 12.91 \text{ x } 0.84}{28} \quad (120)$$

$$= 297.37A$$

Cross sectional area of Rotor bar (A_b)

By selecting the suitable value of rotor bar current density ($\delta_b = 2A/mm^2$) and using eqn (121), the cross sectional area of the rotor bar is calculated as

$$A_b = \frac{I_b}{\delta_b} = \frac{297.37A}{2A/mm^2} = 149mm^2 \quad (121)$$

Length of rotor bar (l_b)

The length of rotor bar is the sum of the length of stator core and allowance length due to skewing of rotor bar.

$$l_b = L + \text{allowance for skewing} = 200\text{mm} + 40\text{mm} = 240\text{mm} \tag{122}$$

Where

Allowance for skewing is 40mm

Resistance for each rotor bar (r_b)

To calculate the resistance of rotor bar, first the material the bar made from is selected. Then, resistivity of that material is read from standard. In this design the bar is made from aluminium whose resistivity is ($\rho_b = 0.0434783 \left(\Omega.\frac{mm^2}{m}\right)$). After knowing the resistivity and using eqn (121) and (122) the value of resistance of each bar is calculated as

$$r_b = \frac{\rho_b l_b}{A_b} = \frac{0.0434783 \left(\Omega.\frac{mm^2}{m}\right) \text{ x } 0.240\text{m}}{149\text{mm}^2} = 70\ \mu\Omega \tag{123}$$

The total bar resistance is calculated by multiplying the number of rotor slot to resistance of each bar which is connected in series

$$R_b = S_r r_b = 28 \text{ x } 70 \text{ x } 10^{-6} = 0.00196\Omega \tag{124}$$

End ring current (I_e)

The current at the two end ring is calculated as

$$I_e = \frac{I_b S_r}{\pi P} = \frac{297.37\text{A x } 28}{3.14 \text{ x } 4} = 663\text{A} \tag{125}$$

Area of end ring (A_e)

To calculate area of end ring, a suitable value of the current density in the ring is identified. Due to the short circuit of the two end rings, maximum amount of current is produced in this point. Therefore to reduce the temperature rise, the value of current density in end ring is higher when compared with current density in stator winding and rotor bar. For this design, current density in rotor end ring is assumed as ($\delta_e = 8\text{A/mm}^2$).

$$A_e = \frac{I_e}{\delta_e} = \frac{663\text{A}}{8\text{A/mm}^2} = 83\text{mm}^2 \tag{126}$$

Resistance of two end ring (R_e)

The two end rings are made from the same material as that of the bar. Therefore, their resistivity is the same as the bar and the resistance of the two end ring is calculated as:

$$R_e = \frac{2\rho_e l_{me}}{A_e} = \frac{2\rho_e \pi D_{me}}{A_e} = \frac{2 \text{ x } 0.043483 \text{ x } 3.14 \text{ x } 0.040\text{m}}{83\text{mm}^2} = 0.0001316\Omega \quad (127)$$

Where

D_{me} is mean diameter of end ring which is taken as 4cm

Flux in rotor core (Φ_c) is half of the flux produced per pole which is

$$\Phi_c = \frac{\Phi}{2} = \frac{0.013345}{2} = 0.0067\text{wb} \quad (128)$$

Area of rotor core (A_{rc})

Before calculating the area of the rotor core depth, the rotor core is first determined. But depth of rotor core is equal to depth of stator core which is 25mm. Then by using this value and eqn (122) the area of rotor core is calculated as:

$$A_{rc} = d_{rc} \text{ x } L_b = 25\text{mm x } 240\text{mm} = 6000\text{mm}^2 \quad (129)$$

Flux density in rotor core (B_{rc})

After determining the flux and area of the rotor core the flux density in the rotor core is calculated as:

$$B_{rc} = \frac{\Phi_c}{A_{rc}} = \frac{0.0067\text{wb}}{0.006\text{m}^2} = 1.1 \text{ Tesla} \quad (130)$$

Rotor inner diameter (D_i)

The inner diameter of the rotor is determined by subtract the core depth and slot depth from outer rotor diameter

$$D_i = D_r - 2d_{rc} - 2d_{rs} = 169\text{mm} - 2 \text{ x } 25\text{mm} - 2 \text{ x } 22\text{mm} = 75\text{mm} \quad (131)$$

Rotor slot pitch (y_{sr})

The distance between the successive rotor slots is calculated as

$$y_{sr} = \frac{\pi D_i}{S_r} = \frac{3.14 \text{ x } 75\text{mm}}{28} = 9\text{mm} \quad (132)$$

3.5.3 Performance Evaluation

The stator and rotor parameters are calculated by using eqn (83) to (132). Based on those parameters the performance of the motor is evaluated. These performance parameters are iron losses in the stator, magneto motive force (mmf) in the air gap, mmf in stator and rotor, magnetizing current, total no load loss, total load loss, full load slip, output torque, efficiency and power factor. These performance parameters are evaluated one by one as follows.

Iron losses

Iron loss is one of the components of no load loss which is occurring in the core of the motor. This loss is directly proportional to the frequency of the rotating magnetic field or supply frequency in the stator. Due to the slip the rotor speed is less than that of the magnetic field speed in the stator. Therefore, when compare frequency of the rotor with that of stator the rotor frequency is very small. Due to this, iron loss in the rotor core is neglected in this calculation. The two iron losses in stator are stator teeth losses and stator core losses.

Stator teeth iron loss ($P_{teethloss}$)

To compute the iron loss in stator teeth, the parameters required are area of stator teeth, volume of the teeth and weight of the teeth which are calculated one by one as follows.

Area of stator teeth (A_{st})

Area of stator teeth is the product of width of the teeth and net core length which are calculated as:

$$A_{st} = w_{st}L_i = 4.85\text{mm x } 180\text{mm} = 873\text{mm}^2 = 0.000873\text{m}^2 \tag{133}$$

Volume of stator teeth (V_{st})

After calculating area of the teeth, volume of stator teeth is calculated by multiplying this area by the height of the teeth.

$$V_{st} = A_{st}h_{st} = 0.000873\text{m}^2 \text{ x } 0..022\text{m} = 1.92 \text{ x } 10^{-5}\text{m}^3 \tag{134}$$

Where

h_{st} =Height of stator teeth which is equal to 22mm

Weight of stator teeth (W_{st})

To get weight of the teeth, the density of the core material is read from standard first. In this design, the core is made from M19_26G steel which has a density of 7650kg/m^3. Then, the weight is calculated as

$$W_{st} = V_{st} \text{ x density of the material} = 1.92\text{x}10^{-5}\text{m}^3 \text{ x } 7650\text{kg/m}^3 = 0.15\text{kg} \quad (135)$$

Finally, the iron loss in the teeth is calculated ~~as~~ by multiplying specific iron loss which is 5.5w/kg for this steel by weight of the teeth.

$$P_{teethloss} = \text{specific iron} \frac{\text{loss}}{\text{Kg}} \text{ x weight of stator teeth} \quad (136)$$
$$=5.5\text{w/kgx}0.15\text{kg}=0.825\text{w}$$

Iron loss in stator core ($P_{coreloss}$)

To compute iron loss in stator core volume and weight of the core are determined first as follows.

Volume of stator core (V_{sc})

Volume of stator core is calculated by using eqn (137) below as:

$$V_{sc} = (D + 2d_{ss} \text{ x } 10^{-3})(\pi L d_{cs} \text{ x } 10^{-3} \text{ m}^3) \quad (137)$$
$$= (0.17m + 2 \text{ x } 12 \text{ x } 10^{-3}m)(3.14 \text{ x } 0.2m \text{ x } 23 \text{ x } 10^{-3}m^3)$$
$$= 0.0028m^3)$$

Weight of stator core (W_{sc})

Weight of the core is calculated by multiplying volume of the core by density of the material that core made from which is similar to density of the teeth.

$$W_{sc} = V_{sc} \text{ x density} = 0.0028\text{m}^3 \text{ x } 7650\text{kg/m}^3 = 21.42\text{kg} \quad (138)$$

To get the iron loss in the stator core, the specific iron loss is multiplied by weight of the core

$$P_{coreloss} = \text{specific iron} \frac{\text{loss}}{\text{kg}} \text{ x weight of stator c} = 5.5\text{w/kg x } 21.42\text{kg} \quad (139)$$
$$= 118\text{w}$$

Total iron loss (P_{iloss})

Total iron loss is the summation of iron loss in stator teeth and iron loss in stator core

$$P_{iloss} = \text{iron loss in teeth} + \text{iron loss in core} = 0.825\text{w} + 118\text{w} = 119\text{w} \quad (140)$$

mmf in air gap (mmf_g)

To calculate the mmf in the air gap, first determine the factors that change the uniformity of the air gap between stator and rotor. These factors change the air gap length and the effective air gap length is determined by considering those factors. The factors are stator slot opening, rotor slot opening and ducts.

Gap construction factor due to stator slot (K_{gss})

The gap factor made by stator slot opening is calculated by using eqn (141) below as

$$K_{gss} = \frac{y_{ss}}{y_{ss} - K_{css}B_{so}} = \frac{15mm}{15mm - 0.5 \text{ x } 1.5mm} = 1.053 \quad (141)$$

Gap construction factor due to rotor slot (K_{gsr})

The gap construction factor due to rotor slot opening is calculated as

$$K_{gsr} = \frac{y_{sr}}{y_{sr} - K_{csr}B_{0r}} = \frac{9mm}{9mm - 0.5 \text{ x } 1.5mm} = 1.09 \quad (142)$$

Gap construction factor due to slot (K_{gs})

The gap construction due to both stator and rotor slot is calculated as

$$K_{gs} = K_{gss}K_{gsr} = 1.053 \text{ x } 1.09 = 1.15 \quad (143)$$

Overall gap construction factor (K_g)

The overall gap construction factor is the multiplication of the factor made by slot and the factor made by ducts. But there are no any ducts between stator and rotor. Therefore gap construction factor due to ducts is 1.

$$K_g = K_{gs}K_d = 1.15 \text{ x } 1 = 1.15 \quad (144)$$

Effective air gap length (l_{ge})

To get the effective air gap length between stator and rotor, the air gap length is determined by the overall gap construction factor.

$$l_{ge} = l_gK_g = 0.56mm \text{ x } 1.15 = 0.644mm \quad (145)$$

Then mmf in the air gap is calculated as

$$mmf_g = \frac{B_gl_{ge}}{2\mu_0} = \frac{1.36B_{av}l_{ge}}{2\mu_0} = \frac{1.36 \text{ x } 0.55 \text{ x } 0.644 \text{ x } 10^{-3}}{2 \text{ x } 4\pi \text{ x } 10^{-7}} \quad (146)$$

$$= 191.176\text{Ampere Turn (A.T)}$$

mmf of stator teeth (mmf_{st})

The stator core is made from M19_26G steel. The BH curve of this steel is shown on figure 3.7 below. Ampere turns per meter required in stator teeth corresponding to flux density in stator teeth are read by using table 3.3. The flux density in stator teeth is calculated using eqn (111) which is equal to 1.4 Tesla. At flux density of 1.4 Tesla 1193.735 ampere per meter is required which is read from Table 3.3. Therefore, ampere turn of stator teeth (AT_{st}) is 1193.735A/m. The magneto motive force in the stator teeth is calculated by using eqn (147) below

$$mmf_{st} = AT_{st}d_{ss} \text{ x } 10^{-3}\text{m} = 1193.735 \text{ x } 22\text{x}10^{-3} = 26.26 \text{ ampere turn (A.T)} \qquad (147)$$

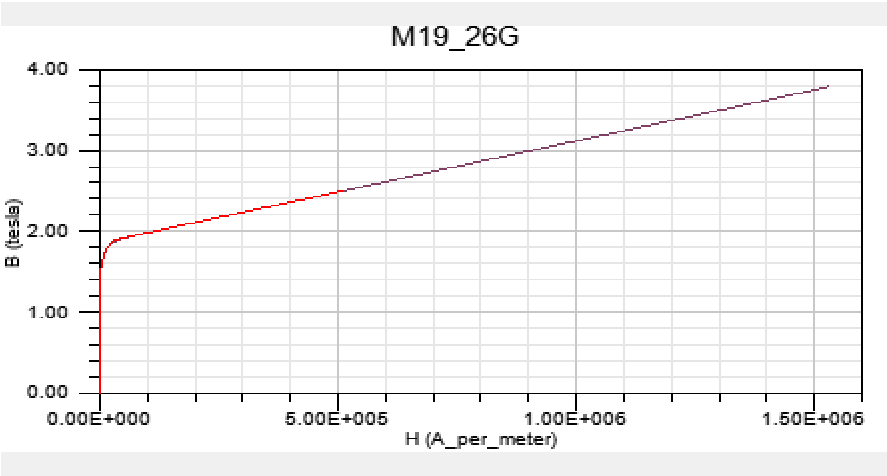


Figure 3. 3 BH curve of M19_26G steel

Table 3. 3: ampere per meter at different flux density for the BH curve in figure 3.3

	H (A_per_meter)	B (tesla)
10	477.46	1.28
11	636.61	1.33
12	795.77	1.36
13	1591.5	1.44
14	3183	1.52
15	4774.6	1.58
16	6366.1	1.63
17	7957.7	1.67
18	15915	1.8

Length of magnetic path through stator core (l_{sc})

The magnetic path through stator core is calculated as

$$l_{sc} = \frac{\pi(D + 2d_{ss}x10^{-3} + 2d_{cs}x10^{-3})}{3P} \quad (148)$$

$$= \frac{3.14(0.170m + 2x22x10^{-3}m + 2x25x10^{-3}m)}{3x4} = 0.069m$$

Flux density in stator core is taken as 1.35 Tesla. At this flux density, the ampere turn per meter required is read from BH curve which give as 742.7167 A/m. Therefore, the ampere turn in stator core (AT_{sc}) is $742.7167A/m$.

mmf in stator core (mmf_{sc})

mmf in stator core is calculated by multiplying the length of the magnetic path in the core by the ampere turn in the core

$$mmf_{sc} = AT_{sc}l_{sc} = 742.7167 \text{ x } 0.069 = 51.24 \text{ ampere turn (A.T)} \quad (149)$$

mmf in rotor teeth (mmf_{rt})

Flux density in rotor teeth is assumed as 1.65T and at this point the ampere turn per meter required is read from the BH curve on figure 3.7. As the rotor and stator are made from the same steel, the ampere turn in rotor teeth read from the curve is equal to ($AT_{rt} = 7161.9Am$), by using the curve used for the stator core mmf calculation. By using this value and rotor teeth depth the magneto motive force in the rotor teeth is calculated as

$$mmf_{rt} = AT_{rt}d_{rs} = 7161.9 \text{ x } 0.022m = 157.56 \text{ ampere turn (A.T)} \quad (150)$$

Length of magnetic path through rotor core (l_{rc})

The mmf of rotor core is determined by fist calculating the magnetic path length in the core which is calculated as

$$l_{rc} = \frac{\pi D_i \text{ x } 10^{-3}}{3p} = \frac{3.14 \text{ x } 75 \text{ x } 10^{-3}m}{3 \text{ x } 4} = 0.0196m \quad (151)$$

mmf in rotor core (mmf_{rc})

Flux density in the rotor core is calculated by eqn (128) which is equal to 1.1 Tesla. At this point, the ampere per meter required in rotor core as read from the BH curve is ($AT_{rc} = 387A/m$). By using eqn (151) and the ampere turn in the rotor core is calculated as

$$mmf_{rc} = AT_{rc}l_{rc} = 88.698x0.0196 = 7.5 \text{ ampere turn (A.T)} \quad (152)$$

Total mmf (AT)

Total mmf in the motor is the sum of the mmf in air gap, mmf in stator and rotor core and mmf in stator and rotor teeth.

$$\mathrm{AT} = \mathrm{mmf_g} + \mathrm{mmf_{st}} + \mathrm{mmf_{sc}} + \mathrm{mmf_{rt}} + \mathrm{mmf_{rc}}\mathrm{AT} \quad (153)$$
$$= (191.176 + 26.26 + 51.24 + 157.56 + 7.5)\mathrm{ampereturn}$$
$$= 433.736\mathrm{Ampere\ Turn}$$

Magnetizing current (I_m)

The magnetizing current is the component of no load current which is calculated as

$$I_m = \frac{\pi P(AT)}{6T_{ph}K_w} = \frac{3.14 \text{ x } 4 \text{ x } 433.736}{6 \text{ x } 134 \text{ x } 0.955} = 7.1A \quad (154)$$

No load loss

The No load loss is the loss when the shaft is not connected to the load but operated within the rated supply voltage. This loss is the sum of total iron loss, stray loss, friction and windage loss.

$$\text{no load loss} = \text{total iron loss} + \text{friction and windage loss} + \text{stray loss} \quad (155)$$

= (119+165+11) w = 240w

Loss component current per phase (I_c)

Loss component current is another component of no load current which is calculated as

$$I_c = \frac{\text{total no load loss}}{3V_{ph}} = \frac{339w}{3 \text{ x } 380v} = 0.21A \quad (156)$$

No load current (I_o)

No load current is the current at no load which is calculated as

$$I_0 = \sqrt{I_c^2 + I_m^2} = \sqrt{0.21^2 + 7.1^2} = 7.103A \quad (157)$$

Load loss (P_{lloss})

Load loss is the power loss occurred when the load is connected to the motor shaft and the motor is operating at rated values. This loss is the sum of the loss in stator copper and loss in rotor conductors.

Load loss=stator conductor loss + rotor conductor loss (158)

Stator conductor loss (P_{culoss})

To get stator copper loss, first the resistance of the conductor in stator winding is calculated using eqn (157).

$$R_s = \frac{\rho_s T_{ph} l_{mts}}{a_s} = \frac{0.021\Omega.\frac{mm^2}{m} \text{ x } 134 \text{ x } 0.95m}{8.6mm^2} = 0.31\Omega \quad (159)$$

By using eqn (102) and (157) the power loss in stator copper is calculated as

$$P_{culoss} = I_s^2 R_s^2 = 12.91^2 \text{ x } 0.31^2 = 160 \text{ W} \quad (160)$$

Rotor conductor loss

Conductor losses in rotor are the sum of the loss in rotor bar and the loss in end ring.

Rotor bar loss ($P_{barloss}$)

The power loss in the rotor bar is calculated as

$$P_{barloss} = I_b^2 R_b = 297.37^2 \text{ x } 0.0019 = 168w \quad (161)$$

End ring loss ($P_{ringloss}$)

The power loss in the end ring is another component of the conductor loss in the rotor which is given as

$$P_{ringloss} = I_{er}^2 R_e = 663^2 \text{ x } 0.000131 = 57.58w \quad (162)$$

Total conductor loss in rotor of squirrel cage type of induction motor is the sum of loss in the bar and end ring.

$$Rotor_{totalohmloss} = P_{barloss} + P_{ringloss} = 168 + 57.58 = 225.58w \quad (163)$$

By using eqn (160) and (163) the total load loss is calculated as

$$P_{lloss} = P_{culoss} + ohmlossbar + ohmlossendring = 160 + 168 + 57.58 = 385.58w \quad (164)$$

Total loss of motor

Total power loss in induction motor is the sum of no load power loss and load power loss.

$$P_{totalloss} = noload\ loss + load\ loss = 240+385.58 = 625.58w \quad (165)$$

Full load slip (S)

Slip is the speed difference between rotating speed of the magnetic field and the rotor which is calculated as

$$S = \frac{Rotor_{totalohmloss}}{Rotor_{totalohmloss} + output\ power} = \frac{225.58w}{225.58w + 11000w} = 0.02 \quad (166)$$

Rotor speed in rpm (N_m)

The rotating speed of the rotor in revolution per minute is calculated as

$$N_m = N_s(1 - S) = 1500(1 - 0.02) = 1470\text{rpm} \tag{167}$$

Rotor frequency (f_r)

Rotor frequency is calculated by multiplying the slip by the supply frequency

$$f_r = Sf_s = 0.02 \text{ x } 50 = 1\text{Hz} \tag{168}$$

Rotor angular speed (ω_m)

$$\omega_m = \frac{N_m\ x\ 2\pi}{60} = \frac{1470\text{rpm x 2 x 3.14}}{60} = 153.86\text{rad/s} \tag{169}$$

Output (rated) torque

The shaft torque or output torque of an induction motor is given as

$$\tau_{sh} = \frac{\text{output power}}{\text{9 x angular speed of shaft}} = \frac{P_{output}}{9\omega_m} = \frac{11000}{9 \text{ x } 153.86} = 79.44\text{N.m} \tag{170}$$

Input power (P_{in})

From the apparent input power the active or useful power converted to the mechanical power is calculated as

$$P_{in} = \text{output power} + \text{total loss} = (11000 + 725)\text{w} = 11.725\text{kw} \tag{171}$$

Rated power factor (pf)

Rated power factor is the power factor at rated power which is calculated as

$$\text{pf} = \frac{\text{Input electrical power convert to mechanical power}}{\text{Total input apparent electrical power}} = \frac{P_{in}}{Q} = \frac{11725\text{ w}}{14714\text{ VA}} = 0.79 \tag{172}$$

Rated efficiency (η)

The rated efficiency of the motor is calculated as

$$\eta = \frac{P_{output}}{P_{output} + P_{totalloss}} = \frac{11000\text{w}}{11000\text{w} + 725\text{w}} = 0.938 = 93.8\% \tag{173}$$

In this chapter the manual design of three phase squirrel cage induction motor is performed. In the next chapter simulation of this design is performed by using rotational machine expert software. Then the result of simulation and manual design is compared.

CHAPTER FOUR

4. SIMULATION AND RESULTS

Simulation is a representation of the functioning of the system. The act of simulating a system first requires that a model of that system must be developed. This model represents the key characteristics, behaviours and feature of the selected system. The system modelled to simulate in this thesis is three phase squirrel cage induction motor and the simulation was performed by using a rotational machine expert (RMxprt) software 17.1 versions. The parameters of stator and rotor calculated in chapter three are used as input of the software. The simulation output or the result of simulations are locked rotor operation, break down operation, rated parameters, data sheet and performance curve of the motor. The aim of this simulation is evaluating the performance of the modelled motor and comparing the result of the simulation with that of the manual design. Before start to use this software let us define its input parameters and expect outcomes in the next topic.

4.1 Overview on Rotational Machine Expert Software

Rotational Machine Expert (RMxprt) is an interactive software package from ANSYS Corporation used for the designing and analysing of electrical machines. When a new project is started in RMxprt, the type of motor is to be selected. The parameters associated with the selected machine are given as input in the property window. The property windows are accessed by clicking each of the machine elements; for example, stator, rotor, and shaft under machine in the project tree. Solution and output options such as the rated output, torque, and load current, etc., are set by adding a solution setup in analysis of the project tree. The basic process in RMxprt for designing of three phase induction motor is illustrated with the help of the flowchart shown below.

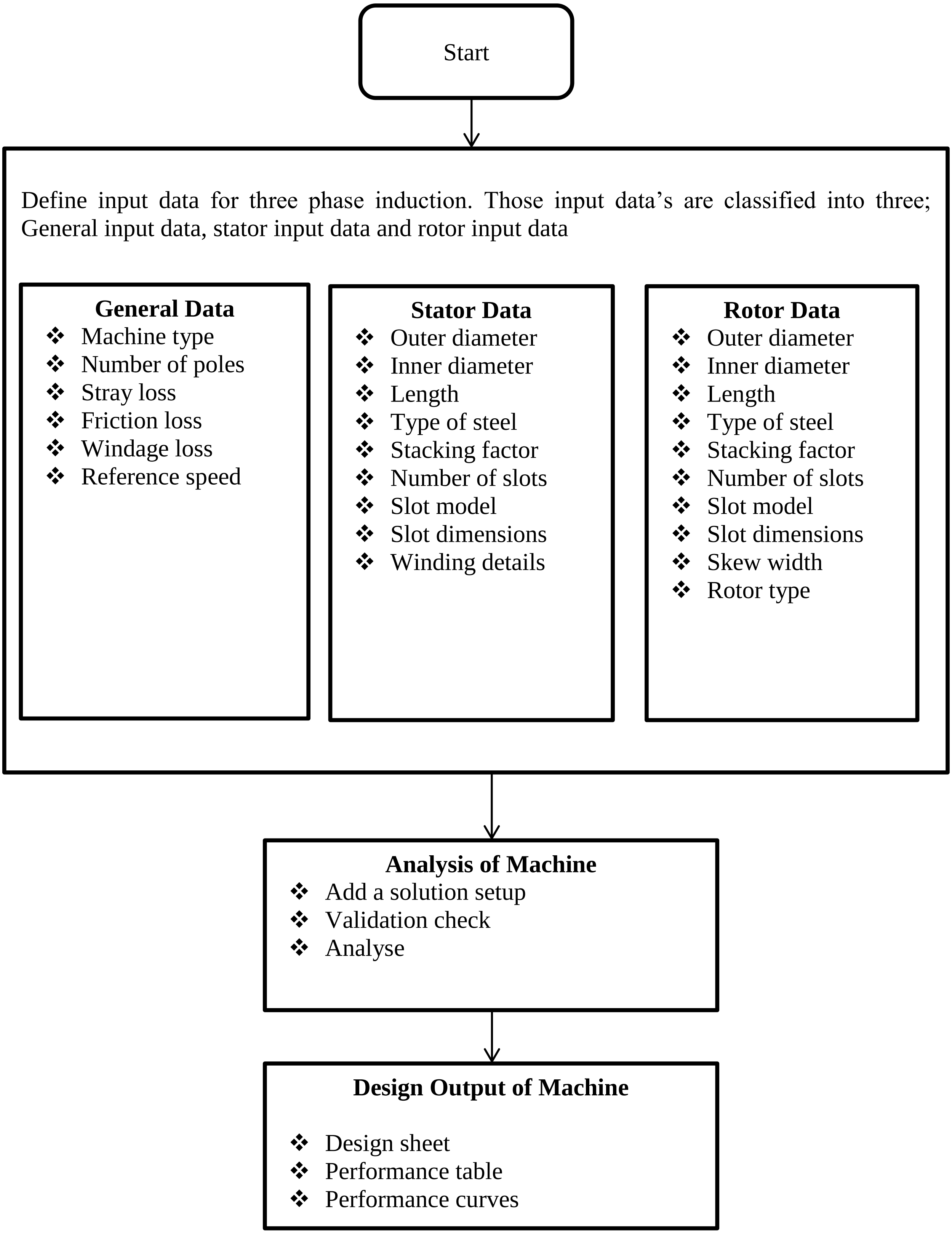


Figure 4. 1 Flowchart for basic process in RMxprt

Now open the software and input data that given in the flowchart. The value of those data is taken from manual modelling. By inputting the input parameters to the software then the software made the model of stator core, stator slot, stator winding, rotor core, rotor slot and the model when the rotor insert in the stator. Those models are described one by one in the following figures.

A model shown in figure 4.2 below was an outer stationary part of induction motor which is called stator core. This stator core was modelled from M19_26G non oriented electric steel which has characteristics of lowest core loss, excellent permeability at low and intermediate inductions and good stamping properties. This stator core model is made with 36 slots which was ready for inserting a stator winding conductors.

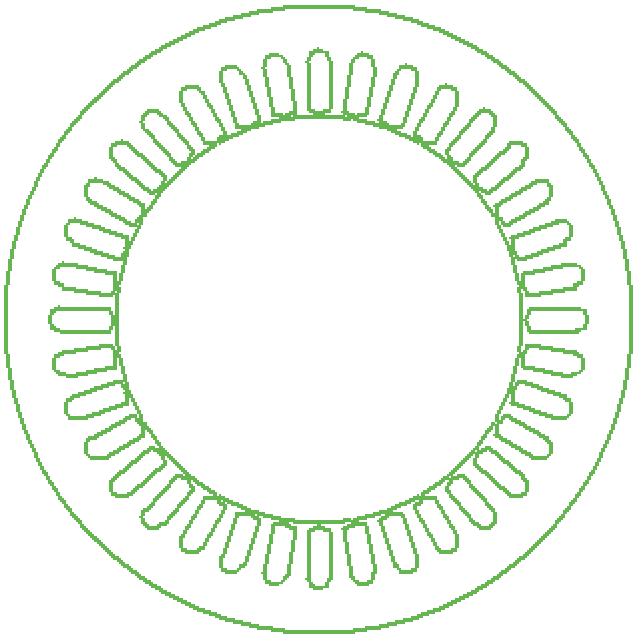


Figure 4. 2 stator core with 36 slots

The figure 4.3 shown below indicates the model of one of stator slot with its dimension and shape. The slot shape and dimension is one of the major factors that affect the motor performance. Therefore the optimized value of the motor performance is get by properly choice the shape and dimensions of the slot. The stator slot shape in figure 4.3 is called tapered type which is selected for optimized design and easier for manufacturing industry.

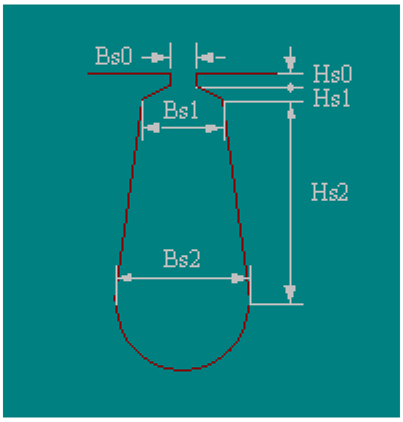


Figure 4. 3 stator slot dimension and shape

A model on figure 4.4 shows when stator winding is inserting in the stator slot. This winding was made from copper wire with concentric type of winding arrangement. Each slot contains twenty six conductors with three slots per pole per phase and four poles. Number of total conductor consumes and conductor per phase was calculated in chapter three and taken as input to the software.

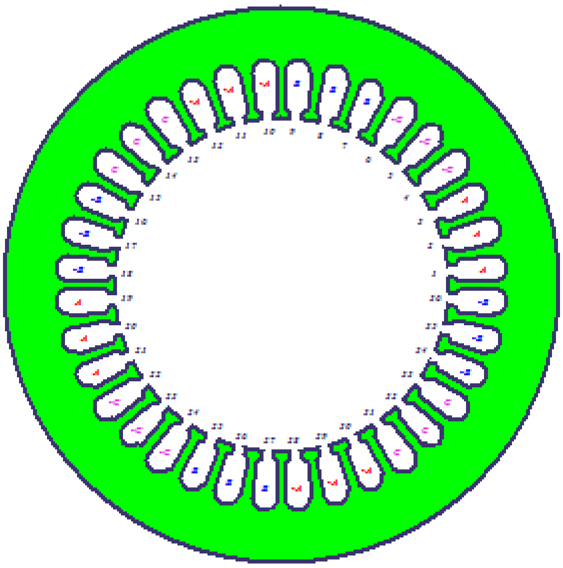


Figure 4. 4 Stator winding with copper conductor

Figure 4.5 shows a model of rotating part of an induction motor which is called rotor core. This rotor core was made from the same steel with stator core shown on figure 4.2. It contains twenty eight slots which is ready for casting rotor bar.

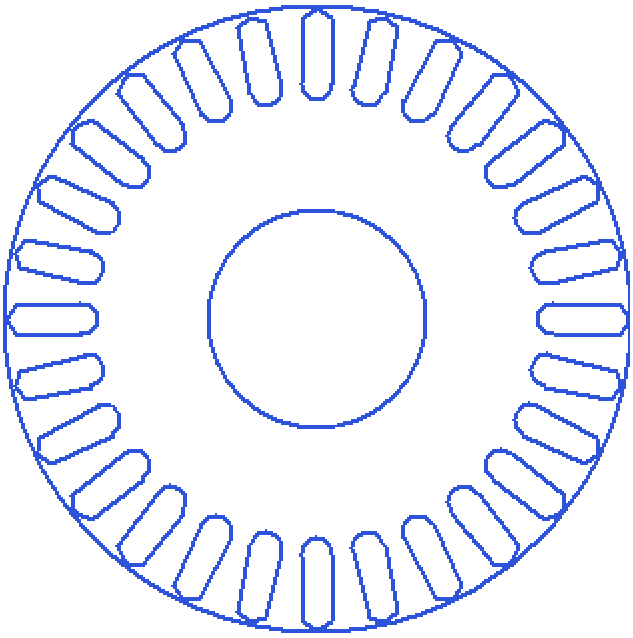


Figure 4. 5 rotor core with slot

The figure 4.6 shown below indicates the model of one of rotor slot with its dimension and shape. This type of rotor slot shape is called tapered type which is choice for optimized design and simplify for manufacturing.

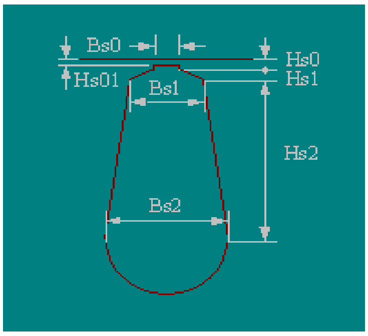


Figure 4. 6 rotor slot dimension and shape

Figure 4.7 below shows when rotor core is inserted into stator core with a suitable air gap between them. It contains the whole model when stator core mode, stator slot model, stator winding, rotor core, rotor slot and shaft are joining together. This is the final model of three phase squirrel cage induction motor. Then to analysing the modelled motor performance first check the validity of the input parameters by clicking on the validity checker. Then if the input parameters are valid the next step is click on the run menu. After clicking the run menu the simulation result is given as output. Those results are different break down operation performance of the motor, different locked rotor operation performance of the motor, rating operation parameters, performance curves and data sheets.

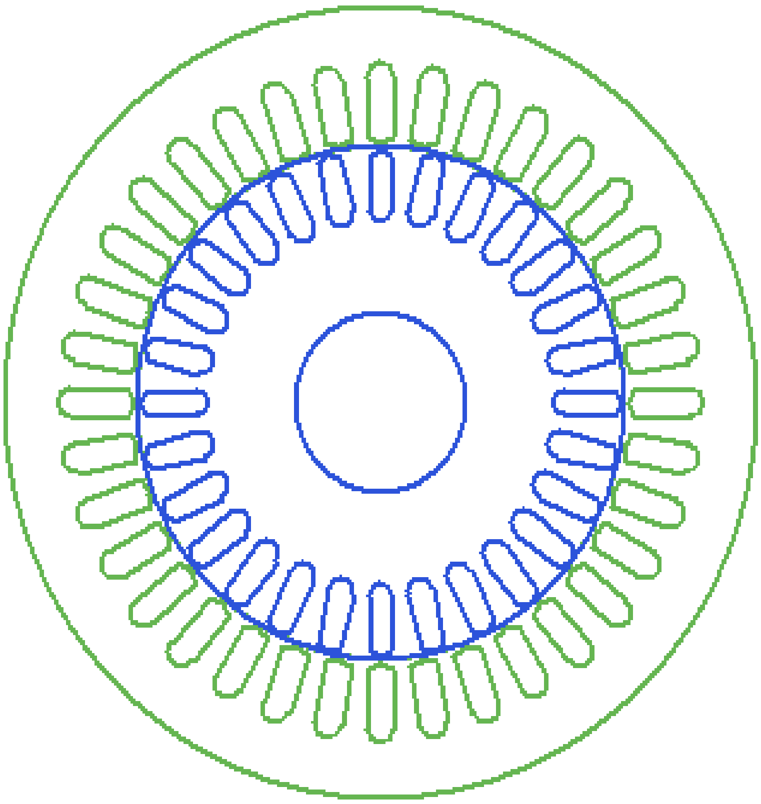


Figure 4. 7 Rotor insert in the stator

4.2 Simulation Results

4.2.1The modelled Motor Performances

This display a Data field with a drop-down menu that allows viewing many different data tables which indicates the performance of the motor as shown below.

Table 4.1 indicates different performance parameters during starting time of rotor to rotate. Those parameter values are called locked rotor parameter values and tell the performance of the motor at starting time.

Table 4. 1 Locked rotor operation

	Name	Value	Units
1	Locked-Rotor Torque	161.281	NewtonMeter
2	Locked-Rotor Phase Current	79155	mA
3	Locked-Rotor Torque Ratio	2.20141	
4	Locked-Rotor Current Ratio	5.92632	
5	Stator Resistance	0.232047	ohm
6	Stator Leakage Reactance	1.64419	ohm
7	Rotor Resistance	1.45938	ohm
8	Rotor Leakage Reactance	2.97587	ohm

Table 4.2 shows the performance of a motor at rated values of supply voltage and frequency. This table indicates the hall performance of a motor at rated value and the motor selection is specially focused on this rated performance with other factors.

Table 4. 2 Rated Performances

	Name	Value	Units
1	Stator Ohmic Loss	124189	mW
2	Rotor Ohmic Loss	512183	mW
3	Iron-Core Loss	149758	mW
4	Frictional and Windage Loss	107576	mW
5	Stray Loss	11000	mW
6	Total Loss	904706	mW
7	Output Power	11000800	mW
8	Input Power	11905600	mW
9	Efficiency	92.401	%
10	Power Factor	0.781178	
11	Rated Torque	73.2626	NewtonMeter
12	Rated Speed	1433.89	rpm
13	Rated Slip	0.0440754	

Table 4.3 shows the break down operation of motor. These parameters are slip, torque and phase current beyond rated value. Those parameters indicate the limit of the operation of the motor to be breakdown or come to stop. Beyond this value the motor is start to come to rest.

Table 4. 3 Break down Operation

	Name	Value	Units
1	Break-Down Slip	0.35	
2	Break-Down Torque	223.287	NewtonMeter
3	Break-Down Torque Ratio	3.04777	
4	Break-Down Phase Current	57788.7	mA

Table 4.4 below shows the value of electric data required at rated operation. Those values are phase current, magnetizing current, current density and specific electric loading.

Table 4. 4 Rated electric data

	Name	Value	Units
1	Stator Phase Current	13356.5	mA
2	Magnetizing Current	4608.3	mA
3	Iron-Core Loss Current	140.78	mA
4	Rotor Phase Current	11295.4	mA
5	Armature Thermal Load	26.7177	A^2/mm^3
6	Specific Electric Loading	23408.3	A_per_meter
7	Armature Current Density	1141380	A_per_m2
8	Rotor Bar Current Density	1532270	A_per_m2
9	Rotor Ring Current Density	8225470	A_per_m2

Table 4.5 indicate the magnetic data during rated operation of motor. These data's are magnetic flux density and ampere turn in different parts of magnetic circuit.

Table 4. 5 Rated magnetic data

	Name	Value	Units
1	Stator-Teeth Flux Density	1.43912	tesla
2	Rotor-Teeth Flux Density	1.67474	tesla
3	Stator-Yoke Flux Density	1.38798	tesla
4	Rotor-Yoke Flux Density	0.411712	tesla
5	Air-Gap Flux Density	0.581482	tesla
6	Stator-Teeth Ampere Turns	31.499	A.T
7	Rotor-Teeth Ampere Turns	164.185	A.T
8	Stator-Yoke Ampere Turns	48.333	A.T
9	Rotor-Yoke Ampere Turns	0.861868	A.T
10	Air-Gap Ampere Turns	191.209	A.T

Table 4.6 shows rated parameters in stator and rotor during rating operation.

Table 4. 6 Rated parameters

	Name	Value	Units
1	Stator Resistance	0.232047	ohm
2	Stator Leakage Reactance	2.89154	ohm
3	Rotor Resistance	1.33815	ohm
4	Rotor Leakage Reactance	7.98487	ohm
5	Iron-Core Loss Resistance	2518.79	ohm
6	Magnetizing Reactance	76.9467	ohm
7	Stator Slot Leakage Reactance	1.50776	ohm
8	Stator End Leakage Reactance	0.475103	ohm
9	Stator Differential Leakage Reactance	0.90867	ohm
10	Rotor Slot Leakage Reactance	2.3232	ohm
11	Rotor End Leakage Reactance	0.100108	ohm
12	Rotor Differential Leakage Reactance	1.52615	ohm
13	Skewing Leakage Reactance	3.51048	ohm

4.2.2 Performance Curves

This displays the plots that were automatically generated by the solver. There are a lot of curves shown below that indicates the performance of the motor at different rating point.

As shown on figure 4.8 a phase current and speed of the motor has inversely proportional. At starting point the phase current is about 6% of rating current and as speed increase the current start to down and finally as the speed of the rotor is equal to synchronous speed the phase current become almost zero because at this point the motor is stop to rotate

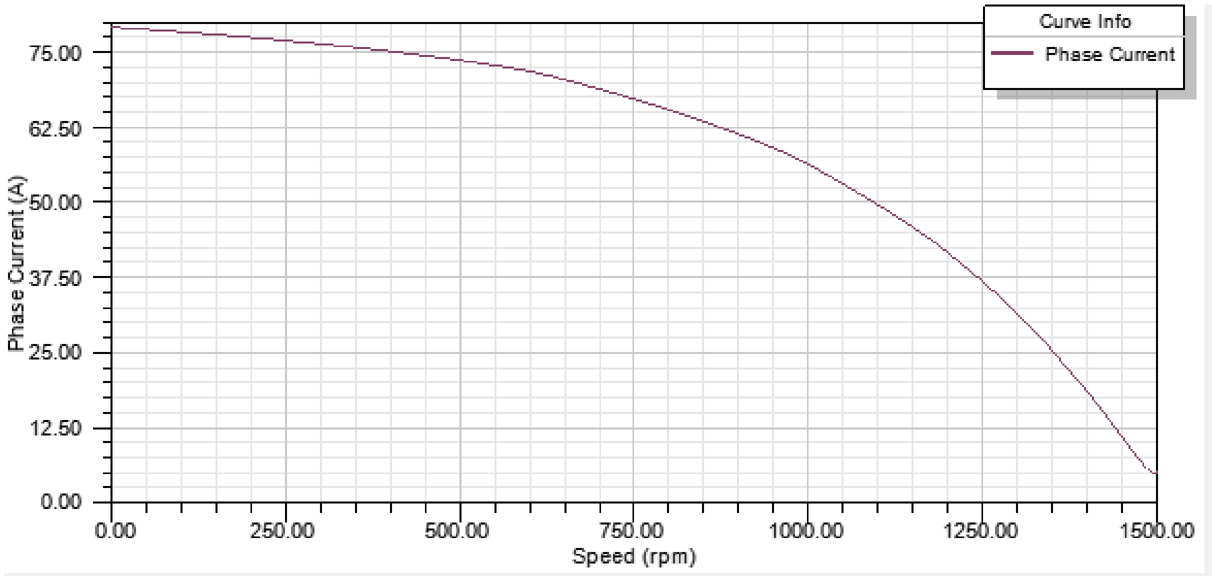


Figure 4. 8 Phase current vs speed curve

Figure 4.9 below shows efficiency vs speed of a motor from starting to stopping on an operation. As shown on the figure efficiency and speed of the motor has directly proportional. To improve the speed of a rotor during design as much as possible maximizes the efficiency doing this also save the life of motor by decreasing losses.

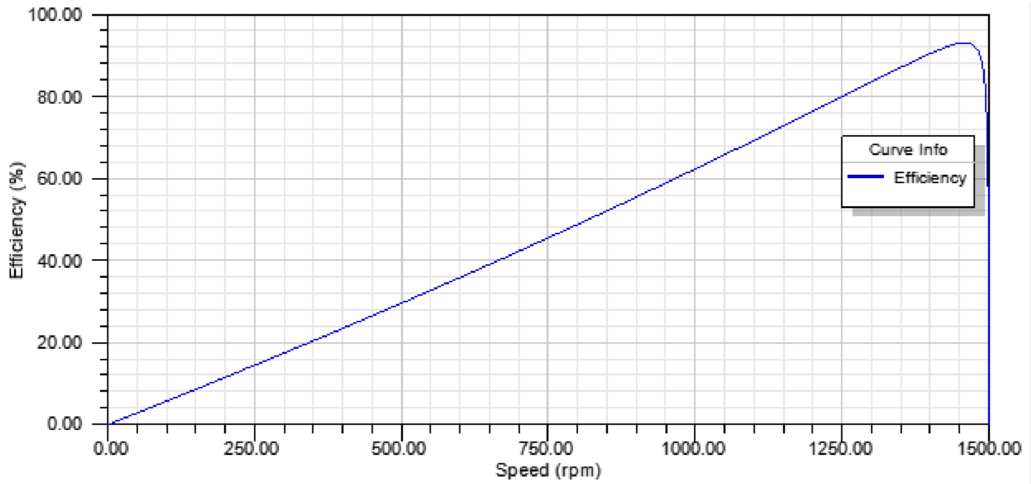


Figure 4. 9 Efficiency vs Speed curve

Figure 4.10 shows a curve of output power vs speed of a motor. The output power and speed is directly proportional until 25kw and 1175 rpm. Beyond this point the two parameters have inversely proportional and finally the rotor is stop to rotate at synchronous speed and there is no any output power or mechanical power at this point.

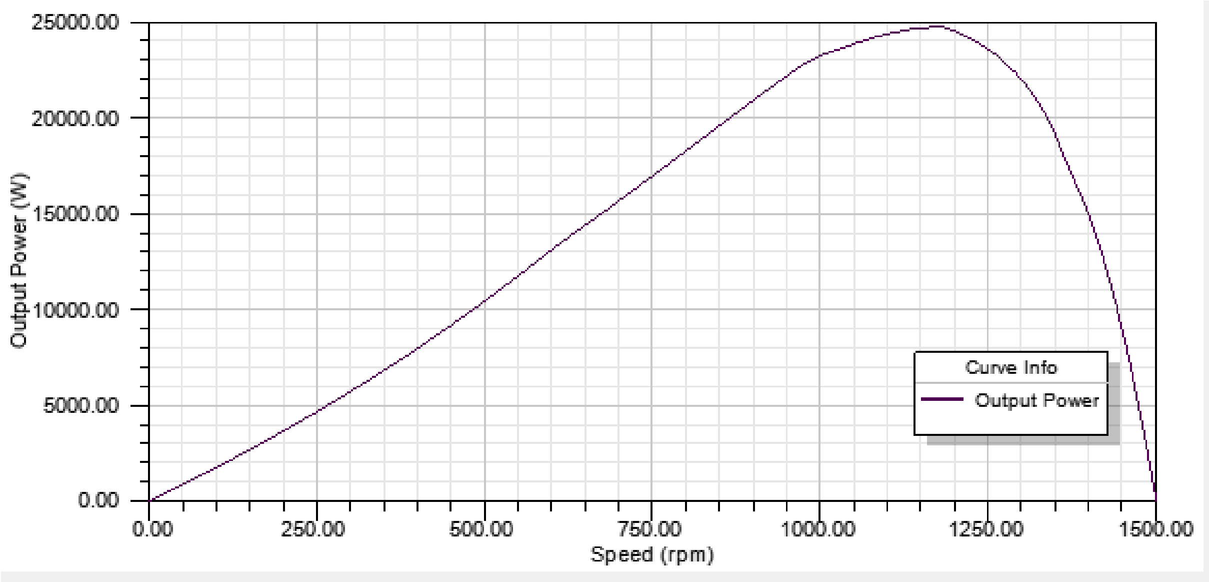


Figure 4. 10 Output power vs Speed curve

As shown on figure 4.11 below torque and speed of motor has directly until the torque is reach its maximum point which is 223.287 Nm and beyond this point the torque is start to fall and stop at synchronous speed. . The locked rotor torque is around 161.3 N-m, twice as that of rated Load torque. While breakdown torque is around 4 times that of rated value.

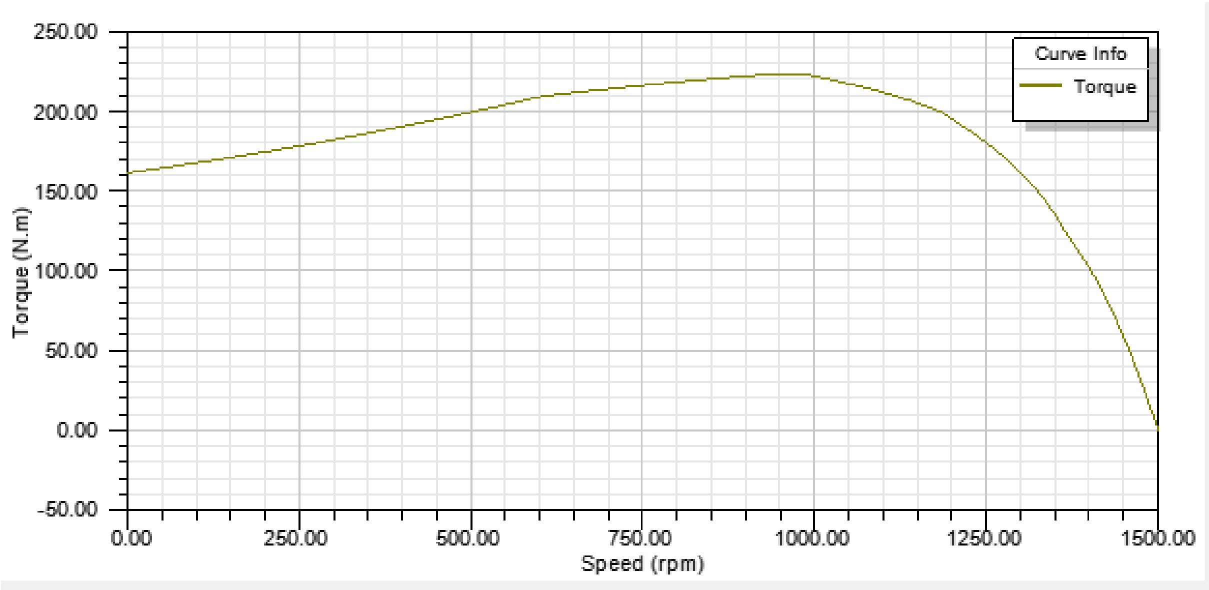


Figure 4. 11 Torque vs Speed curve

Figure 4.12 indicates a curve that shows a phase current vs output power. The two parameters have directly proportional as shown on the curve.

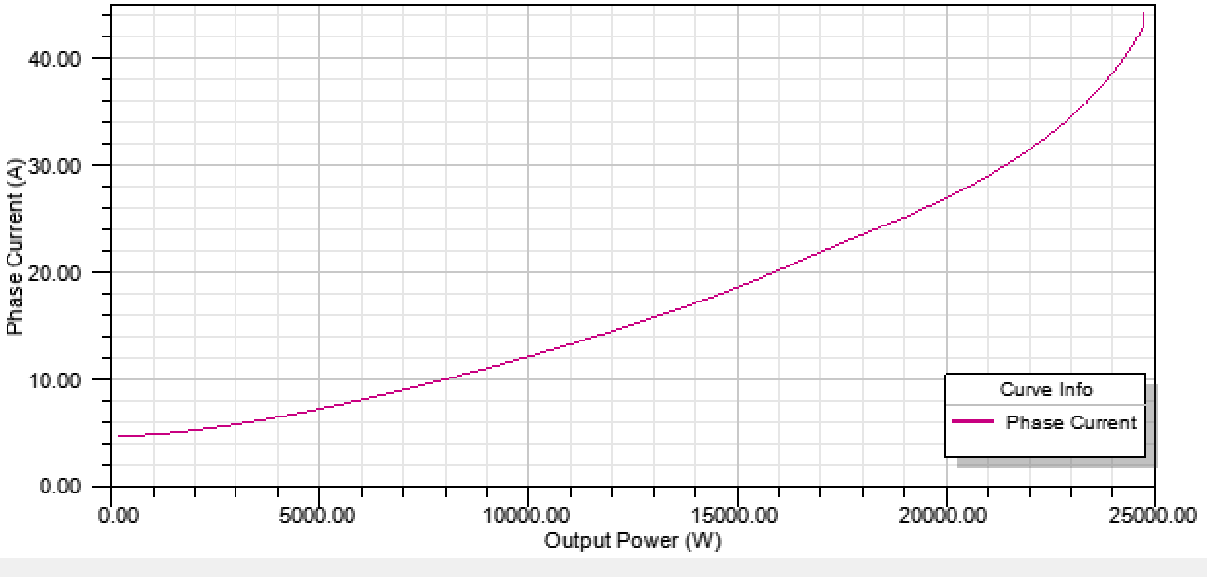


Figure 4. 12 Phase current vs Output power curve

Figure 4.13 shows a curve of efficiency vs output power. The efficiency is almost constant with a little variation from 5kw to 15kw

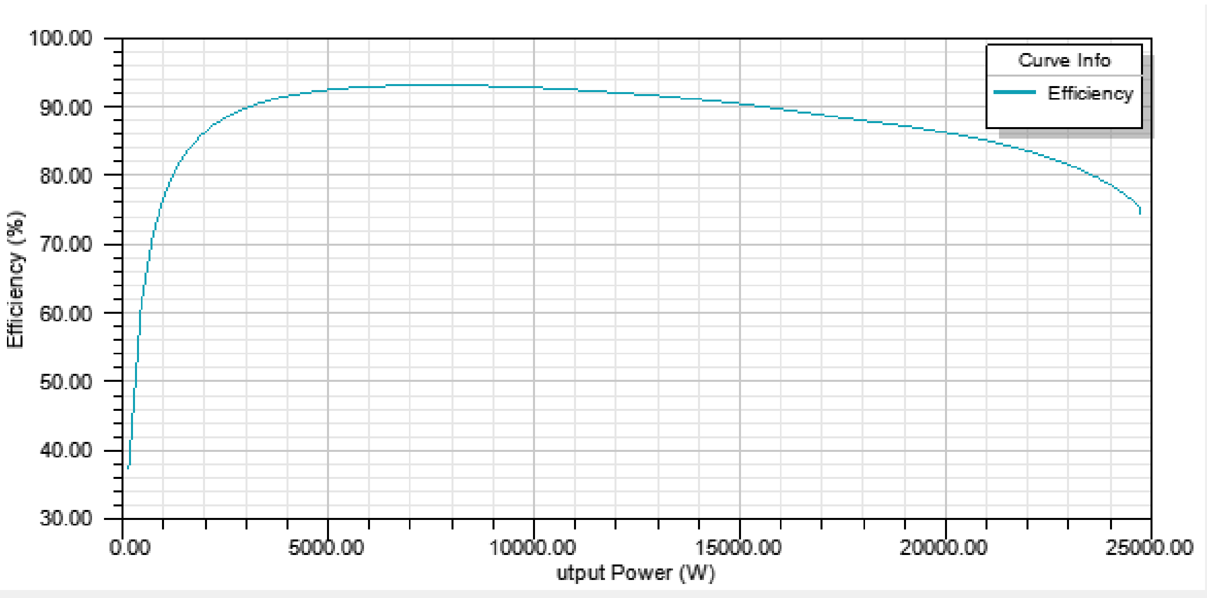


Figure 4. 13 Efficiency vs Output power curve

Figure 4.14 shows a curve of power factor vs output power. From the curve we conclude that the power factor is almost constant and maximum from 10kw to 14kw. Therefore this design is operate with good power factor when the load is varied from 10kw to 14kw.

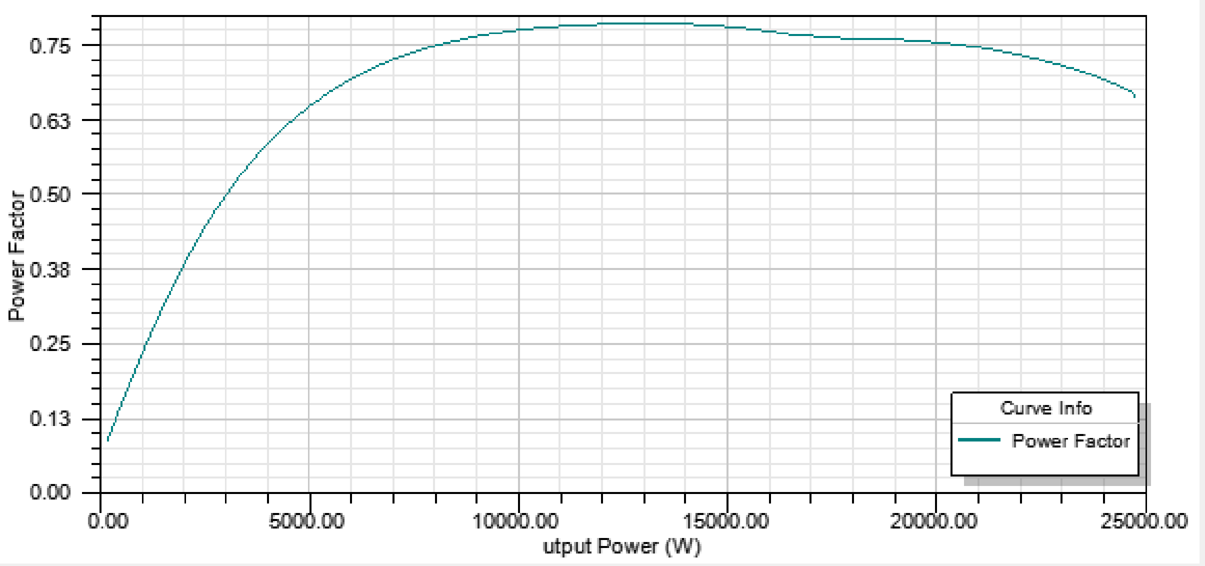


Figure 4. 14 power factor vs output power curve

As shown on figure 4.15 as slip increase the output power is also increase but the speed is decrease because slip is the speed difference between synchronous or field speed and motor shaft speed. Therefore at rated speed the slip is 0.04 for an output power of 11kw.

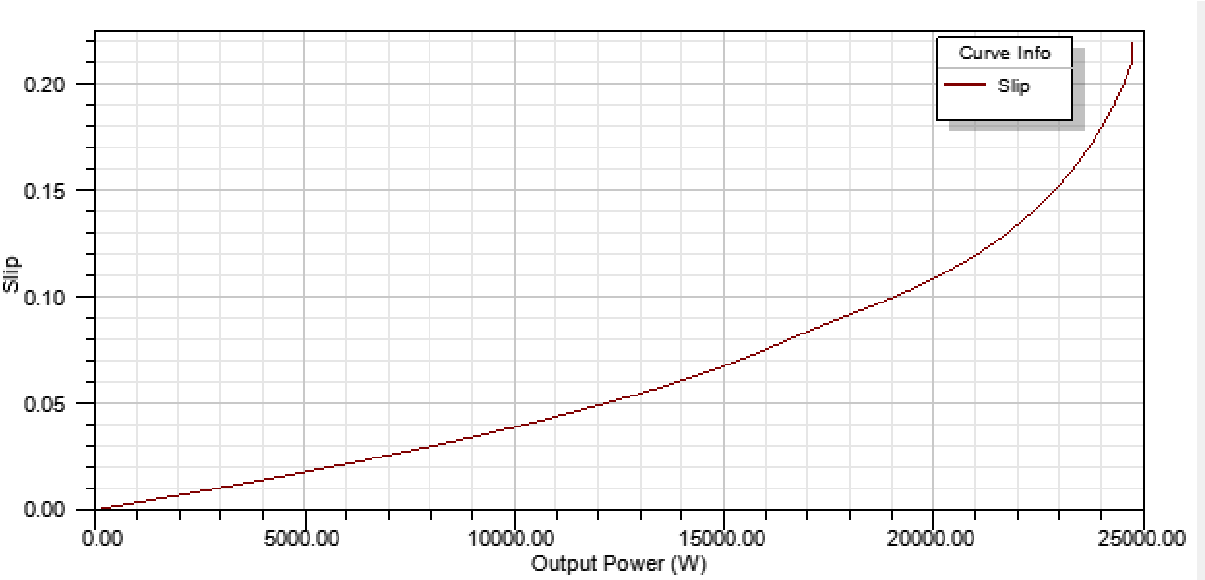


Figure 4. 15 Slip vs Output power curve

As shown on figure 4.16 the torque and output power are directly proportional. This is why output power is the product of rotor speed and shaft torque. But this proportionality is continuous until breakdown (maximum) torque, after this point the torque is start to fall because if the torque is increase rapidly the magnetic field induced in the motor which Couse for saturation.

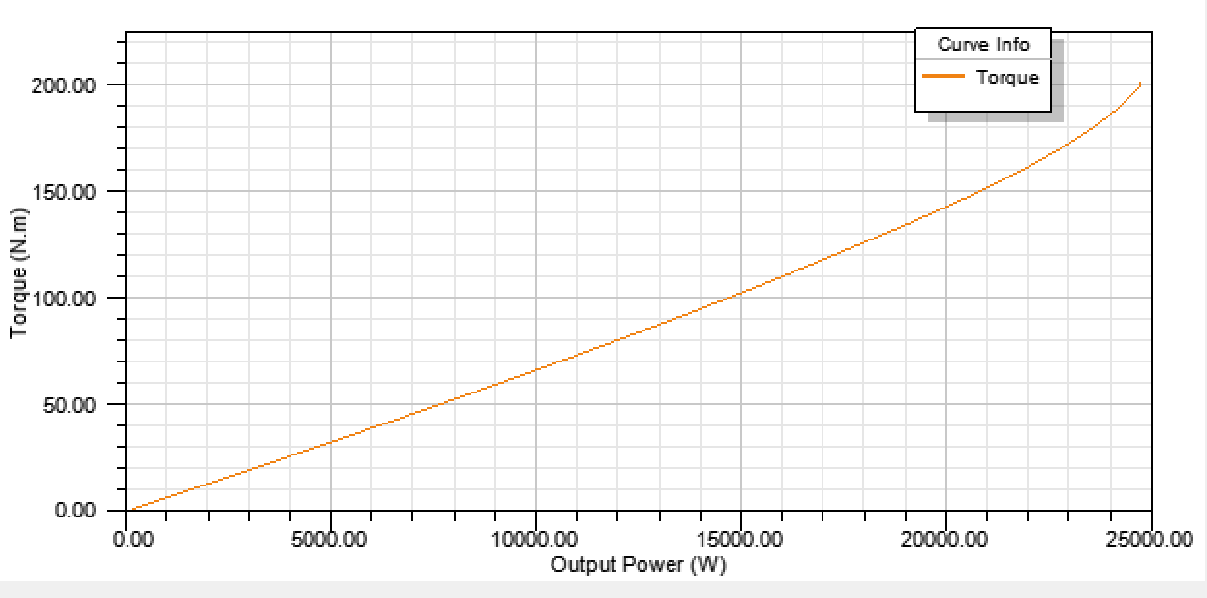


Figure 4. 16 Torque vs Output power Curve

Figure 4.17 shows a curve that indicates torque vs slip of the motor. As the slip increase the rotor speed is decrease. A value of slip one means a rotational speed of rotor is zero which means the motor is at starting point and the value of torque is 161.281Nm as shown on the curve.

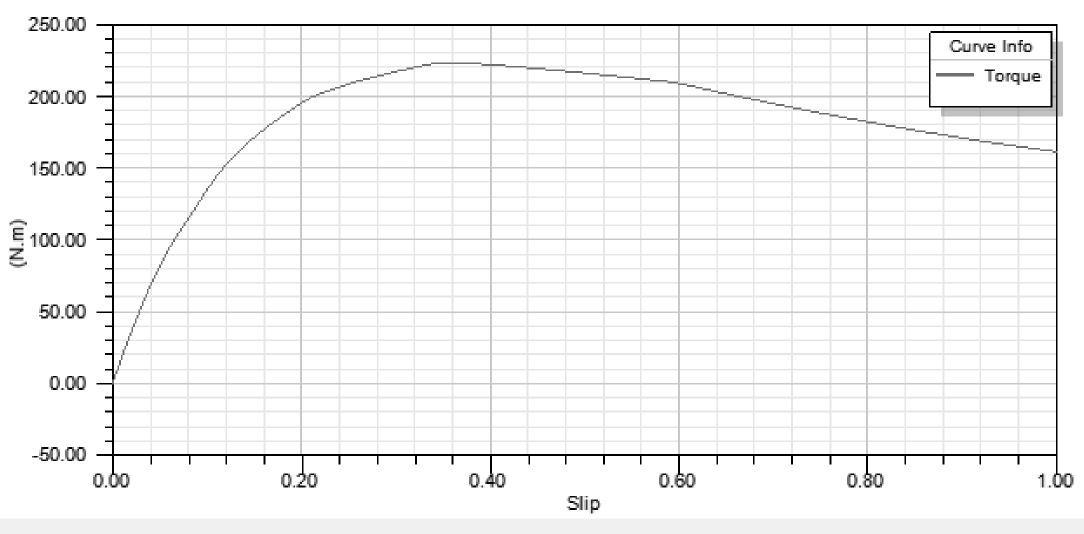


Figure 4. 17 Torque vs Slip Curve

4.3 Design sheet

The result below shows the design data for 11kw. This design sheet indicates the data required for design and materials conception at the end of design. It is subdivided as general data, stator data and rotor data. The material conception shows all the material consumes at the end of design.

4.3.1 General data

General data is the data input to the software. This data is shown in Table 4.7 below.

Table 4. 7 General data required for design

Given Output Power (kW):	11
Rated Voltage (V):	380
Winding Connection:	Delta
Number of Poles:	4
Given Speed (rpm):	1450
Frequency (Hz):	50
Stray Loss (W):	11
Frictional Loss (W):	55
Windage Loss (W):	55
Operation Mode:	Motor
Type of Load:	Constant Power
Operating Temperature (C):	75

4.3.2 Stator data

Stator data is the input data to the software for the stator-model. It is given in Table 4.8 below.

Table 4. 8 Stator data required for design

Number of Stator Slots:	36
Outer Diameter of Stator (mm):	260
Inner Diameter of Stator (mm):	170
Type of Stator Slot:	2
Stator Slot	
hs0 (mm):	1.5
hs1 (mm):	1.5
hs2 (mm):	17
bs0 (mm):	1
bs1 (mm):	10
bs2 (mm):	11
Top Tooth Width (mm):	5.37721
Bottom Tooth Width (mm):	7.34431
Length of Stator Core (mm):	200
Stacking Factor of Stator Core:	0.95
Type of Steel:	M19_29G
Number of lamination sectors	3
Press board thickness (mm):	0
Magnetic press board	No
Number of Parallel Branches:	1

4.3.3 Rotor data

The rotor data to the software is given in Table 4.9 below.

Table 4. 9 Rotor data required for design

Number of Rotor Slots:	28
Air Gap (mm):	0.4
Inner Diameter of Rotor (mm):	60
Type of Rotor Slot:	2
Rotor Slot	
hs0 (mm):	1
hs01 (mm):	1
hs1 (mm):	2
hs2 (mm):	18
bs0 (mm):	1
bs1 (mm):	9
bs2 (mm):	11
Cast Rotor:	Yes
Length of Rotor (mm):	240
Stacking Factor of Rotor Core:	0.95
Type of Steel:	M19_24G
Skew Width:	2.28571
End Length of Bar (mm):	11
Height of End Ring (mm):	11
Width of End Ring (mm):	9
Resistivity of Rotor Bar at 75 Centigrade (ohm.mm^2/m):	0.0434783
Resistivity of Rotor Ring at 75 Centigrade (ohm.mm^2/m):	0.0434783
Magnetic Shaft:	Yes

4.3.4 Material consumptions

Material concumption, shown in Table 4.10 indicates material parameters for software simulation of designed motor.

Table 4. 10 Material conceptions for the design of the motor

Armature Copper Density (kg/m^3):	8900
Rotor Bar Material Density (kg/m^3):	2700
Rotor Ring Material Density (kg/m^3):	2700
Armature Core Steel Density (kg/m^3):	7650
Rotor Core Steel Density (kg/m^3):	7650
Armature Copper Weight (kg):	39.0982
Rotor Bar Material Weight (kg):	4.68473
Rotor Ring Material Weight (kg):	0.262337
Armature Core Steel Weight (kg):	31.8423
Rotor Core Steel Weight (kg):	22.7356
Total Net Weight (kg):	98.6231
Armature Core Steel Consumption (kg):	100.537
Rotor Core Steel Consumption (kg):	51.7205

4.3.5 Detailed data at rated operation

The detailed data, indicated in Table 4.11, indicates the operational parameters of the motor at full load operation for the model-motor.

Table 4. 11 Detailed data at rated operation

Stator Slot Leakage Reactance (ohm):	1.50772
Stator End-Winding Leakage Reactance (ohm):	0.475103
Stator Differential Leakage Reactance (ohm):	0.908666
Rotor Slot Leakage Reactance (ohm):	2.32268
Rotor End-Winding Leakage Reactance (ohm):	0.62494
Rotor Differential Leakage Reactance (ohm):	1.52614
Skewing Leakage Reactance (ohm):	3.51046
Stator Winding Factor:	0.959795
Stator-Teeth Flux Density (Tesla):	1.43912
Rotor-Teeth Flux Density (Tesla):	1.67474
Stator-Yoke Flux Density (Tesla):	1.38798
Rotor-Yoke Flux Density (Tesla):	0.411712
Air-Gap Flux Density (Tesla):	0.581482
Stator-Teeth Ampere Turns (A.T):	31.499
Rotor-Teeth Ampere Turns (A.T):	164.185
Stator-Yoke Ampere Turns (A.T):	48.333
Rotor-Yoke Ampere Turns (A.T):	0.861868
Air-Gap Ampere Turns (A.T):	191.209
Correction Factor for Magnetic Circuit Length of Stator Yoke:	0.480134
Correction Factor for Magnetic Circuit Length of Rotor Yoke:	0.7
Saturation Factor for Teeth:	2.0234
Saturation Factor for Teeth & Yoke:	2.28069
Induced-Voltage Factor:	0.933143
Stator Current Density (A/mm^2):	1.14138
Specific Electric Loading (A/mm):	23.4083
Stator Thermal Load (A^2/mm^3):	26.7177
Rotor Bar Current Density (A/mm^2):	1.53228
Rotor Ring Current Density (A/mm^2):	8.22553

4.4 Maxwell2D (two dimensional) Simulation

The purpose of Maxwell2D simulation is to understanding the distribution of magnetic field in the modelled motor. To open the window of Maxwell2D first the model was performed by RMxprt software. Then right click on setup of this model; under the setup click on create maxwell2D. Now the maxwell2D window is open with quarter part of the modelled motor shown on the screen. On the top the window click on the validation checker; if it is valid then the input parameters were selected. In this paper the input parameters were field overlays. How it is selected and simulate is explained below.

4.4.1 Field Overlays

Field overlays were the way of analysing the distribution of flux lines and flux density in the modelled motor. To select field overlays as input from maxwell2D window first select the hall part of the quarter part of the model; then right click on field overlays; then under this field click on symbol A and B one by one. Symbol A contains flux vector and flux lines and symbol B contains flux density lines and its magnitude. Now after select these symbols click on the setup and adjust the time that the rotor rotates inside the stator. Finally click on the analysis; after a few second the rotating animation is display on the screen and the field distribution is easily understand. The simulation results were flux and flux density distribution in the motor indicated in the following figures.

Figure 4.17 shows magnetic flux line distribution in stator and rotor for the quarter of the cross sectional view of the modelled induction motor. As shown in Figure 4.17 at the left hand of the figure, the flux is symbolized by A vector which is measured by weber per meter (wb/m). The value of this vector is read by checking a colour of the magnetic flux in the figure and looking the corresponding number given within that colour at the left hand side of the Figure. From the figure it is observed that the lines are not so dense and free from magnetic field saturation problem.

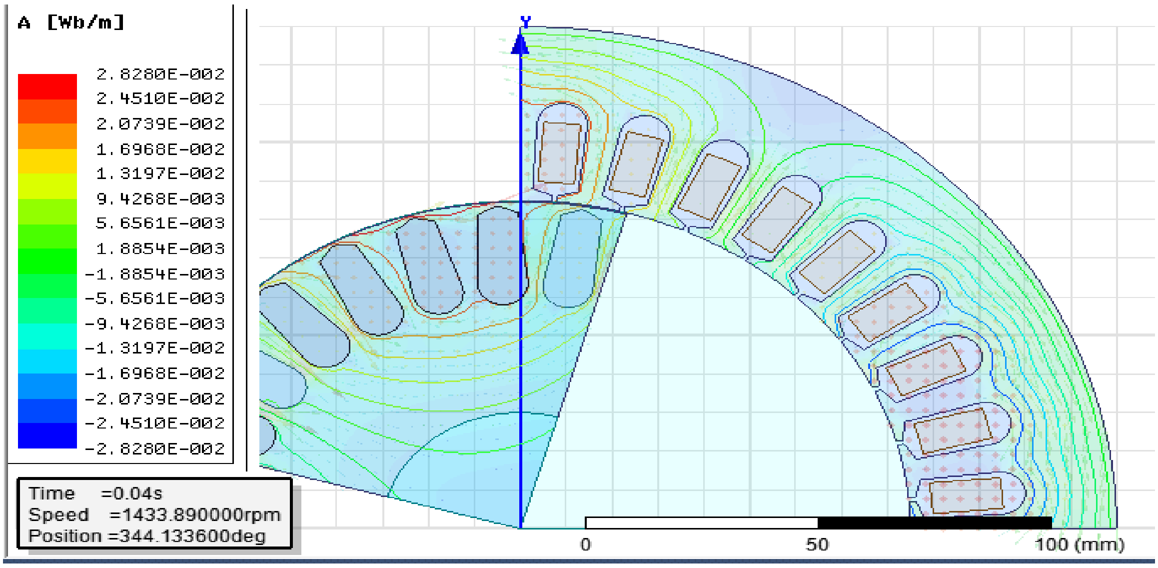


Figure 4. 17 flux line plot

Figure 4.18 indicates the magnitude of flux density in the stator and rotor of the modelled motor at rated speed. It can be observed that the stator yoke flux density is around 1.49T which is in the desired limit

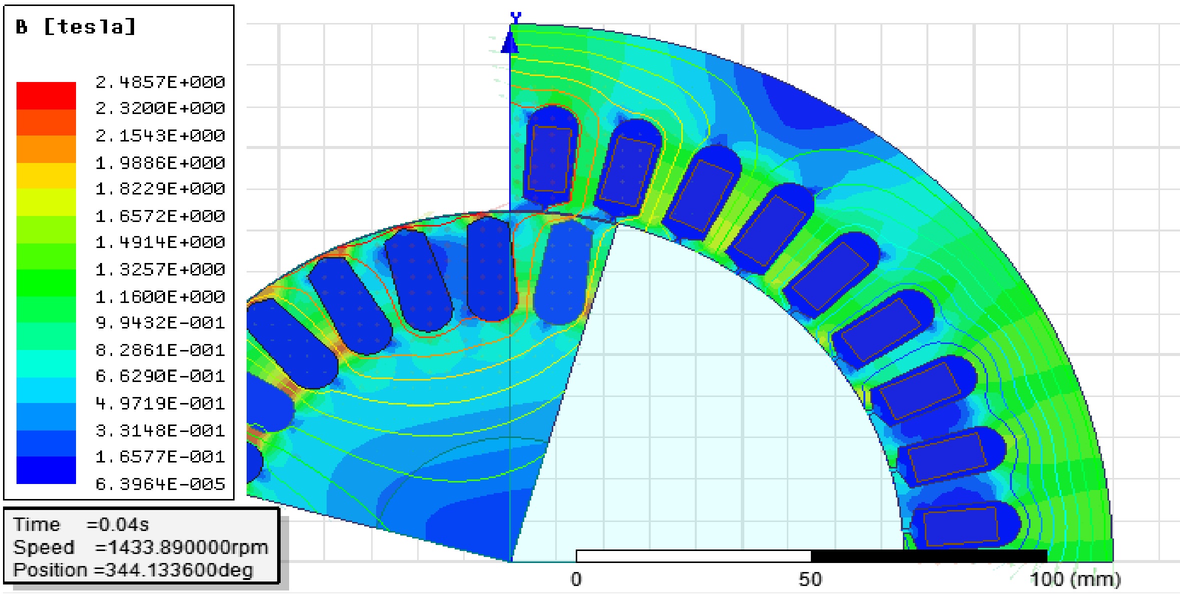
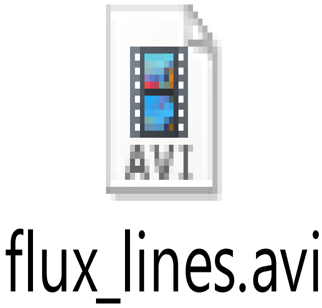


Figure 4. 18 flux density plot

4.5 Video

The video shown in figure 4.21 from A to D is one of the simulation results from maxwell2D. This video shows the animation of the distribution of flux vector and flux density during the rotating of the rotor. The rotating sample time is adjusted by user. To open the video click on each figure then click again on play and see the animation.

A. A video show flux vector



B. A video show flux lines

C. A video show flux density in stator and rotor

D. A video show magnitude of flux density

Figure 4. 19 Video that show flux and flux density distribution

In this chapter, the simulation result from RMxprt and Maxwell was performed. Those results were display in form of tables, curves and videos. In chapter three manual design was performed. Now comparison of the result from simulation and manual was indicated in table 4.12 below.

Table 4.12: Comparison of manual and simulation results

No.	Parameters	Unit	Manual Calculation	Simulation result
1	Stator core diameter	mm	170	170
2	Stator outer diameter	mm	264	260
3	Stator core length	mm	200	200
4	Number of stator slot	_	36	36
5	Number of turns per phase	_	134	134
6	Air gap length	mm	0.56	0.4
7	Rotor outer diameter	mm	169	169.2
8	Rotor inner diameter	mm	60	60
9	Number of rotor slot	_	28	28
10	Rotor length	mm	240	240
11	Stator phase current	A	12.91	13.36
12	Magnetizing current	A	7.37	4.6
13	Iron core loss current	A	0.297	0.14
14	Stator current density	A/mm^2	1.5	1.14
15	Rotor bar current density	A/mm^2	2	1.53
16	Rotor ring current density	A/mm^2	8	8.2
17	Specific electric loading	A/m	25000	23408
18	Specific magnetic loading	A/m	0.55	0.58
19	Stator teeth flux density	T	1.4	1.43
20	Stator core flux density	T	1.35	1.38
21	Rotor teeth flux density	T	1.65	1.67
22	Rotor core flux density	T	1.1	0.41
23	Air gap flux density	T	0.748	0.58
24	Stator teeth ampere turn	A.T	26.26	31.499
25	Stator core ampere turn	A.T	51.24	48.33

26	Rotor teeth ampere turn	A.T	175	164.185
27	Rotor core ampere turn	A.T	7.5	0.86
28	Air gap ampere turn	A.T	191.17	191.209
29	Iron core loss	w	119	149.76
30	Friction and windage loss	w	165	107.576
31	Stray loss	w	11	11
32	Stator ohmic loss	w	160	124.2
33	Rotor ohmic loss	w	225.58	512.2
34	Total loss	w	725	904.706
35	Rated speed	rpm	1470	1433.83
36	Rated torque	Nm	79.44	73.26
37	Rated slip	_	0.02	0.044
38	Output power	kw	11	11
39	Input power	kw	11.725	11.9056
40	Rated efficiency	%	93.8	92.4
41	Rated power factor	_	0.79	0.78

Where

V is Voltage — A/mm^2 is Ampere per square millimetre

Hz is Hearth — A/m is Ampere per meter

Mm is millimetre — W is watt

A is Ampere — kW is kilowatt

T is Tesla — Nm is Newton meter

A.T is Ampere Turn — rpm is Revolution per minute

As it is observed from the table 4.12 there is a very small deviation between the manual design and simulation result. The cause of this deviation is at the time of manual calculation the numbers were taken once and it is constant. But during calculation in software the numbers for example the value of permeability is varied which cause the deviation between the manual and software result. Because of this cause a small deviation between the two result was occurred

A comparison of the simulation result of this thesis with the standard existing motor of the same rating, that is define by the International Electrician Commission (IEC) is described in the table 4.13 below. The table indicates that the simulation result improved the starting (blocked rotor) torque, starting current, rating torque, break down torque and rating efficiency but decrease the rating power factor when compared with the existing one. In analysing of the induction motor performance the efficiency and power factor improved parameters are inversely proportional. That means the parameters applied to improve efficiency of the motor during design has a negative effect on the power factor of the motor. Therefore in this paper the efficiency was improved because the efficiency of the motor has direct effect on the life of the motor. But the power factor is improved with different power factor correction techniques during motor installation.

Table 4. 13: Simulation result comparison with existing motor of 11kw, 4pole 380V, 50Hz

No	Parameters	Simulation Result	Existing Motor
1	Starting (Blocked Rotor) Torque	161.281 Nm	157.52 Nm
2	Starting (Blocked Rotor) Current	79A	160A
3	Rating Torque	73.26 Nm	71.6 Nm
4	Break Down Torque	223.287 Nm	214.8 Nm
5	Rating Efficiency	92.4%	89.8%
6	Rating Power Factor	78%	86.5%

The total material required in this modelled motor with its total cost is shown in table 4.14

Table 4.14 Material required with its cost for the modeled motor

No	Material Required	Quantity	Unit	Unit price in USD	Total price in USD	Total price in Birr 1USD= 27.5Birr
1	Stator copper conductor	30.0982	kg	6.67	260.785	7171.58
2	Aluminum in rotor boar	4.68473	kg	2.17	10.166	279.56
3	Aluminum in rotor ring	0.262337	kg	2.17	0.569	15.65
4	Stator core steel	100.537	kg	0.83	83.446	2294.77
5	Rotor core steel	51.7205	kg	0.83	42.928	1180.52
6	**Grand total**	**196.31**	**kg**		**397.894**	**10942.085**

According to the International Electrician Commission (IEC) the current price of three phase induction motor is $1000 for the rating of 5kW up to 20kW. Again from SIEMENS factory for 0.55kW up to 200kW rating of three phase induction motor their current price is $960 to 11183. When compare this cost with the modeled motor with total cost of $397 the modeled motor has lower cost. Therefore implementing of this motor in Ethiopia has an advantage in decreasing the initial hard currency that the country pays to buy these motors.

CHAPTER FIVE

5. CONCLUSION

Design of induction motor has many parameters associated to every other. Therefore, the optimization problem of design has many local minimum or maximum values as a substitute than global minimum or maximum values. In this thesis, design of three phase squirrel cage induction motor used to be first made manually. Then by way of the assist of RMxprt software, the design and simulation of the motor used to be performed. By using this software, the overall performance parameters have been determined. The best optimized and efficient design was once get via optimizing the shape and dimension of stator and rotor slots. The tapered shape of stator and rotor was selected in this design. Maxwell two dimensional (Maxwell 2D) used to be utilized to analysed the magnetic flux and flux density in the motor. The manual design and simulation end result are compared. The difference between the two outcomes is not immoderate and confirms the modelling correctness of the study. Finally, the model is compared with the parameters of existing motor in terms of locked rotor torque, starting current and rating efficiency is improved.

5.1 RECOMMENDATION

The applications of induction motor in Ethiopia have been start from small home equipment up to higher industry in very wide range. Almost all the motor operate in this country is an induction motor. But this very useful and interest motor is export from foreign country by high hard currency. Therefore to implement this motor in this country to decrease foreign hard currency and increase the industries benefit from their product a standard optimized design of the motor is required. In this thesis a manual design followed by RMxprt software simulation was performed. To get the optimized design this paper focuses on the shape and dimensions of stator and rotor slot which have a direct effect on the performance of induction motor. In future works a prototype or sample of hardware design of this is implementing. As recommend for this country's researcher specially the one who profession on the design of electric machine can work together to implement this very important motor for the country. Again recommend for the industry in Ethiopia highly focus on the area of implementing this very important motor to save the country from foreign hard currency.

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