

**DESIGN OF 5KW, THREE (3) PHASE
SQUIRREL CAGE INDUCTION MOTOR**

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AWARD OF BARCHELOR OF ENGINEERING (B.ENG)**

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DEDICATION

To God almighty and
To my lovely parent Chief Elder And Mrs. Abel Jimoh Olupiti.

DECLARATION

I Abel Sunday Tope hereby declare that this work was done by me and as a project, has never been presented elsewhere for the award of a degree to the best of my knowledge.

I also hereby relinquish the copyright to the Department of Electrical and Electronic Engineering, Federal University of Technology, Minna.

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ABSTRACT

This paper presents the project work whose aim was the design of 5kw squirrel cage industrial three-phase induction motors, making use die cast copper rotor cage and premium electrical steel. The project is concern with industrial low voltage three-phase induction motors, 4 pole, 50 Hz, 400 V, in the 5kW power range. This design can be used or improved on, to manufacture squirrel cage industrial 5kw induction motor. This project is also a practical attempt to employ the power of computers to design workable induction motors. By the use of computer, a lot of time can be saved without compromising accuracy. According to the motor specifications intended, design parameters can be altered and results of such alterations would be ready which can be used for comparison without having to manually recomputed over and over again. The project is devoted to selection of main dimensions, the electromagnetic processes that take place in the induction motor and the active resistance and reactance. On the whole, the project is concerned with the analysis, synthesis, computer aided design and practicability of the squirrel cage induction motor.

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LIST OF ABBREVIATION

SWG = STANDARD WIRE GAUGE

S = SLIP

N_s = SYNCHRONOUS SPEED

K = CONSTANT

α = PROPORTIONAL

Φ = ANGLE

www = WORLD WIDE WEB

SCIM = SQUIRREL CAGE INDUCTION MOTOR

R.P.S = REVOLUTION PER SECOND

R.P.M = REVOLUTION PER MINUTE

EMF = ELECTROMOTIVE FORCE

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CHAPTER ONE

1.0 INTRODUCTION

An AC motor is an electric motor that is driven by an alternating current. It consists of two basic parts, an outside stationary stator having coils supplied with alternating current to produce a rotating magnetic field, and an inside rotor attached to the output shaft that is given a torque by the rotating field. There are two types of AC motors, depending on the type of rotor used.[1] The first is the synchronous motor, which rotates exactly at the supply frequency or a sub-multiple of the supply frequency. The magnetic field on the rotor is either generated by current delivered through slip rings or by a permanent magnet. The second type is the induction motor, which runs slightly slower than the supply frequency. The magnetic field on the rotor of this motor is created by an induced current [4,5].

AC induction motors are the most common motors used in industrial motion control systems, as well as in main powered home appliances. Simple and rugged design, low-cost, low maintenance and direct connection to an AC power source are the main advantages of AC induction motors. Various types of AC induction motors are available in the market. Different motors are suitable for different applications[17].

1.1 AIMS OF THIS PROJECT:-

- To design a squirrel cage induction motor to a given specification (5kw, 3 phase).
- To research and come up with an improved designed
- To provide a comprehensive material on how to design, so as to serve as a reference material to other students and even manufacturer for purpose of studies and improvement on construction.

- To study the performance and behavior of squirrel cage induction motor at various stages of operation. (i.e at standstill, running and loading).
- To provide relevant calculation and relationship between the machine parameters (or variable) to make Application software programmer on writing design software.
- To provide choice guard on motor specification to consumers when motor for constructive application.

1.2 HISTORY

In 1882, Serbian inventor Nikola Tesla identified the rotating magnetic induction field principle used in alternators and pioneered the use of this rotating and inducing electromagnetic field force to generate torque in rotating machines. He exploited this principle in the design of a poly-phase induction motor in 1883. In 1885, Galileo Ferraris independently researched the concept. In 1888, Ferraris published his research in a paper to the Royal Academy of Sciences in Turin.

Introduction of Tesla's motor from 1888 onwards initiated what is sometimes referred to as the Second Industrial Revolution, making possible both the efficient generation and long distance distribution of electrical energy using the alternating current transmission system, also of Tesla's invention (1888). Before widespread use of Tesla's principle of poly-phase induction for rotating machines, all motors operated by continually passing a conductor through a stationary magnetic field (as in homopolar motor).

Initially Tesla suggested that the commutators from a machine could be removed and the device could operate on a rotary field of electromagnetic force. Professor Poeschel, his teacher, stated that would be akin to building a perpetual motion machine. This was because Tesla's teacher had only understood one half of Tesla's ideas. Professor Poeschel had realized that the induced rotating

magnetic field would start the rotor of the motor spinning, but he did not see that the counter electromotive force generated would gradually bring the machine to a stop. Tesla would later obtain U.S. Patent 0,416,194, Electric Motor (December 1889), which resembles the motor seen in many of Tesla's photos. This classic alternating current electro-magnetic motor was an induction motor.

Michail Osipovich Dolivo-Dobrovolsky later invented a three-phase "cage-rotor" in 1890. This type of motor is now used for the vast majority of commercial applications[16,17].

Electric motor family tree

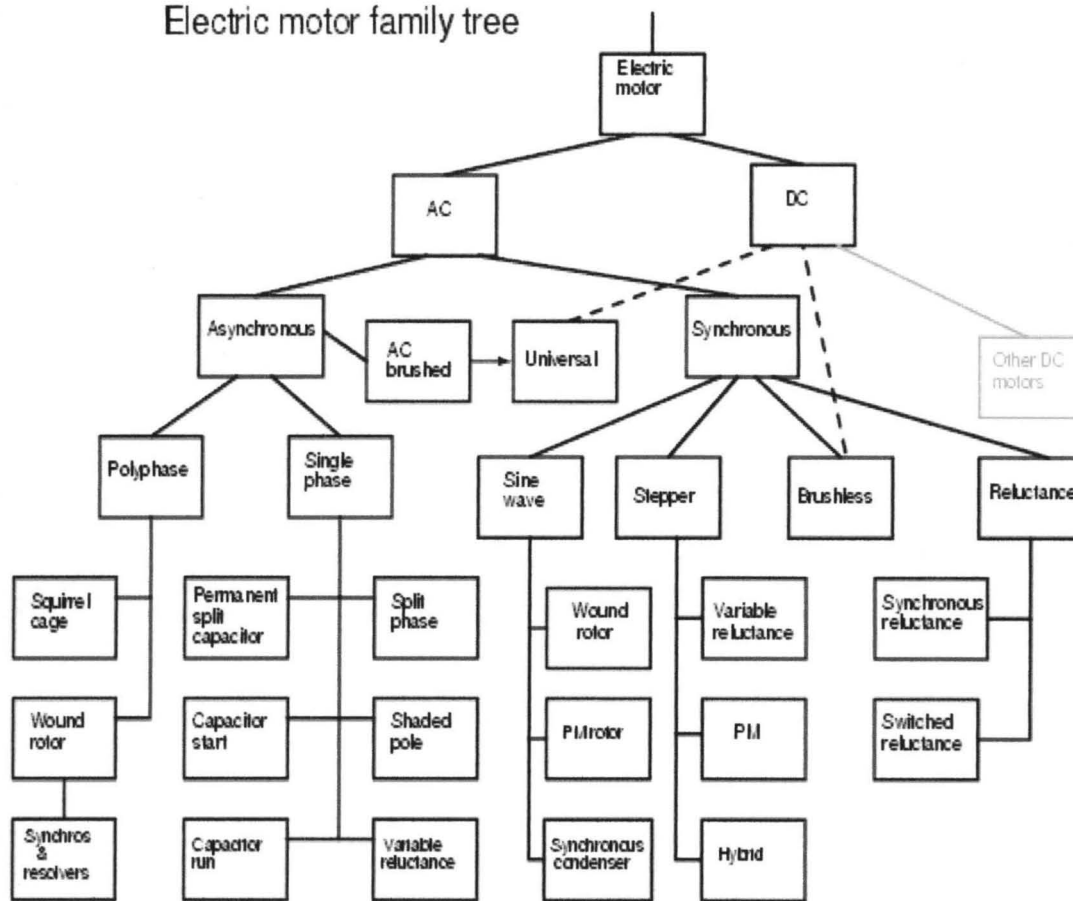


Figure 1.0 electric motor family tree

1.3 CLASSIFICATION OF AC MOTOR

AC motor is broadly classified into two main classes which are as follows:

- Asynchronous motor

The asynchronous motor is further divided into induction motor under which the main ac motor (i.e squirrel cage induction motor) to be design in this project is classified.

1.4 TYPES OF AC INDUCTION MOTORS

Generally, induction motors are categorized based on the number of stator windings. They are:

- Single-phase induction motor
- Three-phase induction motor

1.4.1 Single-Phase Induction Motor

There are probably more single-phase AC induction motors in use today than the total of all the other types put together. It is logical that the least expensive, lowest maintenance type motor should be used most often. The single-phase AC induction motor best fits this description. As the name suggests, this type of motor has only one stator winding (main winding) and operates with a single-phase power supply. In all single-phase induction motors, the rotor is the squirrel cage type[8]

1.4.2 Three-phase ac induction motor

Three-phase AC induction motors are widely used in industrial and commercial applications. They are classified either as squirrel cage or wound-rotor motors[17]. These motors are self-starting and use no capacitor, start winding, centrifugal switch or other starting device. They produce medium to high degrees of starting torque. The power capabilities and efficiency in these motors range from medium to high compared to their Single-phase counterparts. Popular applications include grinders, lathes, drill presses, pumps, compressors, conveyors, also printing equipment, farm equipment, electronic cooling and other mechanical duty applications.

1.5 SQUIRREL CAGE MOTOR

Almost 90% of the three-phase AC Induction motors are of this type[17]. Here, the rotor is of the squirrel cage type and it works as explained earlier. The power ratings range from one-third to

several hundred horsepower in the three-phase motors. Motors of this type, rated one horsepower or larger, cost less and can start heavier loads than their single-phase counterparts. The stator is made up of several thin laminations of aluminum or cast iron. They are punched and clamped together to form a hollow cylinder (stator core) with slots[16]. Coils of insulated wires are inserted into the slots. Each grouping of coils, together with the core it surrounds, forms an electromagnet (a pair of poles) on the application of AC supply. The number of poles of an AC induction motor depends on the internal connection of the stator windings. The stator windings are connected directly to the power source. Internally they are connected in such a way, that on applying AC supply, a rotating magnetic field is created[8].

1.6 WOUND-ROTOR MOTOR

The slip-ring motor or wound-rotor motor is a variation of the squirrel cage induction motor. While the stator is the same as that of the squirrel cage motor, it has a set of windings on the rotor which are not short-circuited, but are terminated to a set of slip rings. These are helpful in adding external resistors and contactors. The slip necessary to generate the maximum torque (pull-out torque) is directly proportional to the rotor resistance. In the slip-ring motor, the effective rotor resistance is increased by adding external resistance through the slip rings.

1.7 METHODOLOGY:

- Consulting relevant material on three phase squirrel cage induction motor.
- Regular visiting of motor and alternator winding workshops.
- Visiting the internet to gather information on the project topic.
- Then plot performance graph using digital computer software and then report the design work according to the standard format of report.

1.8 AREA OF APPLICATIONS

Squirrel cage motor is used in many areas to generate mechanical motion from electricity. Few of these areas are listed below. In constructing:-

- Washing machine.
- Dishwasher
- Standalone fan
- Record player
- Railway traction
- Grinding machine
- Wrist watch
- Industrial conveyors
- Timber planner
- Industrial pumps
- Automobiles
- Aircraft
- Space satellite
- Robotics
- Consumer electronics etc.

Chapter two

2.0 LITERATURE REVIEW

Almost 90 percent of induction motors are squirrel-cage type[2], because this type of rotor has the simplest and most rugged construction imaginable and is almost indestructible. The rotor consists of a cylindrical lamination core with parallel slots for carrying the rotor conductors which, it should be clearly noted, are not wires but consist of heavy bars of copper, aluminum or alloys[1,5]. One bar is placed in each slot, rather the bars are inserted from the end when semi-closed slots are used. the rotor bar are brazed or electrically welded or bolted to two heavy and stout short-circuiting end-rings, thus giving us, what is so picturesquely called, a squirrel-case construction[17].

2.1 THEORIES OF MAGNETISM A BASIS TO INDUCTION MOTOR OPERATION

2.1.1 Magnetism

The principles of magnetism play an important role in the operation of an AC motor[13]. Therefore, in order to understand motors, you must understand magnets. To begin with, all magnets have two characteristics. They attract iron and steel objects, and they interact with other magnets. This later fact is illustrated by the way a compass needle aligns itself with the Earth's magnetic field[14].

2.1.2 Magnetic Lines of Flux

The force that attracts an iron or steel object has continuous magnetic field lines, called lines of flux, that run through the magnet, exit the north pole, and return through the south pole. Although these lines of flux are invisible, the effects of magnetic fields can be made visible. For example, when a sheet of paper is placed on a magnet and iron filings are loosely scattered over the paper, the filings arrange themselves along the invisible lines of flux[9].

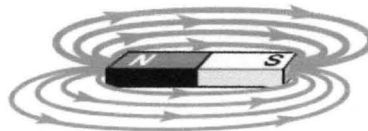


Figure 2.0 illustrating magnetic lines of flux

2.1.3 Unlike Poles Attract

The polarities of magnetic fields affect the interaction between magnets. For example, when the opposite poles of two magnets are brought within range of each other, the lines of flux combine and pull the magnets together[10].

2.1.4 Like Poles Repel

However, when like poles of two magnets are brought within range of each other, their lines of flux push the magnets apart. In summary, unlike poles attract and like poles repel.

The attracting and repelling action of the magnetic fields is essential to the operation of AC motors, but AC motors use electromagnetism

2.1.5 Electromagnetism

When current flows through a conductor, it produces a magnetic field around the conductor. The strength of the magnetic field is proportional to the amount of current.

2.1.6 Left-Hand Rule

The left-hand rule for conductors demonstrates the relationship between the flow of electrons and the direction of the magnetic field created by this current. If a current carrying conductor is grasped with the left hand with the thumb pointing in the direction of electron flow, the fingers point in the direction of the magnetic lines of flux.

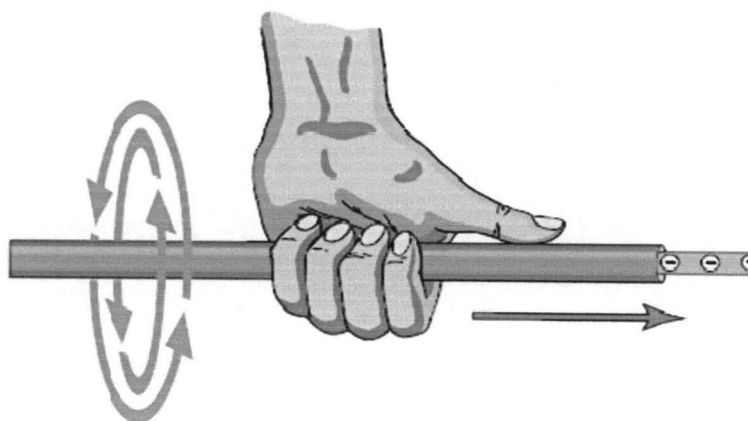


Figure 2.1 showing left-hand rule

2.1.6 Electromagnet

An electromagnet can be made by winding a conductor into a coil and applying a DC voltage. The lines of flux, formed by current flow through the conductor, combine to produce a larger and stronger magnetic field. The center of the coil is known as the core. This simple electromagnet has an air core.

2.1.7 Adding an Iron Core

Iron conducts magnetic flux more easily than air. When an insulated conductor is wound around an iron core, a stronger magnetic field is produced for the same level of current. As shown in figure 2.2

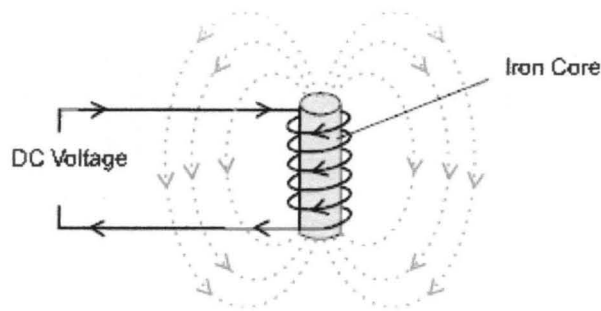


Figure 2.2 showing when an iron core is added

2.1.8 Number of Turns

The strength of the magnetic field created by the electromagnet can be increased further by increasing the number of turns in the coil. The greater the number of turns the stronger the magnetic field for the same level of current.

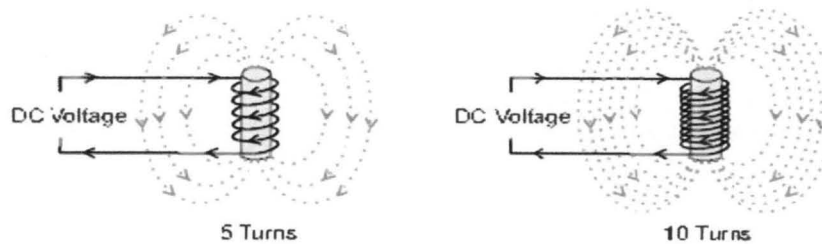


Figure 2.3 showing the effect of number of turns

2.1.9 Induced Voltage Electromagnet

Instead of a permanent magnet rotor, a squirrel cage induction motor induces a current in its rotor, creating an electromagnet. As the following illustration shows, when current is flowing in a stator winding, the electromagnetic field created cuts across the nearest rotor bars[17].

2.2 PRINCIPLE OF OPERATION OF SQUIRREL CAGE INDUCTION MOTOR[5]

When a conductor, such as a rotor bar, passes through a magnetic field, a voltage (emf) is induced in the conductor. The induced voltage causes current flow in the conductor. In a squirrel cage rotor, current flows through the rotor bars and around the end ring and produces a magnetic field around each rotor bar[4,5]. Because the stator windings are connected to an AC source, the current induced in the rotor bars continuously changes and the squirrel cage rotor becomes an electromagnet with alternating north and south poles. The following illustration below shows an instant when winding A1 is a north pole and its field strength is increasing. The expanding field cuts across an adjacent rotor bar, inducing a voltage. The resultant current flow in one rotor bar produces a south pole.

This causes the motor to rotate towards the A1 winding. At any given point in time, the magnetic fields for the stator windings are exerting forces of attraction and repulsion against the various rotor bars. This causes the rotor to rotate, but not exactly at the motor's synchronous speed[16].

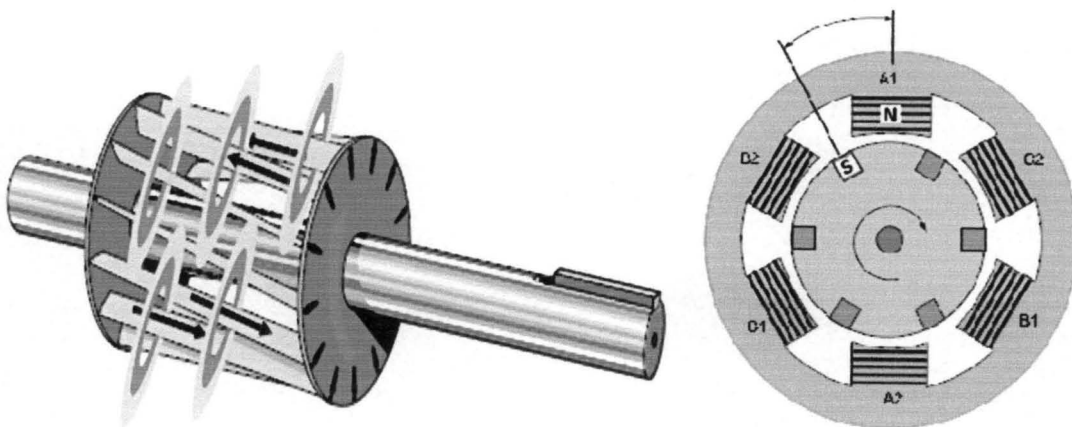


Figure 2.4 illustrating magnetic field behavior around the rotor and stator

2.3 RELATED LAWS OF ELECTROMAGNETISM

2.3.1 Faraday's laws: explain that the frequency of the induced e.m.f is the same as the supply frequency[9].

2.3.2 Fleming's right hand rule: explains that the induce e.m.f magnitude is proportional to the relative velocity between the flux and the conductors and its direction.

2.3.3 Lenz's law: Explains that a current flowing in a conductor as a result of induced emf, moves in a direction opposite to the cause producing it.

2.4 CONSTRUCTIONAL COMPONENT

Three-phase AC squirrel cage induction motors are commonly used in industrial and domestic applications. This type of motor has three main constructional parts namely

- Rotor
- Stator
- The Enclosure

The stator and rotor do the work, and the enclosure protects the stator and rotor[4].

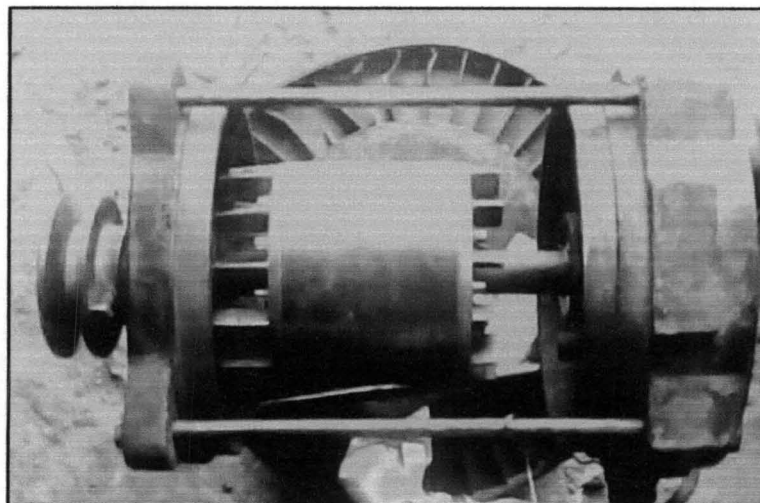
2.5 THE ROTOR

As it has been mentioned in the previous chapter, rotor of induction motor is of two types[4,5], i.e the wound rotor and the squirrel cage rotor. The wound rotor type has been discussed in chapter one, but for the scope of this project work the squirrel cage induction motor shall be discussed and explain.

2.5.1 Squirrel cage rotor

The rotor is made up of several thin steel laminations with evenly spaced bars, which are made up of aluminum or copper, along the periphery. In the most popular type of rotor (squirrel cage rotor), these bars are connected at ends mechanically and electrically by the use of rings[17]. Almost 90%

of induction motors have squirrel cage rotors. This is because the squirrel cage rotor has a simple and rugged construction. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper, aluminum, or alloy bar. These rotor bars are permanently short-circuited at both ends by means of the end rings. This total assembly resembles the look of a squirrel cage, which gives the rotor its name. The rotor slots are not exactly parallel to the shaft. Instead, they are given a skew for two main reasons[16]. The first reason is to make the motor run quietly by reducing magnetic hum and to decrease slot harmonics. The second reason is to help reduce the locking tendency of the rotor. The rotor teeth tend to remain locked under the stator teeth due to direct magnetic attraction between the two. This happens when the number of stator teeth are equal to the number of rotor teeth. The rotor is mounted on the shaft using bearings on each end; one end of the shaft is normally kept longer than the other for driving the load. Some motors may have an accessory shaft on the non-driving end for mounting speed or position sensing devices. Between the stator and the rotor, there exists an air gap, through which due to induction, the energy is transferred from the stator to the rotor. The generated torque forces the rotor and then the load to rotate. Regardless of the type of rotor used, the principle employed for rotation remains the same[8,9].



2.5.2 COMPONENT OF SQUIRREL CAGE ROTOR

- The steel rod metal shaft
- The bearing
- The rings
- The skewed conductor
- Bolt
- Pulley
- Pulley key
- The cooling fan
- The laminated steel sheet.

2.5.2.1 The steel metal shaft:-

This is a strong metal shaft with length some inch longer than the actual length of the motor casing. With a key space made paralleled to the shaft at the frontal part of the entire rod, where the pulley or any other mechanical part will be fixed. The body of the shaft is stepped using the lathe machine to create the bearing position, the ring position and the skewed conductor. Also the other end of shaft is drill cut perpendicularly creating a keying point for cooling fan. And the thickness of the shaft is dependent on the power of motor and its inertia. For example, consider a machine that unwinds a large roll of paper. If the roll is not moving, it takes a force to overcome inertia and start the roll in motion. Once moving, it takes a force in the reverse direction to bring the roll to a stop. And power is

$$\text{Power} = \frac{\text{Force} \times \text{Distance}}{\text{Time}}$$

$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

2.5.2.2 The bearing:-

The bearing is a friction reducing mechanical device that is mounted on the rotor shaft and housed in the motor casing. Bearings, mounted on the shaft, support the rotor and allow it to turn. And the bearings are usually two in number, one in front and the other at the back of the shaft. The positioning of the bearing also determines whether the rotor will be at the middle of the stator or not. So the proper positioning of the bearing is necessary so that the rotor will not be brushing the stator.

Friction occurs when objects contact one another. As we all know, when we try to move one object across the surface of another object, friction increases the force we must apply.

Friction is one of the most significant causes of energy loss in a machine.

2.5.2.3 The ring:-

They are two in number, on which the conductor bars are connected through mechanical and electrical means, after which is attached on the shaft. This constructional setting of the rings and the conductor bars in the slot on the thin laminated sheet.

2.5.2.4 The steel laminations:-

The steel lamination are thin sheet laminated steel containing a number of slot which are evenly spaced depending on the number of conductor bars to be slotted on the rotor. These steel laminations are stacked together to form a cylinder like shape. The rotor slots are not exactly parallel to the shaft. Instead, they are given a skew for two main reasons. The first reason is to make the motor run quietly by reducing magnetic hum and to decrease slot harmonics. The second reason is to help reduce the locking tendency of the rotor. The rotor teeth tend to remain locked under the stator teeth due to direct magnetic attraction between the two. This happens when the number of stator teeth are equal to the number of rotor teeth. The laminations are separated by laminating with vanish.

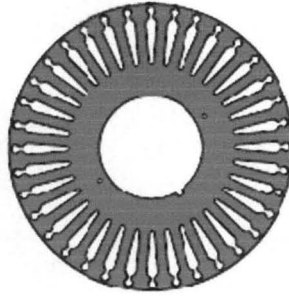


Figure 2.6 showing steel lamination

2.5.2.5 Conductor bars:-

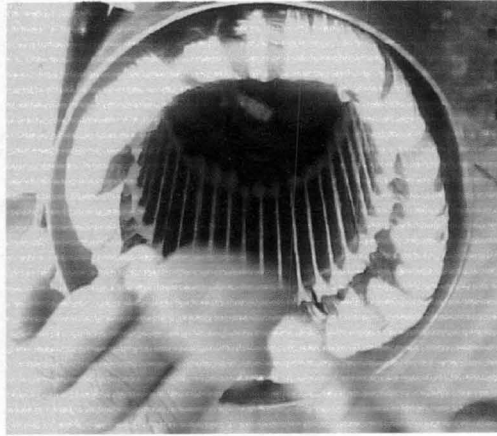
Rather than using coils of wire as conductors, conductor bars are die casted into the slots evenly spaced around the cylinder. Most squirrel cage rotors are made by die casting aluminum to form the conductor bars. The vast majority of the rotor currents will flow through the bars rather than the higher-resistance and usually varnished laminates. Very low voltages at very high currents are typical in the bars and end rings; high efficiency motors will often use cast copper in order to reduce the resistance in the rotor. In order to prevent the currents induced in the squirrel cage from superimposing itself back onto the supply, the squirrel cage is generally constructed with a prime number of bars, or at least a small multiple of a prime number (rarely more than 2). There is an optimum number of bars in any design, and increasing the number of bars beyond that point merely serves to increase the losses of the motor particularly when starting.

2.5.2.6 Cooling fan:-

The cooling fan is constructed together with the rotor, also mounted on the rotor shaft, to cool the motor when the shaft is rotating.

2.5.2.7 The pulley key:-

At the frontal end of the rotor shaft, a key slot position is made on the shaft, which is use to fix- hold the mechanical head (usually a pulley) to output end.



Picture 2.8 of stator taken by me(ABEL S. TOPE)

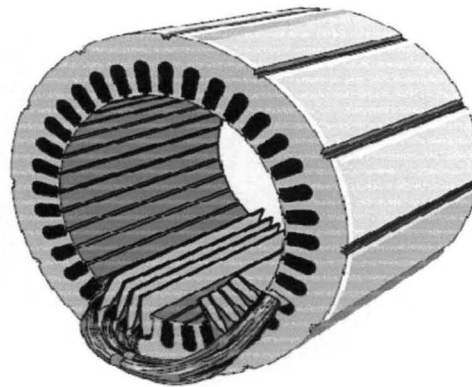


FIGURE2.9 SHOWING A MOTOR'S STATOR

2.6.1 COMPONENT OF A STATOR (i.e OF SQUIRREL CAGE MOTOR)

The stator is made up of a number component that are coupled together to form the stator and after which is then housed in the enclosure for protection. The various components making up the stator are discussed below under the following[1,2]:-

- STATOR CORE
- STATOR WINDINGS

2.6.2 STATOR CORE

The stator is the stationary part of the motor's electromagnetic circuit. The stator core is made up of many thin metal sheets, called laminations.

2.6.2.1 The laminations:-

Laminations are used to reduce energy losses that would result if a solid core were used. The thin laminations are usually made of aluminum or cast iron. They are punched and clamped together to form a hollow cylinder (stator core) with slots as shown in figure below. Coils of insulated wires are inserted into these slots. Each grouping of coils, together with the core it surrounds, forms an electromagnet (a pair of poles) on the application of AC supply.

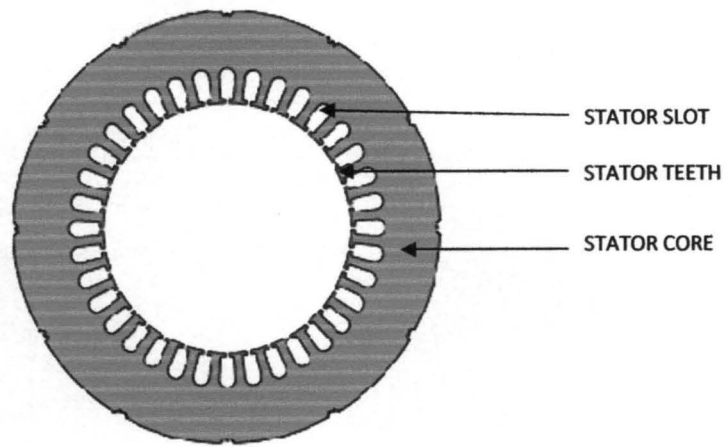
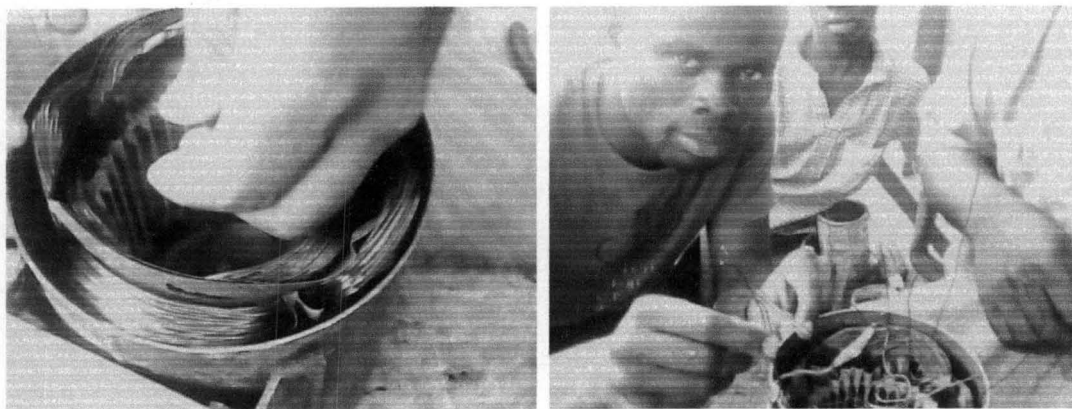


Figure showing stator lamination

2.6.3 THE STATOR WINDING

The winding is done in a logical pattern depending on the type of the winding which shall be discussed shortly. But before then, these winding are wound with insulated copper wire of certain guage or diameter. In the stator there are two coils made on it through the lamination slot, one is the **starting coil** made with a thinner copper wire that generate the starting electromagnetic field and stop generating has started rotating. The second coil is wound at the outer compared to the starting coil and is known as the **running coil**.

2.6.3.1 The number of poles of an AC induction motor depends on the internal connection of the stator windings. The stator windings are connected directly to the power source. Internally they are connected in such a way, that on applying AC supply, a rotating magnetic field is created. Below are set of picture I took during my research and learn from a technician specialize in the winding prepares of electric motor (**Y.K ELECTRICALS**)



PICTURE 2.11 SHOWING THE STATOR WINDING DURING MY TRAINING AND RESEARCH

(ABEL S. TOPE a.k.a olupiti)

2.7 THE ENCLOSURE

The enclosure consists of a frame (or yoke) and two end brackets (or bearing housings). The stator is mounted inside the frame. The rotor fits inside the stator with a slight air gap separating it from the stator. There is no direct physical connection between the rotor and the stator. The enclosure protects the internal parts of the motor from water and other environmental elements. The degree of protection depends upon the type of enclosure. Enclosure types are discussed later in this course.

2.8 SLIP

The difference between the synchronous speed N_s and the actual speed N of the rotor is known as **slip**[8]. Though it may be expressed in so many revolution per second, yet it is usual to express it as a percentage of the synchronous speed. Actually, the term 'slip' is descriptive of the way in which the rotor 'slips back' from synchronism.

Where:-

N = actual speed

N_s = synchronous speed

f = AC power frequency (hertz)

P = Number of poles per phase (an even number)

2.5.2.8 The bolt:-

The bolt used, is of the same length as the rotor and is used to hold the laminated steel sheet together with the end rings.

Below are some pictures taken to illustrate these components.

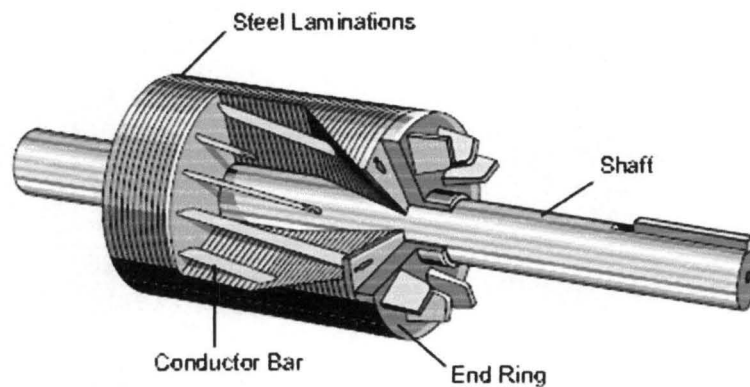


Figure 2.7 showing the cut-away view of squirrel cage rotor

2.6 THE STATOR

The stator is made up of several thin laminations of aluminum or cast iron[2]. They are punched and clamped together to form a hollow cylinder (stator core) with slots as shown in Figure 2.9 and picture 2.8 below. Coils of insulated wires are inserted into these slots. Each grouping of coils, together with the core it surrounds, forms an electromagnet (a pair of poles) on the application of AC supply. The number of poles of an AC induction motor depends on the internal connection of the stator windings. The stator windings are connected directly to the power source. Internally they are connected in such a way, that on applying AC supply, a rotating magnetic field is created.

$$\% \text{ slips} = \frac{(N_s - N) \times 100}{N_s}$$

Sometimes, $N_s - N$ is called the slip speed.

Obviously, rotor (or motor) speed is $N = N_s(1 - S)$.

Chapter three

3.0 DESIGN OF A 5KW, 3 PHASE SQUIRREL CAGE INDUCTION MOTOR

3.1 DESIGN SPECIFICATIONS

The rated data for this design are:

$$\text{Power } P_2 = 5\text{KW}$$

$$\text{Voltage} = 400/230\text{V}$$

$$\text{Efficiency } (\eta) = 70\%$$

$$\text{Power factor} = 0.89$$

$$\text{Speed} = 1500 \text{ r.p.m}$$

$$\text{Number of poles} = 2p = 4$$

$$\text{Frequency } (f) = 50\text{Hz}$$

$$\text{Number of phases} = 3$$

$$\text{Specific electric loading } (q) = 22,500 \text{ amp/cond.}$$

$$\text{Specific magnetic loading } (Bq) = 0.43 \text{ wb/m}^2.$$

3.2 OUTPUT EQUATION

We have that:

$$P_1 = 3 \times V_p \times I_p \times 10^{-3} \quad \text{-----3.1}$$

$$= 3 \times \text{KW}_1 (4.44fN) \times I \times 10^{-3} \quad \text{-----3.2}$$

Utilizing the formula:

$$f = (P/2) \times n$$

substituting in expression for P_1 in equation (16.2)

$$P_1 = 3 \times [KW_1 [4.44 \frac{P}{2} \times n] N \frac{[B\pi DL]}{P} \times [\frac{q\pi D}{6nN}] \times 10^{-3}] \text{-----3.3}$$

$$= 1.11 KW_1 n^2 \times Bq \times D^2 Ln \times 10^{-3} \text{-----3.4}$$

$$= 1.11 KW_1 \times Bq \times D^2 Ln \times 10^{-3} \text{-----3.5}$$

Where P_1 = input to the motor KVA

KW_1 = winding factor i.e $K_d \times K_{sf}$ for the fundamental wave

K_d = pitch shortening factor

B_g = the average ir rated flux density in (wb/m²) T

q = amp-cond. Per unit air gap circumference in amp-cond./m

D = stator bore diameter in m

L = stator length in mm

n = synchronous speed in r.p.s

3.2.1 CALCULATIONS OF THE MAIN DIMENSIONS

The output coefficient G can be expressed as:

$$G = 11KWB_g \times 10^{-3}$$

$$= 11 \times 0.92 \times 22500 \times 0.43 \times 10^{-3} = 97.911$$

$$D^2L = P_1/Gn$$

$$P_1 = \frac{P_2 \times K_E}{\eta \cos \phi} \text{-----3.6}$$

where, $P_2 =$ output power = 5KW (given)

$\eta =$ efficiency = 0.70 (given)

$\cos \phi =$ power factor = 0.89 (given)

$q =$ specific electric loading = 22,500 amp-cond/m

$$P_1 = \frac{5 \times 0.96}{0.70 \times 0.89} = 7.7076 \text{KW}$$

$$F = (P/2) \times n$$

$$50 = (4/2) \times n$$

$$N = 25 \text{ r.p.s}$$

$$D^2L = P_1/Gn$$

$n =$ the number of revolutions per second

$$D^2L = \frac{7.7046}{97.911 \times 25} = 0.00135 \text{m}^{-3}$$

Note: $P = 60F/S$

where $P =$ the number of pole pairs

$$P = (60 \times 50) / 1500 = 2$$

To determine the diameter and length from D^2L product we have to introduce the pole pitch T_p .

$$Y_p = \pi D / 2p = (3.142 \times D) / (2 \times 2) = 0.785D$$

Where the length of the stator L can be expressed as: $L = 0.65Y$ and 0.65 is the ratio of the stator length to the pole pitch

$$L = 0.65 \times 0.785D = 0.51025D$$

$$D^2L = 0.00315\text{m}^3$$

$$0.51025D^3 = 0.00315\text{m}^3$$

$$D^3 = 0.00315 / 0.51025$$

$$D = \sqrt[3]{0.00617} = 0.18344\text{m} = 0.18\text{m}$$

And so $L = (0.51025 \times 0.18) = 0.0936\text{m} = 0.09 = 9\text{cm}$.

Core losses

The pole pitch can now be deduced.

$$Y_p = nD / 2p$$

$$Y_p = (3.142 \times 18) / 4 = 14.139\text{cm} = 0.1414\text{m}$$

The pole is roughly square. The core does require a radial duct, so that the net core length to 0.089m and the iron length can be expressed as:

$$L_2 = 0.9 L_s = 0.9 \times 0.09 = 0.081\text{m}.$$

3.2.2 STATOR CALCULATION

The no. of turns per phase is determined by V_1 , f , ϕ_m , KW_1 and is expressed as:

$$N_1 = \frac{V_1}{4.44 K W_1 f \varnothing_m} \text{-----} 3.7$$

$$= \frac{400}{4.44 \times 0.92 \times 50 \times 5.47 \times 10^{-3}}$$

$$N_1 = 357.9$$

$N_1 = 358$ turns per phase.

The number of stator slots per pole is closer to be 3

Stator Slots

The number of slots with double lap wdg is expressed as:

$$S_1 = 2 M g P \text{-----} 3.8$$

$$= 4 \times 3 \times 3 = 36 \text{ stator slots}$$

Where M = the number of phases

g = the number of slots/pole/phases

P = the number of poles

The slot pitch Y_{S1} is expressed as:

$$Y_{S1} = \pi D / S_1 \text{-----} 3.10$$

$$= (3.142 \times 0.18) / 22 = 0.01571\text{m}$$

The tooth pitch Y_T is expressed as:

$$\begin{aligned} \text{Portion } h_2: \quad \lambda_{s2} &= \frac{h_2}{bp_1} \text{-----3.43} \\ &= \frac{0.0010}{0.012536} = 0.08 \end{aligned}$$

$$\begin{aligned} \text{Portion } h_3: \quad \lambda_{s3} &= \frac{2h_3}{(bp_1 + b_{p1})} \text{-----3.44} \\ &= \frac{2 \times 0.0025}{0.012536 + 0.004} = 0.302 \end{aligned}$$

$$\begin{aligned} \text{Portion } h_4: \quad \lambda_{s4} &= \frac{h_4}{bp_1} \text{-----3.45} \\ &= \frac{0.0015}{0.004} = 0.375 \end{aligned}$$

∴ The specific slot λ_1 of semi closed rectangular slot is:

$$\lambda_1 = \frac{h_1}{Bbp_1} + \frac{h_2}{bp_1} + \frac{2h_3 + h_4}{bp_1 + b_{sp1}} \text{-----3.46}$$

$$= 0.475 + 0.08 + 0.302 + 0.375 = 1.232$$

3.5.1 SLOT REACTANCE PER PHASE OR STATOR

$$X_1 = 15.8 \times 10^{-6} F (N_1^2 / P_{g1}) L_s \lambda_1 \text{ ohm -----3.47}$$

$$= 15.8 \times 10^{-6} \times 50 (358^2 / (2 \times 3)) 0.09 \times 1.232 = 1.9 \Omega.$$

3.5.2 THE SPECIFIC SLOT PERFORMANCE FOR ROTOR

$$\lambda_1 = \frac{L_c}{3bp_2} + \frac{2(bp_2 - Lw)}{\text{slot width} + bsp_2} \text{-----3.48}$$

Where, L_c = length of the conductor in m.

bp_2 = the slot width of the rotor.

Lw = the width of the conductor

bsp_2 = the slot opening in m.

$$\lambda_1 = \frac{L_c}{3bp_2} + \frac{2(bp_2 - Lw)}{3bp_2 + bp_2} = \frac{0.034}{3 \times 0.010} + \frac{2(0.004 - 0.003)}{3 \times 0.004 + 0.001} = 1.287$$

3.5.3 REFERRED SLOT PERFORMANCE OF THE ROTOR

$$\lambda'_2 = \lambda_2 Kw_1^2 S_1 / Kw_2^2 S_2 \text{-----3.49}$$

Kw_1 = winding factor of the rotor (0.92)

Kw_2 = winding factor of the rotor (1)

S_1 = number of slots in the stator

S_2 = number of slots in the rotor.

$$\lambda'_2 = \frac{1.287 \times 0.92^2 \times 36}{1^2 \times 30} = 1.307$$

The total slot reactance of the motor can be expressed as in eqn. (3.47)

$$L_o \lambda_o = K_s Y^2 / \lambda Y S_1 \text{-----3.50}$$

Where, K_s = stack factor

$$L_o \lambda_o = \frac{0.93 \times 0.1492^2}{3.142 \times 0.01571} = 0.42$$

Overhang $X_o = 16.875 \times 0.42$

Reactance $X_o = 7.087 \Omega$

THE ZIGZAG REACTANCE:

The magnetizing current is 2A, the voltage 400 (each per phase) and the magnetizing reactance X_m can be expressed as:

$$X_m = V/I_m \text{ -----3.51}$$

$$= 400/2 = 200 \Omega$$

The required reactance is deuced using the expression:

$$X_Z = 5/6 X_m(1/g_1^2 + 1/g_2^2) \text{ ohm per phase -----3.52}$$

$$= 5/6 \times 200 (1/9^2 + 1/7.5^2) \text{ where, } g_1 = mg_1$$

$$X_Z = 0.83 \times 200 (0.01234 + 0.0178) = 5.023 \Omega$$

The motor is a squirrel cage induction motor there is no differential reactance.

The total phase reactance X_T is

$$X_T = X_{12} + X_o + X_Z \text{ -----3.53}$$

$$= 3.86 + 7.087 + 5.023 = 15.97\Omega$$

3.5.4 ACTIVE RESISTANCE OF STATOR WINDING AND ROTOR

The length of a means conductor L_{mc} in the stator is approximately

$$L_{mc} = L_s + 1.15Y_p + 0.15 \text{ -----3.54}$$

$$Y_T = S_1/2P \quad \text{-----3.11}$$

$$= 36/4 = 9\text{cm} = 0.09\text{m}$$

3.2.3 CONDUCTORS PER SLOT

The number of turns per phase is enclosed in 12 slots giving the number of conductors per slots Z_1 to be expresses:

$$Z_1 = 6N_1 / S_1 \quad \text{-----3.12}$$

$$= (6 \times 358) / 36 = 59.6 \approx 60 \text{ conductor/slot.}$$

Full Load Current

$$I_1 = \frac{P_2}{mV\eta \cos\phi} \quad \text{-----3.13}$$

$$= \frac{5 \times 10^3}{3 \times 400 \times 0.70 \times 0.89} = \frac{5000}{747.6} = 0.688\text{A} \approx 6.69\text{A}$$

3.2.4 AREA OF CONDUCTOR

The area A, required is expressed as:

$$A_1 = I_1/J_1 \quad \text{-----3.14}$$

$$J_1 = \text{current density} = 3.5$$

$$A_1 = 6.6888/3.5 = 1.911\text{mm}^2$$

A_1 is obtainable by connecting two wires in parallel

$$A_1 = 2 \times 0.9555\text{mm}^2 = 1.9111\text{mm}^2$$

The diameter of each wire is expressed as:

$$d = \sqrt{\frac{4A_1}{\pi}} \quad \text{-----3.15}$$

$$d = \sqrt{\frac{4 \times 0.956}{\pi}} = 1.103\text{mm}$$

The diameter of each wire bare is 1.103mm insulated with five d.c to 1.192mm

3.2.5 ROTOR CALCULATION

Rotor Slots:

The number of rotor slots has been chosen as 30. The slot pitch of the rotor can be expressed as:

$$h_{p1} = 24.00\text{mm}, b_{p1} = 12.536\text{mm}, b_{sp} = 4.00\text{mm}, h_1 = 17.88\text{mm}, h_1 = 17.88\text{mm}, h_2 = 1.00\text{mm},$$

$$h_3 = 2.50\text{mm}, h_4 = 2.00\text{mm}$$

$$Y_{s2} = \frac{\pi D}{S_2} \quad \text{-----3.16}$$

$$= 3.142 \times 0.18 = 0.0188\text{m} \approx 0.019\text{m} = 19\text{mm}$$

Equivalent Rotor Current

The equivalent rotor current I'_2 is approximately expressed as:

$$I'_2 = I_1 \cos\theta \quad \text{-----3.17}$$

$$= 6.69 \times 0.89 = 5.95\text{A}$$

The D_{shaft} is 0.0667m because of the direct Keying of shaft to the rotor.

TOTAL MMF OF THE MAGNETIC CIRCUIT OF THE MACHINE.

The total mmf F_{total} of this induction motor can be expressed as the sum of the various mmfs i.e

$$F_{\text{total}} = F_g + F_{t1} + F_{t2} + F_{a1} + F_{a2} \text{ ----} 16.41$$

$$= 355 + 414.2 + 2.53 + 209 + 3.132 = 983.9 \text{ Amp-turn}$$

The saturation of the magnetic at $K\mu$ can be expressed as: $K\mu = F_T/F_g = 983.9/355 = 2.8$

The magnetic current I_m can be expressed as:

$$I_m = \frac{F_T P \mu}{2m_1 N_1 K w_1} = \frac{2 \times 3.142 \times 983.9}{2 \times 3 \times 358 \times 0.92} = 3.128 \approx 3.13A \text{ per phase.}$$

3.5 REACTION AND REACTANCE CALCULATION

CALCULATION OF THE SPECIFIC SLOT

PERFORMANCE OF STATOR.

Portion h_1 :

The specific slot performance of the slot is expressed as:

$$\lambda_{s1} = \frac{h_1}{3bp_1} \text{ -----} 3.42$$

$$= \frac{0.01788}{3 \times 0.012536} = 0.475$$

Inductance = $N \emptyset I$;

Inductance = Linkages/ current = $N^2 \times \mu_o \times (\text{specific slot performance}) \times L$

$$= 0.09 + 1.15 (0.14139) + 0.15 + 0.0425\text{m}$$

The length per phase L_{p1} is : $L_{p1} = 2N_1 L_{mc}$ -----3.55

$$= 2 \times 358 \times 0.4025 = 288.2\text{m}$$

The resistance of the conductor in the stator slot is expressed as:

$$r_1 = \frac{\rho L_p}{A_1} \text{ -----3.56}$$

Where, ρ = resistivity

L_{p1} = length per phase

A_1 = area of conductor (insulated in the stator slot)

At 20°C the resistivity, $\rho = 1/58 \Omega$.

The resistance-temperature coefficient is $1/234.5$ per $^\circ\text{C}$, so that at 75°C , the resistance of a 1m length of copper, 1mm^2 in section is : =

$$\frac{1}{58} \times \frac{234.5 + 75}{234.5 + 20} ; \rho = 0.021 \Omega$$

The resistance of the conductor in the slot at 75°C is :

$$0.021 \times \frac{288.2}{2.7577} = 2.2 \Omega$$

The resistance at the rotor bar at 75°C can be deduced using the expression equation 3.56

$$r_b = \frac{\rho L_b}{A_2}$$

where r_b = resistance of bar

L_b = length of bar

$A_2 =$ Area of the conductor in the stator

$$\therefore r_b = 0.021 \times 0.15 / 113 = 2.78 \times 10^{-5} \Omega.$$

The rings are to be cast with blade for cooling. The area is approximately 172mm^2 and a mean diameter 14.8cm . the resistance of the rings can then be expressed as in equation 3.56. ;

$$r_c = \frac{\rho \pi l}{A_r} = \frac{0.021 \times 14.8 \times 10^{-2}}{172} = 2.4472 \times 10^{-5} \Omega.$$

The equivalent resistance of the rotor is therefore expressed as:

$$r'_2 = \frac{11T^2}{S_2} \left[r_b + 0.1r_c \frac{g_2}{p} \right] \text{-----3.57a}$$

$$\text{or, } r'_2 = \frac{4mKW_1^2 N_1^2}{S_2} \left[r_b + 0.1r_c \frac{g_2}{p} \right] \text{-----3.57a}$$

$$r'_2 = \frac{4 \times 3 \times 0.92^2 \times 358^2}{30} \left[2.78 + \left(0.1 \times 2.4472 \times 10^{-5} \times \frac{7.5}{2} \right) \right]$$

$$= (51265.94 \times 3.6977 \times 10^{-5}) = 51265.94 \times 0.000036977 = 1.89 \Omega \approx 2.0 \Omega$$

Or more directly, using the expression $31'2 2r'_2$ -----3.58

$$31'2 2r'_2 = 71.4\text{W}$$

$$r'_2 = 1.9625 \approx 2.0 \Omega$$

The resistance of the rotor is : $R_1 = r_1 + r_2' = (2.2 + 2.0) \Omega = 4.2 \Omega$

Hence the impedance of the motor is $Z_1 = \sqrt{R_1^2 + X_1^2} =$

$$\sqrt{4.2^2 + 15.97^2} = 16.51 \Omega$$

The short circuited power factor $\cos\theta_{SC}$ is : $\cos\theta_{SC} = R_1 / Z_1 = 4.2/16.51 \Rightarrow$

$$\cos\theta_{SC} = 0.82$$

The short circuited current I_{SC} is: $I_{SC} = \frac{V}{Z_1} = \frac{400}{16.51} = 24.23A$ per phase.

TOTAL LOSSES OF THE STATOR AND ROTOR:

The I^2R loss of the stator on all phases can be deduced using the expression:

$$P_{LS} = 3 I_1^2 r_1 \text{ -----3.59}$$

The I^2R loss in the end – rings is: $P_{Lr} = 2I_C^2 r_C$ -----3.61

$$= 2 \times 964^2 \times 2.4472 \times 10^{-5} = 45.5W$$

3.5.5 CORE LOSSES

Specific mass of steel, $r = 7.8 \times 10^{-3} \text{ kg/m}^3$. The mass of stator yoke

$$\text{mass}_s = \pi(D_a - h_a) h_a K_s l_1 y_C \text{ -----3.62}$$

$$= \pi(0.29 - 0.02276) 0.02276 \times 0.93 \times 7.8 \times 10^{-3} = 3.97Kg$$

The mass of stator tooth zone. $M_1 = h t_1 b_{t(av)} s_1 L_1 K_s y_C$ -----3.63

$$= 0.0322 \times 0.0042 \times 36 \times 0.09 \times 0.93 \times 7.8 \times 10^{-3} = 3.417 \approx 3.42Kg.$$

CORE LOSSES

The core is built on 0.5mm steel blades stator teeth: $\text{Mass}_1 = 3.42Kg$.

The maximum flux density of stator $B_{a1} = 1.44T$. The specific loss, $P_1 = 18.5w$ per Kg at $B_{a1} = 1.44T$. The loss in teeth can be deduced with the expressions.

$$\text{The loss in teeth} = P_1 \times \text{mass}_1 \text{ -----3.64}$$

$$= 18.5 \times 3.42 = 63.27 \approx 63.3W$$

Where, y_c = Specific mass diameter

D_a = the external diameter

h_{a1} = height of the stator core

stator core = $Mass_1 = 3.42Kg$

The specific loss P_2 ; $B_{a2} = 0.59T$ is $P_1 = -1.44W$ per Kg.

The loss in the stator core can be expressed as in equ. 3.64.

$$\text{Loss in core} = P_2 \times Mass_s = 3.97 \times -1.44 = -5.71W$$

The total iron loss = loss in teeth + loss in core. $P_{t1} = 63.3 + -5.71 = 57.59W$

3.6 FRICTION AND WINDAGE LOSSES

The friction and windage are difficult to estimate but they will be small if ball and roller bearing are used. The assumption is to take 1 % of the input power on the friction and windage losses. Then 1% loss of input power is :

$$= 0.01 \times 7.7046 \times 10^3 = 77.046W$$

The no-load becomes: $P_0 = P_{t1} + P_{fW}$ -----3.65

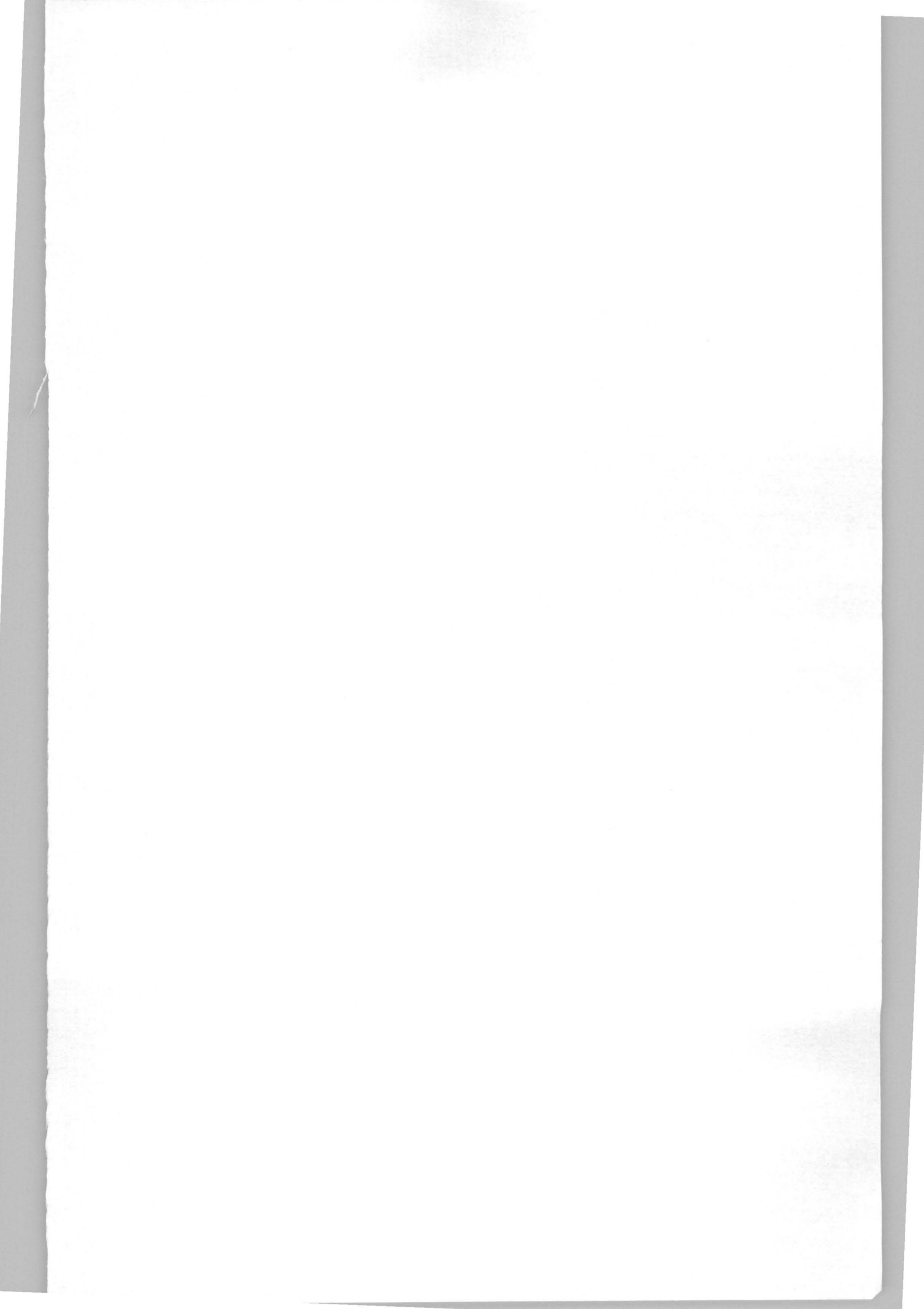
$$= 57.59 + 77.046 = 134.63W$$

The active current is $loa = P_0 / (M \times V)$ -----3.66

$$= 134.64 / (3 \times 400) = 0.1122A$$

And the no-load current I_0 is: $I_0 = \sqrt{I_m^2 + I_m^2} = \sqrt{3.13^2 + 0.1122^2}$

$$= \sqrt{9.796 + 0.012588} = 3.13A$$



The no-load power factor is: $\cos\theta_0 = \frac{I_{0a}}{I_m} = \frac{0.1122}{3.13} = 0.0358$.

3.7 PERFORMANCE CHARACTERISTICS

The full load losses are:

Stator $I_1^2R = 3 \times 6.69^2 \times 2.2 = 295.39$

Rotor $I_1^2R_1 = 3 \times 5.95^2 \times 2.0 = 212.42$

core and teeth 57.58

friction and windage 77.05

Total losses 642.44

input 5×10^3 5000.00

5642.44

The efficiency, η of the motor can be deduced from performance characteristic using the expressions.

$$\eta = 100 \left[\frac{5000}{5642.44} \right] = 86.6 \approx 89\%$$

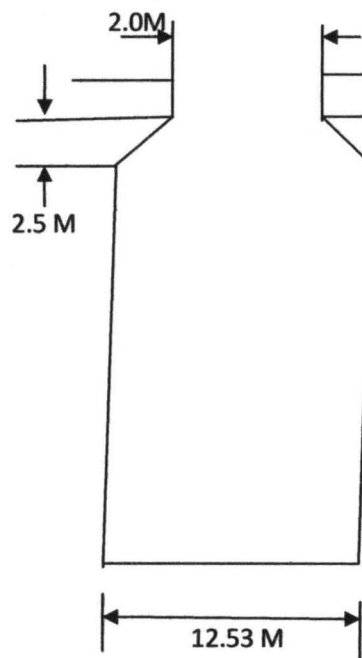
SLIP

The load slip is $I_2'^2 r_2 = SP_2$ -----3.68

$$S_f = \frac{P_{Lr}}{P_2 + P_{Lr} + P_{fw}} = \frac{45.5}{5 \times 10^3 + 45.5 + 77.05} = 0.0089$$

$P_2 + P_{Lr} + P_{fw}$

$5 \times 10^3 + 45.5 + 77.05$



- hp1 = 24m
- bp1 = 12.53m
- bsp = 4.0m
- h₁ = 17.88mm
- h₂ = 1.0mm
- h₃ = 2.50mm
- h₄ = 2.00m

STARTING TORQUE:

For direct starting= $(I_{sc})^2 S_f = \text{starting torque}$

I_2' full load torque

$$= (24.23)^2 \times 0.0089 = 0.8781$$

5.95

Chapter four

4.0 THE PERFORMANCE TEST

In the previous chapter, the following parameter was derived during the design of the 5kw, three (3) phase, squirrel cage induction motor. This is used for this performance test.

4.1 Calculated data:-

$$N_s = \text{Synchronous speed} = 25 \text{ r. p. s}$$

$$I_1 = \text{stator current per phase} = 6.69 \text{ A}$$

$$I_2 = \text{rotor induced current per phase} = 5.95 \text{ A}$$

$$R_2 = \text{Rotor resistance.} = 4.2 \Omega$$

$$X_2 = \text{Rotor reactance} = 15.97 \Omega$$

$$\pi = 3.142$$

$$S = \text{slip} = 0 (0.02) 1$$

$$E_2 = \text{Rotor induced EMF per phase}$$

Since induction motor is a transformer with rotating secondary coil [theraja]. So therefore:

$$V_1 I_1 = V_2 I_2 \dots\dots\dots \text{eqn 4.1}$$

$$\text{Where } V_2 = E_2$$

$$\text{And, } E_2 = (V_1 I_1) / I_2$$

$$(230 \times 6.69) / 5.95 = 258.61 \text{ v}$$

4.2 DERIVATION OF TORQUE EQUATIONS

(A) Derivation of torque at standstill or at starting (i.e when the slip = 1)

:- See Appendix 1

(B) Derivation of torque at running conditions (i.e when slip is not equal)

:- see Appendix 2

4.3 TEST OF PERFORMANCE OF THIS SQUIRREL CAGE INDUCTION MOTOR:-

Using the torque equations the test of performance of this designed motor can be carried out under the following conditions i.e at standstill(at $s=1$), running condition and full-load conditions by varying the slip at rotor resistance (R_2) = 42 Ω and compare it with designing the motor at a lower rotor resistance equal to 2.2 Ω and at higher rotor resistance equal to 6.2 Ω :-

$$\text{- From } T = \frac{3}{2\pi N_s} * \frac{S (E_2)^2 R_2}{(R_2)^2 + (S X_2)^2} \dots\dots\dots\text{eqn 4.2}$$

Where T = torque

4.4 CALCULATION OF RESULT

See Appendix 3(three) for calculation of result by manual mathematical manipulations and

See Appendix 5 for a software program with visual basic to compute the result.

4.5 TABLE OF RESULT

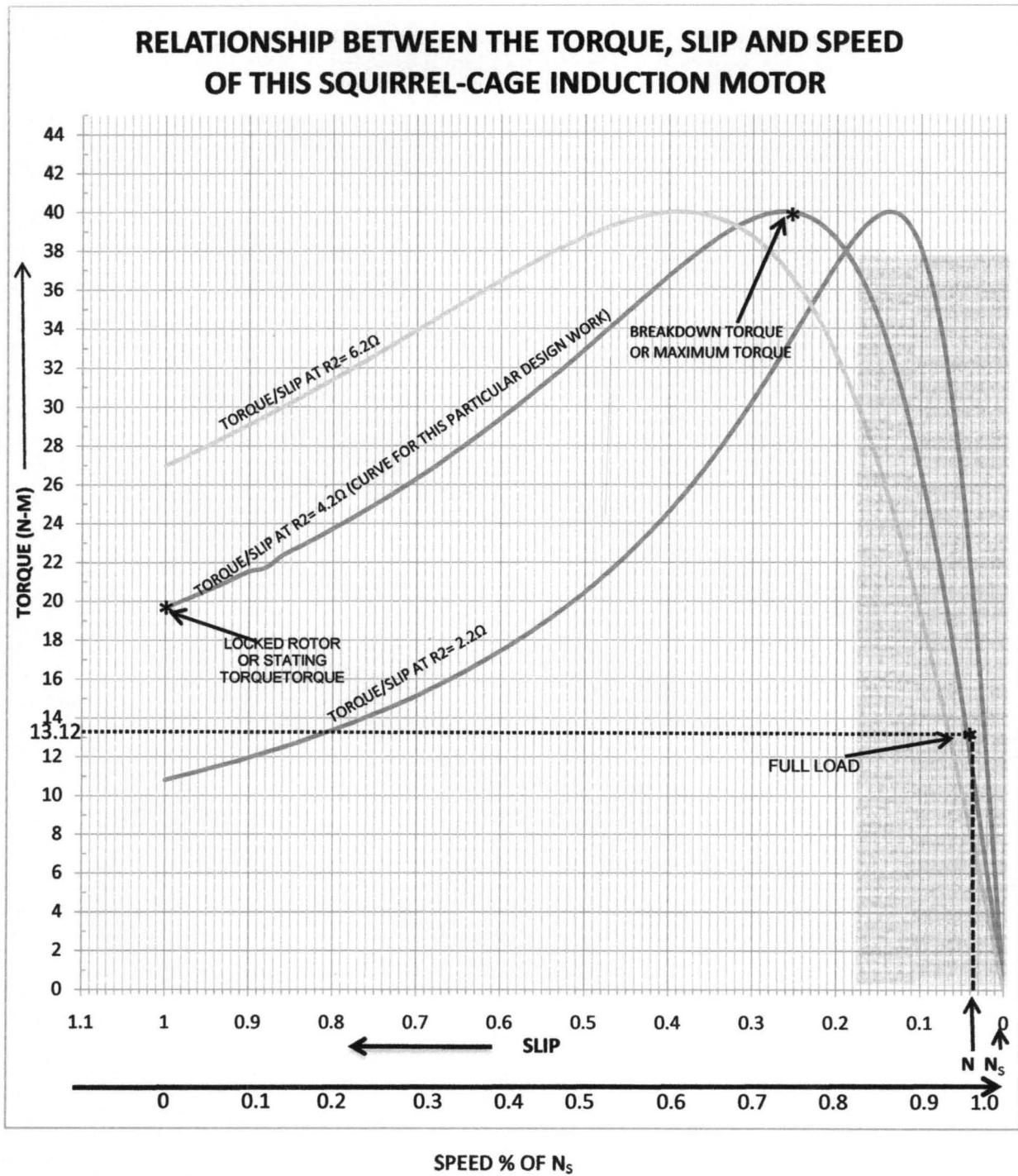
NOTE: Where torque at rotor resistance equal to 4.2Ω is the torque value for this particular design

S/N	SLIP	TORQUE WHEN	TORQUE WHEN	TORQUE WHEN
		ROTOR RESISTANCE IS 4.2Ω	ROTOR RESISTANCE IS 2.2Ω	ROTOR RESISTANCE IS 6.2Ω
1	0.00	0.00 N-m	00.00 N-m	0.00 N-m
2	0.02	6.05 N-m	11.37 N-m	4.11 N-m
3	0.04	11.89 N-m	21.42N-m	8.15 N-m
4	0.06	17.35 N-m	29.28 N-m	12.07 N-m
5	0.08	22.27 N-m	34.74 N-m	15.81 N-m
6	0.10	26.57 N-m	38.03 N-m	19.32N-m
7	0.12	30.21 N-m	39.62 N-m	22.57 N-m
8	0.14	33.17 N-m	39.99 N-m	25.52 N-m
9	0.16	35.52 N-m	39.55 N-m	28.18N-m
10	0.18	37.28 N-m	38.61 N-m	30.52N-m
11	0.20	38.54 N-m	37.37 N-m	32.56 N-m
12	0.22	39.36 N-m	35.98 N-m	34.31 N-m
13	0.24	39.83 N-m	34.53 N-m	35.78N-m
14	0.26	39.99 N-m	33.09 N-m	36.98N-m
15	0.28	39.92 N-m	31.68 N-m	37.95 N-m
16	0.30	39.65 N-m	30.33 N-m	38.70 N-m

17	0.32	39.24 N-m	29.05 N-m	39.26 N-m
18	0.34	38.71 N-m	27.84 N-m	39.64 N-m
19	0.36	38.10 N-m	26.70 N-m	39.88 N-m
20	0.38	37.43 N-m	25.63 N-m	39.98 N-m
21	0.40	36.72 N-m	24.63 N-m	39.99 N-m
22	0.42	35.98 N-m	23.69 N-m	39.87 N-m
23	0.44	35.22 N-m	22.81 N-m	39.68 N-m
24	0.46	34.46 N-m	21.98 N-m	39.42 N-m
25	0.48	33.71 N-m	21.21 N-m	39.11 N-m
26	0.50	32.95 N-m	20.48 N-m	38.75 N-m
27	0.52	32.21 N-m	19.80 N-m	38.34 N-m
28	0.54	31.49 N-m	19.16 N-m	37.91 N-m
29	0.56	30.78 N-m	18.55 N-m	37.45 N-m
30	0.58	30.08 N-m	17.98 N-m	36.97 N-m
31	0.60	29.41 N-m	17.45 N-m	36.48 N-m
32	0.62	28.76 N-m	16.94 N-m	35.98 N-m
33	0.64	28.12 N-m	16.45 N-m	35.47 N-m
34	0.66	27.51 N-m	16.00 N-m	34.96 N-m
35	0.68	26.91 N-m	15.57 N-m	34.44 N-m
36	0.70	26.33 N-m	15.15 N-m	33.93 N-m
37	0.72	25.78 N-m	14.76 N-m	33.41 N-m
38	0.74	25.24 N-m	14.39 N-m	32.91 N-m
39	0.76	24.72 N-m	14.04 N-m	32.40 N-m
40	0.78	24.22 N-m	13.70 N-m	31.91 N-m
41	0.80	23.73 N-m	13.38 N-m	31.42 N-m

42	0.82	23.26 N-m	13.07 N-m	30.94 N-m
43	0.84	22.81 N-m	12.77 N-m	30.46 N-m
44	0.86	22.37 N-m	12.49 N-m	30.00 N-m
45	0.88	21.74 N-m	12.22 N-m	29.54 N-m
46	0.90	21.53 N-m	11.96 N-m	29.09 N-m
47	0.92	21.14 N-m	11.71 N-m	28.65 N-m
48	0.94	20.75 N-m	11.48 N-m	28.22 N-m
49	0.96	20.38 N-m	11.25 N-m	27.80 N-m
50	0.98	20.02 N-m	11.03N-m	27.39 N-m
51	1.00	19.68N-m	10.81 N-m	26.99 N-m

4.6 GRAPH SHOWING THE PERFORMANCE OF SQUIRREL-CAGE INDUCTION MOTOR



4.6.1 From graph above:

Slip at full-load (s)= 0.04

$$\text{From } s = \frac{N_s - N}{N_s}$$

; where N= actual speed

$$N_s = \text{synchronous speed.} = 25 \text{ rps}$$

So therefore,

$$N = N_s(1 - 0.04)$$

$$= 25 (0.96)$$

$$= 24 \text{ rps at full-load}$$

4.6.2 DISCUSSION OF RESULTS

4.6.2.1 Using the torque/slip curve shown above:

A family of torque /slip curves is shown above for a range of $S = 0$ to $s = 1$ with R_2 as the parameter. The blue curve shows the torque /slip behavior of this particular work, while the other two curves are the torque/slip behavior of the same motor but at a lower(at 2.2Ω) and higher(at 6.2Ω) rotor resistance than the actual rotor resistance of this designed motor with $R_2=4.2 \Omega$. And as we have above in equation 4.2 that

$$T = \frac{3}{2\pi N_s} * \frac{S (E_2)^2 R_2}{(R_2)^2 + (S X_2)^2} \dots\dots\dots\text{equ 4.3}$$

It is clear that when $s=0$, $T=0$, hence the curve starts from point 0 (zero). At normal speeds, close to synchronism, the term (sX_2) is small and hence negligible w.r.t. R_2 . Therefore

$$T \propto s/R_2 \quad \text{or} \quad T \propto s \text{ if } R_2 \text{ is constant.}$$

Hence, for low values of slip, the torque/slip curve is approximately a straight line. As slip increase (for increasing load on the motor), the torque also increase and becomes maximum when $S = R_2/X_2$. This torque is known as 'pull-out' or 'breakdown' torque T_b or stalling torque. As the slip further increases (i.e motor speed falls) with further increase in motor load, then R_2 becomes negligible as compared to $(s X_2)$. Therefore, for large values of slip

$$T \propto s / (s X_2)^2 \propto 1/s \quad \dots\dots\dots \text{equ 4.4}$$

Hence, the torque/slip curve is a rectangular hyperbola. So, we see that beyond the point of maximum torque, any further increase in the motor load results in decrease of torque developed by the motor. The result is that the motor slows down and eventually stops. The circuit-breakers will be tripped open if the circuit has been so protected. In fact, the stable operation of the motor lies between the values of $s=0$ and that corresponding to maximum torque. The operating range is shown shaded in the graph above.

4.6.2.2 Using the torque/speed curve:

The torque developed by a conventional three phase motor depends on its speed but the relation between the two cannot be represented by a simple equation. It is easier to show the relationship in the form of a curve (as shown in graph 4.1). in this diagram, T represents the nominal full-load torque of the motor. As seen, the starting torque ($N=0$) is $1.5T$ and the maximum torque (also called breakdown torque) is $2.5T$.

At full-load, the motor runs at a speed of N. when mechanical load increases, motor speed decreases till the motor torque again becomes equal to the load torque. As long as the two torques are in balance, the motor will run at constant (but lower) speed. However, if the load torque exceeds $2.5T$, the motor will suddenly stop.

4.6.3 DEDUCTIONS

4.6.3.1 Starting torque of a squirrel-cage induction motor:

The resistance of squirrel-cage rotor is fixed and small as compared to its reactance which is very large especially at the start because at standstill, the frequency of the rotor currents equals the supply frequency. Hence the starting current I_2 of the rotor, though very large in magnitude, lags by a very large angle behind E_2 , with the result that the starting torque per ampere is very poor. It is roughly 1.5 times the full-load torque, although the starting current is 5 to 7 times the full-load current. Hence, such motors are not useful where the motor has to start against heavy loads.

4.6.3.2 Effect of change in supply voltage on starting torque:

We have seen in equation 4.2 that $T_{st} = \frac{k_1 E_2^2 R_2}{R_2^2 + X_2^2}$ equ 4.5

Now $E_2 \propto$ supply voltage V . so therefore,

$$T_{st} = \frac{k_3 V^2 R_2}{R_2^2 + X_2^2} \dots\dots\dots \text{equ 4.6}$$

Where k_3 is yet another constant. Hence $T_{st} \propto V^2$.

Clearly, the torque is very sensitive to any changes in the supply voltage.

4.6.3.3 Shape of torque/speed curve:

From equation 4.6 above, a squirrel-cage induction motor (SCIM), shape of its torque/speed curve depends on the voltage and frequency applied to its stator[1].

Chapter five

5.0 Conclusion

It is seen that although maximum torque does not depend on R_2 , yet the exact location of T_{\max} is dependent on it. Greater the R_2 , greater is the value of slip at which the maximum torque occurs. However, the speed or slip at which maximum torque occur is determined by the rotor resistance. As seen from above, torque becomes maximum when rotor reactance equals its resistance. Hence, by varying rotor resistance (possible only with slip-ring motors) maximum torque can be made to occur at any desired slip (or motor speed).

Also maximum torque varies inversely as standstill reactance. Hence, it should be kept as small as possible. Likewise maximum torque varies directly as the square of the applied voltage.

For obtaining maximum torque at starting ($s=1$), rotor resistance must be equal to rotor reactance.

5.1 Recommendations:

As the designer of this work, I recommend this work as follows:

1. That this thesis be given to application programmer to write software on it, to help solve the future problem of designing squirrel-cage induction motor.
2. That this thesis be updated on our national local engineering content on the internet.

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APPENDIX

APPENDIX 1: Torque at standstill or Starting Torque

The torque developed by the motor at the instant of starting is called starting torque. In some cases, it is greater than the normal running torque, whereas in some other cases it is somewhat less.

Let $E_2 =$ rotor e.m.f per phase at standstill

$X_2 =$ rotor reactance/phase at standstill

$R_2 =$ rotor resistance/phase

$Z_2 = \sqrt{(R_2^2 + X_2^2)} =$ rotor impedance/phase at standstill.

$$\text{Then, } I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}}$$

$$\cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}}$$

Standstill or starting torque $T_{st} = K_1 E_2 I_2 \cos\phi_2$

Or

$$\frac{K_1 E_2^2 R_2}{(R_2^2 + X_2^2)}$$

$$\text{Now, } K_1 = \frac{3}{2\pi N_s}$$

$$\text{so therefore, } T_{st} = \frac{3}{2\pi N_s} * \frac{E_2^2 R_2}{(R_2^2 + X_2^2)}$$

APPENDIX 2: Torque under running condition

$T \propto E_r I_r \cos\phi_2$ or $T \propto \Phi I_r \cos\phi_2$ (since $E_r \propto \Phi$)

Let E_r = rotor e.m.f per phase under running conditions

X_2 = rotor reactance/phase under running conditions

I_r = rotor current/phase under running conditions

R_2 = rotor resistance/phase

Now $E_r = sE_2$

$$\text{Then, } I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

$$\cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

$$T = \frac{K \cdot s E_2^2 R_2}{(R_2^2 + (s X_2^2))}$$

$$\text{Now, } K = \frac{3}{2\pi N_s}$$

$$\text{so therefore, } T = \frac{3}{2\pi N_s} * \frac{s E_2^2 R_2}{(R_2^2 + (s X_2^2))}$$

APPENDIX 3: Calculation of results

When $R=4.2 \Omega$ and $X_2= 15.97 \Omega$. Then substitute into equation 4.2 and get following

1. At $S= 0.00$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 0.00 \text{ N-m}$
2. At $S= 0.02$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 6.05 \text{ N-m}$
3. At $S= 0.04$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 11.89 \text{ N-m}$
4. At $S= 0.06$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 17.35 \text{ N-m}$
5. At $S= 0.08$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 22.27 \text{ N-m}$
6. At $S= 0.10$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 26.57 \text{ N-m}$
7. At $S= 0.12$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 30.21 \text{ N-m}$
8. At $S= 0.14$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 33.17 \text{ N-m}$
9. At $S= 0.16$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 35.52 \text{ N-m}$
10. At $S= 0.18$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 37.28 \text{ N-m}$
11. At $S= 0.20$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 38.54 \text{ N-m}$
12. At $S= 0.22$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 39.36 \text{ N-m}$
13. At $S= 0.24$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 39.83 \text{ N-m}$
14. At $S= 0.26$; $T= ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 39.99 \text{ N-m}$

- 15 At S= 0.28; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 39.92 \text{ N-m}$
- 16 At S= 0.30; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 39.65 \text{ N-m}$
- 17 At S= 0.32; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 39.24 \text{ N-m}$
- 18 At S= 0.34; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 38.71 \text{ N-m}$
- 19 At S= 0.36; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 38.10 \text{ N-m}$
- 20 At S= 0.38; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 37.43 \text{ N-m}$
- 21 At S= 0.40; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 36.72 \text{ N-m}$
- 22 At S= 0.42; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 35.98 \text{ N-m}$
- 23 At S= 0.44; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 35.22 \text{ N-m}$
- 24 At S= 0.46; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 34.46 \text{ N-m}$
- 25 At S= 0.48; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 33.71 \text{ N-m}$
- 26 At S= 0.50; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 32.95 \text{ N-m}$
- 27 At S= 0.52; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 32.21 \text{ N-m}$
- 28 At S= 0.54; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 31.49 \text{ N-m}$
- 29 At S= 0.56; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 30.78 \text{ N-m}$
- 30 At S= 0.58; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 30.08 \text{ N-m}$
- 31 At S= 0.60; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 29.41 \text{ N-m}$
- 32 At S= 0.62 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 28.76 \text{ N-m}$
- 33 At S= 0.64 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 28.12 \text{ N-m}$
- 34 At S= 0.66 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 27.51 \text{ N-m}$
- 35 At S= 0.68 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 26.91 \text{ N-m}$
- 36 At S= 0.70 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 26.33 \text{ N-m}$
- 37 At S= 0.72 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 25.78 \text{ N-m}$
- 38 At S= 0.74 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 25.24 \text{ N-m}$
- 39 At S= 0.76 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 24.72 \text{ N-m}$

- 40 At S= 0.78 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 24.22 \text{ N-m}$
- 41 At S= 0.80 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 23.73 \text{ N-m}$
- 42 At S= 0.82 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 23.26 \text{ N-m}$
- 43 At S= 0.84 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 22.81 \text{ N-m}$
- 44 At S= 0.86 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 22.37 \text{ N-m}$
- 45 At S= 0.88 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 21.74 \text{ N-m}$
- 46 At S= 0.90 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 21.53 \text{ N-m}$
- 47 At S= 0.92 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 21.14 \text{ N-m}$
- 48 At S= 0.94 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 20.75 \text{ N-m}$
- 49 At S= 0.96 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 20.38 \text{ N-m}$
- 50 At S= 0.98 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 20.02 \text{ N-m}$
- 51 At S= 1.00 ; $T = ((S \times 5365.04) / (17.64 + [S \times 15.97]^2)) = 19.68 \text{ N-m}$

When R= 2.2 Ω and X₂= 15.97 Ω substitute into equation 4.2 and get following

1. At S= 0.00; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 0.00 \text{ N-m}$
2. At S= 0.02; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 11.37 \text{ N-m}$
3. At S= 0.04; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 21.42 \text{ N-m}$
4. At S= 0.06; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 29.28 \text{ N-m}$
5. At S= 0.08; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 34.74 \text{ N-m}$
6. At S= 0.10; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 38.03 \text{ N-m}$
7. At S= 0.12; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 39.62 \text{ N-m}$
8. At S= 0.14; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 39.99 \text{ N-m}$
9. At S= 0.16; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 39.55 \text{ N-m}$
10. At S= 0.18; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 38.61 \text{ N-m}$

11. At S= 0.20; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 37.37 \text{ N-m}$
12. At S= 0.22; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 35.98 \text{ N-m}$
13. At S= 0.24; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 34.53 \text{ N-m}$
14. At S= 0.26; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 33.09 \text{ N-m}$
15. At S= 0.28; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 31.68 \text{ N-m}$
16. At S= 0.30; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 30.33 \text{ N-m}$
17. At S= 0.32; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 29.05 \text{ N-m}$
18. At S= 0.34; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 27.84 \text{ N-m}$
19. At S= 0.36; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 26.70 \text{ N-m}$
20. At S= 0.38; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 25.63 \text{ N-m}$
21. At S= 0.40; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 24.63 \text{ N-m}$
22. At S= 0.42; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 23.69 \text{ N-m}$
23. At S= 0.44; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 22.81 \text{ N-m}$
24. At S= 0.46; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 21.98 \text{ N-m}$
25. At S= 0.48; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 21.21 \text{ N-m}$
26. At S= 0.50; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 20.48 \text{ N-m}$
27. At S= 0.52; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 19.80 \text{ N-m}$
28. At S= 0.54; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 19.16 \text{ N-m}$
29. At S= 0.56; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 18.55 \text{ N-m}$
30. At S= 0.58; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 17.98 \text{ N-m}$
31. At S= 0.60; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 17.45 \text{ N-m}$
32. At S= 0.62; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 16.94 \text{ N-m}$
33. At S= 0.64; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 16.45 \text{ N-m}$
34. At S= 0.66; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 16.00 \text{ N-m}$
35. At S= 0.68; $T = ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 15.57 \text{ N-m}$

36. At $S= 0.70$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 15.15 \text{ N-m}$
37. At $S= 0.72$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 14.76 \text{ N-m}$
38. At $S= 0.74$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 14.39 \text{ N-m}$
39. At $S= 0.76$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 14.04 \text{ N-m}$
40. At $S= 0.78$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 13.70 \text{ N-m}$
41. At $S= 0.80$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 13.38 \text{ N-m}$
42. At $S= 0.82$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 13.07 \text{ N-m}$
43. At $S= 0.84$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 12.77 \text{ N-m}$
44. At $S= 0.86$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 12.49 \text{ N-m}$
45. At $S= 0.88$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 12.22 \text{ N-m}$
46. At $S= 0.90$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 11.96 \text{ N-m}$
47. At $S= 0.92$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 11.71 \text{ N-m}$
48. At $S= 0.94$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 11.48 \text{ N-m}$
49. At $S= 0.96$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 11.25 \text{ N-m}$
50. At $S= 0.98$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 11.03 \text{ N-m}$
51. At $S= 1.00$; $T= ((S \times 2810.3) / (4.84 + [S \times 15.97]^2)) = 10.81 \text{ N-m}$

When $R_2=6.2 \Omega$ and $X_2 = 15.97 \Omega$ we the following results

1. At $S= 0.00$; $T= ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 0.00 \text{ N-m}$
2. At $S= 0.02$; $T= ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 4.11 \text{ N-m}$
3. At $S= 0.04$; $T= ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 8.15 \text{ N-m}$
4. At $S= 0.06$; $T= ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 12.07 \text{ N-m}$
5. At $S= 0.08$; $T= ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 15.81 \text{ N-m}$
6. At $S= 0.10$; $T= ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 19.32 \text{ N-m}$

7. At S= 0.12; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 22.57 \text{ N-m}$
8. At S= 0.14; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 25.52 \text{ N-m}$
9. At S= 0.16; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 28.18 \text{ N-m}$
10. At S= 0.18; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 30.52 \text{ N-m}$
11. At S= 0.20; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 32.56 \text{ N-m}$
12. At S= 0.22; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 34.31 \text{ N-m}$
13. At S= 0.24; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 35.78 \text{ N-m}$
14. At S= 0.26; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 36.98 \text{ N-m}$
15. At S= 0.28; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 37.95 \text{ N-m}$
16. At S= 0.30; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 38.70 \text{ N-m}$
17. At S= 0.32; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 39.26 \text{ N-m}$
18. At S= 0.34; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 39.64 \text{ N-m}$
19. At S= 0.36; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 39.88 \text{ N-m}$
20. At S= 0.38; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 39.98 \text{ N-m}$
21. At S= 0.40; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 39.99 \text{ N-m}$
22. At S= 0.42; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 39.87 \text{ N-m}$
23. At S= 0.44; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 39.68 \text{ N-m}$
24. At S= 0.46; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 39.42 \text{ N-m}$
25. At S= 0.48; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 39.11 \text{ N-m}$
26. At S= 0.50; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 38.75 \text{ N-m}$
27. At S= 0.52; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 38.34 \text{ N-m}$
28. At S= 0.54; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 37.91 \text{ N-m}$
29. At S= 0.56; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 37.45 \text{ N-m}$
30. At S= 0.58; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 36.97 \text{ N-m}$
31. At S= 0.60; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 36.48 \text{ N-m}$

32. At S= 0.62; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 35.98 \text{ N-m}$
33. At S= 0.64; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 35.47 \text{ N-m}$
34. At S= 0.66; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 34.96 \text{ N-m}$
35. At S= 0.68; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 34.44 \text{ N-m}$
36. At S= 0.70; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 33.93 \text{ N-m}$
37. At S= 0.72; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 33.41 \text{ N-m}$
38. At S= 0.74; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 32.91 \text{ N-m}$
39. At S= 0.76; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 32.40 \text{ N-m}$
40. At S= 0.78; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 31.91 \text{ N-m}$
41. At S= 0.80; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 31.42 \text{ N-m}$
42. At S= 0.82; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 30.94 \text{ N-m}$
43. At S= 0.84; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 30.46 \text{ N-m}$
44. At S= 0.86; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 30.00 \text{ N-m}$
45. At S= 0.88; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 29.54 \text{ N-m}$
46. At S= 0.90; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 29.09 \text{ N-m}$
47. At S= 0.92; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 28.65 \text{ N-m}$
48. At S= 0.94; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 28.22 \text{ N-m}$
49. At S= 0.96; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 27.80 \text{ N-m}$
50. At S= 0.98; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 27.39 \text{ N-m}$
51. At S= 1.00; $T = ((S \times 7919.8) / (38.44 + [S \times 15.97]^2)) = 26.99 \text{ N-m}$

APPENDIX 4: TABLE 6.0 (TABLE SHOWING SWG)

SWG (STANDARD WIRE GAUGE) TO MM CONVERSION TABLE

Sometimes you need to convert SWG (Standard Wire Gauge) to mm (millimeter) unit. For converting SWG to mm, you can use this table below:

SWG	Dia(mm)	SWG	Dia(mm)	SWG	Dia(mm)	SWG	Dia(mm)

1	7.6200	14	2.0320	27	0.4166	40	0.1219
2	7.0104	15	1.8288	28	0.3759	41	0.1118
3	6.4008	16	1.6256	29	0.3454	42	0.1016
4	5.8928	17	1.4224	30	0.3150	43	0.0914
5	5.3848	18	1.2192	31	0.2946	44	0.0813
6	4.8768	19	1.0160	32	0.2743	45	0.0711
7	4.4704	20	0.9144	33	0.2540	46	0.0610
8	4.0640	21	0.8128	34	0.2337	47	0.0580
9	3.6576	22	0.7112	35	0.2134	48	0.0406
10	3.2512	23	0.6096	36	0.1930	49	0.0305
11	2.9464	24	0.5588	37	0.1727	50	0.0254
12	2.6416	25	0.5080	38	0.1524		
13	2.2368	26	0.4572	39	0.1321		

APPENDIX 5:-

A VISUAL BASIC PROGRAMMING TO GENERATE THE ABOVE TORQUE VALUE

(A) 'TO COMPUTE FOR T WHEN R=4.2Ω

DIM S, T AS DOUBLE

FOR S=0 TO 1 STEP 0.02

T=[((S*5365.04)/(17.64+(S*15.97)²))]

LABEL1.CAPTION=T

LIST1.ADD ITEM_T

RECORDSET.SAVE

NEXT SUB

END

(B)'TO COMPUTE FOR T WHEN R=2.2Ω

DIM S, T AS DOUBLE

FOR S=0 TO 1 STEP 0.02

T=[((S*2810.3)/(4.84+(S*15.97)²))]

LABEL1.CAPTION=T

LIST1.ADD ITEM_T

RECORDSET.SAVE

NEXT SUB

END

(C)'TO COMPUTE FOR T WHEN R=6.2Ω

DIM S, T AS DOUBLE

FOR S=0 TO 1 STEP 0.02

T=[((S*7919.8)/(38.44+(S*15.97)²))]

LABEL1.CAPTION=T

LIST1.ADD ITEM_T

RECORDSET.SAVE

NEXT SUB

END