DESIGN OF THREE PHASE INDUCTION MOTOR USING MATLAB PROGRAMME

A
Project Report Submitted by

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Under the Guidance of

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CERTIFICATE

This is to certify that the project work titled **DESIGN OF THREE PHASE INDUCTION MOTOR USING MATLAB PROGRAMME** submitted by **T.SUBRAHMANYAM V.K.M.B** [245113734049] in partial fulfillment of requirements for the degree of BACHELOR of ENGINEERING IN ELECTRICAL AND ELECTRONICS awarded by OSMANIA UNIVERSITY, HYDERBAD is bonafide work carried out by him during the academic year 2016-2017.

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CONTENTS

LIST OF ABBREVIATIONS

Symbol	Description	Symbol	Description
poles	Poles	Dr	Rotor Diameter(mm)
phases	Phases	lg	Length of air gap (mm)
kw	Winding Factor	Sr	Rotor Slots
Bav	Specific magnetic loading(T)	Lmts	Mean length of stator turns (mm)
ac	Specific electric loading(A/m)	Di	Inner diameter of Rotor Laminations (mm)
Co	Output Coefficient	Ysr	Rotor slot pitch (mm)
D	Diameter of stator(m)	Ib	Rotor bar current (A)
L	Stator core length (metres)	Im	Magnetizing current per phase (Amp)
Esa	Stator voltage per phase(V)	Brc	Rotor core flux density(T)
f	Frequency(Hz)	Wsr	Width of rotor bar (mm)
eff	Theoretical expected efficiency	Ysb	Rotor slot pitch at bottom in mm
yss	Stator slot pitch(mm)	A	Allowance for skewing (mm)
dss	Depth of stator slot(mm)	Rb	Resistance of each bar (ohms)
pf	Power factor	CLRb	Copper loss in rotor bars(W)
Li	Net active iron length(m)	Ie	End ring current (A)
tau	Pole pitch in mm	Db	Rotor bar current density(A/mm2)
qs	Slots per pole per phase	CLER	Copper loss in End rings (W)
Zss	Conductors per slot	De	Current density in end ring(A/mm2)
Wts	Width of stator teeth(mm)	Doe	Diameter of outer end ring (mm)
Ts	Stator turns per phase	Die	Diameter of inner end ring (mm)
Ss	Stator slots	Dme	Mean diameter of end ring (mm)
Kwss	Winding factor for stator	Vsteeth	Volume of stator teeth (m3)
Kp	Pitch factor of stator	ILst	Iron loss in stator teeth(W)
Kd	Distribution factor of stator	ILsc	Iron loss in stator core (W)
Is	Stator line current(Amp)	qr	Rotor slots per pole per phase
is	Stator current per phase(A)	Io	No load current (Amp)
Acs	Area of stator core(mm2)	X0	Overhang leakage (ohms)
Bcs	Stator core flux density(T)	Xs	Slot leakage reactance (ohms)
dcs	Depth of stator core(mm)	Xm	Magnetizing Reactance(ohms)
Do	Outside diameter including stator laminations (mm)	Il	Loss component of no load current (A)
lcs	Length of flux path in stator core(mm)	Xz	Zig zag leakage(ohms)
lcr	Length of flux path in rotor core (mm)	rs	Resistance of stator winding per phase (ohms)
lge	Length of effective sir gap	AT	Total Ampere turns

Kgss	Gap contraction for stator slots	ATST	MMF required for stator teeth (A/m)

Symbol	Description	Symbol	Description
Kgsr	Gap contraction factor for rotor slots	ATCS	MMF required for stator core(A/m)
Kgs	Gap contraction factor for slots	ATRT	MMF required for rotor teeth(A/m)
Kgd	Gap contraction factor for ducts	ATRC	MMF required for rotor core(A/m)
Kg	Gap contraction factor	ATg	MMF required for air gap (A/m)
Ag	Area of air gap(mm2)	Wt	Tooth width at the root of rotor bar (mm)
St	Ares of stator teeth per pole	FandW loss	Friction and windage loss (Watts)
rsp	Rotor slot permeance	Zs	Impedance of rotor at stand still (ohms)
rsps	Rotor slot permeance referred to stator	Atr	Area of rotor teeth at one third height from narrow end
Tssp	Total specific slot permeance	Btr60	Flux density of rotor teeth at one third height(T)
Bg	Maximum flux density in air gap (T)	BTrt60	Flux density at 60 degrees of rotor teeth(T)
Wtsonethird	Width of rotor tooth at one third height from narrow end (mm)	ATr	Ampere turns of the rotor teeth corresponding to one third height of rotor teeth
Ysb	Slot pitch at bottom of slots(mm)	Wsteeth	Weight of stator teeth(Kg)
ATrc	Ampere turns corresponding to rotor core flux density(A/m)	Fdst	Flux density in stator teeth(T)
ATsc	Ampere turns corresponding to stator core flux density(A/m)	Btssixty	Flux density of stator teeth at 60 degrees
atsst	Ampere turns corresponding to stator teeth flux density	ssl	Stator slot leakage
Isc	Short circuit current per phase (Amp)	Ysb	Slot pitch at bottom of slots(mm)
Pist	Specific Iron loss in stator teeth(W/kg)	Pisc	specific iron loss in stator core (W/kg)
ILst	Iron loss in stator teeth(W)	IL core	Ion loss in stator core)W)

ABSTRACT

The objective of the Project is to design three phase cage induction motor in M-File of MATLAB Software using synthesis method and Circle Diagram. The design aspects are divided into five modules such as calculation of Diameter of Stator (D) and Length of the Stator Core (L), Stator Design, Rotor Design, Calculation of no load & short circuit current and Efficiency at full load.

The MATLAB code thus developed is validated by performing case studies taking two common applications of three phase squirrel cage induction motors used in pumping and compressors.

The MATLAB output generated chiefly no-load current, short circuit current, no-load power factor and short circuit power factor, which are used in the construction of respective Circle Diagram. The Circle Diagram in turn generated full load current per phase, full load power factor, ratio of maximum torque to full load torque & starting torque to full load torque and slip.

The design features developed from MATLAB and performance data obtained from Circle Diagram for 3 and 30 HP motors are in good agreement with those available commercially.

CHAPTER 1

INTRODUCTION

The most commonly used electrical motor for various applications is the AC Induction motor. The Induction motor was invented by NIKOLA TESLA in 1898. The Induction motors are used in industrial applications ranging from small workshops to large industries. They are employed as the prime movers in most of the industries. Some of the applications are: the centrifugal pumps, compressors, crushers, conveyors and drilling machines etc. There are basically two types of induction motors namely Single Phase Induction Motor and Three phase Induction Motor. The design aspects of a motor are kept confidential by the manufacturers for obvious commercial reasons. The design software used in manufacturing the motors are expensive and owned by private companies who cannot disclose the details of it for obvious reasons. Several researchers have worked on developing design software like Visual Basic (Gheorghe Scutaru et al., 2010), Windows programming platform (Deepa Vincent and Bindu R, 2013), Genetic Algorithm (Mehmet Çunkaş and Ramazan Akkaya, 2006), MATLAB (Somasekhar, 2010) besides some free software like that of JMAG-Express Public (https://www.jmag-international.com/express/). In this project, we have developed code for designing of three phase squirrel cage induction motor in M-File of MATLAB software and validating the same taking two applications like motors used in pumping and compressor. The new addition to the earlier reported MATLAB design software programme by Somasekhar 2010, being reported in this Project is inclusion of Reactance of motor in the coding programme. The reactance is sum of that contributed by slot leakage, zig-zag leakage and overhang leakage. Reactance helps in computation of Impedance of rotor which in turn helps in calculation of short circuit current and ratio of I_{sc}/I_{rated} for a given application.

1.1. Motivation

The motivation for taking-up this study is to utilize the rapidly advancing computer aided design (CAD) in all engineering fields including electrical machine design. The computer aided design eliminates the tedious and the consuming hand calculations thereby releasing the designer from numerical drudgery to enable him time to grapple with physical and logical ideas thereby accelerating the design process. The use of computer makes possible more trail designs, and enables sophisticated calculations to be made without intolerable tedium and excessive time. Amongst the many advantages of CAD, the most conspicuous being possibility to select an optimized design with reduction in cost and improvement in performance.

1.2. Project Outline

In this project we develop code for designing of three phase squirrel cage induction motor in M-File of MATLAB software, considering the following five modules such as Separation of Diameter (D) and Length of the Stator Core(L), Stator Design, Rotor Design, Calculation of no load and short circuit current ,Efficiency at full load. The code thus developed is validated by performing two case studies taking two common applications of three phase squirrel cage induction motors (3 HP & 30 HP) such as a pump and a compressor. The output obtained for the two applications in MATLAB is compared with the circle diagram constructed for each application using AUTOCAD 2013 drawing software. The usage of different slots for different ratings of the motor is observed and finally, the project is concluded by drawing machine diagram.

1.3. Report Organization

CHAPTER 1 deals with introduction, motivation and project outline. CHAPTER 2 on theory of induction motors involving aspects on Stator Design, Rotor Design, Calculation of no load current & Short circuit current and Efficiency. The Chapter also gives the Code development procedure adopted in the project including flowcharts. CHAPTER 3 details the Code developed for design of three phase cage induction motor in which two case studies were investigated. The first case study is to design a three phase cage induction motor for pumping water to pre-defined head and the second case study is to design a three phase cage induction motor to drive a reciprocating two stage air compressor. CHAPTER 4 gives the Results. CHAPTER 5 deals with Conclusions of the investigations.

CHAPTER 2

LITERATURE REVIEW

This background literature presented in this Chapter discusses the following three aspects namely, the developments that have taken place on computer aided design of motors, the theory of induction motors and finally code development in MATLAB for design of induction motors along with the flow-charts of the algorithm.

2.1. Computer Aided Design of Induction Motors

Although the design procedures for induction motors are well established, there are some areas which require special attention. The manual design of motor account for lengthy calculations and any changes in parameters for an acceptable design leads to recalculation. Thus considerable time and effort of the designer is required to carry out the calculations accurately. To cite an example, after the completion of calculations of an IM design it has been observed that performance of the machine is not satisfactory and dimension of the machine is uneconomical. To solve this, the designer has to change some design parameters like electric loading, magnetic loading, insulation thickness etc. Hence iterative calculation of the entire design procedure is required to achieve a satisfactory result. The approximations assumed in the manual calculations also lead to inaccurate results. Computer aided design excel in the fact that computers can perform a very large number of calculations to the required degree of accuracy in short time. The essential thing is that it has to be suitably programmed to arrive at the optimum design. The design features of an induction motor are classified as constructional wise and performance wise and the results are combined. [1] The design software used in manufacturing the motors are expensive and owned by private companies who cannot disclose the details of it. So the demand and requirement of design software for educational purpose is on the rise.

Gheorghe Scutaru et al. (2010) developed a program for optimized design or re-design of three-phase induction motors conceived in VISUAL BASIC language. The program structure is modular and can thus be adjusted to the most varied requirements of induction motor design. For its users, the program offers several facilities, i.e. a friendly interface, different ways of formulating the optimum problem, an updatable database including information on the characteristics of the materials used and the manufactured motors, the user's guide that comprises the detailed description of the program and explanations for each computation step.

Deepa Vincent and Bindu R. (2013). presented a software development strategy for the design of three phase squirrel cage induction motors in windows programming platform. The software technologies used are Visual Basic 6 for form design and coding, database developed in Microsoft Access comprising information on standards used and layouts of material characteristics used for manufacturing the motor are plotted in Microsoft Excel. The aim of this software lies in reducing the redesign time during the course of learning the design procedure of induction motor. It enables students to verify their design and analyze the performance of machine by changing relevant parameters in less time. The software is made user friendly as it provides a checklist, an easy design data supply and online design tips in each module.

Free software is also available for the design of induction motors like the one called JMAG-Express Public (https://www.jmag-international.com/express/). This software allows calculation of basic motor properties in one second. by entering the geometry template, materials, winding, and drive conditions as parameters, you can obtain the induced voltage constant, torque constant, inductance properties, current vs. torque properties, revolution speed vs. torque properties, iron loss/copper loss properties, etc. in a split second. When the desired power (W) is specified, the size and comparative loading needed to achieve it are calculated automatically.

Mehmet Çunkaş and Ramazan Akkaya (2006) presents Genetic Algorithm for optimization and three objective functions namely torque, efficiency, and cost are considered. The motor design procedure consists of a system of non-linear equations, which imposes induction motor characteristics, motor performance, magnetic stresses and thermal limits. Computer simulation results are given to show the effectiveness of the proposed design process.

Somasekhar (2010) worked on MATLAB programme for design of induction motor.

2.2. Induction Motors

Our project pertains with the design of a three phase Induction Motor. The two types of three phase Induction motors are:

1. Squirrel cage induction motor
2. Slip ring induction motor.

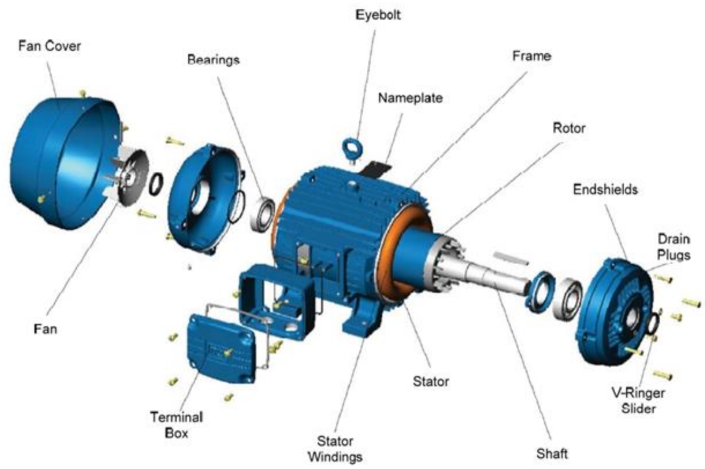


Figure 2.1: A Typical Three Phase Induction Motor

The Induction motor (as shown in Figure 2.1) is an electromechanical conversion device which always runs at a speed less than synchronous speed (asynchronous speed). This is because the rotating magnetic field that is produced in the stator will generate flux in the rotor which will make the rotor to rotate, but due to the lagging of flux current in the rotor with flux current in the stator, the rotor will never reach to its rotating magnetic field speed i.e. the synchronous speed. Synchronous speed is the speed of the rotational magnetic field. An AC three phase Induction motor consists of a stator and a rotor. Fig. 2.2 shows the cross sectional view of the stator of three phase Induction motor and Fig.2.3 shows the coils present inside the three phase Induction motor and also dissembled parts of three phase squirrel cage induction motors.

Fig 2.2: Cross sectional view of stator

Fig 2.3: Dissembled parts of Squirrel cage three phase Induction Motor

2.2.1 Design of Stator

Stator is the stationary part of induction motor. It is a cylindrical structure, built up of dynamo grade laminations. The purpose of stator is to enclose the core and winding. The centre circle (as shown in Fig. 2.4) are used for punching rotor laminations. The stator laminations are welded at several places around the outer cylindrical surface and the stack is later pushed into a frame for assembly.

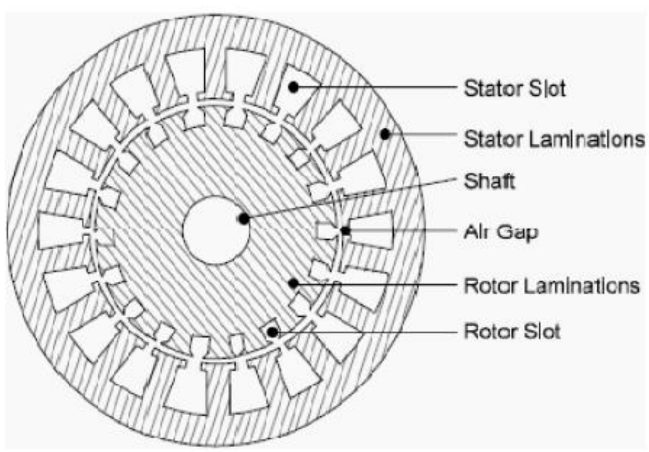


Fig.2.4: Parts of Stator

It is necessary to determine the total number of dovetails for fixing the segments to the frame and also to determine the location and number of dovetails per segment. The distance between adjacent dovetails should not be less than 60mm. The total number of segments is chosen in such a way as to provide an equal number of joints in the core flux paths of alternating poles. This is because, if the flux leaving the stator core from every south pole encounters a core joint when it turns anticlockwise, and no joint when it enter clockwise, the different reluctances offered to the two paths will result into a net difference between the core fluxes in two direction of flow, and the resultant flux links with the shaft. This resultant flux produces an alternating voltage between the two ends of the shaft, giving rise to **shaft currents** which in turn may cause damage of bearings, unless the bearings are insulated from the end shields.

For induction motors the frame should be strong and rigid both during the construction and after assembly of the machine. This is because the length of air gap is very small and if the frame is not rigid the rotor will not remain concentric with stator giving rise to **unbalanced magnetic pull.**

2.2.2. Stator Winding

Fig 2.5 shows the cross sectional view of windings on the stator core. Small motors with small number of slots and having a large number of turns per phase may use single layer mush windings. From the definition of specific magnetic loading (Bav):

Bav= (total flux around air gap)/(area of flux path at the air gap)

Therefore,

$$Bav = (p*\Phi)/(3.14*D*L)$$

$$\text{Flux per pole} = \Phi m = Bav*\tau*L \qquad [2.1.]$$

Stator Turns per phase =Ts

$$Ts = Es/(4.44*\text{frequency}*\Phi m*Kws) \qquad [2.2]$$

where Kws is stator Winding Factor.

Winding Factor is initially assumed to be 0.955 which is the value of Winding factor or infinitely distributed winding with full pitch coils.

Fig 2.5: Coil Winding on stator core.

2.2.3. Stator Conductors

For lower values of current, the round conductors are used,where as for higher currents bar or strip conductors are adopted .The use of the bar or strip conductors gives better space factor for the slots. Mathematically stator conductor per phase (Is) is:

$$Is=Q/(3*E)$$

Area of each stator conductor (as) = Is*δs [2.3]

where δs is the current density of the stator.

Stator slot pitch (Yss)

$$Yss = (pi*D)/Ss \qquad [2.4]$$

Total number of stator conductors =6*Ts

Conductors per slot = Zss = (6*Ts)/Ss [2.5]

When the number of conductors per slot is obtained, an approximate area of the slot is obtained.

Approximate area of each slot = (Zss*as)/(Space Factor)
The space factor varies from 0.25 to 0.4.

High voltage machines have lower space factors owing to large thickness of insulation. After obtaining the area of slot, the dimensions of slot are adjusted accordingly.

2.2.4 Stator Slots

The different shapes of the stator slots(as shown in figure 2.6) has an important effect upon the operating performance of the motor. The slots may be complete open slots or semi-closed slots. Semi enclosed slots are usually preferred for Induction motors because with their use, the air gap contraction factor is small giving a small magnetizing current. Also, there will be less tooth pulsation loss and quieter operation as compared to the open slots.

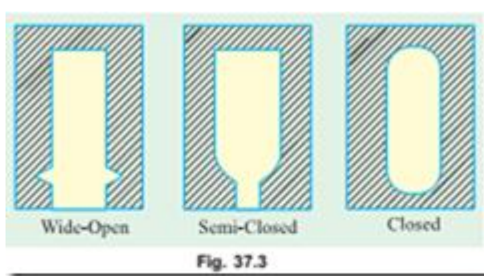


Fig 2.6: Types of slots

Open slots are utilized where it is desired to complete the coils outside the armature and drop them into slots. An advantage of open slots is that their uses avoid excessive slot leakage thereby reducing the leakage reactance.

In general, the number of slots should be selected as such to give an integral number of slots per pole per phase. The width of the slot should be so adjusted such that mean flux density of tooth should not exceed 1.7Wb/m2.The width of the teeth should not be too large as it results in narrow and deep slots. The deeper slots give a large value of leakage reactance.

2.2.5 Materials for Stator Design

The magnetic path, which comprises a set of slotted steel laminations pressed into the cylindrical space inside the outer frame. The magnetic path is laminated to reduce eddy currents, lower losses and lower heating. The stator frames maybe die cast or fabricated machines up to about 50kw rating usually have their frames die cast in a strong silicon aluminium alloy and in some cases with stator core cast in it. The frames of large size machines are fabricated by welding the steel plates. The advantage of fabrication is its adaptability to new design and steel plates. Frames of a small machine are made of a small unit. They are provided with feet by which they are fixed to the base plate. Machines which have radial ventilating ducts ,the stator core is placed inside the frame on the axial ribs thereby providing an annular space for air between core and the frame.

2.2.6 Enclosure for Stators

Various enclosures such as the drip proof (Fig.2.7), weather protected I ,weather protected II, totally enclosed, water -air- cooled. These enclosures are either integral with or are installed on top, bottom, or along sides of the frame.

Fig 2.7: Drip proof machine.

2.2.7 Causes for Vibration

The main reasons for vibration are: (i). Looseness of the parts which can result in shifting during operation, causing a change in balance should be minimized or avoided; (ii). Eccentric rotor is phenomena where the rotor core is not concentric with the journal bearings creates a point of minimum air gap which rotates with the rotor at one time rotational frequency. Associated with this there will be a net balance magnetic force acting at point of minimum air gap greater than force acting at the maximum gap. Since the force acting at the minimum gap is greater than the force acting at the maximum, this net unbalance force will rotate at rotational frequency with minimum air gap causing vibration at one times rotational frequency (as shown in Fig. 2.8)

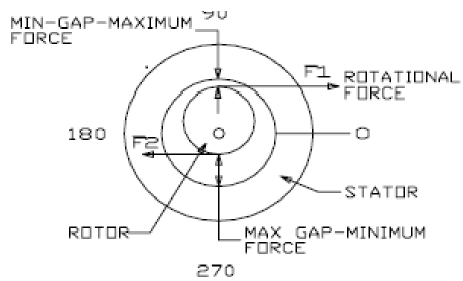


Fig. 2.8: Eccentric view of rotor.

(iii). The frequency of stator tooth is also concern. The tangential forces applied to teeth can excite a resonance condition in the tooth. The tooth is a cantilever beam supported at root by the core. The resonant frequency of cantilever beam is a function of width and beam length. A longer and narrow beam shall produce less resonant frequency; (iv) There can be fatigue and failure of the rotors bars in squirrel cage Induction motor due to continuous running, which leads to the vibration of the induction motor . Fig 2.9 describes performing swaging to reduce the vibration.

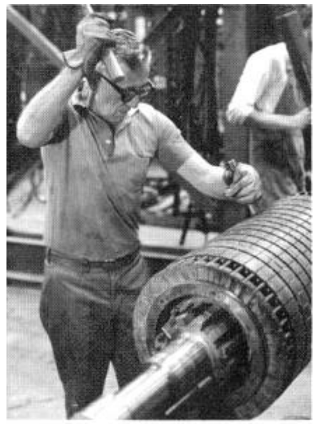


Fig. 2.9: A worker is performing swaging to tighten the bar material in the rotor slot.

2.2.8. Rotor

Rotor is the rotating part of the induction motor. The rotor also consists of a set of slotted silicon steel laminations pressed together to form of a cylindrical magnetic circuit and the electrical circuit. The electrical circuit of the rotor is of the following nature. Squirrel cage rotor consists of a set of copper or aluminum bars installed into the slots, which are connected to an end-ring at each end of the rotor. Fig 2.3 shows the squirrel cage rotor. The construction of this type of rotor along with windings resembles a 'squirrel cage'. Aluminum rotor bars are usually die-cast into the rotor slots, which results in a very rugged construction. Even though the aluminum rotor bars are in direct contact with the steel laminations, practically all the rotor current flows through the aluminum bars and not in the lamination. Most of the induction motor are squirrel cage type. These are having the advantage of rugged and simple in construction and comparatively cheaper. However they have the disadvantage of lower starting torque. In this type, the rotor consists of bars of copper or aluminum accommodated in rotor slots. In case slip ring induction motors the rotor complex in construction and costlier with the advantage that they have the better starting torque. This type of rotor consists of star connected distributed three phase windings. Between stator and rotor is the air gap which is a very critical part. The performance parameters of the motor like magnetizing current, power factor, over load capacity, cooling and noise are affected by length of the air gap. Hence length of the air gap is selected considering the advantages and disadvantages of larger air gap length.

Advantages:

(i) Increased overload capacity

(ii) Increased cooling

(iii) Reduced unbalanced magnetic pull

(iv) Reduced in tooth pulsation

(v) Reduced noise

Disadvantages

(i) Increased Magnetising current

(ii) Reduced power factor

From Fig. 2.10, it can be understood that that the air gap length varies inversely with the power factor.

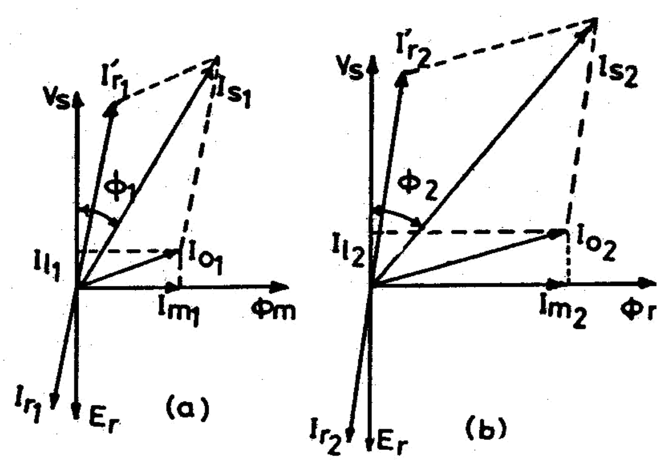


Fig. 2.10: Variation of power factor with air gap length.

Magnetizing 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. Hence in designing the length of the air gap following empirical formula is employed.

Air gap length $l_g = 0.2 + 2\sqrt{DL}$ mm(low power rating)

Air gap length $l_g = 0.2 + D$ mm(above 10 KW)

2.2.9. Number of slots

Proper numbers of rotor slots are to be selected in relation to number of stator slots otherwise undesirable effects will be found at the starting of the motor.

Cogging and Crawling are the two phenomena which are observed due to wrong combination of number of rotor and stator slots. In addition, induction motor may develop unpredictable cusps in torque speed characteristics or the motor may run with lot of noise. Cogging and Crawling phenomena are discussed in the next section.

2.2.10 Crawling

The rotating magnetic field produced in the air gap of the will be usually non sinusoidal and generally contains odd harmonics of the order 3^{rd}, 5^{th} and 7^{th}. The third harmonic flux will produce the three times the magnetic poles of the fundamental, therefore synchronous speed of third harmonic is $1/3^{rd}$ of synchronous speed of fundamental. Similarly the 5^{th} and 7^{th} harmonics will produce the poles five and seven times the fundamental respectively. The presence of harmonics in the flux wave affects the torque speed characteristics. The motor with presence of 7^{th} harmonics is to have a tendency to run the motor at one seventh of its synchronous speed of fundamental. The 7^{th} harmonics will produce a dip in torque speed characteristics at one seventh of its normal speed as shown in torque speed characteristics.

2.2.11. Cogging

In some cases , where the number of rotor slots are not in proper relation to number of stator slots the machine refuses to run and remains stationary. Under such conditions there will be a locking tendency between the rotor and stator. Such a phenomenon is called cogging. Hence in order to avoid such bad effects a proper number of rotor slots are to be selected in relation to number of stator slots. In addition rotor slots will be skewed by one slot pitch to minimize the tendency of cogging, torque defects like synchronous hooks and cusps and noisy operation while running. Effect of skewing will slightly increase the rotor resistance and increases the starting torque. However this will increase the leakage reactance and hence reduces the starting current and power factor.

2.2.12 Selection of number of rotor slots:

The number of rotor slots may be selected using the following guide lines.

1. To avoid cogging and crawling: (a)$S_s \neq S_r$ (b) $S_s - S_r \neq \pm 3P$
2. To avoid synchronous hooks and cusps in torque speed characteristics $\neq \pm P, \pm 2P, \pm 5P$.
3. To avoid noisy operation $S_s - S_r \neq \pm 1, \pm 2, (\pm P \pm 1), (\pm P \pm 2)$

2.2.13 Rotor Bar Current:

Bar current in the rotor of a squirrel cage induction motor may be determined by comparing the mmf developed in rotor and stator.

Hence the current per rotor bar is given by

$I_b = (6 * Is * Kws * Ts * \cos\phi)/Sr$ [2.6]

where K_{ws} – winding factor for the stator

S_r – number of rotor slots

I_s – stator current

Ts-stator turns per phase

2.2.14. Cross sectional area of Rotor bar:

Sectional area of the rotor conductor 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 higher current density can be assumed. Higher current density will lead to reduced sectional area and hence increased resistance, rotor cu losses and reduced efficiency. With increased rotor resistance starting torque will increase. As a guide line the rotor bar current density can be assumed between 4 to 7 Amp/mm^2 . Hence sectional area of the rotor bars can be calculated as $A_b = I_b / \delta_b$ mm^2.

2.2.15 Shape and Size of the Rotor slots:

The closed slots with very small or narrow openings are employed for the rotor slots owing to large leakage reactance. The biggest advantage with it is reduced starting current. On the other side the disadvantage is ,with large leakage reactance, overload capacity is reduced. But most of the motors in market are designed to bear overload capacity. Semiclosed slots give better overload capacity and hence are employed in rotors.

2.2.16 Copper loss in rotor bars:

Knowing the length of the rotor bars and resistance of the rotor bars cu losses in the rotor bars can be calculated.

Length of rotor bar l_b = L + allowance for skewing

Rotor bar resistance = 0.021 x l_b / A_b [2.7]

Copper loss in rotor bars = I_b^2 x r_b x number of rotor bars. [2.8]

2.2.17 End Ring Current:

All the rotor bars are short circuited by connecting them to the end rings . The rotating magnetic field produced will induce an emf in the rotor bars which will be sinusoidal over one pole pitch. As the rotor is a short circuited body, there will be current flow because of this emf induced. The distribution of current in end rings are as shown in Fig 2.11 below. Referring to the figure considering the bars under one pole pitch, half of the number of bars and the end ring carry the current in one direction and the other half in the opposite direction. Hence, the maximum value of current in the end rings is the average of current of half the bars under one pole.

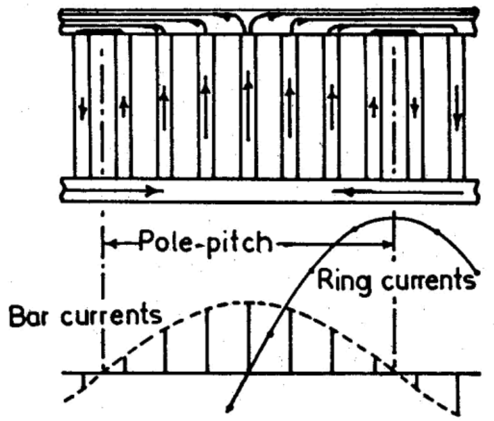


Fig 2.11: Distribution of current in end rings

Maximum end ring current $I_e(\text{max})$ = ½ (Number rotor bars / pole) $*I_b(av)$

$$= \tfrac{1}{2} \times S_r/P \times I_b/1.11$$

Hence rms value of $\quad I_e = 1/2\sqrt{2} \times S_r/P \times I_b/1.11$

$$= 1/\pi \times S_r/P \times I_b/1.11 \qquad [2.9]$$

2.2.18. Area of end ring:

Knowing the end ring current and assuming suitable value for the current density in the end rings cross section for the end ring can be calculated as:

Area of each end ring $A_e = I_e / \delta_e$ mm^2. [2.10]

Current density in end rings varies from 4 to 7A/mm^2.

2.2.19. Copper loss in End Rings:

Mean diameter of the end ring (D_{me}) is assumed as 4 to 6 cms less than that of the rotor. Mean length of the current path in end ring can be calculated as $l_{me} = \pi D_{me}$. The resistance of the end ring can be calculated as

$$r_e = 0.021 \times l_{me} / A_e$$

$$\text{Total copper loss in end rings} = 2 \times I_e^2 \times r_e$$

2.2.20 Equivalent Rotor Resistance:

Knowing the total copper losses in the rotor circuit and the equivalent rotor current equivalent rotor resistance can be calculated as follows.

$$\text{Equivalent rotor resistance } r'_r = \text{Total rotor copper loss} / 3 \times (I_r')^2 \qquad [2.11]$$

2.2.21 Performance Evaluation:

Based on the design data of the stator and rotor of an induction motor, performance of the machine has to be evaluated. The parameters for performance evaluation are iron losses, no load current, no load power factor, leakage reactance etc. Based on the values of these parameters design values of stator and rotor can be justified.

2.2.22 Iron losses:

Iron losses are occurring in all the iron parts due to the varying magnetic field of the machine. Iron loss has two components, hysteresis and eddy current losses occurring in the iron parts depend upon the frequency of the applied voltage. The frequency of the induced voltage in rotor is equal to the slip frequency which is very low and hence the iron losses occurring in the rotor is negligibly small. Hence the iron losses occurring in the induction motor is mainly due to the losses in the stator alone. Iron losses occurring in the stator can be computed as given below.

(a) Losses in stator teeth:

The following steps explain the calculation of iron loss in the stator teeth

(i) Calculate the area of cross section of stator tooth based on the width of the tooth at $1/3^{rd}$ height and iron length of the core as $A'_{ts} = b'_{ts} \times l_i$ m^2

(ii) Calculate the volume of all the teeth in stator $V_{ts} = A'_{ts} \times h_{ts} \times S_s$ m^3

(iii) Compute the weight of all the teeth based on volume and density of the material .
$W_{ts} = V_{ts} \times \rho$. ($\rho$ is density).

(iv) Iron loss /Kg (P_i) is calculated as explained below :
$P_i = P_h + P_e =$ ((area under hysteresis loop)*Frequency/ρ)+
$(K_e * f^2 * B_m^2)$ W/Kg [2.12]
Where :
P_h =Hystersis loss (W/Kg) K_h = Hysteresis co-efficient

B_m=Maximum flux density of stator teeth ,Wb/m^2

K=Steinmetz co-efficient (1.5 to 2.5)

$K_e = (\text{Л}^2 * t^2 / 6\rho)$ t=thickness

P_e=Eddy current loss/Kg

(v) Total iron losses in teeth= Iron loss /kg x weight of all teeth W_{ts}

(vi) Similarly, iron loss in core can be calculated as :

Iron loss/kg x weight of stator core.

(b) Losses in stator core

Similar to the above calculation of iron loss in teeth, iron loss in stator core can be estimated.

i. Calculate the area of cross section of the core as Acs = dcs x li m2.

ii. Calculate the mean diameter of the stator core below the slots as Dmcs= D + 2 dss+ dcs m.

iii. Compute the volume of stator core as Vcs = Acs x π Dmcs m3

iv. Calculate the weight of the stator core as Wcs = Vcs x density.

v. Total iron losses in core = Iron loss /kg x weight of core Wcs

vi. Similar to the calculation of losses in stator teeth,we proceed with the calculation of iron losses in stator core .

vii. Iron loss /Kg (P_i) is calculated as explained below :

$$P_i = P_h+P_e= ((\text{area under hysteresis loop})*\text{Frequency}/\rho)+ (K_e*f^2*B_m^2)\ \text{W/Kg} \quad [2.13]$$

Where :

B_m=Maximum flux density of stator core , Wb/m^2

K=Steinmetz co-efficient (1.5 to 2.5)

K_e=(Л^2*t^2/6ρ) t=thickness

P_e=Eddy current loss/Kg

Therefore, Total iron losses in induction motor = Iron loss in stator core + iron losses in stator teeth.

In addition friction and windage loss can be taken into account by assuming it as 1- 2 % of the output of the motor. **Hence total no load losses=Total iron losses + Friction and windage loss**.

2.2.23. No load current:

As seen from Figure(2.10), the no load current of an induction motor has two components magnetizing component, I_m and iron loss component, I_l. Phase relation between these currents is shown in Figure(2.10).

Thus the no load current $I_0 = \sqrt{(I_m)^2 + (I_l)^2}$ amps [2.14]

2.2.24. Magnetizing current:

Magnetizing current of an induction motor is responsible for producing the required amount of flux in the different parts of the machine. Hence this current can be calculated from all the magnetic circuit of the machine. The ampere turns for all the magnetic circuit such as stator core, stator teeth, air gap, rotor core and rotor teeth gives the total ampere turns required for the magnetic circuit. The details of the magnetic circuit calculations are studied in magnetic circuit calculations. Based on the total ampere turns of the magnetic circuit the magnetizing current can be calculated as

Magnetiszing current $I_m = p\ AT / (1.17\ k_w * T_{ph})$ [2.15]

where p – no of poles, AT – Total ampere turns of the magnetic circuit at 30^0 fromthe centre of the pole, T_{ph} – Number of stator turns per phase.

2.2.25 Iron loss component of current:

This component of current is responsible for supplying the iron losses in the magnetic circuit. Hence this component can be calculated from no load losses and applied voltage.

Iron loss component of current I_w= Total no load losses / (3 x phase voltage) [2.16]

2.2.26 No load Power Factor:

No load power factor of an induction motor is very poor. As the load on the machine increases the power factor improves. No load power factor can be calculated knowing the components of no load current.

2.3. Code Development Using MATLAB Programme

MATLAB is a high level language and interactive environment for numerical computation and programming. It contains mathematical function for linear algebra, Fourier analysis, filtering, optimization. Using MATLAB, we can analyze data, develop algorithm, create models and applications. The language , tools, built in math functions enable us to explore multiple approaches and reach a solution faster than the traditional spreadsheets or traditional programming languages such as C/C++ and Java. Further, MATLAB provides development tools for improvement of code quality, maintainability and maximizing performance. More than a million engineers and scientists in academia use MATLAB .

The design of three phase induction motor is performed using MATLAB software in M-File Script. The entire design of three phase Induction motor is divided into modules as listed below :

- Stator Design
- Rotor Design
- Calculation of No load Current
- Short circuit current
- Efficiency

The detailed design of each module ,necessary for programming in MATLAB is explained in the form of flow chart (**Fig. 2.12 to 2.18**) in following section.

STATOR DESIGN involves following :

- Main Dimensions.
- Output Equation.
- Stator Winding.
- Stator Turns per phase (Ts).
- Stator slot Pitch (Ysg).
- Length of mean turn of winding of stator (Lmts).

ROTOR DESIGN involves following :

- Relation for calculation of air gap length.
- Number of Rotor Slots.
- Design of rotor bars and current.
- Design of End Rings.
- Calculation of copper loss due to Rotor bars and end rings.

NO LOAD CURRENT involves following :

- Magnetizing Current .
- Loss Component of Current.
- Iron loss ,Friction Loss and Windage Loss.
- Calculation of Total no load losses.
- Calculation of No Load Current.

SHORT CIRCUIT CURRENT calculation involves following :

- Determination of permeance per unit length of the slot used.
- Calculation of Slot Leakage Reactance.
- Calculation of Overhang Leakage Reactance and ZigZag Leakage Reactance.

EFFICIENCY calculation involves following :

- Finding total losses of the machine.
- Calculation of input using total losses and calculation of efficiency.

Fig. 2.12 FLOW CHART FOR SEPARATION OF D and L

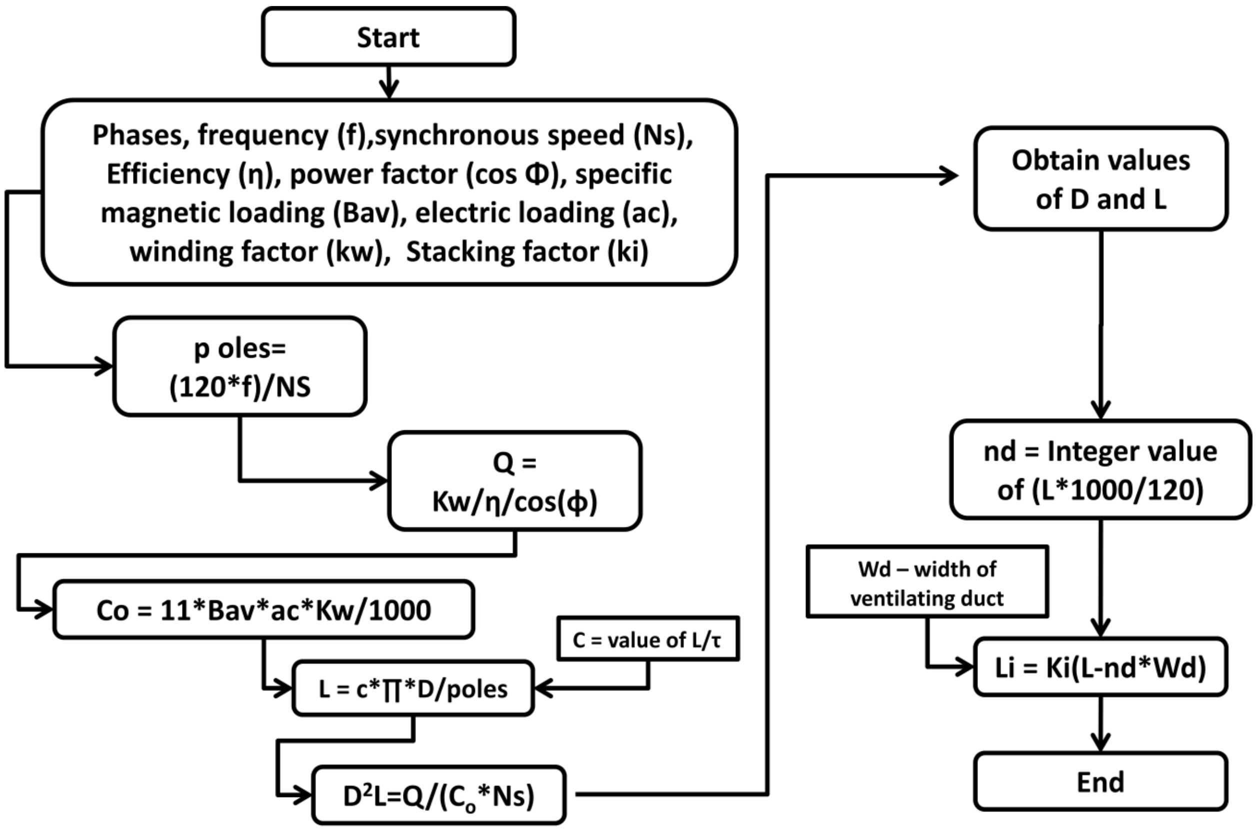


Fig. 2.13 FLOW CHART FOR STATOR DESIGN

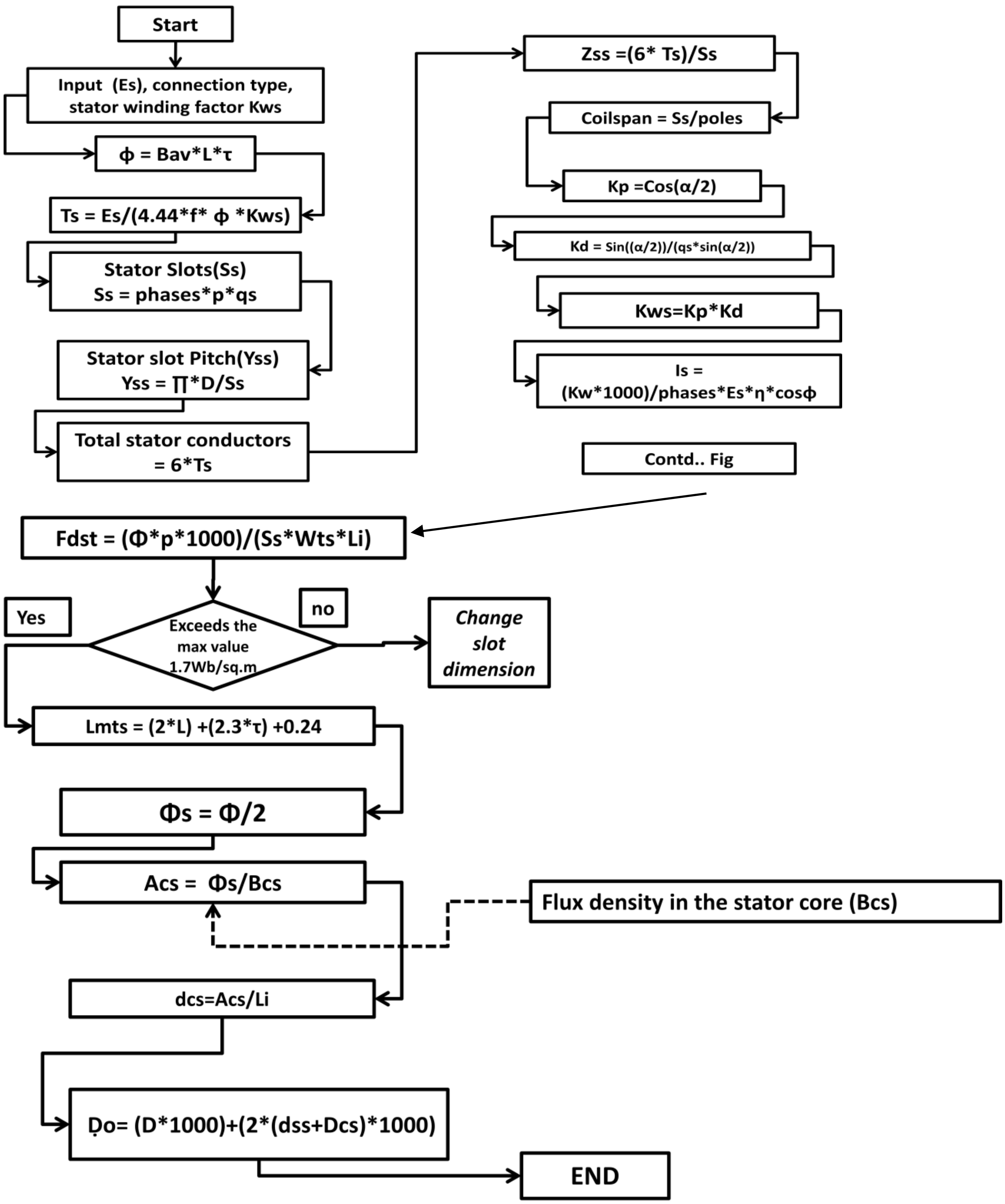


Fig. 2.14. FLOW CHART FOR ROTOR DESIGN

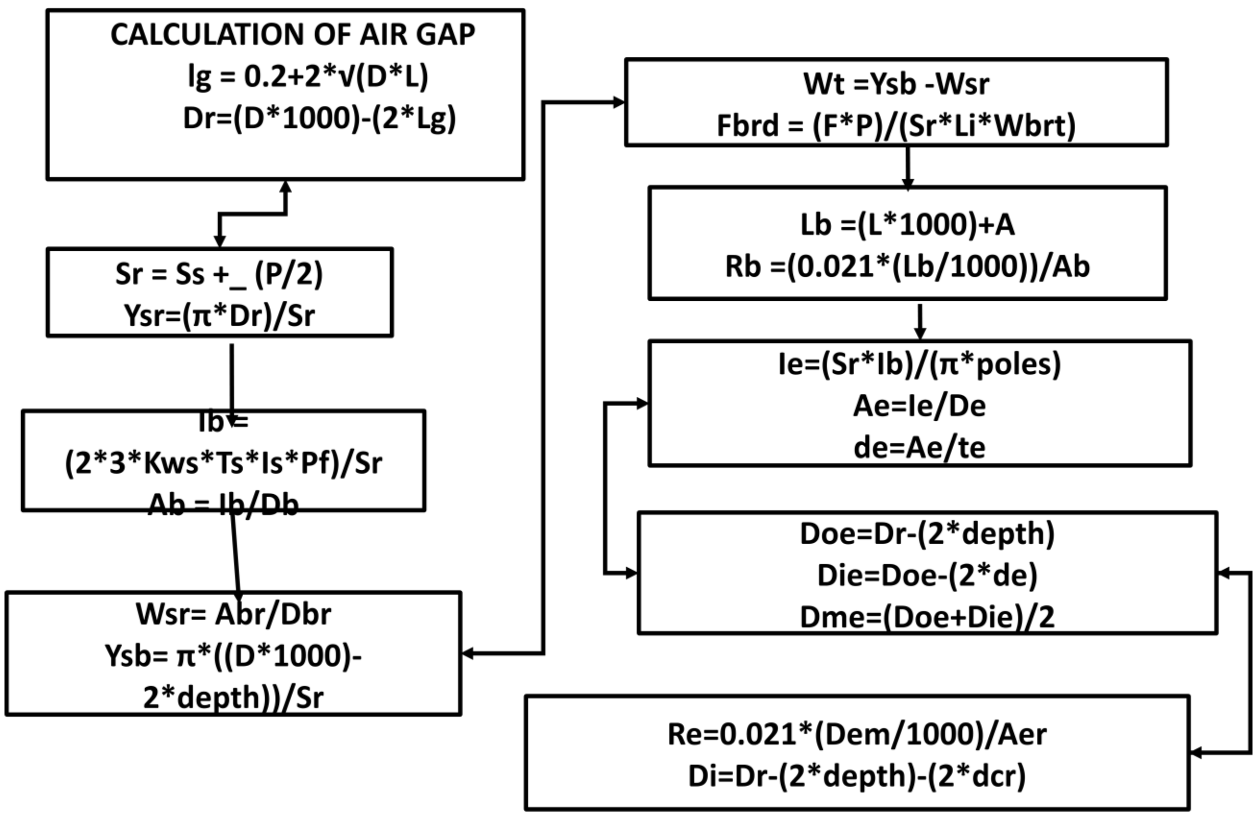


Fig. 2.15 FLOW CHART FOR NO LOAD CURRENT
(Calculation of magnetizing current)

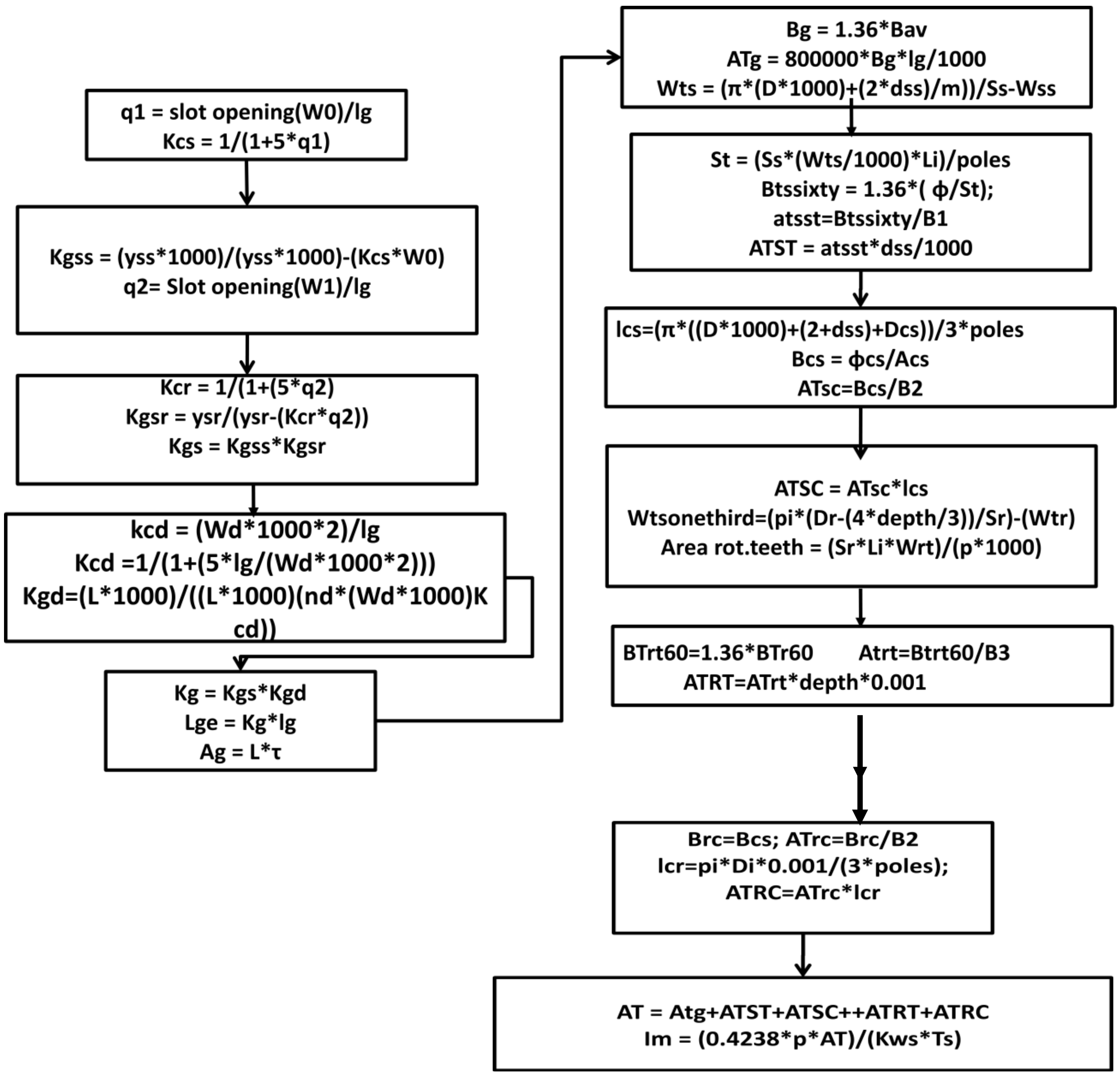


Fig 2.16: LOSS COMPONENT OF NO-LOAD CURRENT
(Calculation of loss component)

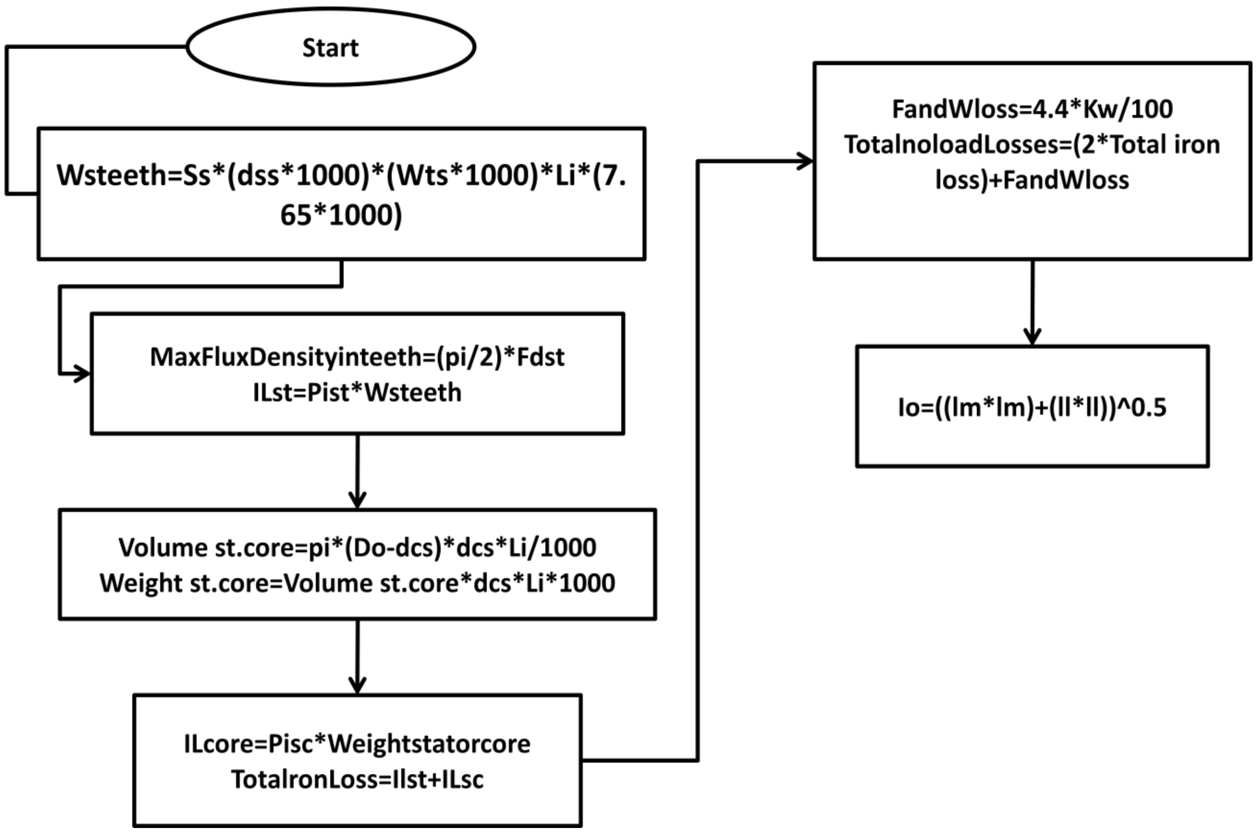


Fig 2.17. FLOW CHART FOR CALCULATION OF SHORT CIRCUIT CURRENT

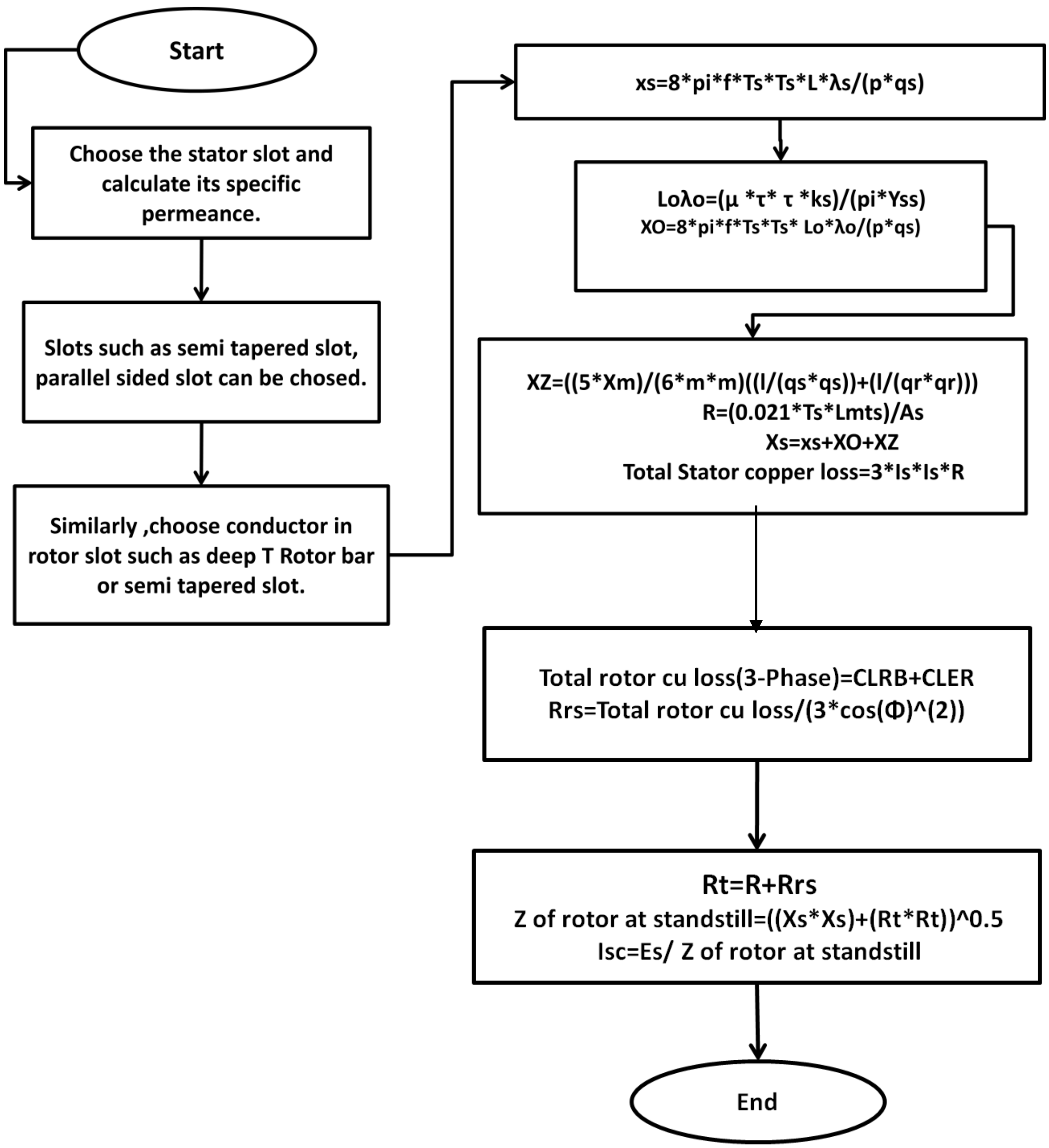
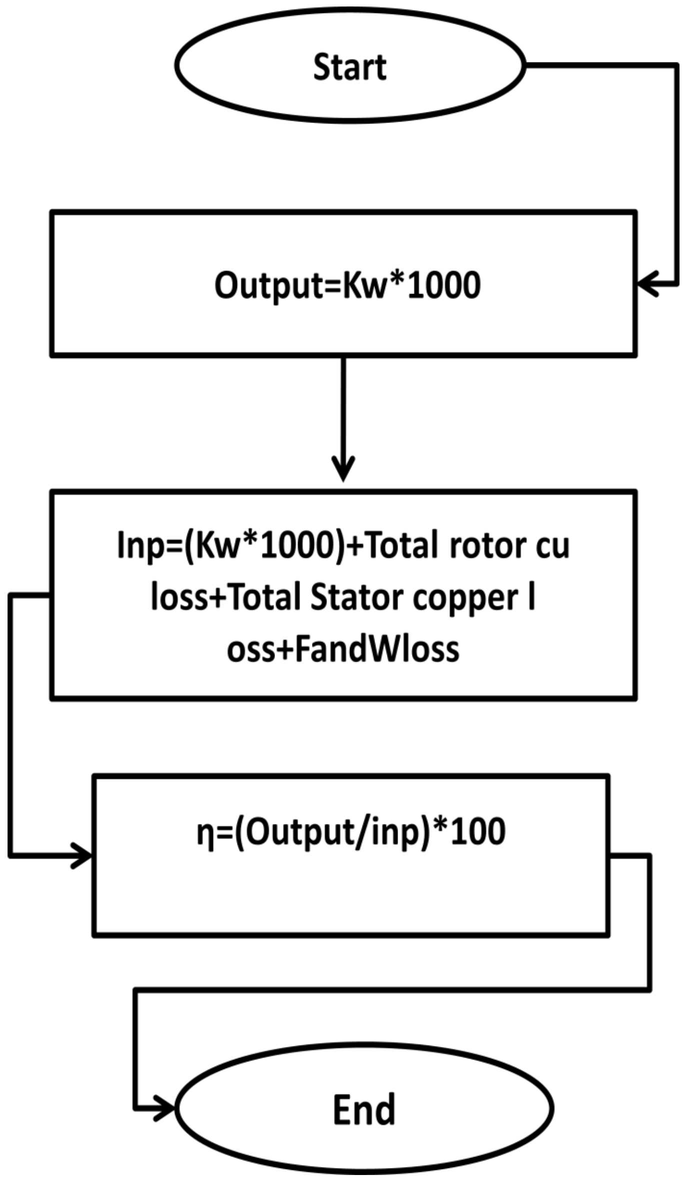


Fig. 2.18. FLOW CHART FOR CALCULATION OF EFFICIENCY



CHAPTER 3

GENERAL CODE STRUCTURE FOR DESIGN OF 3 PHASE INDUCTION MOTOR AND CASE STUDIES

The programme written in the following section is a general code structure for design of three phase squirrel cage induction motor. The two case studies considered for application are:

(i) **Design a three phase Induction Motor to pump water (Sp. Gravity of Water=1000kg/m3) to a height of 26metres with a discharge of 4litres per second and;**

(ii) **Design a three phase induction motor to drive a two stage compressor to deliver 4m^3 of free air per minute at a pressure of 11 bar.**

3.1. General Code Structure

```
Kw=input('Enter KW rating of motor\n');
phases=input('Enter number of phases\n');
Es=input('Enter the  three phase Stator Voltage  \n');
disp('Enter the type of winding : D  for Delta S for star ');
WDG=input('Type letter \n','s');
switch WDG
   case 'S'
     Esa=Es/1.732;fprintf('Stator Voltage per phase  = %d\n',ceil(Esa));
   case 'D'
       Esa=Es; fprintf('Stator Voltage per phase  = %d\n',ceil(Esa));
end
ns=input('Enter the synchronous speed in rps');
eff=input('input efficiency between 0 and 1 ');
if (eff<0)
   fprintf('Efficiency does not exist.Enter only positive value.\n');
break ;
end
pf=input('.enter full load power factor');
if((pf>1)||(pf<-1))
   fprintf('Power Factor is not correct.It is to be changed\n');
```

```
    disp('Enter correct Full Load power factor\n');
    pf=input('enter Full Load  pf\n');
    end
disp('Enter value of ac between 5000 to 45000 ampere conductors per metre \n' );
ac=input('Enter ampere conductors\n');
%f-- Freque.ncy
f=50;
poles=(2*f)/ns;
fprintf('Number of poles = %d\n',poles);
kw=0.955;
%Bav in Wb/m2.Co----Output Coefficient
disp(' Specific Magnetic Loading is directly related to overload capacity.For higher overload
capacity higher Bav value is taken');
disp('For 50Hz machines  design the value of Bav lies between 0.3 to 0.6 Wb/m2');
Bav=input('Enter the Specific Magnetic Loading in Wb/m2 : \n');
Co=11*kw*Bav*ac*10^(-3);
fprintf('Co=%f',Co);
%Q--KVA input;
eff*pf;
fprintf(' product eff*pf = %.2f\n',eff*pf);
Q=Kw/(eff*pf);
fprintf('KVA Input Q=%f\n',Q);
p1=Q/(Co*ns);
disp('For minimum cost L/tau varies from 1.5 to 2');
disp('Good power factor L/tau varies from 1 to 1.25');
disp('For Good Efficiency  L/tau ratio is 1.5');
disp('For good overall design L/tau ratio is 1');
ratio=input('Enter the L/tau ratio\n');
D=(p1/(pi*ratio/poles))^0.33;
fprintf('The value of D in metres  is %f\n',D);
L=(pi*ratio/poles)*D;
fprintf('The length in metres  =%f\n',L);
%Net Iron Length ---Li
Li=0.9*(L);
fprintf('Net Iron Length in metres = %f\n',Li);
tau=(pi*D)/poles;
fprintf('tau----Pole Pitch =%f\n',tau);
Fluxperpole =Bav*tau*L;
fprintf('Flux per pole in Wb =%f\n',Fluxperpole);
%Stator Turns per phase ---Ts
Ts=Esa/(4.44*f*kw*Fluxperpole);
```

```
fprintf('Ts=%d\n',ceil(Ts));
qs=input('Enter the Slots per pole per phase \n');
if(qs<2)
   fprintf('Not possible.Minimum number of slots per pole per phase should be two.\n');
   break;
end

Fluxperpole =Bav*tau*L;
fprintf('Flux per pole in Wb =%f\n',Fluxperpole);
%Stator Turns per phase ---Ts
Ts=Esa/(4.44*f*kw*Fluxperpole);
fprintf('Ts=%d\n',ceil(Ts));
qs=input('Enter the Slots per pole per phase \n');
if(qs<2)
   fprintf('Not possible.Minimum number of slots per pole per phase should be two.\n');
   break;
end
% Stator Slots ---Ss
Ss=phases*poles*qs;
coilspan=Ss/poles;
fprintf('Coil Span =%d\n',coilspan);
%Angle of chording---alpha
if(((coilspan/2)-floor(coilspan/2))==0);
   alpha =180/coilspan;fprintf('Alpha in degrees  is : %f',alpha);
   Kp=cosd(alpha/2);
   fprintf('Kp=%f\n',Kp);
else if(((coilspan/2)-floor(coilspan/2))~=0)
   fprintf('Cs is an odd number hence full pitch winding is used for which Kp=1\n');Kp=1;
   end
end
Kd=sind(60/2)/(qs*sind(60/(2*qs))); %Phase spread is 60 degrees
fprintf('Kd=%f\n',Kd);
Kwss=Kp*Kd;
fprintf('Kwss=%f\n',Kwss);
%Stator Currentper phase ---Is
Is=(Kw*1000)/(3*Esa*pf*eff);
Statorlinecurrent=1.732*Is;
fprintf('Stator Line Current in Amperes is %f\n',Statorlinecurrent);
%Current Density --4A/mm^2
AreaofStatorConductor=Is/4;
%nearest standard conductor has bare diameter of 0.94mm
as=pi*0.95*0.95/4;%as---Area of Stator Conductor
fprintf('Area of Stator Conductor  required=%f\n',AreaofStatorConductor);
%current density for stator conductors---Dels
Dels=Is/as;
fprintf('Current Density for stator conductors ---Dels in A/mm2 =%f',Dels);
```

```
Zss*as;
fprintf('Space Required for bare conductor in each slot =%f\n',Zss*as);
spacefactor=input('Enter Space Factor\n');
Zss*as/spacefactor;
fprintf('Area of each slot in mm^2 = %f\n',Zss*as/spacefactor);
%Minimum width of stator teeth ---Wts
Wts=Fluxperpole*poles/(1.7*Ss*Li);
fprintf('Wts in mm is =%f',Wts);
lip=input('Input lip in mm\n');
wedge= input('Wedge in mm \n');
h=input('Input height in mm \n');
slack=input('Enter the slack length in mm\n');
%Depth of slot---Dss
Dss=lip+wedge+h+slack;
Ws=pi*((D*1000)+2*(lip+wedge))/Ss +(2*pi*h/Ss);
fprintf('Depth of Stator Slot in mm = %0.2f\n',Dss);fprintf('Width of the slot at bottom in mm =
%0.2f\n',Ws);
%Length of mean turn ---Lmts
Lmts=(2*L*1000)+(2.3*pi*D*1000/poles)+24;
fprintf('Mean Length of Turn in mm  = %0.2f',Lmts);
%Flux Density in Stator Tooth---Fdst
Fdst=Fluxperpole*poles/(Ss*Li*dss*10^(-3));
fprintf('Flux Density in Stator Tooth in Wb/m2 =%f\n',Fdst);
if(Fdst>=1.7)
   fprintf('Change the Slot Dimensions and start\n');
   break
end
%Flux in Stator Core----Fluxstc
Fluxstc=Fluxperpole/2;
Acs=Fluxstc/1.2;fprintf('Acs =%f\n',Acs);
%Depth of Stator Core---dcs
dcs=Acs/Li;fprintf('dcs in mm =%0.1f\n',dcs*1000);
%Flux Density in Stator core----Bcs
%nearest core depth in mm----ceil(dcs*1000)

Bcs=1.2*(dcs*1000)/ceil(dcs*1000);
fprintf('Flux Density in Stator Core=%0.2f\n',Bcs);
%Outside Diameter of stator Lamination----Do
Do=(D*1000)+(2*Dss)+(2*dcs*1000);
fprintf('Depth of Stator Core and Outside Diameter(in mm ) are  =%f and %f\n',dcs,Do);
%-----------------------------------------------------------------------------------------------
   disp('For Squirrel Cage Induction Rotor');
   lg=0.2+(2*sqrt(D*L));
fprintf('\n THE LENGTH OF AIR GAP OF THE INDUCTION MOTOR in mm =%.4f  \n',lg);
Dr = (D*1000)-(2*lg);
fprintf('\n THE OUTER DIAMETER OF ROTOR in mm =%.4f mm \n',Dr);
```

```
% to find no of rotor slots
disp('In order to avoid synchronous cusps the difference of stator and rotor slots should not be +1*poles or -1*Poles or a multiple of poles');
disp('Difference of Stator slots and Rotor slots should not be equal to 3*poles for 3 phase Induction motor to avoid magnetic locking');
disp('Hence poles/2 is considered for calculation rotor slots');
Sr=Ss-(poles/2);
fprintf('the no of rotor slots is =%d\n',Sr);
Ysr=(3.14*D*1000)/Sr;
fprintf('the rotor slot pitch in mm =%d\n',floor(Ysr));
%to find the rotor bar current
Ib=pf*((6*Is*Ts)/Sr);
fprintf('\n the rotor bar current in Amperes  =%.4f amps\n',Ib);
% to find  rotor bar cross sectional area
Db=input('Rotor bar current density in A/mm2=\n');
if((Db<4)||(Db>7));
   fprintf('Not within limits\n');
   break;
end;
Ab = Ib /Db;
fprintf('\n THE  AREA OF  each ROTOR BAR =%f \n',Ab);
Wsr=input(‘Enter the width of rotor slot’);
depth=input(‘Enter the depth of the rotor slot’);
%dcr----Depth of Rotor Core
dcr=input(‘Enter the depth of rotor core’);
%Di----Inner Diameter of Rotor Lamination
Di=Dr-(2*depth)-(2*dcr);fprintf('Inner Diameter of Rotor Lamination = %f\n',Di);
Ysb=3.14*((1000*D)-(2*depth))/Sr ;
fprintf('\n the slot pitch at bottom in mm is  =%f\n',Ysb);
Wt=Ysb-Wsr;
fprintf('\n  the tooth width at root in mm is  =%f\n',Wt);
%copper loss in rotor bars
A=input('\n the allowance for skewing =%f\n');
Lb=(L*1000)+A;
fprintf(' the length of rotor bar in mm is  =%f\n',Lb);
Rb=0.021*Lb*0.001/Ab;
CL=Sr*Ib*Ib*Rb;
fprintf('the copper loss in rotor bars in Watts is=%f\n',CL);
%End Ring Current
Ie= (Sr*Ib)/(3.14*poles);
fprintf(' the end ring current in Amperes =%f\n',Ie);
%Area of end ring
De=6; % End ring current density is 4 to 6A/mm2
Ae = Ie/De;
fprintf(' the area of end rings=%f\n',Ae);
%Copper loss in End Rings
```

```
Dme=input('mean diameter in mm=\n');
Re= 0.021*(Dme*0.001*3.14/ Ae );
CR=2*Ie*Ie*Re;
fprintf(' the total copper loss in end rings=%f\n',CR);
Totalrotorcopperloss=CL+CR;
fprintf('Total Rotor  Copper Loss = %d',Totalrotorcopperloss);
%------------------------NO LOAD CURRENT
%Kgss----gap contraction factor for stator slots
slotopening=input('Enter the slot opening for stator slot  in mm\n');
gaplength=lg
qi=slotopening/gaplength;
 %Gap length is air gap length ----lg
q=[2 3 4 5 6 7 8 9 10];
Kcs=[0.3 0.42 0.52 0.6 0.68 0.72 0.78 0.82 0.85];

Kcsi=interp1(q,Kcs,qi);

%-----------------------------------------------
Kgss=Yss/(Yss-Kcsi*slotopening);
fprintf('gap contraction factor for stator slots =%0.3f\n',Kgss);
 %Gap length is air gap length ----lg
Slotopening=input('Enter the slot opening for Rotor slot  in mm\n');
Gaplength=lg
Qi=Slotopening/Gaplength;

%Gap Contraction factor for rotor slots----Kcsr
Q=[2 3 4 5 6 7 8 9 10];
Kcsr=[0.3 0.42 0.52 0.6 0.68 0.72 0.78 0.82 0.85];

Kcsri=interp1(Q,Kcsr,Qi);
Kgsr=Ysr/(Ysr-Kcsri*Slotopening);
fprintf('gap contraction factor for rotor slots=%0.3f\n',Kgsr);

Kgs=(Kgss*Kgsr);
fprintf('gap contraction factor for slots=%0.3f\n',Kgs);
%Gap Contraction Factor for ducts---kgd
Kgd=1;
Kg=(Kgs*Kgd);
fprintf('gap contraction factor=%f\n',Kg);
%area of air gap---Ag
Ag=pi*D*L/poles;
fprintf('area of air gap in metres =%f\n',Ag);
Bgs=1.36*Bav;
% Length if effective air gapo---lge
lge=Kg*lg;
 fprintf('effective length of air gap=%f\n',lge);
```

```
ATg=800000*Kg*Bgs*lg;
fprintf('Air gap in Ampere Turns/metre =%f\n',ATg);
%----------------------------------stator teeth-------
St=(Ss/poles)*Wts*Li;
fprintf('area of teeth per pole=%f\n',St);
Btssti=1.36*Fdst;
fprintf('flux density in stator teeth in wb/m^2 =%f\n',Btssti);
atts=[140 240 280 300 400 1200 2000 2200];
Btsst=[0.6 1 1.185 1.2 1.4 1.52 1.575 1.6 ];
attsi=interp1(Btsst,atts,Btssti);
St=attsi*dss*10^(-3);
fprintf('mmf required for stator teeth=%f\n',St);
%area stator core----Acs
Acs=Li*dcs;
fprintf('area of stator core in m2 =%f\n',Acs);
Lcs=(pi*(D+(2*Dss*0.001)+dcs))/(3*poles);
%Length of magnetic path through sttor core----Lcs
fprintf('length of stator core in metres =%f\n',Lcs);


atcs=[140 240 290 300 400 1200 2000 2200];
Bcs=[0.6 1 1.185 1.2 1.4 1.52 1.575 1.6 ];
Bcsi=1.2*dcs*1000/ceil(dcs*1000);
atcsi=interp1(Bcs,atcs,Bcsi);
fprintf('atcsi =%f\n',atcsi);
ATcs=atcsi*Lcs;
fprintf('mmf required for stator core=%f\n',ATcs);
%rotor teeth------
Wtsonethird=(pi*(Dr-(4*depth/3))/Sr)-(Wsr);
fprintf('Wtsonethird in mm =%f\n',Wtsonethird);
Atr=(Sr/poles)*Wtsonethird*0.001*Li;
fprintf('Atr=%f',Atr);
%Flux Density in rotor teeth at 1/3 height in Wb/m2
Btronethird=1.36*Wt/Wtsonethird;
atr=[140 240 290 300 400 1200 2000 2200];
Btrsixty=[0.4 1 1.185 1.2 1.4 1.52 1.64 1.7];
Btrsixtyi=1.36*Btronethird;
fprintf('Btrsixty=%0.2f',Btrsixtyi);
%Corresponding to this flux density atr=2000A/m
atri=interp1(Btrsixty,atr,Btrsixtyi);fprintf('atri=%f\n',atri);
ATr=atri*depth*0.001;
fprintf('MMF required for rotor teeth ATr=%f\n',ATr);
%Rotor Core
Acr=Li*dcr;

%atcr----Ampere Turns corresponding to Rotor core
```

```
Bcri=1.14;
atcr=[140 240 290 300 400 1200 2000 2200];
Bcr=[0.4 1 1.185 1.2 1.4 1.52 1.64 1.7];
atcri=interp1(Bcr,atcr,Bcri);fprintf('atcri=%f\n',atcri);
%lcr----Length of Flux path in Rotor Core
lcr=pi*Di*0.001/(3*poles);
ATcr=atcri*lcr;
fprintf('MMF for rotor core ATcr=%f\n',ATcr);
AT=ATg+St+ATcs+ATr+ATcr;
fprintf('Total AT = %f\n',AT);
Im=0.427*poles*AT/(Kwss*Ts);
fprintf('Im=%d\n',Im);
%Volume of stator teeth----Vsteeth
Vsteeth=Ss*Dss*0.001*Wts*Li*0.001;
Wsteeth=Vsteeth*(7.6)*10^(3);
MaxFluxDensityinteeth=(pi/2)*Fdst;
%Corresponding to MaxFluxDensityinteeth calculate IronLoss/Kg .
%Iron loss in stator teeth----ILst
ILst=(Iron Loss/kg)*Wsteeth;
fprintf('Iron Loss in Stator Teeth = %d\n',ILst);
%Iron Loss in Stator core----Ilsc
Volumestatorcore=3.14*((Do*0.001)-dcs)*dcs*Li;fprintf('Volumestatorcore =
%f\n',Volumestatorcore);
Weightstatorcore=Volumestatorcore*7.6*10^(3);
%Corresponding to Bcs calculate Iron Loss/Kg
ILcore=Weightstatorcore*(Iron loss/kg);
TotalIronLoss=ILst+ILcore;
fprintf('Total Iron Loss in Watts  = %d\n',2*TotalIronLoss);
Il=(2*TotalIronLoss)/(phases*Esa);
fprintf('Il=%f\n',Il);
Io=sqrt((Im*Im)+(Il*Il));fprintf('No Load Current = %d\n',Io);
fprintf('No Load Current as expressed as percentage of Stator Current = %d\n',(Io*100/Is));
FandWLoss=1.5*Kw*1000/100;
fprintf('Total No Load Loss=%d\n',(TotalIronLoss+FandWLoss));
%Short Circuit Current
%Stator Slot Leakage calculation for semi tapered slot
h1=h;
h2=0;
h3=wedge;
h4=lip;
w0=slotopening ; w1=input(‘w1’);w2=input(‘Enter w2’);
%Ws---Width at bottom of slot

c=((2*h1)/(3*Ws+3*w2))+(2*h2)/(w1+w2)+(2*h3)/(w1+w0)+(h4/w0);
ssl=4*c*pi*10^(-7);
fprintf('Specific Slot Permeance =%f\n',ssl);
```

```
%Rotor Slot Leakage for parallel sided slot
h5=input('Enter height of rotor bar');
h6=1;w01=Slotopening;
c1=(h5/(3*Wsr))+(h2/Wsr)+((2*h6)/(Wsr+w01))+(h4/w01);
rsp=4*pi*(c1)*10^(-7);
fprintf('Rotor Slot Permeance =%f\n',rsp);
rsps=rsp*(Ss/Sr)*Kwss^2;
Tssp=ssl+rsps;
fprintf('Total Specific Slot Permeance= %f\n',Tssp);
%Slot Leakage Reactance----Xs
Xs=8*pi*f*Ts*Ts*L*Tssp/(poles*qs);
fprintf('Slot Leakage Reactance =%f\n',Xs);
% Overhang Leakage---X0
X0=8*pi*f*Ts*Ts*(4*pi*10^((-7)))*(tau^(2))*0.875/(pi*Yss*poles*qs);
fprintf('Overhang Leakage Reactance=%f\n',X0);
%Zigzag Leakage----Xz
Xm=Esa/Im;qr=Sr/poles/phases;
Xz=(5/6)*(Xm/(phases*phases))*((1/(qs*qs))+(1/(qr*qr)));
fprintf('Zigzag Leakage Reactance=%f\n',Xz);
fprintf('Total Leakage Reactance referred to Stator in ohms = %f',(Xs+X0+Xz));
%Resistance of stator winding per phase ----rs
rs=Lmts*Ts*resistivitycopper/(as*1000);
fprintf('Resistance of stator winding per phase in ohms=%0.2f\n',rs);
Totalstatorcopperloss=phases*Is*Is*rs;fprintf('Total stator copper
loss=%d\n',Totalstatorcopperloss);
rotorcopperlossperphase=Totalrotorcopperloss/phases;
fprintf('Rotor Copper Loss per phase = %0.1f\n',rotorcopperlossperphase);
Rotorresistancereferredtostator=rotorcopperlossperphase/(Is*Is*pf*pf);
fprintf('Rotor resistance referred to stator = %0.2f',Rotorresistancereferredtostator);
%input----inp
inp=(Kw*1000)+Totalstatorcopperloss+TotalIronLoss+Totalrotorcopperloss+FandWLoss;
fprintf('Input= %d\n',inp);
efficiency=(Kw*1000)/inp;
```

3.2. Applications

3.2.1. Case Study 1

Design a three phase Induction Motor to pump water (Sp. Gravity of Water=1000kg/m3) to a height of 26 metres with a discharge of 4litres per second.

Given:

Rated Voltage = 415 V

Efficiency of Motor=80%

Efficiency of pump=60%

Solution :Water power= ρ*Q*g*H/1000

Work done in kw= ρ*Q*g*H/(1000*Ƞmotor*Ƞpump)
= 1000*9.8*4*0.001*26/(0.8*0.6)
= 2.125KW

Work done in HP is =2.125/0.746=2.84HP.

Nearest available rating of motor is 3HP greater than 2.84HP.

Group A 230 grade 0.5mm thick non-oriented electrical sheet laminations is used for the design. The B (Wb/m^2) Vs H (A/m) characteristics considered are given in Table 3.1.below **(**Courtesy : Precision Pressing Division of M/S Guest keen , Williams.)

Table 3.1. B and H characteristics for 3 phase induction motor

B(Wb/m^2)	**H(A/m)**
1.3	400
1.38	800
1.48	1600
1.72	8000
1.92	24000

Relation between B(Wb/m^2) and H(A/m) is B = aH/(1+bH)

Equation (1) : 1.38=a(800)/(1+(b*800))

Equation (2) : 1.48=a(1600)/(1+(b*1600))

Solving equations(1) and (2) for a and b we get a=0.0045 and b=0.0019.

Therefore B=(0.0045H)/(1+0.0019H) or H=B/(0.0045-0.0019B).

The design of three phase squirrel cage Induction motor for rating of 3HP is written below

The three phase squirrel cage induction motor is designed for ratio (L/ τ) =1.5 for good efficiency.

```
Head=input('Enter the total head(in metres) needed to pump the water');
%Q discharge;
Q=input('Enter the discharge in liters per second\n');
%g=9.81m/s2 andSpecific gravity of water =1000Kg/m3
Waterpower=1000*9.81*Q*(Head*0.001)/1000;
Efficiencyofpump=input('Efficiency of pump');
Efficiencyofmotor=input('Enter the efficiency of motor');
%Work done in KW=WKW
WKW=Waterpower/(Efficiencyofpump*Efficiencyofmotor);
fprintf('Work done in KW is %f\n',WKW);
Hp=(WKW)/0.746;
fprintf('The  nearest rating of the Motor in HP is %f\n',ceil(Hp));
HP=ceil(Hp);
Kw=0.746*HP;
phases=3;
Es=415;
f=50;
poles=8;
% winding in Stator
       Esa=Es/1.732;
 %Synchronous speed ---ns
ns=(2*f)/poles;
fprintf('Speed in RPS is = %d\n',ns);
kw=0.955;
eff=0.81;

pf=0.71;
disp('For 50Hz machines  design the value of Bav lies between 0.3 to 0.6 Wb/m2');
Bav=0.4;%Bav in Wb/m2
ac=13250;%ac is ampere conductors per metre.
%Output Coefficient ---Co
Co=11*kw*Bav*ac*10^(-3);
fprintf('Co=%f\n',Co);
%Q--KVA input;
eff*pf;
fprintf(' product eff*pf = %.2f\n',eff*pf);
Q=Kw/(eff*pf);
fprintf('KVA Input Q=%f\n',Q);
p1=Q/(Co*ns);
disp('For minimum cost L/tau varies from 1.5 to 2');
disp('Good power factor L/tau varies from 1 to 1.25');
disp('For Good Efficiency  L/tau ratio is 1.5');
disp('For good overall design L/tau ratio is 1');
ratio=1.5;
D=(p1/(pi*ratio/poles))^0.33;
```

```
fprintf('The value of D in metres  is %f\n',D);
L=(pi*ratio/poles)*D;
fprintf('The length in metres  =%f\n',L);
%Net Iron Length ---Li
Li=0.9*(L);
fprintf('Net Iron Length in metres = %f\n',Li);
tau=(pi*D)/poles;
fprintf('tau----Pole Pitch =%f\n',tau);
Fluxperpole =Bav*tau*L;
fprintf('Flux per pole in Wb =%f\n',Fluxperpole);
%Stator Turns per phase ---Ts
Ts=Esa/(4.44*f*kw*Fluxperpole);
fprintf('Ts=%d\n',ceil(Ts));
qs=2;
%(qs>=2)  that is two or more slots per pole per phase is good for design.
% Stator Slots ---Ss
Ss=phases*poles*qs;
coilspan=Ss/poles;
fprintf('Coil Span =%d\n',coilspan);
%Angle of chording---alpha
if(((coilspan/2)-floor(coilspan/2))==0);
    alpha =180/coilspan;fprintf('Alpha in degrees  is : %f',alpha);
    Kp=cosd(alpha/2);
    fprintf('Kp=%f\n',Kp);
else if(((coilspan/2)-floor(coilspan/2))~=0)
    %fprintf('Cs is an odd number hence full pitch winding is used for which Kp=1\n');
    Kp=1;
    end
end
Kd=sind(60/2)/(qs*sind(60/(2*qs)));
fprintf('Kd=%f\n',Kd);
Kwss=Kp*Kd;
fprintf('Kwss=%f\n',Kwss);
%Stator Line Current ---Is
Is=(Kw*1000)/(3*Esa*pf*eff);
fprintf('Stator Line Current in Amperes is %f\n ',Is);
StatorConductors=6*Ts;fprintf('Stator Conductors = %f\n',StatorConductors);
%Stator Slot Pitch Yss
yss = pi*(D*1000)/Ss;
fprintf('Stator slot pitch in mm is %f\n',yss);
if(yss>25);
    fprintf('the stator slot pitch of small induction motor should be less than 25mm.');
   break;
end
currentdensity=4;
AreaofStatorConductor=Is/currentdensity;
```

```
fprintf('Area of Stator Conductor  required in mm2=%f\n',AreaofStatorConductor);
Zss=(phases*poles*Ts)/Ss;
statorconductorsperslot=(phases*poles*Ts)/Ss;
fprintf('Stator Conductors per slot=%f\n',ceil(statorconductorsperslot));
Zss*AreaofStatorConductor;
fprintf('Space Required for bare conductor in each slot =%f\n',Zss*AreaofStatorConductor);
%Slot Dimensions------------------------------
spacefactor=0.4;
(Zss*AreaofStatorConductor)/spacefactor;
fprintf('Area of each slot in mm^2 = %f\n',Zss*AreaofStatorConductor/spacefactor);
%Minimum width of stator teeth ---Wts----------------------------
Wts=Fluxperpole*poles*1000/(1.7*Ss*Li);
fprintf('Minimum Width of stator teeth in mm is =%.1f\n',Wts);

lip=1;wedge=1.95;height=12.5;
dss=lip+wedge+height;
fprintf('Depth of stator Slot is %0.2f\n',floor(dss));
%Flux Density in Stator Tooth---Fdst-------------------------------------
Fdst=Fluxperpole*poles/(Ss*Li*6*10^(-3));
if(Fdst>=1.7)
   fprintf('Change the Slot Dimensions and start\n');
   break
end
fprintf('Flux Density in Stator Tooth in Wb/m2 =%f\n',Fdst);
%Stator Core
%area of stator core----Acs.Flux  density in stator core is assumed as 1.5wb/m2.
Acs=Fluxperpole/(2*1.5);
dcs=Acs/(Li);
fprintf('Depth of stator Core in mm  =%0.2f\n',dcs*1000);
Bcs=(dcs*1000*1.5)/(ceil(dcs*1000));
fprintf('Value of Stator core flux density in Wb/m2 is %0.2f\n',Bcs);
Do=(D*1000)+(2*dss+2*dcs*1000);
fprintf('Outside diameter including Laminations in mm =%0.2f\n',Do);
lg=0.2+(2*sqrt(D*L));
fprintf(' THE LENGTH OF AIR GAP OF THE INDUCTION MOTOR in mm =%.4f  \n',lg);
Dr = D*1000-(2*lg);
fprintf(' THE OUTER DIAMETER OF ROTOR in mm =%.4f mm \n',Dr);
Lmts=(2*L*1000)+(2.3*tau*1000)+24;
fprintf('Mean length of turns in mm =%0.3f\n',Lmts);
% to find no of rotor slots
disp('In order to avoid synchronous cusps the difference of stator and rotor slots should not be
+1*poles or -1*Poles or a multiple of poles');
Sr=Ss-(9*poles/4);
fprintf('the no of rotor slots is =%d\n',Sr);
Ysr=(3.14*D*1000)/Sr;
fprintf('the rotor slot pitch in mm =%d\n',Ysr);
```

```
if(Ysr>25)
fprintf('Modify the value of rotor slots');
end
%to find the rotor bar current
Ib=pf*((phases*qs*Kwss*Is*Ts)/Sr);%Power Factor is 0.71
fprintf('\n the rotor bar current in Amperes=%0.4f\n',Ib);
% to find  rotor bar cross sectional area
Db=6;%Current Density
Ab = Ib /Db;
fprintf('\n THE  AREA OF  each ROTOR BAR in mm2 =%f\n',Ab);
Wsr=6 ;
depth=8.5;
k=Wsr*depth;
if(k<=Ab)
   fprintf('Change the values of the width of rotor bar and depth such that it is slightly greater or
equal to area of rotor bar');
   break;
end
%Rotor core
%dcr----Depth of Rotor Core
dcr=dcs;
%Di----Inner Diameter of Rotor Lamination
Di=Dr-(2*depth)-(2*dcr);
fprintf('Inner Diameter of Rotor Lamination in mm =%f\n',Di);
 %the slot pitch at bottom of rotor bar in mm is  ;
 Ysb=3.14*((1000*D)-(2*depth))/Sr ;
Wt=Ysb-Wsr;
fprintf('\n  the tooth width at root of rotor bar in mm is  =%f\n',Wt);
Fdrt=Fluxperpole/((Sr/poles)*Li*(Wt*0.001));
fprintf('Flux density at root of rotor bar is %f\n',Fdrt);
if(Fdrt>1.7)
   fprintf('Modify the rotor slots and dimensions of rotor bar \n');
end
%copper loss in rotor bars
%A---Allowance for skewing in mm
A=12;
Lb=(L*1000)+A;
fprintf(' the length of rotor bar  in mm is  =%f\n',Lb);
Rb=0.021*Lb*0.001/Ab;
CLRb=Sr*Rb*(Ib^(2));
fprintf('the copper loss in rotor bars in Watts is=%f\n',CLRb);
%End Ring Current
Ie= (Sr*Ib)/(3.14*poles);
fprintf(' the end ring current in Amperes=%f\n',Ie);
%----------------------Area of end ring
De=6;
```

```
Ae = Ie/De;
fprintf(' the area of end rings in mm2 =%f\n',Ae);
%Copper loss in End Rings
%Diameter of outer end ring and inner ring are Doe and Die.
Doe=Dr-(2*depth);
Die=Doe-(2*10);
Dme=(Doe+Die)/2;
fprintf('Mean Diameter of end ring in mm is %f\n',Dme);
%Resistance of each end ring Re
Re= 0.021*(Dme*0.001*3.14/ Ae );
%Copper loss in two end rings ---Cr
CLER=2*Ie*Ie*Re;
fprintf(' the total copper loss in end rings in watts =%f\n',CLER);
Totalrotorcopperloss=CLRb+CLER;
fprintf('Total Rotot Copper Loss in watts = %f\n',Totalrotorcopperloss);
%------------------------------------------------------------
slotopening=2;
gaplength=lg;
qi=slotopening/gaplength;
Kcs=1/(1+(5*lg/2));
fprintf('Carter coefficient is %f\n',Kcs);
Kgss=yss/(yss-(Kcs*2));
fprintf('gap contraction factor for stator slots =%0.3f\n',Kgss);

%Gap Contraction factor for rotor slots----Kcsr
Kcsr=1/(1+(5*lg/2));
Kgsr=Ysr/(Ysr-Kcsr*2);
fprintf('gap contraction factor for rotor slots=%0.3f\n',Kgsr);

Kgs=(Kgss*Kgsr);
fprintf('gap contraction factor for slots=%0.3f\n',Kgs);
%Gap Contraction Factor for ducts---kgd
Kgd=1;
Kg=(Kgs*Kgd);
fprintf('gap contraction factor=%f\n',Kg);
%--------area of air gap---Ag
Ag=pi*D*L/poles;
fprintf('area of air gap in m2 =%f\n',Ag);
Bg=1.36*Bav;
% Length of effective air gap---lge
lge=Kg*lg;
 fprintf('effective length of air gap in mm =%f\n',lge);
ATg=800000*Kg*Bg*0.3*10^(-3);
fprintf('Air gap in Ampere Turns/metre =%f\n',ATg);
%--------stator teeth-------
St=(Ss/poles)*Wts*Li;
```

```
fprintf('area of stator teeth per pole in mm2=%f\n',St);
Btssixty=1.36*Fdst;
fprintf('Value of Btssixty is %0.2f\n',floor(Btssixty));
B1=(0.0045-(0.0019*(Btssixty)));
atsst=Btssixty/B1;
fprintf('The ampere turns for stator teeth corresponding to Btssixty are %d\n',atsst);
ATST=atsst*dss*0.001;
fprintf('MMF required for stator teeth are %f\n',ATST);
%------Stator Core---------
%length of magnetic path through stator core ---lcs;
lcs=(pi*(D+(2*dss*0.001)+dcs))/(3*poles);
fprintf('length of stator core in metres =%f\n',lcs);
B2=(0.0045-(0.0019*floor(Bcs)));
ATsc=Bcs/B2;
fprintf('The ampere turns required for Stator core corresp. to Bcs  are %0.2f\n',ATsc);
ATCS=ATsc*lcs;
fprintf('MMF required for stator core =%0.3f\n',ATCS);
%rotor teeth------
Wtsonethird=(pi*(Dr-(4*depth/3))/Sr)-(Wsr);
fprintf('Wtsonethird in mm =%f\n',Wtsonethird);
%Flux density of rotor teeth at one-third height Btr60
Btr60=((1.36*Wt)/Wtsonethird);
fprintf('Flux density in rotor teeth at one third height is %0.2f\n',Btr60);
%Area of rotor teeth at one third height from narrow end.---Atr
Atr=(Sr/poles)*Wtsonethird*0.001*Li;
%fprintf('Atr=%f\n',Atr);
BTrt60=1.36*Btr60;fprintf('BTrt60=%f\n',BTrt60);
B3=(0.0045-(0.0019*(BTrt60)));
ATrt=(BTrt60)/B3;
fprintf('Ampere turns of the rotor teeth corresponding to one third height of rotor teeth is
%f\n',ATrt);
ATRT=ATrt*depth*0.001;
fprintf('MMF required for rotor teeth are %0.3f\n',ATRT);
Brc=Bcs;
ATrc=Brc/B2;
fprintf('Ampere turns corresponding to rotor core flux density is %f\n',ATrc);
%lcr----Length of Flux path in Rotor Core
lcr=pi*Di*0.001/(3*poles);
ATRC=ATrc*lcr;
fprintf('MMF for rotor core ATcr=%f\n',ATRC);
AT=ATg+ATST+ATCS+ATRT+ATRC;
fprintf('Total AT = %f\n',AT);
Im=0.427*poles*AT/(Kwss*Ts);

fprintf('Im in Amperes =%0.3f\n',Im);
Vsteeth=Ss*dss*0.001*6*Li*0.001;
```

```
Wsteeth=Vsteeth*(7.6)*10^(3);
fprintf('Weight of stator teeth in Kg =%f\n',Wsteeth);
Mfdt=MaxFluxDensityinteeth; MaxFluxDensityinteeth=(pi/2)*Fdst;
 %Hystersis loss per cycle is 400J/m3.
ILst=((400*f/7650)+(((pi^(2))*(f^(2))*(Mfdt(2))*(0.0005^(2)))/(6*densitycopper*resistivitycop
per)))*Wsteeth;

fprintf('Iron Loss in Stator Teeth = %d\n',ILst);
%Iron Loss in Stator core----Ilsc
Volumestatorcore=3.14*((Do*0.001)-dcs)*dcs*Li;
fprintf('Volume of stator core in kg/m3 = %f\n',Volumestatorcore);
Weightstatorcore=Volumestatorcore*7.65*10^(3);
fprintf('Weight of stator core in kg is %f\n',Weightstatorcore);
ILcore=Weightstatorcore*((400*f/7650)+(((pi^(2))*(f^(2))*(Bcs^(2))*(0.0005^(2)))/(6*densityc
opper*resistivitycopper)));
TotalIronLoss=ILst+ILcore;
fprintf('Total Iron Loss in Watts  = %f\n',2*TotalIronLoss);
FandWLoss=4.4*Kw*1000/100;
TotalNoLoadLosses=(2*TotalIronLoss)+FandWLoss;
fprintf('Total No Load Loss=%f\n',TotalNoLoadLosses);
Il=(TotalNoLoadLosses)/(phases*Esa);
fprintf('Loss component of no load current =%f\n',Il);
Io=sqrt((Im*Im)+(Il*Il));
fprintf('No Load Current in Amperes = %d\n',Io);
fprintf('No Load Current as expressed as percentage of Stator Current = %d\n',(Io*100/Is));
%Short Circuit Current
%Stator Slot Leakage
h1=height;
h2=0;
h3=wedge;
h4=lip;
w0=2;w1=(pi*((D*1000)+(2*lip+2*wedge))/Ss)-Wts;w2=11;
%ws---Width at bottom of slot
Ws=14.2;
c=((2*h1)/(3*Ws+3*w2))+(2*h2)/(w1+w2)+(2*h3)/(w1+w0)+(h4/w0);
ssl=4*c*pi*10^(-7);
fprintf('Specific Slot Permeance =%f\n',ssl);
%Rotor Slot Leakage
h5=6;h7=0.3;
h6=1;w01=2;WSr=5.5;
c1=(h5/(3*WSr))+(h7/WSr)+((2*h6)/(WSr+w01))+(h4/w01);
rsp=4*pi*(c1)*10^(-7);
fprintf('Rotor Slot Permeance =%f\n',rsp);
rsps=rsp*(Ss/Sr)*Kwss^2;
Tssp=ssl+rsps;
fprintf('Total Specific Slot Permeance= %f\n',Tssp);
```

```
%Slot Leakage Reactance----Xs
Xs=8*pi*f*Ts*Ts*L*Tssp/(poles*qs);
fprintf('Slot Leakage Reactance in ohms =%0.3f\n',Xs);
% Overhang Leakage---X0
X0=8*pi*f*(Ts^(2))*(4*pi*10^(-7)*0.875*tau*tau)/(pi*8*yss*10^(-3));
fprintf('Overhang Leakage Reactance in ohms=%f\n',X0);
%Zigzag Leakage----Xz
Xm=Esa/Im;qr=Sr/poles/phases;
Xz=(5/6)*(Xm/(phases*phases))*((1/(qs*qs))+(1/(qr*qr)));
fprintf('Zigzag Leakage Reactance in ohms =%0.3f\n',Xz);
fprintf('Total Leakage Reactance referred to Stator in ohms = %f\n',(Xs+X0+Xz));
%Resistance of stator winding per phase ----rs
resistivitycopper=0.021;
rs=Lmts*Ts*resistivitycopper/(AreaofStatorConductor*1000);
fprintf('Resistance of stator winding per phase in ohms=%0.2f\n',rs);
Totalstatorcopperloss=phases*Is*Is*rs;
fprintf('Total stator copper loss in watts=%d\n',Totalstatorcopperloss);
rotorcopperlossperphase=Totalrotorcopperloss/phases;
fprintf('Rotor Copper Loss per phase in watts = %0.1f\n',rotorcopperlossperphase);
Rotorresistancereferredtostator=rotorcopperlossperphase/(((Is^(2))*(pf^(2))));
fprintf('Rotor resistance referred to stator in ohms= %0.2f\n',Rotorresistancereferredtostator);
%input----inp
inp=(Kw*1000)+Totalstatorcopperloss+TotalIronLoss+Totalrotorcopperloss+FandWLoss;
fprintf('Input in watts = %d\n',inp);
efficiency=(Kw*1000)/inp;
fprintf('Calculated Efficiency = %0.4f\n',efficiency*100);
slip=1/((Kw*1000/Totalrotorcopperloss)+1);fprintf('Slip is %f\n',slip);
Nr=750*(1-slip);fprintf('Speed of Rotor in RPM is %f\n',Nr);
Zs=sqrt(((rs+Rotorresistancereferredtostator)^(2))+(Xs+X0+Xz)^(2));
Isc=Es/Zs;fprintf('Short Circuit current per phase in Amperes is %0.2f\n',Isc);
fprintf('ratio of short circuit current is %0.2f\n',Isc/Is);
%Total Impadance of rotor at stand still is TIR
TIR=sqrt(((rs+Rotorresistancereferredtostator)^(2))+(Xs+X0+Xz)^(2));
fprintf('Impedance of Rotor  at stand still in ohms is %f\n',TIR);
%No load power factor----Nlpf
Nlpf=(Il/Io);
fprintf('No load power factor is %f\n',Nlpf);
fprintf('No load power factor in degrees is %f\n',acosd(Nlpf));
%short circuit power factor----pfsc
scpf=(Rotorresistancereferredtostator+rs)/sqrt((Rotorresistancereferredtostator+rs)^(2)+(Xs+X0
+Xz)^(2));
fprintf('short circuit  power factor is %f\n',scpf);
fprintf('short circuit power factor in degrees is %f\n',acosd(scpf));
```

3.2.2. Case Study 2

Design a three phase induction motor to drive a two stage compressor to deliver $4m^3$ of free air per minute at a pressure of 11 bar.

Assume that compression follows the law $PV^{1.34}$=constant .(n=1.2 to 1.3 for air)

$V_1=4m^3$, P_1=1bar (absolute)

P_2= 11bar (absolute)

$P_1V_1^{1.34}=P_2V_2^{1.34}$

$V_2=V_1*(P_1/P_2)^{(1/1.34)}$

$= 4*(1/11)^{(1/1.34)} = 0.668\ m^3/min$

Work done in delivering the compressed air by compressor is

$= (n/n-1)*(P_2V_2-P_1V_1)$

$=(1.34/1.34-1)*(11*0.668-1*4)*10^5$ N.m/minute=131905 N.m/minute

= 21.991N.m/sec = 21.991KW

Rating equivalent in HP =21.991/0.746=29.479 HP.

Nearest available rating of motor=30HP

Group A 230 grade 0.5mm thick non-oriented electrical sheet laminations is used for the design. Table 3.2. for $B(Wb/m^2)$ Vs H(A/m) characteristics is given below : **(**Courtesy : Precision Pressing Division of M/S Guest keen , Williams.)

Table 3.2. B and H characteristics for 3 phase induction motor

$B(Wb/m^2)$	H(A/m)
1.3	400
1.38	800
1.48	1600
1.72	8000
1.92	24000

Relation between $B(Wb/m^2)$ and H(A/m) is B = aH/(1+bH)

Equation (1) : 1.38=a(800)/(1+(b*800))

Equation (2) : 1.48=a(1600)/(1+(b*1600))

Solving equations(1) and (2) for a and b we get a=0.0045 and b=0.0019.

Therefore B=(0.0045H)/(1+0.0019H) or H=B/(0.0045-0.0019B).

The design of three phase squirrel cage Induction motor for rating of 30HP is written below :

This motor is designed for good power factor and good overall design by taking ratio (L/tau) =1.24

```
%P1= 1 atm
P1=1;
P2=input('Enter the pressure in bar');
V1=input('Enter V1 in m3');
%Gamma for air lies between 1.2 to 1.4
gamma=1.34;
K=((P1/P2)^(1/1.34));
V2=K*V1;
fprintf('V2 in m3/min is %f\n',V2);
%Work done in watts Wwatt
Wwatt=(gamma/(gamma-1))*((P2*V2)-(P1*V1))*((10^(5)))/(60*1000);
fprintf('Work done in kilo watt by compressor is %f\n',Wwatt);
HP=floor(Wwatt)/0.746;
Hp=ceil(HP);
fprintf('Nearest available rating of motor in HP is %f\n',Hp);
Kw=0.746*Hp;
phases=3;
Es=415;
f=50;
poles=4;
% winding in Stator
      Esa=Es
 %Synchronous speed ---ns
 Ns=(120*f)/poles;
ns=(2*f)/poles;
fprintf('Speed in RPS is = %d\n',ns); kw=0.955; eff=0.925;
```

```
pf=0.86;
disp('For 50Hz machines  design the value of Bav lies between 0.3 to 0.6 Wb/m2');
Bav=0.32;%Bav in Wb/m2
ac=16300;%ac is ampere conductors per metre.
%Output Coefficient ---Co
Co=11*kw*Bav*ac*10^(-3);
fprintf('Co=%f\n',Co);
%Q--KVA input;
eff*pf;
fprintf(' product eff*pf = %.2f\n',eff*pf);
Q=Kw/(eff*pf);
fprintf('KVA Input Q=%f\n',Q);
p1=Q/(Co*ns);
disp('For minimum cost L/tau varies from 1.5 to 2');
disp('Good power factor L/tau varies from 1 to 1.25');
disp('For Good Efficiency  L/tau ratio is 1.5');
disp('For good overall design L/tau ratio is 1');
ratio=1.24;
D=(p1/(pi*ratio/poles))^0.33;
fprintf('The value of D in metres  is %f\n',D);
L=(pi*ratio/poles)*D;
fprintf('The length in metres  =%f\n',L);
%Net Iron Length ---Li
nd=8;Kcd=0.87;wd=8;
Li=0.9*(L-(nd*wd*0.001));
fprintf('Net Iron Length in metres = %f\n',Li);
tau=(pi*D)/poles;
fprintf('tau----Pole Pitch =%f\n',tau);
Fluxperpole =Bav*tau*L;
fprintf('Flux per pole in Wb =%f\n',Fluxperpole);
%Stator Turns per phase ---Ts
Ts=Esa/(4.44*f*kw*Fluxperpole);
fprintf('Ts=%d\n',ceil(Ts));
qs=3;
%(qs<2)is not good for design.
% Stator Slots ---Ss
Ss=phases*poles*qs;
coilspan=Ss/poles;
fprintf('Coil Span =%d\n',coilspan);
%Angle of chording---alpha
if(((coilspan/2)-floor(coilspan/2))==0);
```

```
    alpha =180/coilspan;fprintf('Alpha in degrees  is : %f',alpha);
    Kp=cosd(alpha/2);
    fprintf('Kp=%f\n',Kp);
else if(((coilspan/2)-floor(coilspan/2))~=0)
    %fprintf('Cs is an odd number hence full pitch winding is used for which Kp=1\n');
    Kp=1;
    end
end
Kd=sind(60/2)/(qs*sind(60/(2*qs)));
fprintf('Kd=%f\n',Kd);
Kwss=Kp*Kd;
fprintf('Kwss=%f\n',Kwss);
%Stator Line Current ---Is
is=(22*1000)/(3*Esa*pf*eff);
fprintf('Stator Current per phase in Amperes =%f\n',is);
Is=1.732*is;
fprintf('Stator Line Current in Amperes is %0.3f\n ',Is);
StatorConductors=6*ceil(Ts);fprintf('Stator Conductors = %d\n',StatorConductors);
%Stator Slot Pitch Yss
yss = pi*(D*1000)/Ss;
fprintf('Stator slot pitch in mm is %f\n',yss);
if(yss>25);
    fprintf('the stator slot pitch of induction motor should be less than 25mm.');
    disp('Change the slots per pole per phase');
   break;
end
currentdensity=3.51;
AreaofStatorConductor=is/(currentdensity);
fprintf('Area of Stator Conductor  required in mm2=%0.3f\n',ceil(AreaofStatorConductor));
%Designer specification of area of stator conductor of 7mm2 is 6.25*1.13.
disp('Designer specification of area of stator conductor of 7mm2 is 6.25*1.13');
Zss=(6*Ts)/Ss;
statorconductorsperslot=(6*Ts)/Ss;fprintf('Stator Conductors per
slot=%0.1f\n',floor(statorconductorsperslot));
%slot insulation=0.3mm and slack=1mm
slotinsl=0.3;
slack=1;lip=1;wedge=2;
dss=(floor(statorconductorsperslot)*1.13)+lip+(3*slotinsl)+slack+wedge;
fprintf('Total depth of stator slot in mm is = %.1f\n',dss);
WSt=(pi*((D*1000)+(2*(dss)))/Ss)-11;
```

```
fprintf('Width at the root of stator teeth  in mm is %f\n',WSt);
%Flux Density at root of stator teeth Fdst
Fdst=Fluxperpole/((Ss/poles)*WSt*Li*0.001);
fprintf('Flux density at root of stator tooth is %f\n',Fdst);
%Stator Core
%area of stator core----Acs.Flux  density in stator core is assumed as 1.5wb/m2.
Acs=Fluxperpole/(2*1.45);
dcs=Acs/(Li);
fprintf('Depth of stator Core in mm  =%0.2f\n',dcs*1000);
Bcs=(dcs*1000*1.5)/(ceil(dcs*1000));
fprintf('Value of Stator core flux density in Wb/m2 is %0.2f\n',Bcs);
Do=(D*1000)+(2*dss)+(2*dcs*1000);
fprintf('Outside diameter including Laminations in mm =%0.2f\n',Do);
Lmts=(2*L*1000)+(2.3*tau*1000)+24;
fprintf('Mean length of turns in mm =%0.3f\n',Lmts);
%Calculation of air gap length and Rotor Design
lg=0.2+D;
fprintf(' THE LENGTH OF AIR GAP OF THE INDUCTION MOTOR in mm =%.4f  \n',lg);
Dr = D*1000-(2*(1.0*lg));
fprintf(' THE OUTER DIAMETER OF ROTOR in mm =%.4f mm \n',Dr);
% to find no of rotor slots
disp('In order to avoid synchronous cusps the difference of stator and rotor slots should not be
+1*poles or -1*Poles or a multiple of poles');


Sr=Ss+(9*poles/4);
fprintf('the no of rotor slots is =%d\n',Sr);
Ysr=(3.14*D*1000)/Sr;
fprintf('the rotor slot pitch in mm =%0.4f\n',Ysr);
if(Ysr>25)
fprintf('Modify the value of rotor slots');
break;
end
%to find the rotor bar current
Ib=0.86*((6*Is*Kwss*Ts)/Sr);
fprintf('\n the rotor bar current in Amperes  =%.4f\n',Ib);
% to find  rotor bar cross sectional area
Db=4.5;%Current Density
Ab = Ib /Db;
fprintf('\n THE  AREA OF  each ROTOR BAR in mm2 =%f \n',ceil(Ab));
```

```
%designer specification to use Deep T rotor bars of ((10*7.9)+(10*1))
disp('designer specification to use Deep T rotor bars of ((10.4*6.7)+(10*2.2))');
depth=19.4;
width=7.1;
Ysb=pi*((D*1000)-(2*depth))/Sr;
Wtr=(pi*((D*1000)-(2*depth))/Sr)-7.1;
fprintf('Width at root of rotor teeth in mm is %f\n',Wtr);
%Flux Density at root of rotor teeth Fdrt
Fdrt=Fluxperpole/((Ss/poles)*Li*Wtr*0.001);
fprintf('Flux density at root of rotor tooth is %f\n',Fdrt);
if(Fdrt>1.7);
    fprintf('Verify the value of width at rotor of rotor teeth and calculate Fdrt');
    break;
end

dcr=dcs;
Di=Dr-(2*depth)-(2*dcr);fprintf('Inner Diameter of Rotor Lamination in mm =%f\n',Di);
 %the slot pitch at bottom of rotor bar in mm is  ;


%copper loss in rotor bars
%A---Allowance for skewing in mm
A=10;
Lb=(L*1000)+A;
fprintf(' the length of rotor bar in mm is  =%f\n',Lb);
Rb=0.021*Lb*0.001/Ab;
CLRb=Sr*Rb*(Ib^(2));
fprintf('the copper loss in rotor bars in Watts is=%f\n',CLRb);
%End Ring Current
Ie= (Sr*Ib)/(3.14*poles);
fprintf(' the end ring current in Amperes =%f\n',Ie);
De=4%End ring current density is 4 A/mm2;
Ae = Ie/De;
fprintf(' the area of end rings in mm2=%f\n',Ae);
%Copper loss in End Rings
%Diameter of outer end ring and inner ring are Doe and Die.
Doe=Dr-(2*depth);
Die=Doe-(2*50);
Dme=(Doe+Die)/2;
fprintf('Mean Diameter of end ring in mm is %f\n',Dme);
```

```
%Resistance of each end ring Re
Re= 0.021*(Dme*0.001*3.14/ Ae );
%Copper loss in two end rings ---Cr
%Since two ed rings are present,Copper loss n two end rings are 2times.
CLER=2*Ie*Ie*Re;
fprintf(' the total copper loss in end rings in watts =%0.3f\n',CLER);
Totalrotorcopperloss=CLRb+CLER;
fprintf('Total Rotor[ Copper Loss in watts = %0.3f\n',Totalrotorcopperloss);
%-----------------------------------------------------------
slotopening=5;
gaplength=lg;
qi=slotopening/gaplength;
Kcs=1/(1+(5*lg/slotopening));
fprintf('Carter coefficient is %f\n',Kcs);
Kgss=yss/(yss-(Kcs*5));
fprintf('gap contraction factor for stator slots =%0.3f\n',Kgss);

%Gap Contraction factor for rotor slots----Kcsr
Kcsr=1/(1+(5*lg/2.2));
Kgsr=Ysr/(Ysr-Kcsr*2.2);
fprintf('gap contraction factor for rotor slots=%0.3f\n',Kgsr);

Kgs=(Kgss*Kgsr);
fprintf('gap contraction factor for slots=%0.3f\n',Kgs);
%Gap Contraction Factor for Ducts
nd=8;Kcd=0.87;wd=8;
Kgd=(L*1000)/((L*1000)-(nd*wd*Kcd));
fprintf('Gap Contraction Factor for ducts is %f\n',Kgd);
Kg=Kgs*Kgd;
lge=Kg*lg;Bgs=1.36*Bav;
 fprintf('effective length of air gap in mm =%f\n',lge);
ATg=800000*Kg*Bgs*lg*10^(-3);
fprintf('MMF of Air Gap is %f\n',ATg);
St=(Ss/poles)*WSt*Li;
fprintf('area of teeth per pole in mm2=%f\n',St);
Btssixty=1.36*Fdst;
fprintf('Value of Btssixty is %f\',floor(Btssixty));
B1=(0.0045-(0.0019*(Btssixty)));
atsst=Btssixty/B1;
fprintf('The ampere turns for stator core corresponding to Btssixty are %d\n',atsst);
```

```
ATST=atsst*dss*0.001;
fprintf('MMF required for stator teeth are %f\n',ATST);
%------Stator Core---------
%length of magnetic path through stator core ---lcs;
lcs=(pi*(D+(2*dss*0.001)+dcs))/(3*poles);
fprintf('length of stator core in metres =%f\n',lcs);
B2=(0.0045-(0.0019*floor(Bcs)));
ATsc=Bcs/B2;
fprintf('The ampere conductors required for Stator core corresp. to Bcs  are %0.2f\n',ATsc);
ATCS=ATsc*lcs;
fprintf('MMF required for stator core =%0.3f\n',ATCS);
%rotor teeth------
Wtsonethird=(pi*(Dr-(4*depth/3))/Sr)-(Wtr);
fprintf('Wtsonethird in mm =%f\n',Wtsonethird);
%Flux density of rotor teeth at one-third height Btr60
Btr60=((1.36*Wtr)/Wtsonethird);
fprintf('Flux density in rotor teeth at one third height is %0.2f\n',Btr60);
Atr=(Sr/poles)*Wtsonethird*0.001*Li;%Area of rotor teeth at one third height from narrow
end.---Atr

BTrt60=1.36*Btr60;fprintf('BTrt60=%f\n',BTrt60);
B3=(0.0045-(0.0019*(BTrt60)));
ATrt=(BTrt60)/B3;
fprintf('Ampere turns of the rotor teeth corresponding to Btr60 is %f\n',ATrt);
ATRT=ATrt*depth*0.001;
fprintf('MMF required for rotor teeth are %0.3f\n',ATRT);
Brc=Bcs;
%atcr----Ampere Turns corresponding to Rotor core
ATrc=Brc/B2;
fprintf('Ampere turns corresponding to rotor core flux density is %f\n',ATrc);
%lcr----Length of Flux path in Rotor Core
lcr=pi*Di*0.001/(3*poles);
ATRC=ATrc*lcr;
fprintf('MMF for rotor core ATcr=%f\n',ATRC);
AT=ATg+ATST+ATCS+ATRT+ATRC;
fprintf('Total AT = %f\n',AT);
Im=0.427*poles*AT/(Kwss*Ts);
fprintf('Magnetizing Current in Amperes is %f\n',Im);
Vsteeth=Ss*dss*0.001*WSt*Li*0.001;
Wsteeth=Vsteeth*7.6*10^(3);
```

```
fprintf('Weight of stator teeth in Kg =%f\n',Wsteeth);
Mfdt=MaxFluxDensityinteeth;MaxFluxDensityinteeth=(pi/2)*Fdst;
ILst=((400*f/7650)+(((pi^(2))*(f^(2))*(Mfdt^(2))*(0.0005^(2)))/(6*densitycopper*resistivitycopper)))*Wsteeth;
fprintf('Iron Loss in Stator Teeth = %d\n',ILst);
Volumestatorcore=3.14*((Do*0.001)-dcs)*dcs*Li;fprintf('Volume of stator core in Kg/m3 = %f\n',Volumestatorcore);
Weightstatorcore=Volumestatorcore*7.65*10^(3);
ILcore=Weightstatorcore*((400*f/7650)+(((pi^(2))*(f^(2))*(Bcs^(2))*(0.0005^(2)))/(6*densitycopper*resistivitycopper)));
TotalIronLoss=ILst+ILcore;
fprintf('Total Iron Loss in Watts  = %d\n',2*TotalIronLoss);
FandWLoss=1.8*Kw*1000/100;
Totalnoloadloss=(2*TotalIronLoss)+FandWLoss
fprintf('Total No Load Loss in Watts =%d\n',Totalnoloadloss);
%Loss component of No Load current ---Il
Il=(Totalnoloadloss)/(phases*Esa);
fprintf('Loss Component of No Load Current in Amperes=%f\n',Il);
Io=sqrt((Im*Im)+(Il*Il));fprintf('No Load Current in Amperes = %f\n',Io);
fprintf('No Load Current as expressed as percentage of Stator Current = %d\n',(Io*100/Is));
%Short Circuit Current
%Stator Slot Leakage
h1=Zss*1.13;
h2=1;   h3=2;  h4=1; ws1=10.3; w0=5;
c0=4*pi*(10^(-7))*((h1/(3*ws1))+(h2/ws1)+(2*h3/(ws1+w0))+(h4/w0));
fprintf('Specific Slot Permeance of Stator =%f\n',c0);
a1=10.4*7.1;a2=10*2.2;
H1=10.4;H2=9;H3=1;Ws=7.1;W0=2.2;
c1=4*pi*(10^(-7))*(((H1*a1*a1/(3*Ws))+(H2/w0)*((a1*a1)+(a1*a2)+(a2*a2)/3))/((a1+a2)^(2))+(H3/Ws));
fprintf('Specific Slot Permeance of Rotor is %f\n',c1);
c2=c1*Kwss^(2)*Ss/Sr
SlotLeakageReactance=8*pi*f*(Ts^(2))*L*(c0+c2)/(poles*qs);
fprintf('Slot leakage Reactance is %f\n',SlotLeakageReactance);
% Overhang Leakage---X0
X0=8*pi*f*(Ts^(2))*(4*pi*10^(-7)*tau*tau)/(poles*qs*pi*yss*10^(-3));
fprintf('Overhang Leakage Reactance in ohms=%f\n',X0);
%Zigzag Leakage----Xz
Xm=Esa/Im;qr=Sr/poles/phases;
Xz=(5/6)*(Xm/(phases*phases))*((1/(qs*qs))+(1/(qr*qr)));
fprintf('Zigzag Leakage Reactance in ohms =%0.3f\n',Xz);
```

```
Xs=SlotLeakageReactance;
fprintf('Total Leakage Reactance referred to Stator in ohms = %f',(Xs+X0+Xz))
%Resistance of stator winding per phase ----rs
resistivitycopper=0.021;
rs=Lmts*Ts*resistivitycopper/(AreaofStatorConductor*1000);
fprintf('Resistance of stator winding per phase in ohms=%0.2f\n',rs);
Totalstatorcopperloss=phases*Is*Is*rs;fprintf('Total stator copper loss in watts=%d\n',Totalstatorcopperloss);
rotorcopperlossperphase=Totalrotorcopperloss/phases;
fprintf('Rotor Copper Loss per phase in watts = %0.1f\n',rotorcopperlossperphase);
Rotorresistancereferredtostator=rotorcopperlossperphase/((is^(2))*(pf^(2)));
fprintf('Rotor resistance referred to stator in ohms= %0.2f\n',Rotorresistancereferredtostator);

%input----inp
inp=(Kw*1000)+Totalstatorcopperloss+TotalIronLoss+Totalrotorcopperloss+FandWLoss;
fprintf('Input in watts = %d\n',inp);
efficiency=(Kw*1000)/inp;
fprintf('Efficiency is= %f\n',efficiency*100);
slip=1/((Kw*1000/Totalrotorcopperloss)+1);fprintf('Slip is %f\n',slip);
Nr=Ns*(1-slip);fprintf('Speed of Rotor in RPM is %f\n',Nr);

%Total Impadance of rotor at stand still is TIR
TIR=sqrt(((rs+Rotorresistancereferredtostator)^(2))+(Xs+X0+Xz)^(2));fprintf('Rotor Resistance at stand still in ohms is %f\n',TIR);
%No Load power factor calculation---Nlpf
Nlpf=(Il/Io);
fprintf('No load power factor is %f\n',acosd(Nlpf));
%Short circuit power factor ----scpf
scpf=((rs+Rotorresistancereferredtostator)/sqrt(((rs+Rotorresistancereferredtostator)^(2))+(Xs+X0+Xz)^(2)));
fprintf('Short circuit power factor %f\n',acosd(scpf));
Isc=Es/TIR;fprintf('Short Circuit current per phase  in Amperes is %0.2f\n',Isc);
fprintf('ratio of short circuit current to stator per phase current is %0.2f\n',Isc/is);
```

CHAPTER 4

RESULTS

4.1. Output for CASE STUDY 1 - Design a three phase Induction Motor to pump water (Sp. Gravity of Water=1000 kg/m^3) to a height of 26 metre discharging 4 litres per second.

Enter the total head (in metres) needed to pump the water26
Enter the discharge in liters per second
4
Efficiency of pump0.6
Enter the efficiency of motor0.8
Work done in KW is 2.125500
The nearest rating of the Motor in HP is 3.000000
Speed in RPS is = 1.250000e+01
For 50Hz machines design the value of Bav lies between 0.3 to 0.6 Wb/m2
Co=55.676500
product eff*pf = 0.58
KVA Input Q=3.891497
For minimum cost L/tau varies from 1.5 to 2
Good power factor L/tau varies from 1 to 1.25
For Good Efficiency L/tau ratio is 1.5
For good overall design L/tau ratio is 1
The value of D in metres is 0.215049
The length in metres =0.126674
Net Iron Length in metres = 0.114007
tau----Pole Pitch =0.084449
Flux per pole in Wb =0.004279
Ts=265
Coil Span =6
Alpha in degrees is : 30.000000Kp=0.965926
Kd=0.965926
Kwss=0.933013
Stator Line Current in Amperes is 5.413713
Stator Conductors = 1584.714003

Stator slot pitch in mm is 14.074897
Area of Stator Conductor required in mm2=1.353428
Stator Conductors per slot=133.000000
Space Required for bare conductor in each slot =178.733067
Area of each slot in mm^2 = 446.832669
Minimum Width of stator teeth in mm is =3.7
Depth of stator Slot is 15.00
Flux Density in Stator Tooth in Wb/m2 =1.042585
Depth of stator Core in mm =12.51
Value of Stator core flux density in Wb/m2 is 1.44
Outside diameter including Laminations in mm =270.97
THE LENGTH OF AIR GAP OF THE INDUCTION MOTOR in mm =0.5301
THE OUTER DIAMETER OF ROTOR in mm =213.9884 mm
Mean length of turns in mm =471.582
In order to avoid synchronous cusps the difference of stator and rotor slots should not be +1*poles or -1*Poles or a multiple of poles
the no of rotor slots is =30
the rotor slot pitch in mm =2.250842e+01
the rotor bar current in Amperes=189.4396
THE AREA OF each ROTOR BAR in mm2 =31.573269
Inner Diameter of Rotor Lamination in mm =196.163372
the tooth width in mm and flux density in Wb/m2 at root of rotor bar =14.645352 and 0.68
the length of rotor bar in mm is =138.674075
the copper loss in rotor bars in Watts is=99.301972
the end ring current in Amperes=226.241575
the area of end rings in mm2 =37.706929
Mean Diameter of end ring in mm is 186.188394
the total copper loss in end rings in watts =33.331527
Total Rotor Copper Loss in watts = 132.633500
Carter coefficient is 0.430062
gap contraction factor for stator slots =1.065
gap contraction factor for rotor slots=1.033
gap contraction factor for slots=1.101
gap contraction factor=1.100689
area of air gap in m2 =0.010698
effective length of air gap in mm =0.583472
Air gap in Ampere Turns/metre =143.705918
area of stator teeth per pole in mm2=2.517070
Value of Btssixty is 1.00
The ampere turns for stator teeth corresponding to Btssixty are 7.851310e+02

MMF required for stator teeth are 12.130275
length of stator core in metres =0.033832
The ampere turns required for Stator core corresp. to Bcs are 555.22
MMF required for stator core =18.784
Wtsonethird in mm =15.166138
Flux density in rotor teeth at one third height is 1.31
BTrt60=1.786087
Ampere turns of the rotor teeth corresponding to one third height of rotor teeth is 1614.272905
MMF required for rotor teeth are 14.367
Ampere turns corresponding to rotor core flux density is 555.222772
MMF for rotor core ATcr=14.256858
Total AT = 203.244534
Im in Amperes =2.817
Weight of stator teeth in Kg =3.855359
Iron Loss in Stator Teeth = 1.349376e+01
Volume of stator core in kg/m3 = 0.001158
Weight of stator core in kg is 8.855370
Total Iron Loss in Watts = 90.746179
Total No Load Loss=189.218179
Loss component of no load current =0.263234
No Load Current in Amperes = 2.829677e+00
No Load Current as expressed as percentage of Stator Current = 5.226869e+01
Specific Slot Permeance =0.000001
Rotor Slot Permeance =0.000001
Total Specific Slot Permeance= 0.000003
Slot Leakage Reactance in ohms =2.314
Overhang Leakage Reactance in ohms=1.943278
Zigzag Leakage Reactance in ohms =7.008
Total Leakage Reactance referred to Stator in ohms = 11.265325
Resistance of stator winding per phase in ohms=1.93
Total stator copper loss in watts=1.699231e+02
Rotor Copper Loss per phase in watts = 44.2
Rotor resistance referred to stator in ohms= 2.99
Input in watts = 2.684402e+03
Calculated Efficiency = 83.8503
Slip is 0.055949
Speed of Rotor in RPM is 708.038590
Short Circuit current per phase in Amperes is 33.54
ratio of short circuit current is 6.2
Impedance of Rotor at stand still in ohms is 12.379462

No load power factor is 0.093026
No load power factor in degrees is 85.56
short circuit power factor is 0.391782
short circuit power factor in degrees is 66.52

3 HP Induction Motor

The selection of rotor slots for 3 HP induction motor is determined from the plot illustrated in **Fig. 4.1**. Further, the **Circle diagram (Fig 4.2)** was used in calculation of the following factors:

- Rotor copper loss per phase =LK*Powerscale=1.8*23.96=40.12 Watts/phase
- Tstarting/Tfull load=BG/AK=(283.05)/(101.7)=2.68
- Tmaximum/Tfull load=MN/AK=(306.3)/(101.7)=3.02
- Efficiency at full load=AL/AH=(96.3)/(112.74)=85.4%
- Slip at full load=LK/AK=1.8/33.9=0.054=5.4%

Table 4.1. Representation of calculations using Circle diagram in AUTOCAD

Parameters	Output
Stator Full load current per phase	5.15 Amp
Tstarting/Tfull load	2.68
Tmax/Tfull load	3.02
Rotor Copper loss per phase in watts	40.12Watts
Power factor at full load	Cosd(40)=0.76
Slip at full load	5.4%

Table 4.2. Comparison of MATLAB output and Circle Diagram Output

Parameters	MATLAB OUTPUT	CIRCLE DIAGRAM OUTPUT
Stator full load current per phase	5.41Amp	5.15Amp
Rotor copper loss per phase	44.2Watts/phase	40.12Watts/phase
Slip at full load	5.559%	5.4%
Efficiency at full load	83.85%	85.4%

The machine diagram of 3 phase 3 HP cage induction motor is drawn using MATLAB output in AUTOCAD 2013 as shown in **Figure 4.3**, the slots used in the machine diagram are shown in **Figure 4.4.**

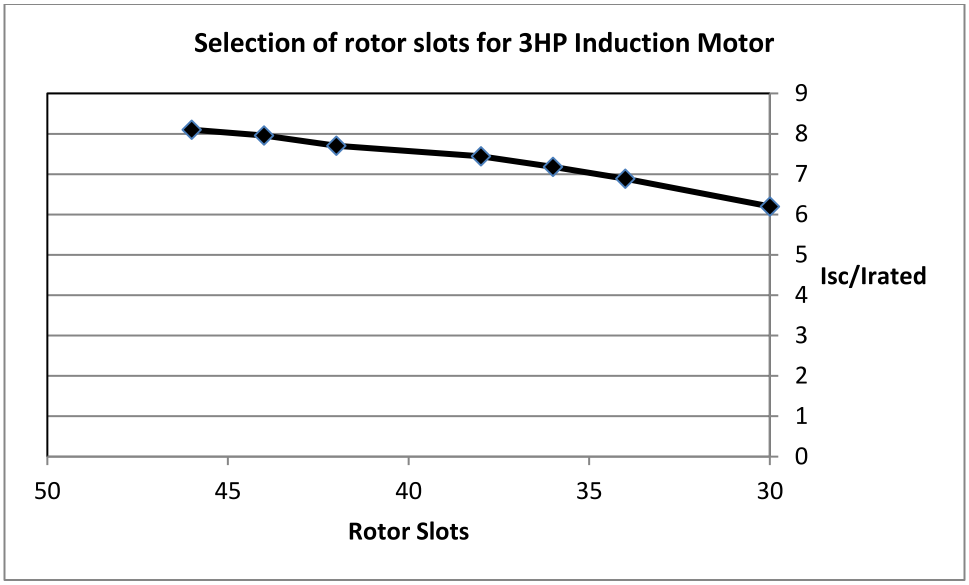
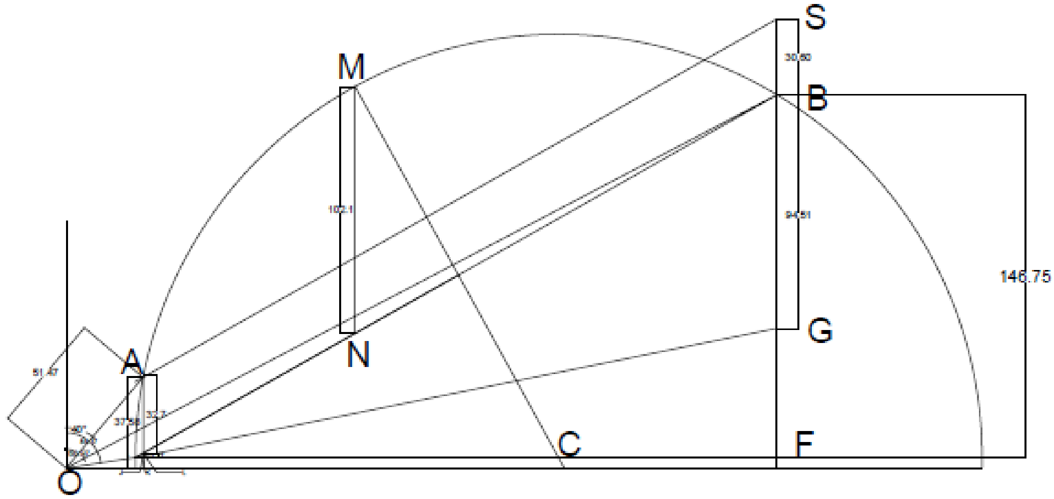


Fig 4.1: Selection of rotor slots for 3 HP induction motor.



All Dimensions are in mm

Fig. 4.2 Circle Diagram of 3 Phase 3HP Cage Induction Motor by AUTOCADD 2013

Current Scale :
1mm=0.1Amp/phase
Power Scale :
1mm=23.96Watts/phase

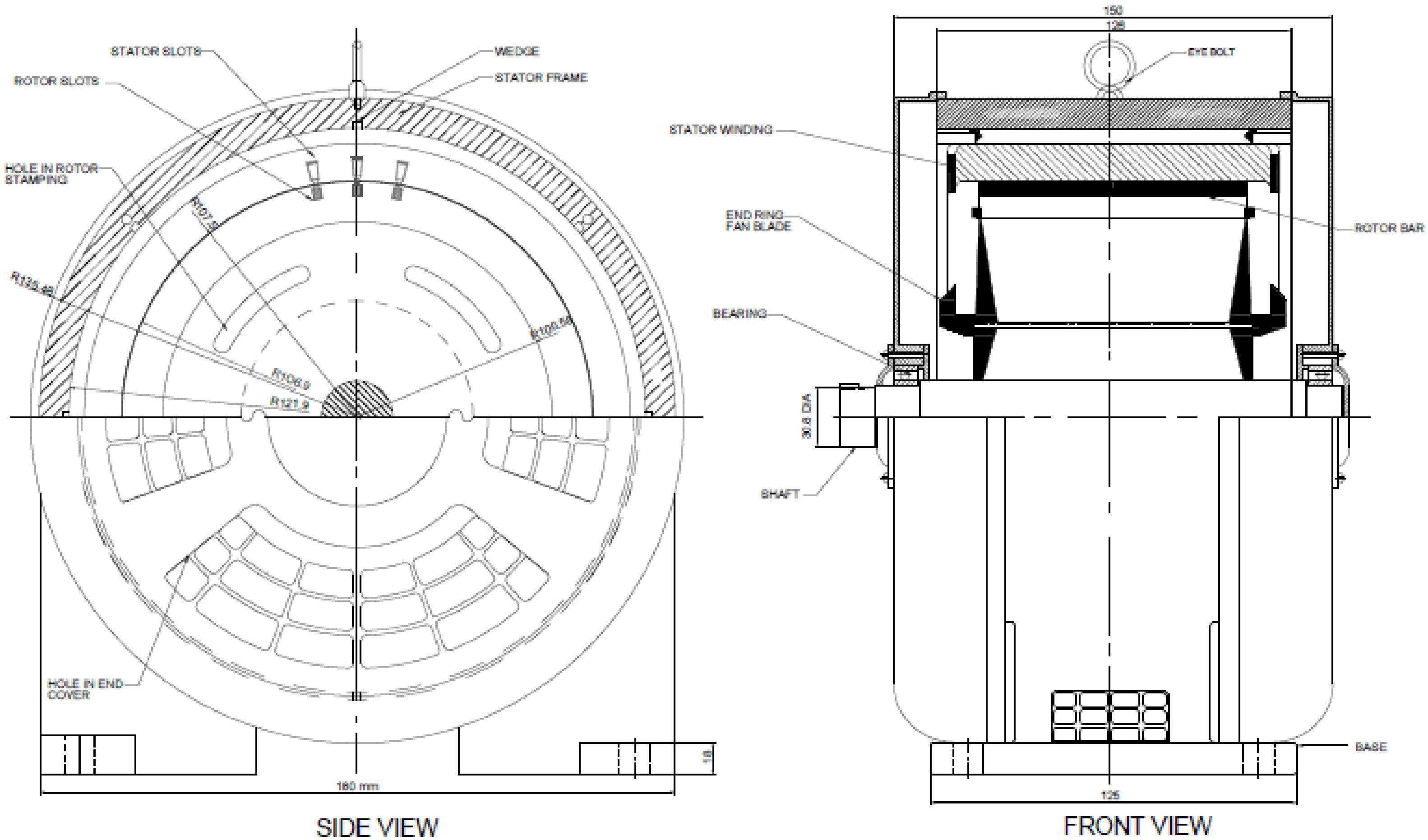


Fig 4.3: 3 HP, 3-PHASE INDUCTION MOTOR

NOTE:
ALL DIMENSIONS ARE IN mm.

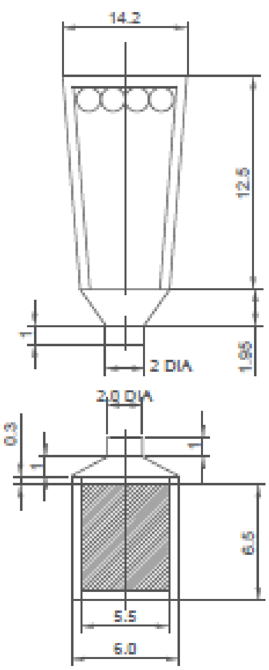


Fig 4.4

3 HP CAGE MOTOR STATOR AND ROTOR SLOTS

4.2. Output of Case Study II - Design a three phase induction motor to drive a two stage compressor to deliver $4m^3$ of free air per minute at a pressure of 11 bar

Enter the pressure in bar   11
Enter V1 in (m3)   4
V2 in m3/min is 0.668192
Work done in kilo watt by compressor is 22.005638
Nearest available rating of motor in HP is 30.000000
Esa =   415
Speed in RPS is = 25
For 50Hz machines design the value of Bav lies between 0.3 to 0.6 Wb/m2
Co=54.794080
product eff*pf = 0.80
KVA Input Q=28.133250
For minimum cost L/tau varies from 1.5 to 2
Good power factor L/tau varies from 1 to 1.25
For Good Efficiency L/tau ratio is 1.5
For good overall design L/tau ratio is 1
The value of D in metres is 0.279854
The length in metres =0.272548
Net Iron Length in metres = 0.187693
tau----Pole Pitch =0.219797
Flux per pole in Wb =0.019170
Ts=103
Coil Span =9
Kd=0.959795
Kwss=0.959795
Stator Current per phase in Amperes =22.213303
Stator Line Current in Amperes is 38.473
Stator Conductors = 618
Stator slot pitch in mm is 24.421865
Area of Stator Conductor required in mm2=7.000
Designer specification of area of stator conductor of 7mm2 is 6.25*1.13
Stator Conductors per slot=17.0
Total depth of stator slot in mm is = 24.1
Width at the root of stator teeth in mm is 17.522211
Flux density at root of stator tooth is 0.643687
Depth of stator Core in mm =35.22
Value of Stator core flux density in Wb/m2 is 1.47

Outside diameter including Laminations in mm = 398.51
Mean length of turns in mm =1074.629
THE LENGTH OF AIR GAP OF THE INDUCTION MOTOR in mm =0.4799
THE OUTER DIAMETER OF ROTOR in mm =278.8942
In order to avoid synchronous cusps the difference of stator and rotor slots should not be +1*poles or -1*Poles or a multiple of poles
the no of rotor slots is =49
the rotor slot pitch in mm =17.9335
the rotor bar current in Amperes =397.0732
THE AREA OF each ROTOR BAR in mm2 =89.000000
designer specification to use Deep T rotor bars of ((10.4*6.7)+(10*2.2))
Width at root of rotor teeth in mm is 8.754966
Flux density at root of rotor tooth is 1.29
Inner Diameter of Rotor Lamination in mm =240.023808
the length of rotor bar in mm is =282.548008
the copper loss in rotor bars in Watts is=519.506213
the end ring current in Amperes =1549.091419
De (Current density of end ring) A/mm2=4
the area of end rings in mm2=387.272855
Mean Diameter of end ring in mm is 190.094245
the total copper loss in end rings in watts =155.341
Total Rotor Copper Loss in watts = 674.847
Carter coefficient is 0.675742
gap contraction factor for stator slots =1.161
gap contraction factor for rotor slots=1.062
gap contraction factor for slots=1.233
Gap Contraction Factor for ducts is 1.256746
effective length of air gap in mm =0.743511
MMF of Air Gap is 258.860795
area of teeth per pole in mm2=29.781033
Warning: Escape sequence '\' is not valid. See 'help sprintf' for valid escape sequences.
> In Mediuminductionmotor2 at 224
Value of Btssixty is 0.875414.The ampere turns for stator core corresponding to Btssixty are 3.086015e+02
MMF required for stator teeth are 7.440381
length of stator core in metres =0.095110
The ampere conductors required for Stator core corresp. to Bcs are 564.40
MMF required for stator core =53.679
Wtsonethird in mm =7.467679
Flux density in rotor teeth at one third height is 1.59

BTrt60=2.168436
Ampere turns of the rotor teeth corresponding to Btr60 is 5706.843929
MMF required for rotor teeth are 110.713
Ampere turns corresponding to rotor core flux density is 564.395022
MMF for rotor core ATcr=35.465503
Total AT = 466.158880
Magnetizing Current in Amperes is 8.123924
Weight of stator teeth in Kg =21.827830
Iron Loss in Stator Teeth in watts = 5.70662e+01
Volume of stator core in Kg/m3 = 0.007541
Total Iron Loss in Watts = 4.157555e+02
Total no load loss in watts = 818.5955
Total No Load Loss in Watts =818.5955
Loss Component of No Load Current in Amperes=0.657506
No Load Current in Amperes = 8.180489
No Load Current as expressed as percentage of Stator Current = 2.118471e+01
Specific Slot Permeance of Stator =0.000001
Specific Slot Permeance of Rotor is 0.000002
c2 = 1.6109e-06
Slot leakage Reactance in ohm is 0.921021
Overhang Leakage Reactance in ohms=0.863987
Zigzag Leakage Reactance in ohms =0.809
Total Leakage Reactance referred to Stator in ohms = 2.594241
Resistance of stator winding per phase in ohms=0.36
Total stator copper loss in watts=1.616934e+03
Rotor Copper Loss per phase in watts = 224.9
Rotor resistance referred to stator in ohms= 0.64
Input in watts = 2.528250e+04
Efficiency in percentage is= 88.519731
Slip is 0.029271
Speed of Rotor in RPM is 1456.092955
Rotor Resistance at stand still in ohms is 2.773357
No load power factor is 86.571070
Short circuit power factor 68.306601
Short Circuit current per phase in Amperes is 156.45
ratio of short circuit current to stator per phase current is 7.04

30 HP Induction Motor

The selection of rotor slots for 30 HP induction motor is determined from the plot illustrated in **Fig. 4.5**. Further, the **Circle diagram (Fig 4.6)** was used in calculation of the following factors:

- Rotor copper loss per phase =LK*Powerscale=5.17*41.5=215.5Watts/phase
- Tstarting/Tfull load=BG/AK=(903)/(544.8)=1.31
- Tmaximum/Tfull load=MN/AK=(1590)/(544.8)=2.92
- Efficiency at full load=AL/AH=(529.8)/(576)=91.3 %
- Slip at full load=LK/AK=5/194=0.023=2.7%

Table 4.3: .Representation of calculations of Circle diagram in AUTOCAD

Parameters	Output
Stator Full load current per phase	21.9Amp
Tstarting/Tfull load	1.31
Tmax/Tfull load	2.79
Rotor Copper loss per phase in watts	215.5Watts
Power factor at full load	Cosd(29)=0.87
Slip at full load	2.9%

Table 4.4: Comparison of MATLAB output and Circle diagram output

Parameters	MATLAB OUTPUT	CIRCLE DIAGRAM OUTPUT
Stator full load current per phase	22.2Amp	21.9Amp
Rotor copper loss per phase	224.9Watts/phase	215.5Watts/phase
Slip at full load	2.9%	2.7%
Efficiency at full load	88.5%	91.3%

The machine diagram of 3 phase 30 HP cage induction motor is drawn using MATLAB output in AUTOCAD 2013 as shown in **Figure 4.6**, the slots used in the machine diagram are shown in **Figure 4.7.**

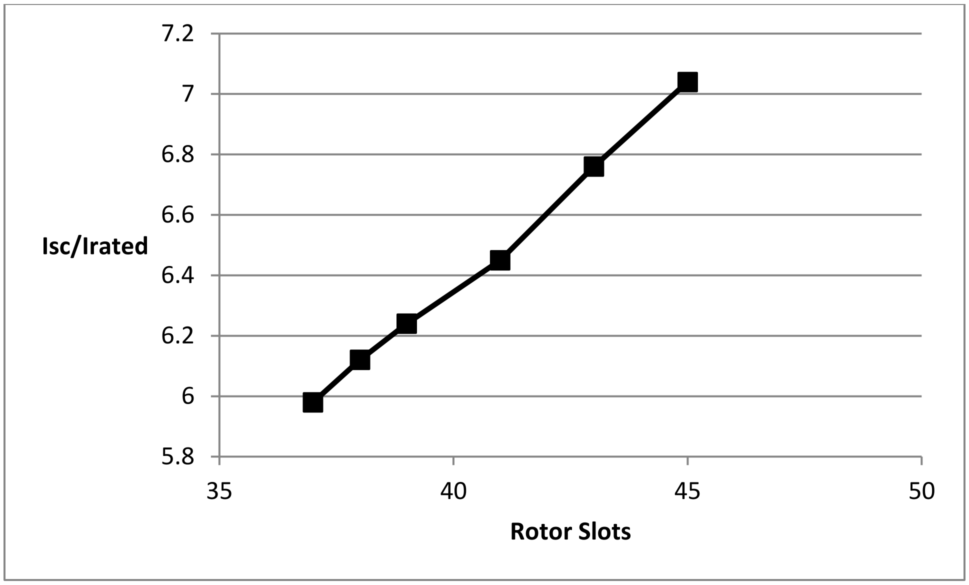


Fig 4.5 : Selection of rotor slots for 30HP 3 phase cage induction motor

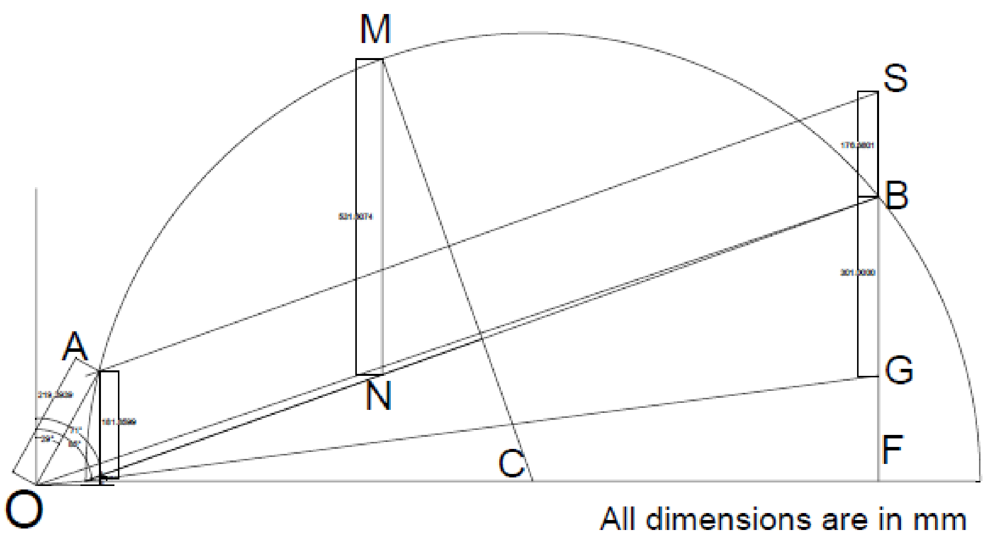


Fig 4.6: Design of 3 Phase 30 HP Cage Induction Motor by AUTOCAD -2013

Current Scale :
1mm=0.1Amp/phase
Power Scale :
1mm=23.96Watts/phase

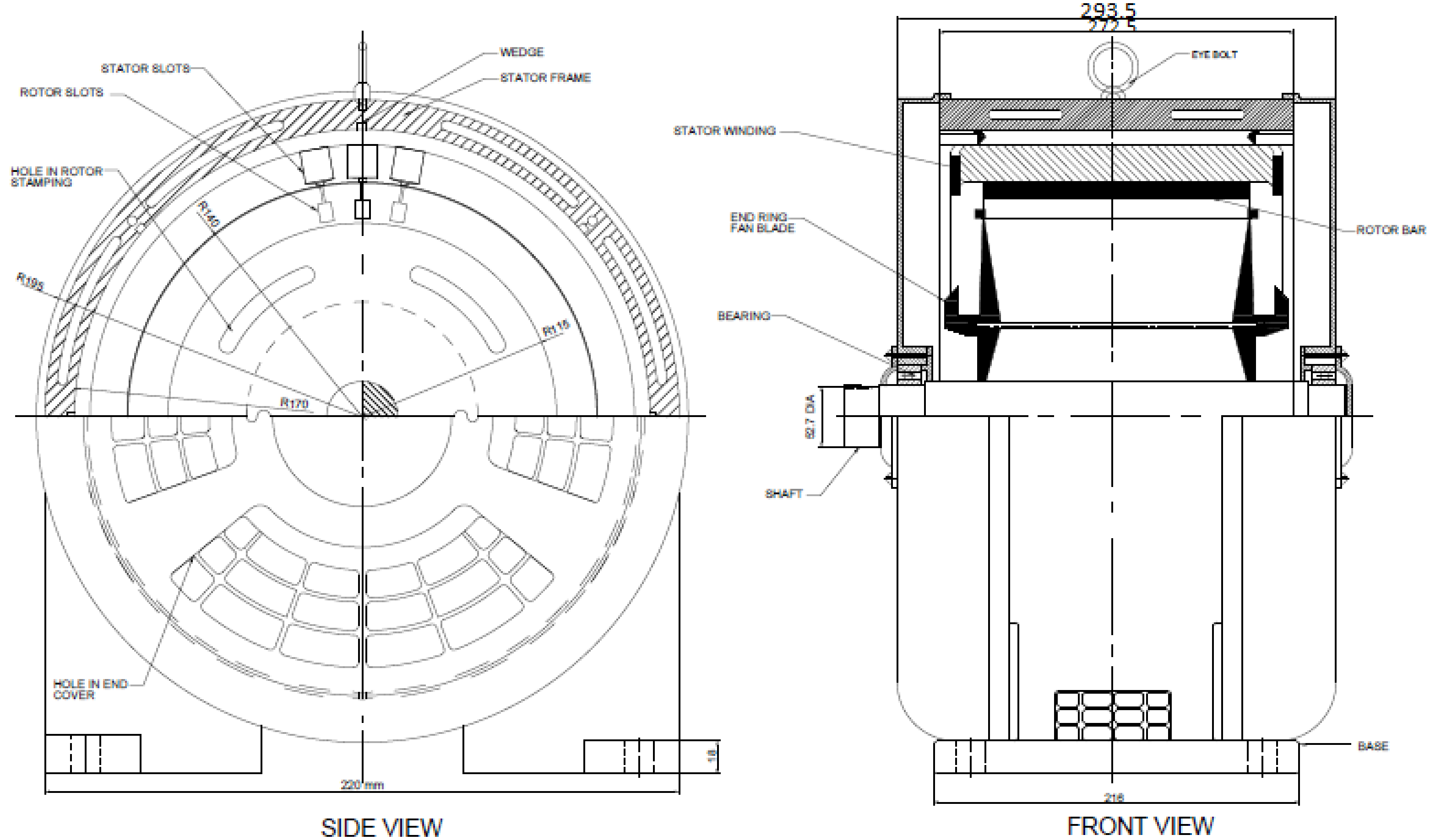


Fig 4.7: 30 HP, 3-PHASE INDUCTION MOTOR

NOTE:
ALL DIMENSIONS ARE IN mm.

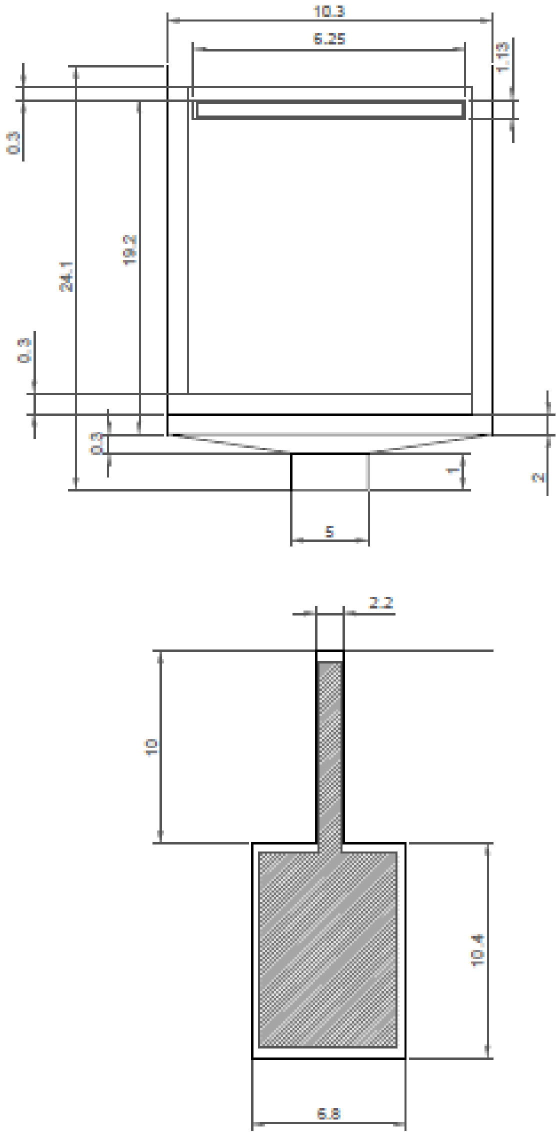


Fig. 4.8

30 HP,CAGE MOTOR STATOR AND ROTOR SLOTS

CHAPTER 5

CONCLUSIONS

- Design of three phase squirrel cage induction motor in M-File of MATLAB Software using synthesis method and Circle Diagram has been carried out.
- The design aspects are divided into five modules such as calculation of Diameter of Stator (D) and Length of the Stator Core (L), Stator Design, Rotor Design, Calculation of no load & short circuit current and Efficiency at full load.
- The MATLAB code thus developed is validated by performing case studies taking two common applications of three phase squirrel cage induction motors namely pumping and compressors.
- The code developed in MATLAB generated chiefly no-load current, short circuit current, no-load power factor and short circuit power factor. These inputs are used in the construction of Circle Diagram.
- The Circle Diagram in turn generated full load current per phase, full load power factor, ratio of maximum torque to full load torque & starting torque to full load torque and slip.
- The design values of three phase cage induction motor thus obtained for two differently rated motors namely 3H.P and 30H.P have been compared with the values of commercially available models in the market. The comparisons are:

- 3HP Induction Motor for Pump

Parameter	Design output value	Commercially available design value
Stator current per phase	5.15Amp/phase	5.4Amp/phase
Full load power factor	0.76	0.71
Tstarting/Tfull load	2.68	2
Isc/Irated	6.2	6
Tmaximum/Tfull load	3	2
Efficiency	85.4%	81%

- The efficiency of the designed three phase 3HP cage induction motor is slightly greater than that of the commercially available design. The ratio of starting torque to full load torque and ratio of maximum torque to full load torque of the designed motor is better than commercially available design.

- (b) 30HP Induction Motor for Compressor

Parameter	Design output value	Commercially available design value
Stator current per phase	21.9Amp/phase	22.2Amp/phase
Full load power factor	0.87	0.86
Tstarting/Tfull load	2.92	2.3
Isc/Irated	7	7
Tmaximum/Tfull load	1.66	2.1
Efficiency	91.3%	92.5%

- The efficiency of the designed 30 HP induction motor is approximately equal to the available commercial design. It can be concluded that the ratio of starting torque to full load torque and the full load power factor of the designed motor is slightly better than that of the commercially available motor .

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APPENDIX

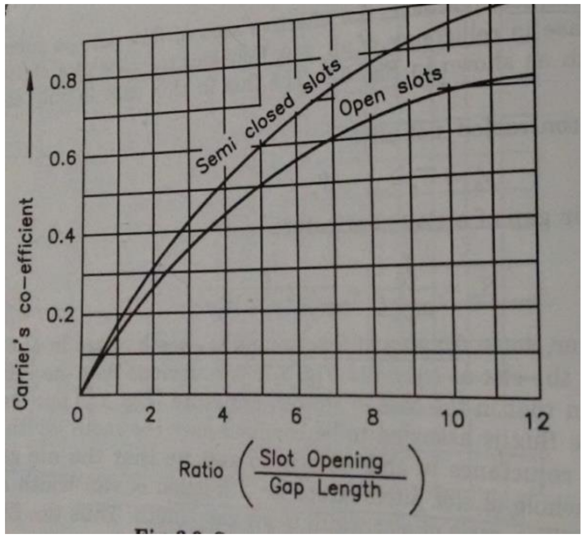

Fig. A1: Variation of Karter's co-efficient with the ratio of slot opening with gap length.

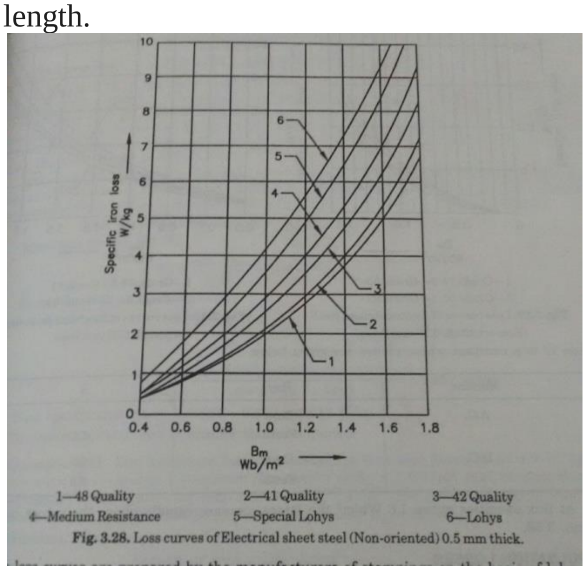

Fig. A2:Variation of specific iron loss(W/kg) with flux density (Wb/m2) of non oriented electrical sheet steel (0.5mm thick)