Design, Analysis and Performance Improvement of Three Phase Induction Motor

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Power Electronics, Machines & Drives)

By

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May 2015

Certificate

This is to certify that the Major Project Report entitled "Design,Analysis and Performance Improvement of Three Phase Induction Motor"submitted by **Mr. Darshan U. Thakar (Roll No: 13MEEP18)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Power Electronics, Machines & Drives of Nirma University is the record of work carried out by him/her under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Undertaking for Originality of the Work

I, Thakar Darshan Upendrabhai, Roll.No.13MEEP18 , give undertaking that the Major Project entitled "Design, Analysis and Performance Improvement Of Three Phase Induction Motor" submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in Power Electronics, Machines and Drives of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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Acknowledgement

Success of any work depends upon the dedication, sincerity and hard work.It also requires some ingredients such as motivation, encouragement and time.

First of all, I would like to thank my project guide Prof. Amit N. Patel, whose keen interest and excellent knowledge base helped me to finalize the topic of the dissertation work. His constant support and interest in the subject equipped me with a great understanding of different aspects of the required architecture for the project work. He has shown keen interest in this dissertation work right from beginning and has been a great motivating factor in outlining the flow of my work.

My sincere thanks to Prof Dr.P.N.Tekwani, Head of Electrical Engineering Department and Prof T.H.Panchal, P.G Co-ordinator, department of Electrical Engineering, Nirma University. I would like to thank all the other faculty members of Department of Electrical Engineering, Nirma University.

Finally, I would like to thank my parents, family and all my friends who encouraged me and supported me throughout the project work.

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Abstract

Electrical motors are the most popular machines used in commercial and industrial applications. Electrical motors are an important part of any electrical system because they consume about 65% to 70% of all electricity generated. They offers reasonable performance, low maintains, robust construction, a manageable torque-speed curve, stable operation under load and satisfactory efficiency. The first goal of this project is to design induction motor by conventional method. After that CAD programming is carried out for the whole design of Induction Motor. On the basis of CAD program, detailed FE analysis is carried out to validate CAD program. It is always desirable to achieve higher operational efficiency. So in this project the refinement in conventional induction motor design is carried out to improve motor efficiency and that is validated in FE software also.PWM inverter-fed induction motor drives are used in many industrial and commercial applications.PWM inverters provides many benefits including improved speed control of induction motor, reduced energy consumption and extended diagnostics. The power supplied to the motor by a PWM inverter has some adverse effects like damage in insulation, harmonic distortion, temperature rise, damage in bearing. To overcome this, it is necessary to modify the design of conventional induction motor for PWM frequency converter. So, certain modifications are suggested to improve performance of induction motor which is energized from inverter.

Nomenclature

V_{ph} .... Input phase voltage in volt

I_{ph} .... Input phase current in ampere

$cos\phi$ .... Input Power factor

η .... Efficiency of motor

f .... Frequency of supply

P .... Number of Poles

N $_s$ .... Synchronous Speed in RPM

B_{av} .... Average value of fundamental flux density

τ_p .... Pole Pitch

D .... Inner diameter of stator

L .... Stack Length

δ_s .... Current density in stator

K_{ws} .... winding factor for the stator

S_s .... number of stator slots

Z'_s .... number of conductors/stator slots

T_s .... Stator Turns per phase

K_{wr} .... Winding factor for the rotor

S_r .... Number of rotor slots

Z'_r .... Number of conductors/rotor slots

a_b .... Area of rotor bar

I_b .... Rotor bar current

δ_b .... Current Density in Rotor bar

I_e .... End ring current

δ_e .... Current Density in Endring

r_e .... Resistance of the end ring

r'_r .... Equivalent rotor resistance

T_c .... Critical Temperature

Abbreviations

IM . . . . Induction Motor

CAD . . . . Computer Aided Design

FEA . . . . Finite Element Analysis

EEM . . . . Energy Efficient Motor

PWM . . . . Pulse Width Modulation

VFD . . . . Variable Frequency Drives

VSI . . . . Voltage Source Inverter

CSI . . . . Current Source Inverter

NEMA . . . . National Electrical Manufacture Association

CIV . . . . Corona Inception Noltage

THHN . . . . Thermoplastic High Heat-Resistant Nylon-Coated

XLPE . . . . Cross-linked polyethylene

EMI . . . . Electro-magnetic Interference

LTS . . . . Low Temperature Super Conductor

HTS . . . . High Temperature Super Conductor

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Chapter 1

Introduction

Electrical Drives have a major impact on the consumption of electricity.Three phase induction motors are the most widely used motor in various electrical drives.In industry, About 70% motors are induction motors.Recently the prices of oil increase and the rates of electricity are highly depend on the rates of oil which is increasing .So it is necessary to improve the efficiency and reduces the operating cost of induction motors. To achieve minimum energy cost or maximum efficiency, the induction motor should either redesigned or fed through an inverter.

1.1 Features and Application of Induction Motor

With the almost universal adoption of a.c. system of distribution of electric energy for light and power, the field of application of a.c. Motors has widened considerably during recent years.The induction motor is most widely used motor in domestic and industrial application.

Advantages

- It has simple and rugged construction.
- It is relatively cheap.
- It requires little maintenance.
- It has high efficiency and reasonably good power factor.
- It has self-starting torque.

Disadvantages

- It is essentially a constant speed motor and its speed cannot be changed easily.
- Its starting torque is inferior to d.c. shunt motor.

Application Induction motors are used everywhere in our daily life still some of the main advantages are listed below :

- **Industrial Section :** Induction motors are most common motors used in any kind of Industry including it be an electrical or otherwise. No matter what a company produce but when it comes to a motor it is none other than an Induction motor. For large operations 3-Phase Induction and for small operations single phase or Fractional Horse Power (FHP) industion motors are employed.
- **Domestic sections :** Our home is a place where we can see many Induction motors doing their job. Motor of refrigerator, water pump motor, cooler motor are some of very common examples.

1.2 Performance Improvement of Three Phase Induction Motor

The concept of green earth also requires lesser energy consumption levels in all walks of life.The Earth's resources are finite and as the world population and aspirations of the developing nations continue to increase, energy consumption in all its forms becomes an ever more important issue.Now a days, the three-phase squirrel cage induction motor has remained an ideal prime mover. It is, therefore, imperative that the energy consumed by such motors be optimized.

1.2.1 Energy Efficient Three Phase Induction Motor

The electric motors consume over half of all electricity and so, the need for energy conservation is accelerating the requirement for increased levels of electric motor efficiency. Improving efficiency to higher level through the selection of an appropriate

combination of the design factors can be effective way to reduce the consumption of electricity. In order to maximize efficiency, new technology has been developed such as copper die-casting motor,reduction of electrical and magnetic loading , low core loss electrical steel and modified rotor bar design. However, these methods bring cost-rise and need special manufacturing technology.
The initial cost of energy efficient motors are more compare to standard induction motor but the operating cost of energy efficient motors are lower compare to standard induction motors.The another benefit of energy efficient induction motor is the long life.The energy efficient motors are designed to get same output with less amount of input i.e. higher efficiency.The energy efficient motors consist of more copper and iron and due to that lower friction and windage losses compared to standard induction motors.The energy efficient motors consist of 1 to 8% more efficiency compare to standard induction motors.

1.2.2 Inverter Fed Three Phase Induction Motor

Basically the induction motor is a constant speed machine. Speed of the induction motor will vary minor depending upon the load due to increase in a slip.Large variation of speed can be obtained only by varying the frequency of the supply by use of variable frequency or speed drives. A supply to the induction motor is given from a PWM converter. Frequency converter is used to generate the variable voltage and frequency required to control the speed of induction motor. Converter gives inversion of voltage coming from the link DC into an alternate signal of variable amplitude and frequency. Damage in insulation, harmonic, temperature rise, damage in bearing, etc are the problems present in the motor when operated with PWM converter. To overcome this, it is necessary to modify the design of conventional induction motor for PWM frequency converter.

1.3 Scope of the Work

The work is devided into three parts.The design of Three phase induction motor is carried out by conventional method.The CAD programming is carried out for the whole design of Induction Motor.By outcome of CAD program ,detail F.E. analysis is carried out to validate CAD program.This design is validated from cad as well as FE software. It is always desirable to achieve higher operational efficiency. So in this project the refinement in conventional Induction Motor design is carried out to improve motor efficiency and that is validated in F.E. software.Many applications required speed control of Induction motor to increase operational efficiency. With voltage source inverter the frequency and voltage of Induction motor is vary to control the speed. So, Induction Motor should be compatible with inverter because the output of inverter is not pure sine wave.So, certain modifications are suggested to improve performance of induction motor which is energized from inverter.

1.4 Literature Survey

Literature survey plays a very important role in project. Literature survey consists of three phase induction motor related papers that include different topologies related to performance improvement of induction motor, energy efficient motor and design implementation of inverter fed motor. Papers were taken from I.E.E.E conference proceedings, journal proceedings and other standard publication.

In this paper titled Design Strategies,New Materials and Technology To Improve Induction Motors Efficiency explained a comparison between four different design strategies with the aim to improve the efficiency of three-phase induction motors substitution of die-caste copper cage for aluminium cage with standard and "premium" electrical steels; design optimisation of copper cage motor by changing the stator winding and the stack length only; design optimisation of copper cage motor by changing the stator winding, the stack length and the stator and rotor slot shapes.[1]

In this paper titled Induction Motor Efficiency Improvement By Core Lengthing explained possibility of induction motor efficiency improvement by the core lengthening. Procedure for turns number choosing according to core length is described here.[2]

In this paper titled Improvements in Energy Efficiency Of Induction Motors By The Use Of Magnetic Wedges investigates the impact on the motor performance by employing magnetic versus non-magnetic wedges during starting and normal operation. The key functions of magnetic wedges in the slots of large induction motors are to reduce the air gap flux distortion, magnetizing current, the starting (inrush) current and temperature rise.[3]

In this paper titled Winding type influence on efficiency of an induction motor presents an analysis of the winding type influence on the efficiency of an induction motor. The aim of this work is to choose such a type of stator winding that the induction motor will have the best efficiency by employing minimum winding (copper) mass. The analytical calculations of electromagnetic characteristics were performed to select the best suited winding type and consequently ensuring the best efficiency and performance of the induction motor in question.[4]

In this paper titled Stator Slot Shape Design of Induction Motors for Iron Loss reduction presents The shape design of stator slot of 3-phase cage induction motors for iron loss reduction.[5]

In this paper titled Efficiency Increase of an Induction Motor by Improving Cooling Performance presents the relationship between the efficiency or the losses and the temperature of coils with experiments as well as simulations by changing parameters such as the load and the flow rate of cooling air. The losses and the efficiency are calculated from an equivalent circuit method as well as experiments.[6]

In this paper titled A New Approach to Mitigate CM and DM Voltage dv/dt Value in PWM Inverter Drive Motor Systems presents a novel techniques for reducing the high common-mode(CM) and differential mode(DM) voltage dv/dt value generated by PWM inverter simultaneously.[7]

In this paper titled Shaft Grounding-A Solution to Motor Bearing Currents presents problems associated with inverter driven induction motor and solutions of that problems.Shaft grounding is one of the technique to improve the performance of inverter driven induction motor.[8]

In this paper titled Evaluation of Motor Power Cables for PWM AC Drive presents the characteristics required for vfd drives.The problems associated with vfd cables and it's solutions are presented.[9]

In this paper titled Inverter Surge Resistant Enameled Wire with Nano composite

Insulating Material present the innovative technique to reduce stress of vfd drives [10]

In this paper titled Riding the Reflected Wave -IGBT Drive Technology Demands New Motor and Cable Considerations. presents reflected wave phenomena in vfd drives.The problems and solution of reflected wave in vfd drives are presented. [11]

Chapter 2

Design of Induction Motor

The designing an induction motor is to calculate the complete physical parameters of the machine as well as satisfy the customer requirement.

a. Main dimensions calculation

b. Stator Design

c. Rotor Design

d. Performance Estimation

2.1 Main Dimensions Calculation

Output Equation

The output equation gives the mathematical expression between the various physical and electrical parameters of the electrical machine. Output of a 3-phase IM is

$$Q = 3V_{ph} \times I_{ph} \times cos\phi \times \eta \times 10^{-3} \quad kW \tag{2.1}$$

Where,

V_{ph} = Input phase voltage in volt

I_{ph} = Input phase current in ampere

$cos\phi$ = Input Power factor

η = Efficiency of motor

but,

$$V_{ph} = 4.44 \times f \times \phi \times T_{ph} \times K_w \tag{2.2}$$

so,equation (2.1) can be written as

$$Q = 3(4.44 \times K_w \times f \times \phi \times T_{ph}) \times I_{ph} \times cos\phi \times \eta \times 10^{-3} \quad kW \tag{2.3}$$

Where,

f = frequency of supply =PN/120

P = Number of Poles.

N = Speed in RPM

K_w= Winding factor =0.955 $\phi = B_{av} \times \tau_p \times$L

B_{av} = Average value of fundamental flux density

τ_p = Pole Pitch=π D/P

D = Inner diameter of stator.

L = Length of the IM .

Total ampere conductor on ststor=6$I_{ph}T_{ph}$

Total Ampere conductors is known as total electric loading

Specific electric loading = It is defined as electric loading per meter of periphery, denoted by ac .

ac=6T_{ph} I_{ph}/π D

so,T_{ph} I_{ph}=ac.π D/6

Putting the values of f,ϕ & T_{ph} I_{ph} in equation (2.3) we get

$$Q = 11 \times B_{av} \times ac \times \cos\phi \times \eta D^2 L n_s \quad kW \tag{2.4}$$

So,finally the equation becomes

$$Q = C_0 D^2 L n_s \quad KW \tag{2.5}$$

Where,C_0=Outut Co officient=$11 \times B_{av} \times ac \times cos\phi \times \eta$

Choice of Specific magnetic loadings

Advantages of Higher value of specific magnetic loading(B_{av})

- Cost decreases
- Size reduces
- Overloading capacity increases

Disadvantages of Higher value of specific magnetic loading B_{av}

- Increase Iron losses
- Decrease efficiency
- Increase p.f.

For 50 Hz machine the value of flux density is 0.35 to 0.6 Tesla.

Choice of Specific electrical loadings

Advantages of Higher value of specific electrical loadings (ac)

- Size reduces
- Cost reduces

Disadvantages of Higher value of specific electrical loadings (ac)

- Copper requirement increases
- Copper losses increases
- Temperature rise increases
- Overload capacity decreases

The range of specific electrical loading is 5000 to 45000 ampere conductor per meter.

Separation of D and L

The product D^2L is obtained from equation 2.4 is split up into two components D and L. The output equation gives the relation between D^2L product and output of the machine. The separation of D and L for induction motor is obtained by some assumption.The ratio of core length to pole pitch ratio for various design features is :

i. For minimum cost 1.5 to 2.0

ii. For good efficiency 1.4 to 1.6

iii. For good over all design 1.0 to 1.1

iv. For good power factor 1.0 to 1.3

2.2 Design of Stator

Shapes of stator slots

There are generally two types of slots are used in induction motor i.e. open type of slots and semi enclosed slots.Semi-enclosed slots are usually preferred for induction motors. An induction motor with semi enclosed slots has low tooth pulsation loss, less noise, less magnetizing current and reduced overload capacity. The operating performance of the induction motors depends upon the stator slots shapes. and so, it is needed to select suitable number of slots.

Number of stator slots

The number of stator slots must be properly selected during the designing because this number affects the weight , cost and operating characteristics of the induction motor. Though there are no rules for selecting the number of stator slots but considering the advantages and disadvantages of selecting higher number slots comprise has to be set for selecting the number of slots. Following are the advantages and disadvantages of selecting higher number of slots

Advantages

- Reduction of leakage reactance.
- Reduction in tooth pulsation losses.
- Higher over load capacity.

Disadvantages:

- Cost increases

- Weight increases
- Magnetizing current increases
- Iron losses increases
- Poor cooling
- Temperature rise increases
- Efficiency decreases

Based on the above advantages the number of slots/pole/phase is selected as three or more for integral slot winding. However for fractional slot windings,the number of slots/pole/phase may be selected as 3.5. So selected number of slots should satisfy the consideration of stator slot pitch at the air gap surface, which is in between 1.5 to 2.5 cm.

Stator slot pitch τ_{ss}=π D/S_{ss} where S_{ss} is the number of stator slots.

Turns per phase

EMF equation of an induction motor is given by

$$V_{ph} = 4.44 \times f \times \phi \times T_{ph} \times K_w \tag{2.6}$$

So, the number of turns per phase can be obtained from emf equation

$$T_{ph} = \frac{V_{ph}}{4.44 \times f \times \phi \times K_w} \tag{2.7}$$

Conductor cross section area

The cross section area of stator conductors can be estimated from the stator current per phase and suitably assumed value of current density for the stator windings.The cross sectional area of the stator conductor a_s=I_s/δ_s.where, δ_s is the current density in stator windings.A suitable value of current density has to be assumed by considering the advantages and disadvantages.

Advantages of higher value of current density

- The cross section area reduces
- Weight reduces
- Cost reduces

Disadvantages of higher value of current density

- Resistance increases
- Cu loss increases
- Temperature rise increases
- Efficiency reduces.

Stator slot area

The slot area is the area occupied by the conductors and the insulation. Once the number of conductors per slot is decided approximate area of the slot can be estimated.

Slot space factor = Area of copper in the slot /Area of each slot

The range of the space factorvis in between between 0.4 to 0.6.

Length of the mean Turn

Length of the mean turn is calculated using the formula l_{mt}=2L+2.3τ_p+0.24

where L is the gross length of the stator and τ_p is the pole pitch in meter.

Resistance of stator winding Resistance of the stator winding per phase is calculated using the below formula.

r_s= (0.021 x l_{mt} x T_{ph}) / a_s where l_{mt} is in meter and a_s is in mm ^{2}. So, resistance of stator winding copper losses in stator winding can be calculated as

Total cu loss in stator winding = 3 $(I_s)^2$ r_s

2.3 Design of Rotor

Choice of air gap length

The air gap is the very critical part of the machine. The performance parameters of the motor like power factor, magnetizing current, over load capacity, cooling and noise are affected by length of the air gap. Hence length of the air gap is selected by considering the advantages and disadvantages of larger air gap length.

Advantages:

- Increase in overload capacity
- Cooling increases
- Reduction in unbalanced magnetic pull
- Reduction in tooth pulsation loss
- Reduction in noise

Disadvantages:

- Increasing in magnetizing current
- Reduction in power factor

Number of rotor bars

The starting of the induction motor is depend upon the proper selection of number of stator and rotor slots.Crawling and cogging are the two common phenomena which are observed due to wrong combination of number of stator and rotor slots.The number of rotor slots may be selected using the following guide lines.

(i) To avoid crawling and cogging: (a)$S_s \neq S_r$ (b) $S_s \neq S_r \pm 3P$

(ii) To avoid synchronous cusps $S_s \neq S_r \pm P, \pm 2P, \pm 5P$.

(iii) To avoid noisy operation $S_s \neq S_r \pm 1, \pm 2, (\pm P \pm 1), (\pm P \pm 2)$

Rotor Bar Current

The rotor bar current of a squirrel cage induction motor is determined by comparing the mmf developed in stator and rotor.

Hence the current per rotor bar is given by $I_b=(K_{ws}\times S_s\times Z'_s)\times I'_r/(K_{wr}\times S_r\times Z'_r)$

where K_{ws} stator winding factor,

S_s number of stator slots, Z'_s number of conductors per stator slots,

K_{wr} Rotor winding factor,

S_r number of rotor slots,Z'_r number of conductors per rotor slots and I'_r equivalent rotor current in terms of stator current and is given by $I'_r = 0.85\ I_b$.

Cross sectional area of Rotor bar

The cross sectional area of the rotor conductor is calculated by rotor bar current and assumed value of current density for rotor bars. Because the 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 copper losses and reduction in efficiency. The starting torque will increase by increasing the rotor resistance. The rotor bar current density is generally assumed between 4 to 7 A/mm^2.

Hence cross sectional area of the rotor bars can be calculated as $a_b = I_b / \delta_b$ mm^2.

Shape and Size of the Rotor slots

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

(i) As the rotor is closed the rotor surface is smooth at the air gap and hence the motor draws lower magnetizing current.

(ii) Reduced noise as the air gap characteristics are better

(iii) increased leakage reactance and reduced starting current.

(iv) Over load capacity is reduced

(v) Undesirable and complex air gap characteristics.

From the above it can be concluded that semi enclosed slots are more suitable and hence are employed in rotors.

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 $= 0.021 \text{ x } l_b / A_b$

Copper loss in rotor bars $= I_b^2 \times r_b \times$number of rotor bars.

End Ring Current

All the rotor bars are short circuited by connecting them to the end rings at both the end rings. The rotating magnetic filed 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.

Maximum end ring current I_e(max) = 1/2 x (Number rotor bars per pole) I_b(av)

So,I_e(max)= 1/2 x S_r/P x I_b/1.11

Hence rms value of end ring current

$$I_e = \frac{S_r I_b}{\pi P} \tag{2.8}$$

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,

where,current density in the end ring may be assume as 4.5 to 7.5 A/mm^2.

Copper loss in End Rings

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 x l_{me} / A_e

Total copper loss in end rings = 2 x $I_e{}^2$x r_e

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.

Equivalent rotor resistance r'_r= Total rotor copper loss/3 x $(Ir')^2$

2.4 Performance Estimation

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.

Calculation of Iron losses

Iron losses are generally produce in all the iron parts due to the varying magnetic field of the machine. Iron losses have two components, hysteresis and eddy current losses occurring in the iron parts,which are 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 so, the iron losses occurring in the rotor is very 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) Iron loss in stator teeth: The following steps explain the calculation of iron loss in the stator teeth

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

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

(iii) Calculation of the weight of the teeth based on volume and density of the material as $W_{ts} = V_{ts}$ x density.

(iv)By referring the graph of flux density vs watt/kg,the iron loss/kg can be found.

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

(b) Losses in stator core

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

(i) Calculate the cross section area of the core as $A_{cs} = d_{cs}$ x l_i m^2

(ii) Compute the mean diameter of the stator core below the slots as Dmcs= D + 2 h_{ts} +d_{cs} m

(iii) Calculate the volume of stator core as $V_{cs} = A_{cs}$ xπD_{mcs} m^3

(iv) Compute the weight of the stator core as $W_{cs} = V_{cs}$ x density

(v)By referring the graph of flux density vs watt/kg,the iron loss/kg can be found.

(vi) Total iron losses in core = Iron loss /kg x weight of core W_{cs}. 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% to 2% percent of the out put of the motor.

Hence total no load losses = Total iron losses + Friction and windage loss.

No load current

There are two component of no load current first one is,iron loss component, I_w and second is magnetizing component I_m . Thus the no load current $I_0 = \sqrt{(I_m)^2 + (I_w)^2}$ amps

Magnetizing current: This current is responsible for the production of flux in in the different parts of the induction motor. So, this current can be evaluated from all the magnetic circuit of the induction motor. 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. Based on the total ampere turns of the magnetic circuit the magnetizing current can be calculated as

Magnetizing current $I_m = p\ AT_{60} / (1.17\ k_w\ T_{ph})$

where p no of pairs of poles, AT_{60} Total ampere turns of the magnetic circuit at 60^o from the centre of the pole, T_{ph} Number of stator turns per phase.

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 evaluated from no load losses and applied voltage.

Iron loss component of current Iw= Total no load losses / (3 x phase voltage)

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.

No load power factor $\cos\phi_0 = I_w / I_0$.

Chapter 3

CAD and FE analysis of Standard Induction Motor

Now a days the induction motor is the most widely used motor because of it's construction features. The induction motors are the first preferences for industry so it is needed to design the motor very quickly as well as very accurately. The basic design of an induction motor is the dimensioning of the magnetic and electric circuits which is generally carried out by applying analytical equations. However, accurate performance estimation of the induction motor is carried out using computer aided design . With this Computer aided design (CAD) , the effect of a single parameter on the dynamical performance of the machine can be effectively studied by using a computer programming language.

Sequential Steps for Design of Induction Motor

- Calculation of main dimensions .
- Calculation of number and size of stator slots, conductor size, stator tooth flux density, copper losses and weight of copper, core flux density, height of core, iron losses
- Calculation of air gap length, rotor diameter, no. of rotor slots, conductor size, copper losses, flux densities in tooth and core, weight of rotor .
- Calculation of carter Co-efficient and ampere-turns for air gap, stator tooth,

stator core, rotor tooth, rotor core and total No-load AT, magnetizing current, no-Load power factor.

- Calculation of reactance, short-circuit current, and short circuit power factor.

- Calculation of total losses, efficiency and total weight of motor.

3.1 Flow chart

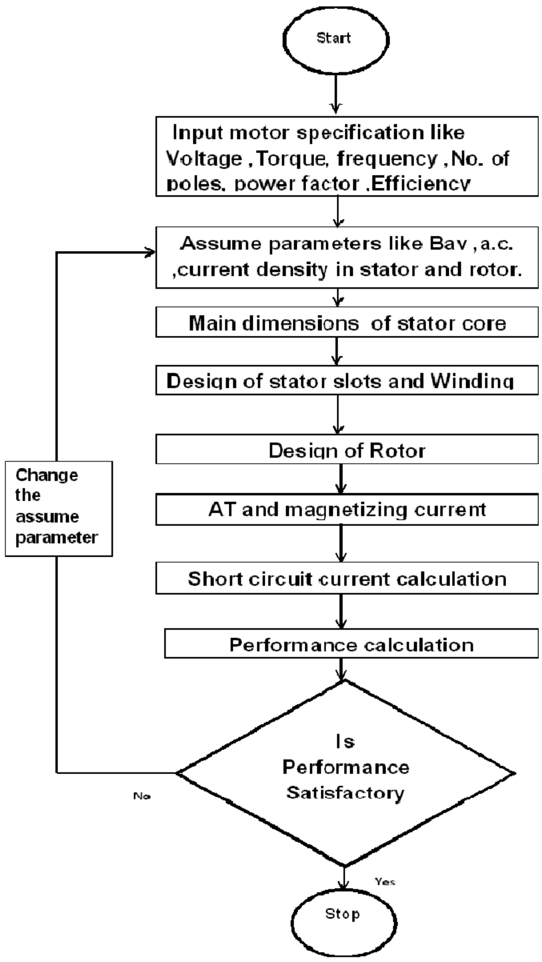


Figure 3.1: Flow chart of Design of three phase Induction Motor

3.2 CAD of 2.2 kW,415 V,50 Hz,4 pole,1440 rpm,3-phase IM

It is needed to assume some parameters of the motor before the design.The Table 3.1 shows the assume parameters.

Table 3.1: Assume Parameters

Sr. No.	Parameters	Values
1	Efficiency (η)	0.80
2	power factor	0.85
3	Specific magnetic loading B_{av}	0.44 Wb/m^2
4	Specific electric loading ac	21000 A/m
5	L/τ	1.5
6	current density of stator δ_s	4 A/m^2
7	current density of rotor bar δ_b	6 A/m^2
8	flux density in teeth	1.12 Wb/m^2
9	flux density in stator core	1.185 Wb/m^2

The CAD uses computer in design process.Using the same specifications as in the analytical method, the obtained CAD output values are shown in Table 3.2.

Table 3.2: CAD result

Sr No.	Motor Parameters	Calculated Values
1	Output coefficient C_0	96.58
2	Stack Length L	0.123 m
3	Inner Diameter D	0.104 m
4	Stator Turns per phase T_s	427
5	Stator Current per phase I_s	2.77 A
6	Area of Stator Conductor a_s	0.674 mm^2
7	Width of Stator Slot W_{ss}	13.2 mm
8	Depth of Stator Slot d_{ss}	21 mm
9	Length of mean turn L_{mts}	0.68 mm

10	Area of Stator Core A_{cs}	1.89×10^{-3} m ^{2}
11	Outer Diameter D_o	186 mm
12	Length of air gap l_g	0.426 mm
13	Diameter of Rotor D_r	0.103 m
14	Rotor bar Current I_b	247.41 A
15	Area of each rotor bar a_b	41.23 mm ^{2}
16	Width of Rotor Slot W_{sr}	4.3 mm
17	Depth of Rotor Slot d_{sr}	8.3 mm
18	Length of each bar L_b	165 mm
19	Resistance of each bar r_b	$77.7 \times 10^{-6}\Omega$
20	Total copper loss in bars	101 W
21	End ring current I_e	428 A
22	Area of End ring a_e	80 mm ^{2}
23	Outer diameter of end ring	85.8 mm
24	Outer diameter of end ring	65.8 mm
25	Mean diameter of end ring D_e	75.8 mm
26	Full load slip s	0.056
27	Volume of stator teeth	0.34×10^{-3} m^3 Ω
28	Weight of stator teeth	2.6 kg
29	Volume of stator core	0.985×10^{-3} m^3 Ω
30	Weight of stator core	4.9 kg
31	Iron loss in stator teeth	30 W
32	Iron loss in stator core	37 W
33	Total Iron loss	134 W
34	Friction and windage loss	33 W
35	Total No loss	167 W
36	Resistance of stator winding r_s	3.37 Ω
37	Total stator cu loss	193 W
38	Total rotor cu loss	124 W
39	Total loss at full load	484 W
40	Input at full load	2684
42	Efficiency at full load η	81.96 %

3.3 Different Methods of FEA

MotorSolve IM is the most accurate design and analysis software for induction motors and generators due to its automated finite element results module. The easy to use template based interface includes dozens of editable rotor and stator types. The automated coil winding feature determines all optimal balanced layouts available for the current design. MotorSolve IM is a comprehensive tool within which modeling,design iteration and design validation can be carried out for induction machines. To facilitate this, user friendly and powerful modeling features as well as multiple types of analysis options of varying degrees of approximation and complexity have been implemented. These include equivalent circuit based analysis, AC analysis, PWM and dynamical motion simulations.

Different methods of FE analysis

MotorSolve IM is a FEA based analysis software. Its four analysis options can accurately model various induction motor related parameters and effects such as leakage inductance, slotting, deep bar effect, skewing, effects of switching on motor characteristics due to inverter fed phases, etc. The interface allows the user to compute the machine characteristics at various speeds (and other variables) as well as those at a single operating point.

a. **Equivalent Circuit Analysis**

   This method provides a quick way to generate a chart of performance results, as a function of speed, for the selected design(s) driven by an ideal voltage source at different frequencies. Each curve is calculated using an equivalent circuit model of the machine obtained through time-harmonic FEA.

b. **AC Analysis - machine characteristics and losses predicted with greater precision**

   AC analysis is the second of four analysis types in MotorSolve IM. This method differs from equivalent circuit calculations in that variations of the circuit parameters with slip are taken into account in addition to material non-linearities. Hence, machine characteristics and losses are predicted with greater precision.

c. **PWM Analysis - studying the effects of switching on the machine performance**
The PWM analysis is the most powerful of all the analysis methods. It simulates the motor connected to a three-phase bridge operating in current regulation mode using delta-PWM (current driven) or space vector PWM (voltage driven). PWM analysis is important for studying the effects of switching on the machine performance. The complete 3-phase bridge circuit equations are solved in PWM taking mutual and self couplings into account.

d. **Motion Analysis - complete FEA based dynamical simulation of the model**
The motion analysis is more accurate than the PWM analysis as it performs a time-stepping finite element analysis, which takes into account the saturation of magnetic materials at every time step. However, it assumes the supply is an ideal source, so switching effects are not taken into account. The Motion analysis is also more computationally expensive.

3.4 FEA of 2.2 kW,415 V,50 Hz,4 pole,1440 rpm,3-phase IM

Finite Element Analysis is carried out to verify the CAD result. FEA of 2.2 kW,400V,3-phase,50 Hz,1500 r.p.m. squirrel cage Induction Motor is carried out and results are shown in Table 3.3

Table 3.3: FEA of 2.2 kW,415 V,3-phase,50 Hz,3-phase IM

Sr.No.	Parameters	Values
1	Supply Type	Voltage Driven
2	Supply Voltage	415 V
3	Synchronous Speed	1500 r.p.m
4	Rated slip	5.5

5	Outer Diameter	126 mm
6	Airgap thickness	0.43 mm
7	Stack length	122.9 mm
8	Number of bars	22
9	Number of phases	3
10	Number of poles	4
11	Number of slots	24
12	Rotor bar area	41.23 mm^2
13	Stator inner Diameter	104.4 mm
14	Stator outer Diameter	186 mm
15	Stator slot area	189 mm^2
16	Stator slot depth	22.86 mm
17	Connection Type	Delta
18	Winding Type	Lap Winding
19	Coil Span	6
20	Number of layers	1
21	Number of Turns/Coil	104

FEA output of 2.2 kW,415 V,3-phase,50 Hz,1440 rpm 3-phase Induction Motor is shown in Table 3.4.

Table 3.4: FEA output of 2.2 kW,415 V,3-phase,50 Hz,3-phase IM

1	Output Power P_o	2.2 kW
2	Input Power P_i	2.68 kW
3	Efficiency %	81.7%
4	Power factor	0.814
5	Total loss (kW)	0.490
6	Torque(N.m)	15
7	RMS current (A)	4.48

Flux density plot

The flux density plot of 2.2 kW,415 V,3-phase,50 Hz squirrel cage Induction Motor is shown below

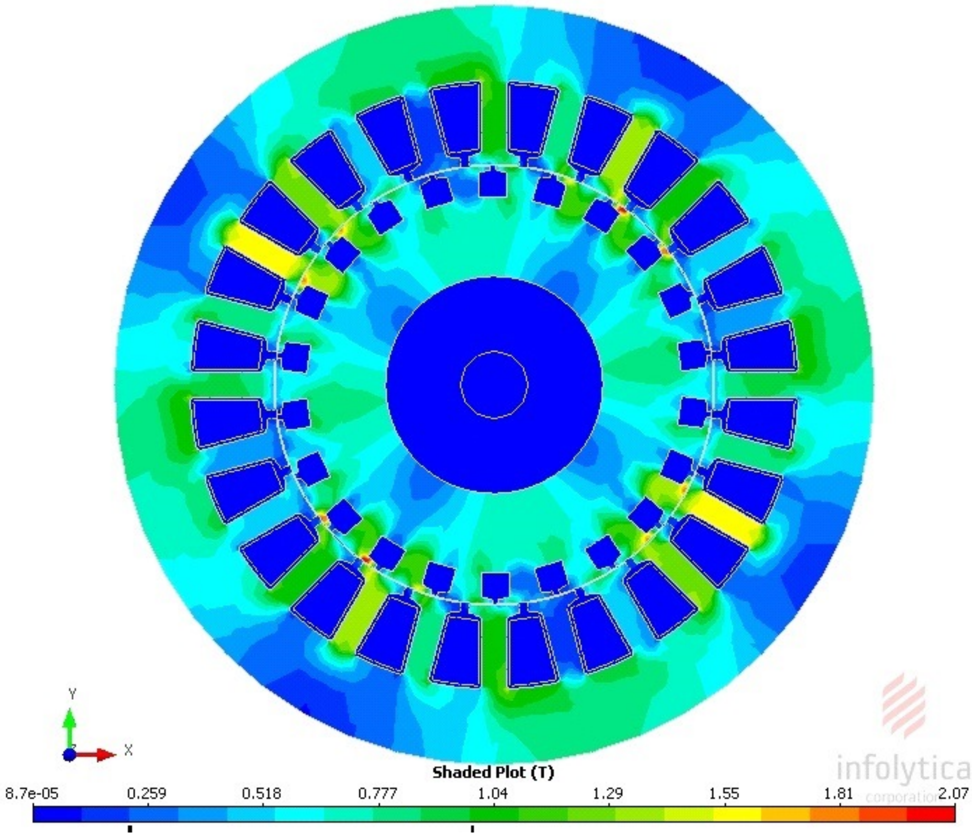


Figure 3.2: Flux density plot of three phase Induction Motor

Table 3.5: Flux Density Comparison

Sr.No.	Flux density	CAD	FE software
1	Flux density in stator teeth(Wb/m^2)	1.50	1.57
2	Flux density in stator core(Wb/m^2)	1.185	1.12
3	Flux density in Rotor teeth(Wb/m^2)	1.36	1.37

3.5 Comparison between CAD and FEA

Comparative Analysis of 2.2 kW,415 V,50 Hz,4 pole,1440 rpm,3-phase IM
A comparison of CAD and FE results is given in Table 3.6. It is observed that the results are within the acceptance tolerance; however, the minor difference between the two result can be attributed to the empirical design coefficients and formulae used in the CAD program.

Table 3.6: Comparative Analysis of 2.2 kW,415 V,50 Hz,4 Pole,1440 rpm IM

Sr No.	Parameters	CAD	FE Software
1	Output Power P_o(kW)	2.2	2.2
2	Input Power P_i (kW)	2.7	2.68
3	Efficiency (%)	81.87	81.8
4	Power factor	0.821	0.814
5	Total loss (kW)	0.488	0.490
6	Torque(N.m)	15	15
7	RMS current (A)	4.48	4.48
8	Flux density in stator teeth(Wb/m^2)	1.50	1.57
9	Flux density in stator core(Wb/m^2)	1.185	1.12

Comparative Analysis of 3.73 kW,415 V,50 Hz,4 Pole,1440 rpm ,3-phase, IM The comparison of CAD and FE of 3.73 kW,415 V,50 Hz,4 Pole Induction motor is shown in Table 3.7.

Table 3.7: Comparative Analysis of 3.73 kW,415 V,50 Hz,4 Pole,1440 rpm IM.

Sr No.	Parameters	CAD	FE Software
1	Output Power P_o(kW)	3.73	3.73
2	Input Power P_i(kW)	4.34	4.37

3	Efficiency (%)	85.96	85.80
4	Power factor	0.80	0.804
5	Total loss (kW)	0.609	0.620
6	Torque(N.m)	24.5	24.5
7	RMS current (A)	7.2	7.2
8	Flux density in stator teeth(Wb/m^2)	1.50	1.58
9	Flux density in stator core(Wb/m^2)	1.2	1.19

Comparative Analysis of 37 kW,415 V,50 Hz,4 Pole,1440 rpm,3-phase IM

The comparison of CAD and FE of 37 kW,415 V,50 Hz,4 Pole Induction motor is shown in Table 3.8.

Table 3.8: Comparative Analysis of 37 kW,415 V,50 Hz,4 Pole,1440 rpm IM

Sr No.	Parameters	CAD	FE Software
1	Output Power P$_o$(kW)	37 kW	37 kW
2	Input Power P$_i$(kW)	39.7 kW	39.8 kW
3	Efficiency (%)	92.9	92.7
4	Power factor	0.80	0.80
5	Total loss (kW)	2.78 kW	2.91 kW
6	Torque(N.m)	244	244
7	RMS current (A)	67.7	67.7
8	Flux density in stator teeth(Wb/m^2)	1.70	1.72
9	Flux density in stator core(Wb/m^2)	1.25	1.29

Chapter 4

Design of Energy Efficient Three Phase Induction Motor

Electrical Drives have a major impact on the consumption of electricity.Three phase induction motors are the most widely used motor in various electrical drives.About 70% of all electrical energy consumed in India is used for driving electric motors and out of them about 55% of which is consumed by industrial motors.Improving efficiency in electric drives is important, mainly, for two reasons: economic saving and reduction of environmental pollution

Motors are known as ”energy-efficient” if they meet or exceed the efficiency levels listed in the National Electric Manufacturers Association’s (NEMA’s) publication.Energy efficient motors having the efficiency 2 to 8% more than standard motors.

Advantages Of Energy Efficient Motor

- Design changes, better materials and manufacturing improvements reduces motor losses hence better efficiency.
- New motors run cooler since they generate less copper loss heat producing less stress on windings hence last longer, reduced down time and lower repair cost.
- Saves money and energy.
- Near uniform efficiency from 50% to 100% of full load even at part load conditions

- Substantial saving after payback period.
- Higher power factor, less noise, lower no-load losses.
- Extended lubrication cycles due to cooler operation.
- Better tolerance to thermal stresses resulting from stalls or frequent starting.
- Increased bearing life.
- Less sensitive to abnormal conditions such as impaired ventilation, under and over voltage and phase imbalance.
- Green house gas emission reduction.

Disadvantages Of Energy Efficient Motor

- Higher initial cost
- Higher the material cost.

4.1 Different Methods for Efficiency Improvement

Reduction of Electric and Magnetic Loading

The reduction of electrical and magnetic loading can be considered as a simplest and very effective method for getting a higher efficiency motor.But,reduction of electrical and magnetic loading increase the volume of the motor.But increasing the axial length if the core has to be compatible with the external frame of the original induction motor. The increase of the motor axial length with a constant rated power can be considered equivalent to a power derating of a bigger machine.So, the air gap flux density and current density in energy efficient motor are lower than in the standard motors and, as consequence, motor losses can be reduces.

Replacing the aluminium bar by copper bar

By replacing the aluminium bar by copper bar in standard induction motor,the efficiency of the copper bar induction motor increases. The specific resistance of aluminium is 2.6 $\times 10^{-6}$ $\Omega.cm$.while specific resistance of the copper is 1.6 $\times 10^{-6} \Omega.cm$.So,by replacing the aluminium bar by rotor bar reduce the heat loss.But the mass density of copper is 8900 kg/m^3 while mass density of aluminium is 2700 kg/m^3.So, the weight of the motor increase by replacing the aluminium bar by cu bar.

High performance electrical steel

The magnetic material plays an important role in the improvement of the motor performance . The main features of the steel are the magnetic permeability and the specific losses. Moreover, the choice of a best electrical steel depends on several aspects such as cost,annealing, workability, storehouse demands and "business tradition".The iron loss per kg for different material at 1.5 T flux density is shown below.

Table 4.1: Comparison of Different Magnetic Material

Material with Grade	Iron Loss(W/kg)
M 15-26	3.30
M 15-29	3.08
M 19-24	4.05
M 19-26	3.28
M 19-29	3.17
M 27-24	4.55
M 27-26	3.70
M 27-29	3.36
M 36-24	4.72
M 36-26	3.74
M 36-29	3.69
M 43-26	3.28
M 45-24	5.04
M 45-29	3.65
M 47-24	4.02
M 47-29	3.48

Increasing conductor's volume

Standard-efficiency motors employ aluminium or copper conductors of a size no longer than that needed to deliver the required horsepower. But energy efficient induction motors consist of bigger copper conductors to lower the winding resistance.Generally the size of the conductors are 35% to 40% larger than needed to simply satisfy the motor output horsepower requirement.

Modified Rotor bar design

By changing the shape of the rotor bar,the rotor cage losses can be reduces.

Modification in fan design

Because the energy efficient induction motors designed for high efficiency so, run cooler than standard type of induction motor. The design modification incorporate a smaller cooling fan, reducing windage losses and resulting in quieter operation.

Improvements in cooling performance

The efficiency is strongly affected by the coil temperatures variation caused by the internal and the external cooling methods. The coil temperature reduction causes the efficiency increase by 0.25% at 100% load and the efficiency increase by 0.5% at 125% load. The improvement of the cooling performances increases the efficiency of the motor by reducing the coil temperature. Nevertheless, the fan efficiency as well as the fan performances should be considered for the optimum fan designs to increase the total efficiency of the motor.

Wedging with soft Ferrite

If the ferrite materials wedged into the stator slots of the motors, the Carter's coefficient for the motor reduces, and the exciting current decreases for decreasing the primary copper loss. In the use of the ferrite wedges, the pulsation of air gap flux will be regulated, and the pulsation loss of tooth become reduces. As the results, the motor efficiency will be improved.

Reduction in lamination thickness

By reducing the thickness of the lamination in rotor and stator steel also lowers eddy current losses so,improve the efficiency.

Reduction in air gap length

By reducing the air gap between stator and rotor , the intensity of the magnetic flux will increase, so improving the motor ability to deliver the same torque at a reduced power.

4.2 CAD of 2.2 kW,415 V,50 Hz,4 pole,1440 rpm,3-phase EEIM

It is needed to assume some parameters of the motor before the design.The below table shows the assume parameters.

Table 4.2: Assume Parameters

Sr. No.	Parameters	Values
1	Efficiency (η)	0.88
2	power factor	0.85
3	Specific magnetic loading B_{av}	0.40 Wb/m^2
4	Specific electric loading ac	20000 A/m
5	L/τ	1.5
6	current density of stator δ_s	3.5 A/m^2
7	current density of rotor bar δ_b	5.5 A/m^2
8	flux density in teeth	1.12 Wb/m^2
9	flux density in stator core	1.185 Wb/m^2

The CAD uses computer in design process.Using the same specifications as in the analytical method, the obtained CAD output values are shown in Table 4.3.

Table 4.3: CAD result

Sr No.	Motor Parameters	Calculated Values
1	Output coefficient C_0	71.242
2	Stack Length L	0.155 m
3	Inner Diameter D	0.116 m
4	Stator Turns per phase T_s	427
5	Stator Current per phase I_s	2.77 A
6	Area of Stator Conductor a_s	0.674 mm ^{2}
7	Width of Stator Slot W_{ss}	13.2 mm
8	Depth of Stator Slot d_{ss}	21 mm
9	Length of mean turn L_{mts}	0.68 mm
10	Area of Stator Core A_{cs}	1.89×10^{-3} m ^{2}
11	Outer Diameter D_o	186 mm
12	Length of air gap l_g	0.426 mm
13	Diameter of Rotor D_r	0.103 m
14	Rotor bar Current I_b	247.41 A
15	Area of each rotor bar a_b	41.23 mm ^{2}
16	Width of Rotor Slot W_{sr}	4.3 mm
17	Depth of Rotor Slot d_{sr}	8.3 mm
18	Length of each bar L_b	165 mm
19	Resistance of each bar r_b	$77.7 \times 10^{-6} \Omega$
20	Total copper loss in bars	101 W
21	End ring current I_e	428 A
22	Area of End ring a_e	80 mm ^{2}
23	Outer diameter of end ring	85.8 mm
24	Outer diameter of end ring	65.8 mm
25	Mean diameter of end ring D_e	75.8 mm
26	Full load slip s	0.056
27	Volume of stator teeth	0.34×10^{-3} m^3 Ω
28	Weight of stator teeth	2.6 kg

29	Volume of stator core	0.985×10^{-3} m^3 Ω
30	Weight of stator core	4.9 kg
31	Iron loss in stator teeth	25 W
32	Iron loss in stator core	25 W
33	Total Iron loss	100 W
34	Friction and windage loss	20 W
35	Total No loss	120 W
36	Resistance of stator winding r_s	3.37 Ω
37	Total stator cu loss	150 W
38	Total rotor cu loss	80 W
39	Total loss at full load	328 W
40	Input at full load	2528
42	Efficiency at full load η	87.0 %

4.3 FEA of 2.2 kW,415 V,50 Hz,4 pole,1440 rpm,3-phase EEIM

Finite Element Analysis is carried out to verify the CAD result. FEA of 2.2 kW,415 V,3-phase,50 Hz,1440 rpm energy efficient induction motor is carried out.The Table 4.4 shows the input parameters for FEA.

Table 4.4: FEA of 2.2 kW,415 V,3-phase,50 Hz,3-phase IM

1	Supply Type	Voltage Driven
2	Supply Voltage	415 V
3	Synchronous Speed	1500 r.p.m
4	Rated slip	5.5
5	Outer Diameter	126 mm
6	Airgap thickness	0.43 mm
7	Stack length	122.9 mm

8	Number of bars	22
9	Number of phases	3
10	Number of poles	4
11	Number of slots	24
12	Rotor bar area	41.23 mm^2
13	Stator inner Diameter	104.4 mm
14	Stator outer Diameter	186 mm
15	Stator slot area	189 mm^2
16	Stator slot depth	22.86 mm
17	Connection Type	Delta
18	Winding Type	Lap Winding
19	Coil Span	6
20	Number of layers	1
21	Number of Turns/Coil	104

FEA output of 2.2 kW,415 V,3-phase,50 Hz,1440 rpm 3-phase energy efficient induction motor is shown in Table 3.3.

Table 4.5: FEA output of 2.2 kW,415 V,3-phase,50 Hz,3-phase IM

1	Output Power P_o(kW)	2.2
2	Input Power P_i(kW)	2.68
4	Power factor	0.814
5	Total loss (kW)	0.320
6	Torque(N.m)	15
7	RMS current (A)	4.48

4.4 Comparison between standard and energy efficient induction motor

Comparison between standard and EEIM of 2.2 kW,415 V,3-phase,50 Hz,4 pole,1440 rpm The Table 4.6 shows the result of energy efficient motor after applying the different methods listed above.

Table 4.6: Comparison of standard and EEIM of 2.2 kW,415 V,3-phase,50 Hz,4 pole,1440 rpm

Parameters	Standard Motor	Energy Efficient Motor
Torque (N.m)	15	15
Output Power(kW)	2.2	2.2
Input Power(kW)	2.68	2.52
Efficiency(%)	82.0	87.3
RMS Voltage(V)	415	415
RMS Current(A)	4.48	4.48
Power Factor	0.82	0.84
Total Losses(kW)	0.480	0.320

Comparison between standard and EEIM of 3.7 kW,415 V,3-phase,50 Hz,4 pole,1440 rpm

The Table 4.7 shows the result of energy efficient motor after applying the different methods listed above.

Table 4.7: Comparison of standard and EEIM of 3.7 kW,415 V,3-phase,50 Hz,4 pole,1440 rpm

Parameters	Standard Motor	Energy Efficient Motor
Torque (N.m)	24.5	24.5
Output Power(kW)	3.7	3.7
Input Power(kW)	4.37	4.14
Efficiency(%)	84.5	89.3
RMS Voltage(V)	415	415
RMS Current(A)	7.2	7.2
Power Factor	0.826	0.827
Total Losses(kW)	0.67	0.443

Comparison of standard and energy efficient motor of 37 kW,415 V,3-phase,50 Hz,4 pole,1440 rpm IM The Table 4.8 shows the result of energy efficient motor after applying the different methods listed above.

Table 4.8: Comparison of standard and EEIM of 37 kW,415 V,3-phase,50 Hz,4 pole,1440 rpm

Parameters	Standard Motor	Energy Efficient Motor
Torque (N.m)	244	244
Output Power(kW)	37	37
Input Power(kW)	40.6	39.6
Efficiency(%)	91.1	93.3
RMS Voltage(V)	415	415
RMS Current(A)	67.7	67.7
Power Factor	0.824	0.83
Total Losses(kW)	3.6	2.6

4.5 Calculation of Pay back Period

By applying energy efficient induction motor in place of standard induction motor, The motivation for applying an energy-efficient motor in place of standard motor is to accomplish the delivery of the required mechanical power to the load with a minimum of wasted energy in the form of motor losses. So, it is motor losses that are the central area of concern in evaluating alternate motor choices for a particular application.

The motor losses (in kW) are calculated as

$$L_s = hp \times 0.746[\frac{1.0}{\eta - 1}] \tag{4.1}$$

Where, hp = horsepower output, η = efficiency expressed as a decimal value.

The changing in motor losses are

$$L_s = hp \times 0.746[\frac{1.0}{\eta_1} - \frac{1.0}{\eta_2}] \tag{4.2}$$

Where,η_1=Efficiency of Standard Motor,η_2=Efficiency of Energy Efficient Motor

The saving in rupees

$$S = L_s \times H \times C \tag{4.3}$$

Where,H=Operating time per hour,C=cost of Energy in Rs./kWh The payback period is the time to pay back the cost differential between two motors with differing efficiencies is made using

$$PBP = \frac{CD}{S} \tag{4.4}$$

Where, CD=cost difference of two motors If the motors operating time per day is 10 hours/day then below table shows the pay back period of three different rating motors.

Table 4.9: Payback Period Calculation

Parameters	2.2 kW	3.73 kW	37 kW
Efficiency of Standard IM(%)	82.0	84.5	91.1
Efficiency of Energy efficient IM(%)	87.3	89.3	93.3
Saving in losses(kW)	0.1569	0.248	0.7144
CD(in rupees)	2890	3680	22110
PBP(in months)	8.4	6.8	16

Chapter 5

Design Modification of Energy Efficient Inverter Driven Three Phase Induction Motor

Basically the induction motor is a constant speed machine. Speed of the induction motor will vary minor depending upon the load due to increase in a slip.Large variation of speed can be obtained only by varying the frequency of the supply by use of variable frequency or speed drives. PWM inverter is used to generate the variable voltage and frequency required to control the speed of induction motor.
The motor driven by inverter consist of below listed problems.

- Efficiency degradation due to harmonic content
- Motor and cable insulation stress due to high dv/dt
- Corona
- Electromagnetic Interference (EMI)
- Bearing failure due to common mode voltage and bearing shaft current
- Mechanical vibration

5.1 Problem of reduction in efficiency and its solution

Efficiency Degradation in Inverter fed Induction Motor

An induction motor driven by PWM voltage presents a lower efficiency than when driven by purely sinusoidal voltage because of the losses increase caused by harmonics.These harmonics will increase the electrical losses which decrease efficiency. This increase in losses will also result in an increase in temperature of the motor, which further reduces efficiency. The current produced from the PWM voltage input to the motor consist of numerous harmonics of various magnitudes.These harmonic currents does not contributing to torque production,but produces I^2R heat in the motor,which reduces the efficiency of the motor.

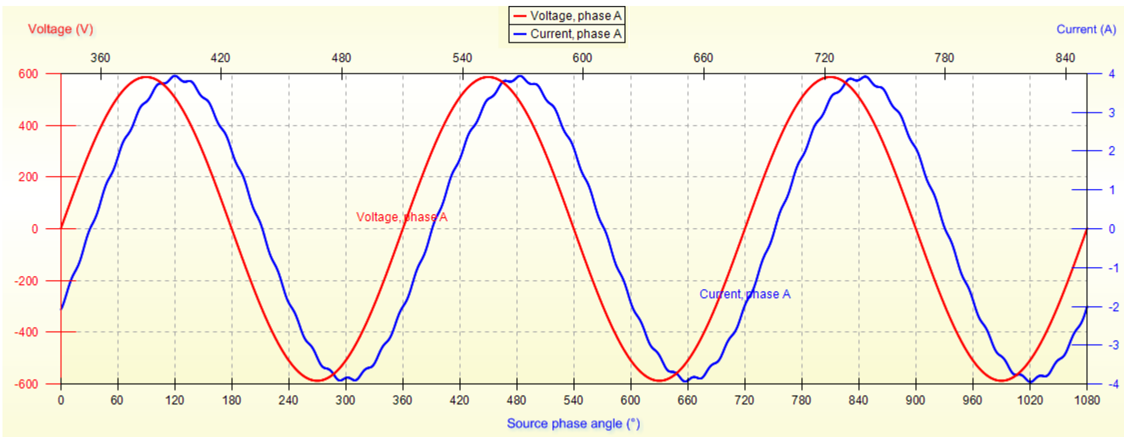


Figure 5.1: Voltage and Current waveform of induction motor driven by pure sine wave

Figure 5.1 shows the voltage and current waveform of induction motor driven by pure sine wave, while Figure 5.2 shows the voltage and current waveform of induction motor driven by PWM inverter.

Selection of PWM switching frequency

The selection of the PWM switching frequency is a compromise between the losses in the inverter and losses in the motor .

- If the switching frequency is low than the losses in the motor are higher because

Figure 5.2: Voltage and Current waveform of induction motor driven by PWM inverter

the current waveform consist of harmonics.

- If the switching frequency increases than motor losses are reduced but the losses in the inverter will increase due to increased number of commutations. Losses in the motor cable also increase due to the leakage current through the shunt capacitance of the cable.

The switching frequency increases by using IGBT devices in inverter and getting relatively smooth sinusoidal current waveform so,motor losses reduces.
The figure 5.3 shows the voltage and current waveform of induction motor driven by PWM inverter consist of high switching frequency.

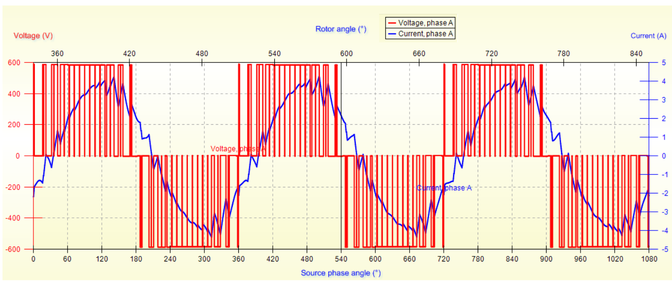


Figure 5.3: Voltage and Current waveform of induction motor driven by high switching frequency PWM inverter

FE analysis of 2.2 kW,415 V,4-pole,3-phase induction motor is carried out for different switching frequency and results are shown in the table.

Table 5.1: Comparison of Motor and Inverter efficiency at different switching frequency

Switching Frequency(Hz)	Inverter Efficiency(%)	Motor Efficiency(%)
600	97.65	82.4
800	97.61	83.9
1000	97.5	84.3
2000	97.2	84.80
4000	96.6	84.83
8000	95.3	84.86
10000	94.7	84.89

Arnon5:

- Arnon5 is frequently used as laminations in high speed, high efficiency motors and generators. For modern drive application which consist of high efficiency, high performance, it is necessary to operate a.c. devices at higher frequencies, i.e., 400 Hz to 10 kHz.By reduction in the thickness of the standard silicon ferromagnetic steels 0.25 mm or more, core loss due to eddy currents is excessive.

- Non oriented electrical steels with thin laminations (down to 0.127 mm thick) for ferromagnetic cores of high frequency rotating machinery and other power devices are manufactured by Arnold Magnetic Technologies Corporation, Rochester, NY, U.S.A.

- Arnold has two standard non oriented lamination products: Arnon 5 and Arnon 7. If the frequencies increases above 400 Hz, they consist of less than half the core loss of standard gauge non-oriented silicon steel laminations.

- Arnon is best for higher frequency motors and generators above 400 Hz where using the thinner material offsets the less efficient effects of increased eddy currents and subsequent heat buildup. Using thin laminations of Arnon produces a more efficient unit and frees up design constraints by allowing for fully enclosing the motor without external cooling.

- Arnon is proven to lower core loss by as much as 50% compared to other materials. Some motors using Arnon have been tested to exceed 97% efficiency.

The below table shows the difference between arnon 5 with conventional silicon steel.

Table 5.2: Comparision of M19 with Arnon5

Properties	M19	Arnon5
Lamination Thickness(mm)	0.356 to 0.635	0.127
Watt/kg at 1 T and 50 Hz	1.1	1.2
Watt/kg at 1 T and 400 Hz	26.4	10.4
Watt/kg at 1.5 T and 50 Hz	56	23.39
Watt/kg at 1 T and 1000 Hz	88	32

The below figure shows the B-H curve of Arnon5 material.

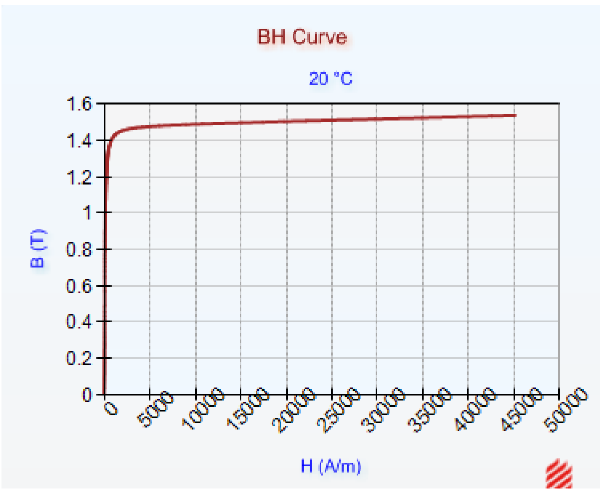


Figure 5.4: B-H curve of Arnon5 material

F.E. Analysis of Inverter Driven Induction Motor

The below Table 5.3 shows the comparative analysis of 2.2 kW,415 V,50 Hz,4-pole,3-phase IM with pure sinusoidal supply and PWM inverter(with low and high switching frequency).The table shows that as the switching frequency increases the harmonic content in current wave decrease so efficiency of the motor increases.

Table 5.3: Comparative Analysis of 2.2 kW,415 V,50 Hz,4-pole

Motor Parameters	Pure Sine	PWM Bridge	PWM Bridge (High S/W Frq.)	PWM Bridge (High S/W Frq.) & Arnon5)
Torque(N.m)	15	15	15	15
O/P(kW)	2.2	2.2	2.2	2.2
I/P(kW)	2.68	2.75	2.65	2.64
RMS Voltage(V)	415	415	415	415
RMS Current(A)	4.68	4.89	4.70	4.70
Efficiency(%)	82.0	80.0	82.8	83.4
Total iron losses(kW)	0.150	0.178	0.178	0.125
Total cu losses(kW)	0.310	0.350	0.257	0.257

The Table 5.4 shows the comparative analysis of 3.7 kW,415 V,50 Hz,4-pole,3-phase IM.

Table 5.4: Comparative Analysis of 3.7 kW,415V,50Hz,4-pole

Motor Parameters	Pure Sine	PWM Bridge	PWM Bridge (High S/W Frq.)	PWM Bridge (High S/W Frq.) & Arnon5)
Torque(N.m)	24.6	24.6	24.6	24.6
O/P(kW)	3.73	3.73	3.73	3.73
I/P(kW)	4.21	4.36	4.27	4.21
RMS Voltage(V)	415	415	415	415
RMS Current(A)	7.4	7.7	7.51	7.51
Efficiency(%)	84.5	81.4	83.1	85.1
Total iron losses(kW)	0.276	0.373	0.373	0.266
Total cu losses(kW)	0.380	0.450	0.355	0.355

The Table 5.5 shows the comparative analysis of 37 kW,415 V,50 Hz,4-pole,3-phase IM.

Table 5.5: Comparative Analysis of 37 kW,415 V,50 Hz,4-pole

Motor Parameters	Pure Sine	PWM Bridge	PWM Bridge (High S/W Frq.)	PWM Bridge (High S/W Frq.) & Arnon5)
Torque(N.m)	246	246	246	246
O/P(kW)	37.3	37.3	37.3	37.3
I/P(kW)	39.47	40.23	39.93	39.7
RMS Voltage(V)	415	415	415	415
RMS Current(A)	66.3	68.3	66.6	66.6
Efficiency(%)	91.1	89.3	90.4	92.0
Total iron losses(kW)	1.36	1.88	1.88	1.16
Total cu losses(kW)	2.2	2.50	2.0	2.0

5.2 Problems associated with common mode voltage and shaft current and its solution

When the induction motor is supplied by 3-phase sine wave supply, each phase voltage is displaced 120^0 from its companions. Their sum at the neutral point of the motor winding and will become zero. Adding all 3-phases at any point in the 360^0 cycle and their sum will will always zero volts . For example, in Figure 4, at the left-most vertical marking phase A is at zero volts, phase B is 70% negative and phase C is 70% positive.so, by adding this three phases then their sum becomes zero volt.

Unlike 3-phase sine wave supply, the VFD output has only two states. With only two output states it is not possible to create a completely symmetrical 3 phase waveform and due to that an unbalance occurs. The result is an output voltage waveform where the neutral bounces between the positive and negative DC bus levels, creating a very large common mode voltage.

For VSI or CSI, the CMV contains high dv/dt so its frequency content can be in the megahertz (MHz) range. Common mode currents (I) are created due to capacitive coupling of the common mode voltage. since I = C dv/dt, where C is the capacitance

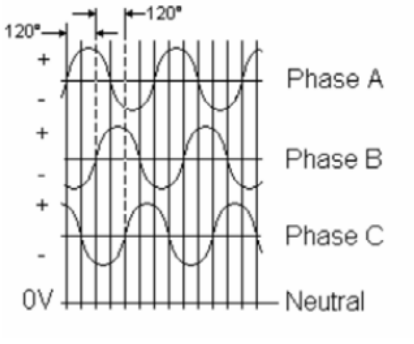


Fig. 4

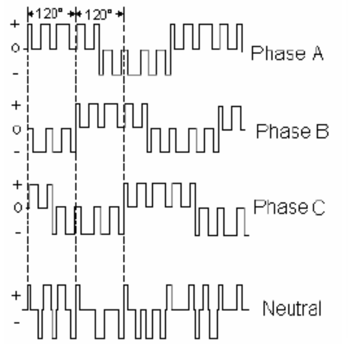


Fig. 5

of the common mode circuit element.

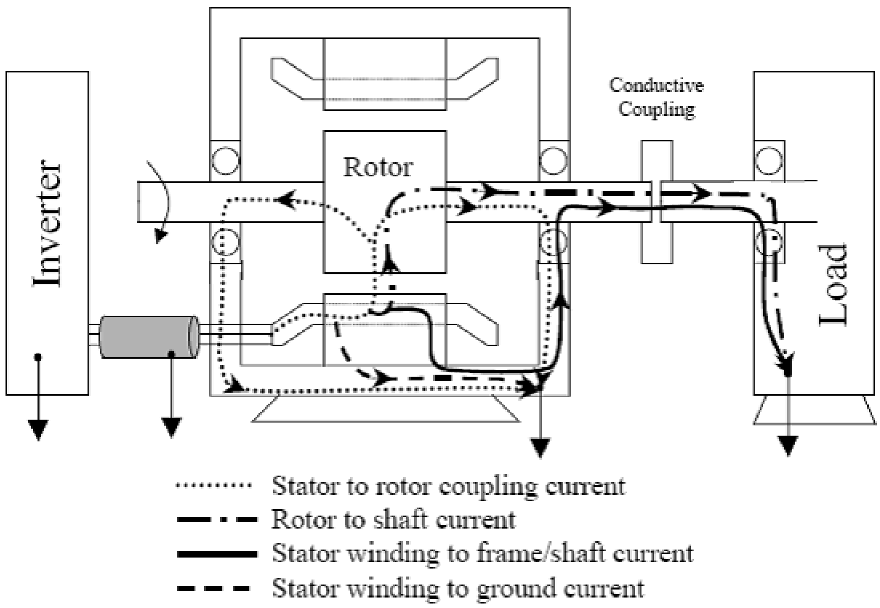


Figure 5.5: Different Bearing current Paths

There are many potential current paths through which this capacitive coupling from the motor stator winding to ground. In above figure, the various paths of capacitive coupled current are presented. The high rate of change of voltage created in the stator winding couples capacitive with the stator core and frame and with the rotor.

- The dotted current path represents a capacitive current coupled to the rotor through the air gap, with a return path through the motor bearings, motor ground connection and finally to the drive ground.

- The current path consist of dot-dashed in above figure is also capacitively coupled from the stator winding to the rotor across the air gap. This current flows through a conductive coupling, and through at least one load bearing, to the load ground and back to the drive ground. The same two bearing current phenomena discussed for the dotted current can occur with the dot-dash current, only now the conductive or insulating state of the load bearing will determine the type of current flow. The rotor to shaft current may damage in the load bearing .

- The current path which consist of solid line (stator winding to frame/shaft) in above figure indicates capacitively coupled current between the stator winding and the frame. As shown, this current find path through the stator winding insulation (which is capacitively conductive at high frequencies) and, with a poor motor to inverter high frequency ground connection, flows through the motor frame, the motor bearing, the motor shaft, the conductive coupling, the load bearing, the load ground and finally go to the drive ground. Current through this path may damage the motor and load bearings, as well as the motor to load coupling.

- For the reduction of bearing damage, the preferred path for all these currents is the dashed (or stator winding to ground) path in above figure. In this path, no current flows through the motor or load bearings.

Effects of electric current flow through the bearing

The combination of capacitive discharge currents and high frequency is problematic because it induces and bearing currents and shaft voltages.When the voltage increases beyond some limit,it will to discharges to ground.But this discharging path is through the bearings because these bearings are the path of least resistance. The lubricant film in the bearing is a major barrier to cross, and when a threshold voltage occurs that is strong enough to overcome the lubricant film thickness, then a discharge occurs. Then the voltage charges up again, like a capacitor would do. It is the same

set-up as used in electrical discharge machining (EDM), but in motors this is not controlled and leads to "electrical erosion".
Because of the passage of electric current in the contact zone of raceways and rolling elements, heat is generated causing local melting of the bearing metal surface.

Micro-cratering

Due to frequency converters are more and more used ,micro-cratering is the most common effect of electric current passage. The damaged surface appears dull and characterized by molten pit marks. Multiple micro-craters cover the rolling element and raceway surfaces. The size of crater are very small and consist of 5 to 8 μ m in diameter, disregarding if it is on the inner ring, outer ring or a rolling element. The real shape of these craters can only be seen under a microscope in very high magnification.

Figure 5.6: Micro-cratering

Fluting or washboard

Fluting or washboard is the patterns of multiple grey lines across the raceways. They appear shiny and molten. Due to mechanical resonance vibration caused by the dynamic effect of the rolling elements when they are over-rolling smaller craters this fluting is generated. This means that fluting is not a primary failure mode produced by the current flow through the bearing itself but it is a secondary bearing damage that becomes visible only after time and has its initial point from craters.

Grease-blackening

Figure 5.7: Fluting

Current discharges through the bearings also cause the lubricant to change its composition and degrade rapidly. The local high temperature causes additives and the base oil to react, and it can cause burning or charring of the base oil. Additives will be used up more quickly. Thus the lubricant gets black discolored grease affected by current discharges Fluting or washboard in raceway The dull surface of the ball bearing is a sign of micro catering. A rapid breakdown of the grease is a typical failure mode that results from current passage through the bearings.

Figure 5.8: Grease-blackening

Strategies for mitigating VFD induced shaft voltages in motors

1. Faraday shield: Faraday shield is the conductive shield,which is put between stator and rotor.The faraday shield provide capacitive barrier which bloch the current flow through the bearings.But this solution is very expensive and not possible to implement.

2. Insulated bearings: Insulated bearing consist of a nonconductive layer in between

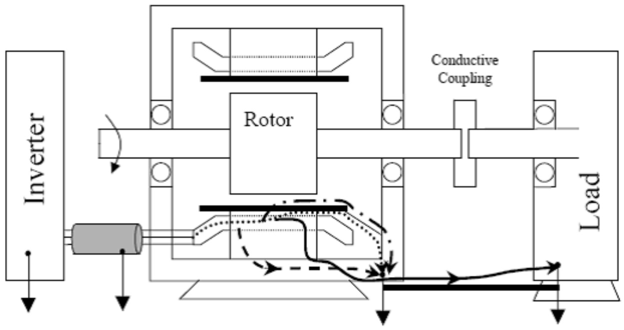


Figure 5.9: Shielded Induction Motor

rolling element and raceway.This insulation layer is made of using resin or ceramic layer which prevent the bearing current to flow through bearings.But the current will find the another path to flow and that path may be through attached tachometer or attached pump or even through the load.This method is costly so generally applied to larger sized motors.

Figure 5.10: Insulated bearings

3. Ceramic bearings: Ceramic bearings consist of insulated rolling element and generally made of ceramics which prevent the bearing current to flow through bearings.But the current will find the another path to flow and that path may be through attached tachometer or attached pump or even through the load.This method is costly so generally applied to larger sized motors.

4. Grounding brush: Grounding brush technology is the innovative and practical technology.A metal brush provide a low resistance path to ground.This method is less costly compare to another methods.

Figure 5.11: Ceramic Bearings

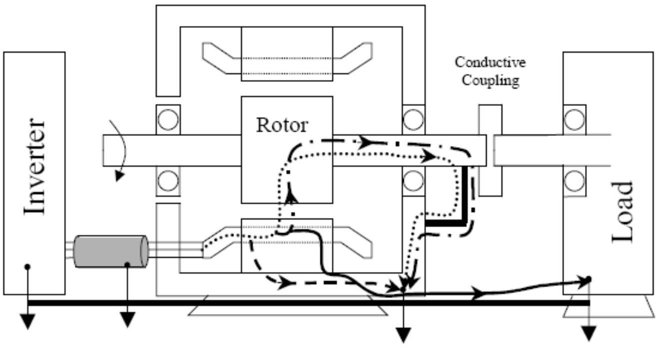


Figure 5.12: Induction Motor with Grounding Brush

Grounding brush require extra space and mounting arrangement.This brush produce high heat at high speeds.

Grounding brushes consist of some problems listed below:

- Due to mechanical contact with the shaft,they are subject to wear .
- The effectiveness of this metal brush reduces due to collection of contaminations on their bristles.
- Some oxidation occur on the surface of metal brush which reduces the effectiveness of the grounding.
- The maintenance is required on a regular basis which increase their lifetime cost.

5. Shaft grounding ring (SGR): This is a very innovative solution for protection of bearing due to shaft voltage voltage and bearing current.The shaft grounding ring is made of using conductive micro fibers to flow the shaft current and provide a very low resistance path from shaft to the frame of the motor and protect the motor bearings. .This innovative technology uses the principles of ionization to increase the electron-transfer rate and get extremely efficient discharge of the high frequency shaft voltages induced by VFDs. This method consist of low cost solution which can be applied to any size of induction motor.

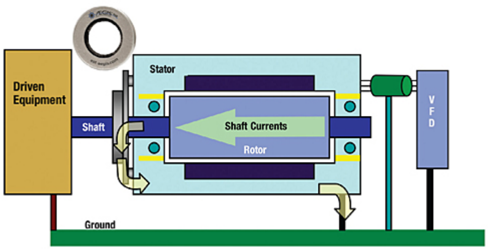


Figure 5.13: Induction Motor with Grounding Brush

Shaft grounding ring is the simplest and commonly used method because of it's low cost. The idea of the grounding the motor shaft is to provide a lower impedance path to the motor frame than through the bearings. This lower impedance path may be established with the shaft grounding ring.
To improve the performance of the brush grounding ring the brush wire material has been replaced with micro-diameter conductive fibers.The figure 5.13 shows a motor with shaft grounding ring installed on the drive-end of the motor shaft, respectively. This micro-fiber brush construction provides several advantages listed below.

- First, the micro-fibers consist of is very low wear rate.

- Micro-fiber generate very low heat so suitable for high speed application.

- The micro-fiber consist of very high current rating compare to conventional brush.

5.3 Issues with VFD cable and its solution

5.3.1 High Rate of Rise of Voltage(dv/dt)

In VFD devices, semiconductor switches are used to switch the DC bus power to the output. These switches have two states: ”on” or ”off”. The PWM continually switches between these two states with a constant frequency but with variable pulse widths. The widths of the pulses determine the effective output voltage. Smaller pulse widths result in lower effective voltage and larger pulse widths result in higher effective voltage. Depending on the drive, the frequency of these pulses is between 4 and 20 kHz. Instead of steep pulses, a sinusoidal waveform of the voltage and current is desired at the motor.

Modern semiconductor switches (IGBTs) are very sophisticated and allow for high pulse rise times of more than 3 kV/μs in VFD applications. These constantly occurring steep voltage impulses stress the cable insulation.

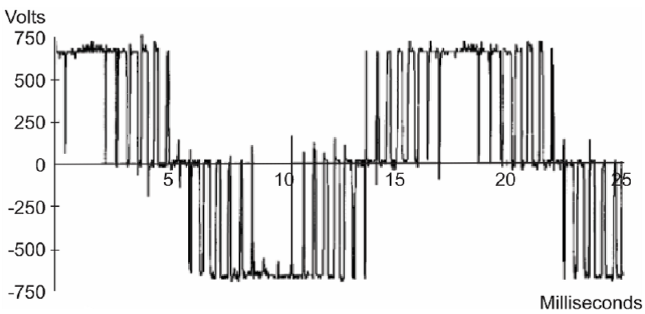


Figure 5.14: Output voltage of a 415 V variable-frequency drive

Figure 5.14 shows the typical output voltage of a 415 V variable-frequency drive. As expected, the voltage reaches a level of approximately 587 V which is the DC bus voltage. (AC line voltage x 1.414 (sqrt. of2)) Figure 5.15 shows the magnification of one voltage pulse is shown, as it appears at the motor end of the cable. It can be seen that the voltage not only reaches the 587V of the DC bus, but spikes up to almost twice that value. Thus, more than 1,174V would stress the cable.

So,for the solution of this problem the cable rating should be 2 kV.

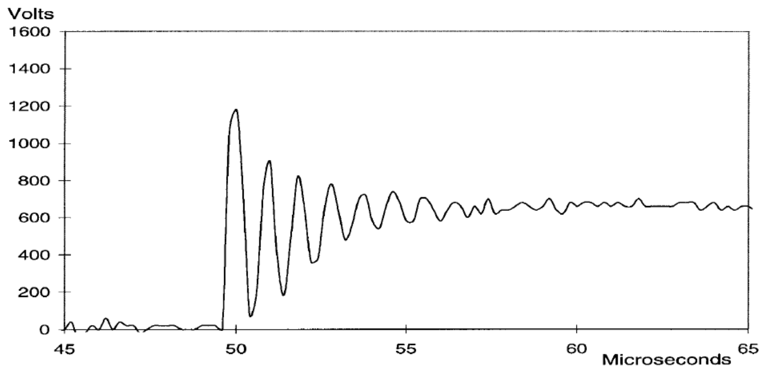


Figure 5.15: Magnification of one voltage pulse

5.3.2 Reflected Wave

Another issue with cables VFD cable is the reflected wave phenomenon. Both the cable and the motor have an electrical characteristic, which is called the electrical surge impedance. The electrical impedance applies to sinusoidal AC currents and is comparable to the electrical resistance in a DC circuit. When the motor impedance is larger than the conductor cable impedance, the voltage wave form will reflect at the motor terminals, creating a so called "standing wave" or also known as "reflected wave".

This reflected wave results in a voltage pulse reflected back from the motor to the drive. Long cable lengths between the motor and drive increase the probability of the reflected wave. A reflected pulse combined with a second pulse coming from the drive may raise the voltage at the cable to up to 2 times of its nominal voltage (DC bus voltage), even for very short cable lengths. This over voltage increases with the cable length.

It is desired to use a cable with impedance values as close as possible matched to the motor impedance. Please note that especially for smaller motors it is impossible to design a cable that matches the motor impedance, but the goal is to use a cable with the best possible match to the motor's impedance.

The following algorithmic chart shows the large delta between motor and cable impedance but also shows that XLPE insulation offers a closer match than for example PVC. For that reason it is recommended to use XLPE in particular with smaller motors.

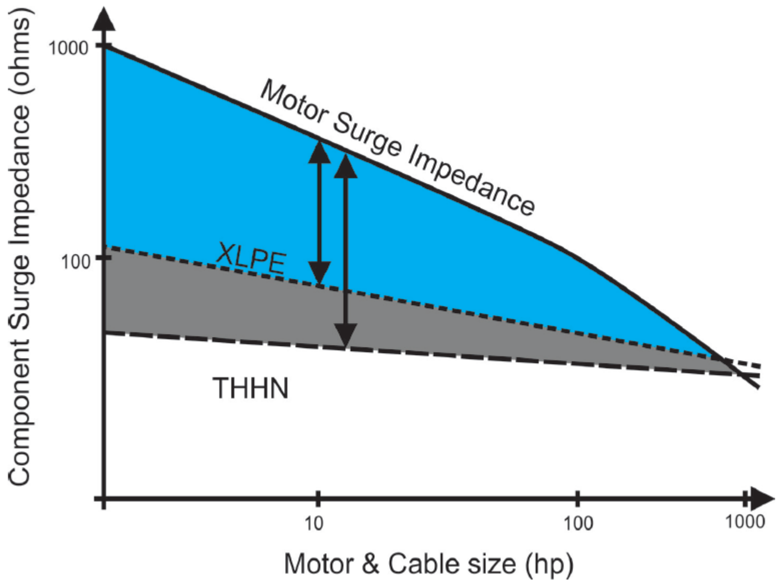


Figure 5.16: Surge impedance of different insulation material

Comparison of insulation materials

There is a great variety of insulation materials available. For industrial applications, especially in conjunction with the use of electrical motors, the most commonly used conductor insulation materials are polyvinyl chloride (PVC), PVC/Nylon aka THHN, cross-linked polyethylene (XLPE) and thermoplastic elastomer (TPE). Each of these materials has specific advantages and disadvantages as listed below:

Polyvinyl chloride (PVC)

PVC is commonly used in multi-conductor control cables. The material comes in many different formulations, for example with improved oil - or improved heat resistance.

Advantages:

- Inexpensive
- Flame retardant properties

- Flexible
- Easy to strip/process

Disadvantages:

- The CIV reduces with humid environments
- No TC-ER rating available because of brittleness and insufficient crush resistance.
- Disadvantageous electrical characteristics for high-frequency applications
- Not halogen-free. In case of a fire, gaseous hydrogen chloride (HCI) is formed. This acidic gas is highly toxic, poses health hazards and can damage machinery
- Poor weather and cold resistance

Polyvinyl chloride with nylon coating (THHN)

In order to improve the mechanical strength of PVC insulation it is possible to coat it with a thin layer of nylon. This type of insulation is called THHN (Thermoplastic High Heat-Resistant Nylon-Coated).

Advantages:

- TC-ER rating available due to good crush resistance of the Nylon
- Good resistance to petroleum by-products and chemical agents
- Better resistance against abrasion due to nylon coating

Disadvantages:

- Difficult to strip and/or process due to the nylon coating
- Disadvantageous electrical characteristics for high-frequency applications
- Total insulation wall thickness not adequate for voltage spikes

XLPE CABLE -Cross-linked polyethylene (XLPE)

XLPE CABLE is Cross-Linked Polyethylene insulated cable. Polyethylene has a linear molecular structure as shown in fig. A and bunched as in fig. B.

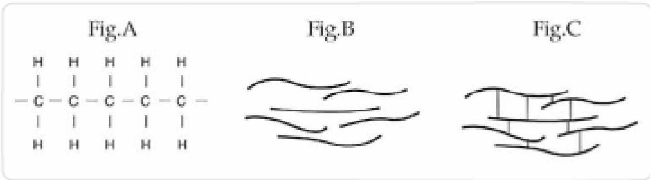


Figure 5.17: Internal Construction of XLPE

Molecules of simple Polyethylene, which are not bonded chemically, will be deformed at high temperature, while Molecules of XLPE ,bonded in a three-dimensional network as shown in fig. C, has a strong resistance to deformation even at high temperature. The excellent electrical and physical properties of Cross-linked Polyethylene make it an ideal insulation material. It has excellent heatproof and waterproof characteristics, and resists weathering, chemicals and oil. The excellent resistance to thermal deformation and excellent aging property of Cross- Linked Polyethylene permit it to I carry larger allowable currents under normal, emergency or short circuit conditions. Cross-linking alters the molecular structure of the insulation material to achieve better mechanical characteristics. This can be done by a chemical or radiation treatment.

Advantages: Thermo-set insulation does not melt under high temperatures. Thermoplastic material such as PVC can deform, melt or drip under excessive heat. Thermoset material, such as XLPE has a higher temperature stability and won't deform or melt. Therefore thermo-set insulation materials are much safer for use on VFDs.

- High CIV due to very good dielectric properties
- Provides very good protection against corona discharges in humid environments
- Good impact and abrasion resistance
- TC-ER rating available

- Lower cable capacitance than PVC, reducing cable charging currents and allowing longer cable runs
- Higher temperature rating than PVC

Disadvantages:

- More rigid than PVC, not as flexible
- Longer processing time due to cross linking

5.3.3 Corona Inception Voltage(CIV)

High voltage levels result in a high electric field, which may be strong enough to ionize the air between the conductor insulation and the cable jacket. If the voltage level is high enough, the ionized air can initiate a partial discharge mechanism known as a corona. The voltage level that causes a corona discharge is referred to as the corona inception voltage (CIV). Corona discharges produce ultraviolet light and large amounts of ozone which degrades the insulation. As the insulation degrades, gases are released, creating new voids and cracks in the insulation. This accelerates the degradation and leads to premature cable failure eventually. A hissing sound and micro arches can occur during a corona discharge.

Table 5.6: Difference between XLPE and PVC insulation

Drive HP	Insulation Thickness (mm)	XLPE Insulation		PVC Insulation	
		Specified Voltage (Vpk)	CIV Test (Vpk)	Specified Voltage (Vpk)	CIV Test(Vpk)
0.5-5	0.762	4242	4942	2828	2723
7.5-20	0.762	4242	4942	2828	2723
30	0.762	4242	4942	2828	3062
50	1.14	4949	5819	2828	3613
125	1.40	5656	6309	3535	4450
250-500	1.65	7071	6749	4242	4793

The material of the insulation and the thickness of the insulation can also affect the CIV of the cable.If the thickness of the insulation increases then reduction in the probability of a corona discharge. As shown in Table 5.6 the CIV of XLPE cable is in between 4912 V to 4212 V while for THHN cable is in between 2828 V to 2723 V for 0.5 to 5 h.p. motor. So, XLPE insulation is recommended insulation material.

5.4 Electromagnetic Interferences(EMI) and its solution

Electromagnetic signals are the result of electrical currents and voltages. Whenever electricity is used to drive equipment, an electromagnetic signal ensues as well Where the signals are unintended, can be called as electromagnetic noise. It is this noise that can cause equipment to malfunction, and manufacturers must therefore take steps to reduce the effects of noise.

Shielded cables

Cable shielding is a very effective method to improve susceptibility and reduce emission. If shielded cables are used, the ends of the shield must be connected to ground.The effectiveness of the shielded cable is depend on the ground. If none of the cable ends is connected to ground then the shield becomes ineffective. Induced fields cannot be diverted and ground currents cannot be reduced. If shields are connected on only one side, they become effective against electric fields. However, once the resonance frequency of the shield is reached, the shield becomes ineffective and even amplification can occur. If both ends of the shield are connected to ground then the shield become more effective and electrical and magnetic fields can be reduced
For grounding the vfd cable, a number of general rules apply:

- Each electrical circuit should have an independent ground connection in order to avoid different potentials.
- The method of grounding depends on the frequency of the signal

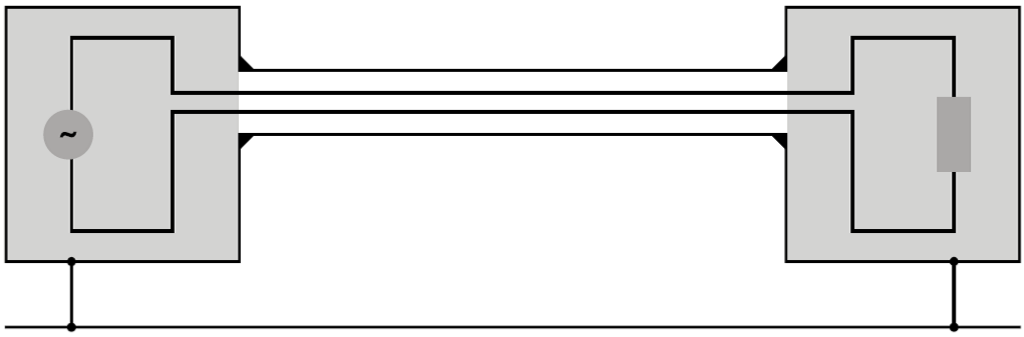


Figure 5.18: Shilded vfd drive system

- For lower frequencies, the dimensions of the circuit are small compared to the wavelength and resonances are not occur. So,the cable grounding on one side is sufficient and should be done on the transmission side, with the receiver side floating. This method is called single-point grounding.
- For higher frequencies, the wavelength is small against the dimensions and resonances are occur. In order to reduces the noise wave, cables with some special characteristic impedances are used and grounded on both ends. In some cases, cables are additionally grounded at several points. This type of grounding is called multi-point grounding.

Chapter 6

Application of Super Magnetic Material (Hiperco50) in Three Phase Induction Motor

Hiperco50 consist of an alloy of 49% Iron, 48.75% Cobalt, 1.9% Vanadium, 0.05% Manganese, 0.05% Niobium and 0.05% Silicon.Hiperco50 has the highest flux density of all soft-magnetic alloys .Hiperco50 maintains its strength after heat treating making it best choice for applications that experience high forces (e.g. rotating parts).

Applications

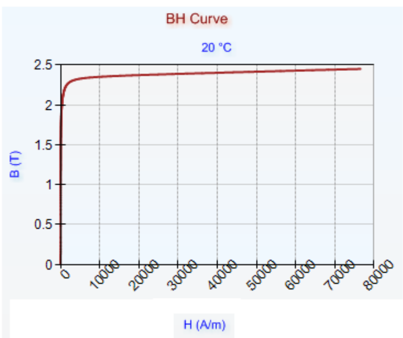
- Special Motors for the Aerospace Industry (e.g. applications where high magnetic saturation and high strength is required with as little weight as possible)
- Electromagnets for medical applications (e.g. to focus beams for radiation therapy in medical radiology applications)
- Electrical Generators
- Specialty Transformers (e.g. electrical circuits and magnetic circuits where frequencies must be varied)
- Pole Pieces for Electromagnets
- Magnetic Bearings (e.g. applications where rotating parts are levitated)

6.1 Comparison of physical properties of Hiperco50 with conventional electrical steels.

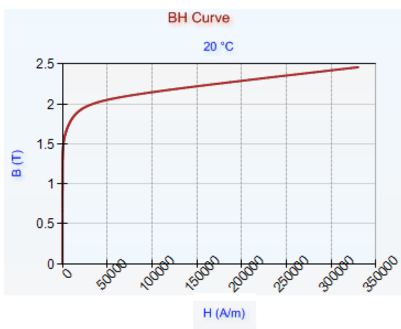
Table 6.1: Comparison of Hiperco50 with conventional M19 magnetic material

Sr No.	Property	Hiperco-50	M19-29
1	Saturation flux density, T	2.44	1.9
2	Relative permeability	10000	8300
3	Curie temperature, ^{0}C	940	760
4	Electric conductivity, S/m	2.38	2.00
5	Core losses at 60 Hz and 1.5 T, W/kg	1.73	3.08
6	Core losses at 400 Hz and 1.5 T, W/kg	17.47	44

The B-H curve of Hiperco50 and M19 magnetic material is shown below.



B-H curve of Hiperco 50



B-H curve of M19-29

6.2 Design of 2.2 kW,415 V,50,Hz,4-pole,3-phase Induction Motor with Hiperco50

The design of three phase induction motor with Hiperco 50 is carried out and below tables shows the results.

Table 6.2: Comparison of Performance Parameters using M19 and Hiperco50 magnetic material

Motor Parameters	Hiperco-50	M19-29
Bore Diameter(D)	82.1	105
Stack Length(L)	96.7	125
Depth of stator core(dcs)	8	13
Tooth Width	4	7
Torque(N.m)	15	15
Output Power(kW)	2.2	2.2
Input Power(kW)	2.64	2.67
Efficiency(%)	83.3	82.1
RMS current(A)	4.91	4.91
Power factor	0.794	0.799
Flux Density in Airgap(T)	0.9	0.4
Flux Density in stator core(T)	2.26	1.35
Flux Density in stator teeth(T)	2.33	1.66
Rotor Core Mass	3.12	3.8
Rotor Bar Mass	0.181	0.234
Rotor End ring Mass	0.33	0.487
Stator Core Mass	6	10.8
Stator Winding Mass	3.20	3.28
Total Mass	12.831	18.601

It is observed that the bore diameter, stack length ,stator back iron depth and width of teeth reduces by replacing M19 material with Hiperco50.So,the requirement of magnetic material reduces and so that the weight of the motor reduces.

Flux Density plot of M19-29 material

The Figure 6.1 shows the flux density plot induction motor using M19 magnetic material.

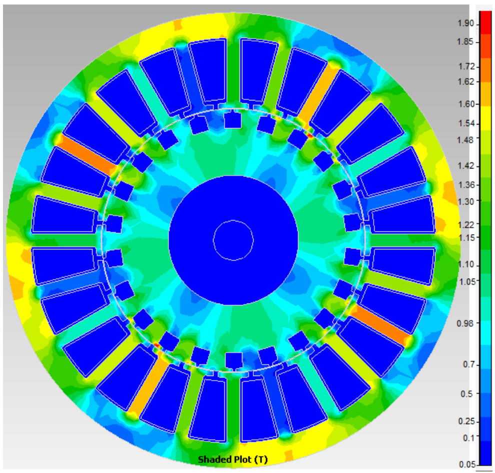


Figure 6.1: Flux density plot of M19-29 material

Flux Density plot of Hiperco50 material

The Figure 6.2 shows the flux density plot of IM with hiperco50

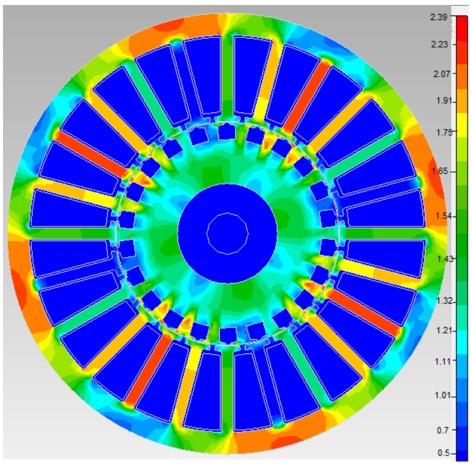


Figure 6.2: Flux density plot of Hiperco50

Chapter 7

Application of HTS(High Temperature Superconductor) in Three Phase Induction Motor

Induction motors are the most widely used electrical machines in industry. The squirrel cage type induction motor is the most popular type of induction motor because of it's construction features like robustness and cheapness. The main drawback of induction motor is the starting torque. The starting torque of induction motor is low.

In a squirrel cage type induction motor, the starting current is very high because of the starting resistance is low so, the starting torque is low. In order to improve the starting torque, the resistance of the secondary winding should be controlled. In a conventional induction motor, a deep-slot type rotor is adopted, but its effect is limited. If a superconductor is used in the rotor, the torque -speed characteristics of induction motor can be improved.

During starting the slip of induction motor is one,so large current is induced in the rotor circuit and high frequency is applied to the rotor circuit. These large current and high frequency make HTS tapes quench at the starting of induction motors. Therefore high starting torque can be obtained. As the speed of rotor builds up, HTS tapes which are used as short bars become super conducting state again because current and frequency of the rotor circuit decrease. After the HTS tapes recover from quench, resistance of the rotor circuit is completely zero if we neglect the joint resistance between short bars and short rings. In that case, power loss in rotor circuit which is generated in conventional induction motors is eliminated. In HTS induction motors, large current in rotor circuit can be induced at very low slip because of no resistance.

7.1 General Concepts of Superconductors

Superconductors are high current density conductors of electricity, until a critical temperature (T_c) or current level (ρ_c) is exceeded.
There are generally two types of super conductor.
(1)Low temperature super conductor.(LTS)
The LTS consist of critical temperature T_c = 20K (-253^{o}C).
(2)High temperature super conductor.(HTS)
The HTS consist of critical temperature T_c = 90K (-183^{o}C).
Above T_c or ρ_c the superconductor "quenches" and becomes a "normal" conventional conductor.

Different types of HTS material

The development of superconductor rotating machines has been pursued since low temperature superconductors (LTS), which operate at 4K, became available in the mid-1960s. The small thermal margin and the complex and expensive cooling systems of these early LTS devices prevented market acceptance. It was not until the advent of HTS, which operate at 30-40 K and have simpler cooling systems, that economically viable superconductor rotating machines became possible.

Bi-2223: "First Generation Wire"

The high temperature superconductor (HTS) $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$, commonly called Bi-2223, Is the commercially available HTS wire, which is known as first generation (1G) HTS wire. The composite structure of 1G HTS wire is composed of 30% to 40% Bi-2223 embedded in a silver alloy matrix. The maximum current density corresponds to an engineering critical current density of close to 18,000 A/cm^2, and high critical current density of 45,000 A/cm^2. Bi-2223 wire also shows good performance in higher fields at lower temperatures.

Bi-2212

A Bi-2212 round wire of high critical current density in high magnetic field has been developed. It can carry more than 200 kA/cm^2 in a magnetic field of 10 T and 180 kA/cm^2 in a magnetic field of 20 T at 4.2 K, which exceeds the current-carrying capability of all conventional metallic superconductors.

YBCO Wire:"Second Generation Wire"

The high temperature superconductor $YBa_2Ca_3O_7$, which is called as YBCO, is the second generation (2G) super conducting material. This YBCO is the alternative to Bi-2223 1G HTS material.

The cost of 2G wire is expected to provide similar or improved electrical properties at 2-5 times lower than 1G HTS wire.

7.2 FEA of HTS Induction motor

The FEA is carried out for standard induction motor, induction motor using HTS in end rings and induction motor using HTS in rotor bars and end rings.

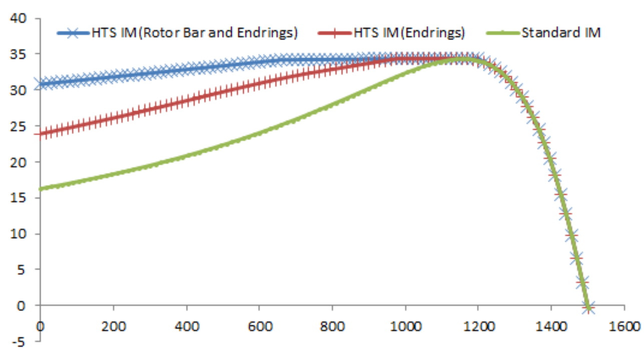


Figure 7.1: Comparison of Torque-Speed Characteristics

The above graph shows that by inserting the hts material in place of conventional copper in end rings of induction motor, the starting torque of the motor increases and by inserting the hts material in rotor bar and end rings the starting torque further increases.

Table 7.1: Comparative Analysis of 2.2 kW,415 V,50 Hz,4-pole,1440 rpm IM

Motor Parameters	Standard IM	HTS IM (end rings)	HTS IM (Rotor bar and end rings)
Torque(N.m)	15	15	15
O/P(kW)	2.2	2.2	2.2
I/P(kW)	2.67	2.66	2.65
RMS Voltage(V)	415	415	415
RMS Current(A)	4.68	4.68	4.68
Efficiency(%)	82	82.5	83
Total iron Losses(kW)	0.15	0.15	0.15
Total cu Losses(kW)	0.310	0.300	0.290

The comparative analysis of standard induction motor with HTS induction motor is shown in Table 7.1.

Chapter 8

Conclusion and Future Work

8.1 Conclusion

- CAD programme is done for 2.2 kW,415 V,50 Hz,4 Pole induction motor ;3.7 kW,415 V,50 Hz,4 Pole induction motor and 37 kW,415 V,50 Hz,4 Pole induction motor based on design equation.

- Based on this CAD programme developed FE model is prepared for 2.2 kW,415 V,50 Hz,4 Pole induction motor ;3.7 kW,415 V,50 Hz,4 Pole induction motor and 37 kW,415 V,50 Hz,4 Pole induction motor.The CAD results are fairly matching with FE analysis.

- Improving efficiency in electric drives is important, mainly, for two reasons: economic saving and reduction of environmental pollution.So,design of energy efficient three phase induction motor is carried out and payback period is calculated.Design modification of energy efficient inverter driven three phase induction motor is carried out.

- Application of superior magnetic material(Hiperco-50) in the three phase induction motor is carried out ,which shows that by applied this material in induction motor compact and energy efficient motor can be made.

- The main drawback of induction motor is the starting torque. The starting torque of induction motor is low. The application of HTS(High Temperature

Superconductor) in induction motor is carried out to improve the starting torque of induction motor.

8.2 Future Work

Improvement in the design of three phase inverter driven induction motor will be carried out to get compactness,high efficiency and reliability.

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Appendix A

List of Publication

[1] Prof Amit N. Patel, Darshan U. Thakar :"CAD and FE Analysis of Three Phase Induction Motor".International conference on multidisciplinary research and practice (ICMRP-2014) held during 30th November 2014 at Ahmedabad Management Association, ATIRA Campus,IIM-A Road, Ahmedabad, Gujarat, India and published in International Journal of Research and Scientific Innovation(IJRSI) ISSN: 2321 - 2705 Volume I and Issue VIII,pp.400-402.

[2] Prof Amit N. Patel, Darshan U. Thakar :"Performance Improvement of Three Phase Induction Motor using Super Magnetic Material" 6th International Conference on Innovation In Electrical And Electronics Engineering - ICIEEE-2015,ISBN : 978-93-85225-26-6, May-2015.