Design And Analysis of Standard And Energy-Efficient Three-Phase Induction Motor

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09MEE011

DEPARTMENT OF ELECTRICAL ENGINEERING

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Design And Analysis of Standard And Energy-Efficient Three-Phase Induction Motor

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Submitted in partial fulfillment of the requirements

For the degree of

Master of Technology in Electrical Engineering

(Power Electronics, Machines and Drives)

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Certificate

This is to certify that the Major Project Report entitled **"Design And Analysis of Standard And Energy-Efficient Three-Phase Induction Motor"** submitted by **Ms.Urvashi G.Patel** (09MEE011), 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 her under our supervision and guidance. The work submitted has reached a level required for being accepted for examination. The results embodied in this major project to the best of my knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

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. Energy consumed during mining and production of raw materials together with energy consumed during manufacturing processes all adds to depletion of resources. The energy consumed in machine manufacture is a function of the amount and type of materials used and from this aspect small is beautiful.However, obtaining more output from less material requires a thorough understanding of the processes involved. Specifically in relation to motors, it involves identifying losses and minimizing those which have particular influence in a given applications.In industry, the major energy consumption is in various mechanical gadgets, which are driven by electric motors. To date 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.

This m.tech project attempts at understanding/explaining the energy dissipated as "losses" by motors. Then it classifies the losses and indicates the strategies to control and minimize them. All these are done maintaining the sizes and the inter changeability of energy efficient motors with the standard or existing ones. The justification for using higher initial cost energy-efficient motor, compared to standard motors, is the crucial parameter for promulgating energy efficient motors. Using advanced techniques, matlab program is developed for standard induction motor and optimized matlab program for energy efficient induction motor will developed by incorporating new design techniques.and and Analysis of above both motors(standard as well as energy efficient) & comparison of various performance parameters

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Abbreviations

P .... power input [watts]
v .... supply voltage[volts]
f .... supply frequency[hz]
p .... no. of poles
kw .... winding factor
Bav .... specific magnetic loading [wb/m^2]
ac .... specific electric loading [amp/mm]
N .... rated speed [rpm]
ns .... synchronous speed [rpm]
wms .... synchronous speed[rps]
c0 .... output co-efficient
Q .... kVA input[kVA]
eff .... efficiency
pf .... power factor
T .... pole pitch[mm]
L .... stator bore length[mm]
D .... stator bore diameter[mm]
Li .... net iron length[mm]
nd .... no. of ventilating ducts
wd .... width of ventilating duct[mm]
sd .... type of starting connection
Es .... stator voltage per phase[volts]
fym .... flux per pole[wb]
Ts .... stator turns per phase
yss .... stator slot pitch[mm]

qs .... slots per pole per phase

Ss .... stator slots

Zs .... total stator conductors

Zss .... stator conductors per pole

wdg .... type of winding

Cs .... coil span

alpha .... chording factor

Kp .... pitch factor

Kd .... distribution factor

Is .... stator current per phase[amp]

con .... stator conductors per pole

Iline .... stator line current[amp]

delta .... stator current $[amp/mm^2]$

d .... enter standard diameter[mm]

as .... area of stator conductors $[mm^2]$

sf .... space factor

Aslot .... area of stator slot$[mm^2]$

Lmt .... length of mean turn[mm]

Bmt .... flux density in stator teeth$[wb/mm^2$

wts .... minimum width of stator teeth[mm]

fys .... flux in stator core[wb]

Bcs1 .... flux density in stator core$[wb/mm^2]$

Acs .... area of stator core$[mm^2]$

dcs .... depth of stator core[mm]

h .... height of stator teeth[mm]

wedge .... wedge[mm]

lip .... lip[mm]

dss .... depth of stator slot[mm]

slack .... slack

lg .... length of airgap[m]

Dr .... rotor diameter[mm]

Sr .... no. of rotor slots

ysr .... rotor slot pitch[mm]

Ib .... rotor bar current[amp]

density .... rotor current density [amp/mm^2]

ar .... rotor bar area[mm^2]

Wsr .... width of rotor slot[mm]

Dsr .... depth of rotor slot[mm]

B11 .... flux density at root of rotor teeth [wb/mm^2]

W11 .... tooth width at root [mm]

E1 .... extension of bar beyond the core [mm]

l1 .... increase in the length due to skewing [mm]

Rb .... resistance of rotor barΩ

Pcu-bars .... copper losses in rotor bars[watts]

Ie .... end ring current[amp]

den-endring .... current density in end ring[amp/mm^2]

area-endring .... area of end ring[wb/mm^2]

De .... depth of end ring[mm]

Te .... thickness of end ring[mm]

ae .... area of end ring[mm^2]

De-o .... outer diameter of end ring

De-i .... inner diameter of endring

De-mean .... mean diameter of end ring

Pcu-endring .... copper losses in end ring[watts]

Pcu-total .... total copper losses in rotor[watts]

Bcr .... flux density in rotor core [wb/mm^2]

Ws .... stator width opening[mm]

Wr .... rotor width opening[mm]

Kcs .... casters co-efficient of stator slot[mm]

Kcr .... casters co-efficient of rotor slot[mm]

Kgss .... air gap contraction factor for stator slot

Kgsr .... air gap contraction factor for rotor slots

Kgs .... air gap contraction factor

Ag .... area of air gap[mm^2]

Bg-60 .... flux density for air gap[wb/mm^2]

Bts-60 .... flux density in stator teeth[wb/mm^2]

Bcs .... flux density in stator core[wb/mm^2]

Btr-60 .... flux density in rotor teeth[wb/mm^2]

Bcr .... flux density in rotor core[wb/mm^2]

ATg .... mmf required for air gap[amp]

Ats .... mmf required for stator teeth[amp]

Acs .... mmf required for stator core

Atr .... mmf required for rotor teeth[amp]

Acr .... mmf required for rotor core[amp]

Lcs .... length of magnetic path through stator core[m]

Lcr .... length of magnetic path through rotor core[m]

AT-T .... total mmf required[amp]

Im .... magnetizing current[amp]

weight-st .... weight of stator teeth[kg]

Loss-st .... loss per kg in stator teeth

Ironloss-st .... iron losses in stator teeth[watts]

weight-sc .... weight of stator core[kg]

Loss-sc .... loss per kg in stator core

Loss-T .... loss per kg in stator

F-W-Loss .... friction and windage losses[watts]

No-Load-Loss .... no load losses[watts]

IL .... loss component of no load current[amp]

I0 .... no load current[amp]

Xs .... total leakage reactance [Ω]

Rs .... stator resistance [Ω]

copperloss-stator .... copper losses in stator[watts]

Pcu-rotor .... copper losses in rotor[watts]

Zs .... impendence of stator[Ω]

C .... cooling co-efficient

Total-loss .... total losses of motor[watts]

Isc .... short circuit current[amp]

Pf-sc .... short circuit power factor

Nomenclature

EEM .... Energy-efficient motor

IM .... Induction motor

OEM .... Ordinary induction motor

VSD .... Variable speed drive

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Chapter 1

Introduction

A drive system is composed of several subsystems such as: - Power electronics - gearbox or/and coupling - Controller for speed or/and position - load e.g. Pump, fan, compressor.-Electric motor Although big energy savings can be achieved by looking at the complete system and in particular through the implementation of variable-speed drives, here the focus is on the electric motor itself. About 90% of the total motor electricity consumption is done with ac. Three phase induction motors in the power range from 0.75 kw to 750 kW. A breakdown of the electricity consumption by end-use is given in table given below:

Table 1.1: Energy consumption by various load

Type of load	Industrial sector	Tertiary sector
Motors	69%	36%
lighting	6%	30%
others	25%	36%

1.1 General Introduction To A.C. Motors

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. As a result, motor manufactures have tired, over the last few decades, to perfect various types of a.c. Motors suitable for all classes of industrial drives and for both single and three-phase a.c. Supply. Different a.c. Motors may, however, be classified and divided into various groups from the following different points of view:

a. As regards their principle of operation

- Synchronous motors
  (1) plain
  (2) super
- Asynchronous motors
  - induction motors
    (1) squirrel cage
      i. single
      ii. double
    (2) slip-ring(external resistance)
- Commutator motors
  (1) series
    i. single-phase
    ii. universal
  (2) Compensated
    i. conductively
    ii. inductively

   (3) Shunt
      i. simple
      ii. compensated
   (4) Repulsion-start induction
      i. straight
      ii. compensated
   (5) Repulsion induction

b. As regards the type of current

   - Single-phase
   - Three-phase

c. As regards their speed

   - Constant speed
   - Variable speed
   - Adjustable speed

d. As regards their structural features

   - Open
   - Enclosed
   - Semi-Enclosed
   - Ventilated
   - Pipe-Ventilated
   - Reverted Frame Eye

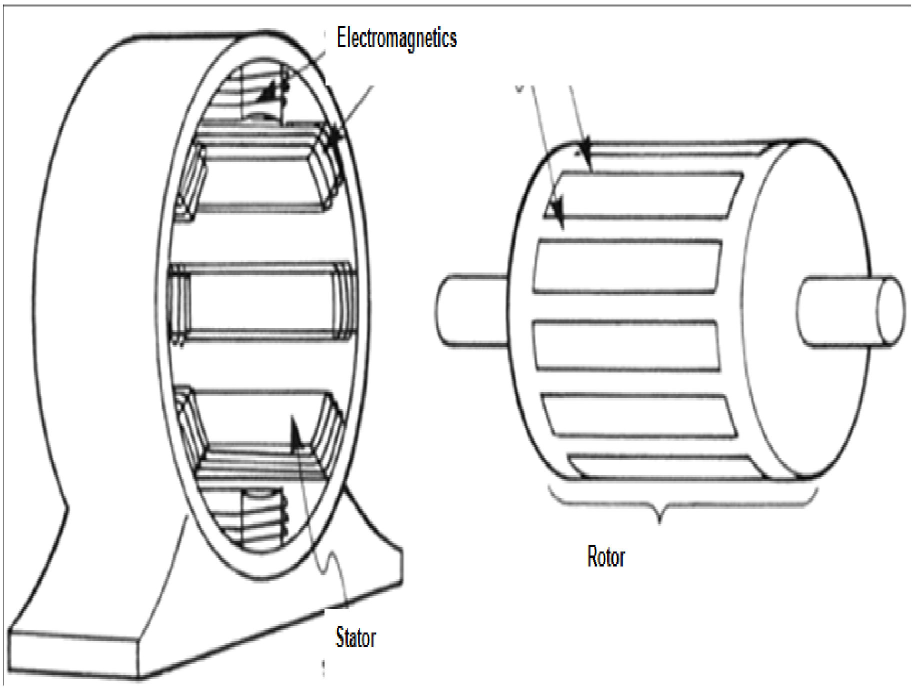

Figure 1.1: operating principle of induction motor

1.2 Induction Motors:General Principle

As a general rule, conversion of electrical power into mechanical power takes place in the rotating part of an electric motor. In d.c. motors, the electric power conducted directly to the armature. Hence, in this sense, a d.c. motor can be called a conduction motor. However, in a.c motors, the rotor does not receive electric power by conduction but by induction in exactly the same way as the secondary of a 2-winding transformer receives its power from the primary. This is why such motors are known as induction motors.

1.3 Advantages

- It has very simple and extremely rugged, almost unbreakable construction(especially squirrel-cage type).

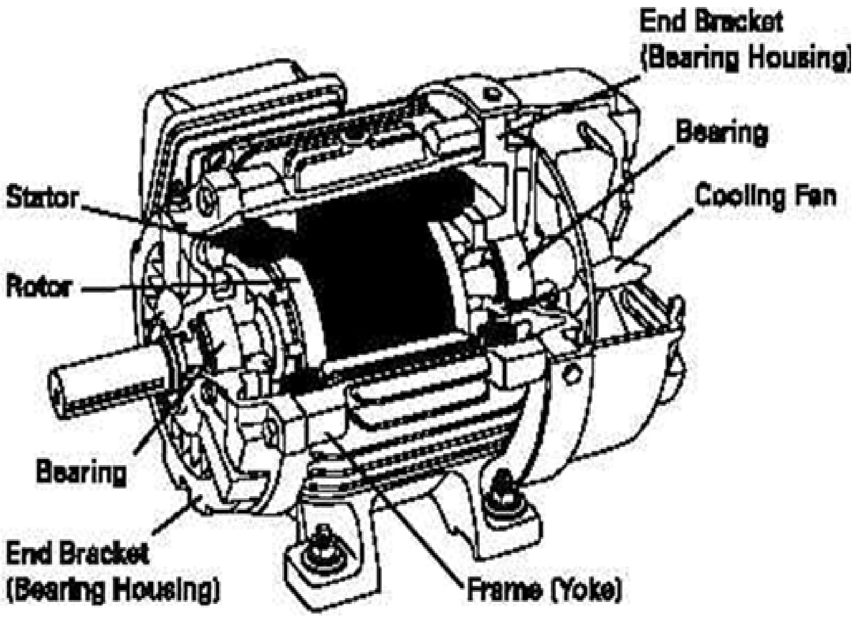

Figure 1.2: construction of induction motor

- Its cost is low and it is very reliable.
- It has sufficiently high efficiency. In normal condition, no brushes are needed, hence friction losses are reduced. It has a reasonably good power factor.
- It requires minimum of maintenance.
- It starts up from rest and needs no extra starting motor and has not to be synchronized. Its starting arrangement is simple especially for squirrel-cage type motor.

1.4 Disadvantages

- Its speed cannot be varied without sacrificing some of its efficiency.
- Just like a d.c. shunt motor, its speed decreases with increase in load.

- Its starting torque is somewhat inferior that as a d.c shunt motor.

1.5 Construction of an Induction motor

An induction motor has two main electrical components:

- Stator:The stator is made up of a number of stamping with slots to carry three-phase windings. It is wound for a definite number of poles. The windings are geometrically spaced 120° degrees apart.
- Rotor:Induction motors use two types of rotors:
  a. A squirrel-cage rotor: It consists of thick conducting bars embedded in parallel slots. These bars are short-circuited at both ends by means of short-circuiting rings.
  b. A wound rotor: It has a three-phase, double-layer, distributed winding. It is wound for as many poles as the stator. The three phases are wired internally and the other ends are connected to slip-rings mounted on a shaft with brushes resting on them.

1.6 Comparison between squirrel-cage and slip-ring induction motors

- No slip rings, brush gear, short circuiting devices, rotor terminals for starting rheostats are required. The star delta starter is sufficient for starting.
- It has cheaper and rugged in construction.
- It has a slightly higher efficiency.
- It has better space factor for rotor slots, a shorter overhang and consequently a smaller copper loss.

- It has bare end rings, a large space for fans and thus the cooling conditions are better.
- It has a smaller rotor overhang leakage which gives a better power factor and a greater pull out torque and overload capacity.

1.7 Classification of induction motors

- Single-phase induction motors: These only have one stator winding, operate with a single-phase power supply, have a squirrel cage rotor, and require a device to get the motor started. This is by far the most common type of motor used in household appliances, such as fans, washing machines and clothes dryers, and for applications for up to 3 to 4 horsepower.
- Three-phase induction motors:The rotating magnetic field is produced by the balanced three-phase supply. These motors have high power capabilities, can have squirrel cage or wound rotors (although 90% have a squirrel cage rotor), and are self-starting. It is estimated that about 70% of motors in industry are of this type, are used in, for example, pumps, compressors, conveyor belts, heavy-duty electrical networks, and grinders. They are available in 1/3 to hundreds of horsepower ratings.

1.8 losses

Within a motor there are a number of losses that cannot be reclaimed, this is due to the materials being used in manufacturing and the physical / mechanical characteristics of the materials involved when in use; these are as per following:

- Core loss
- Stator I^2R losses

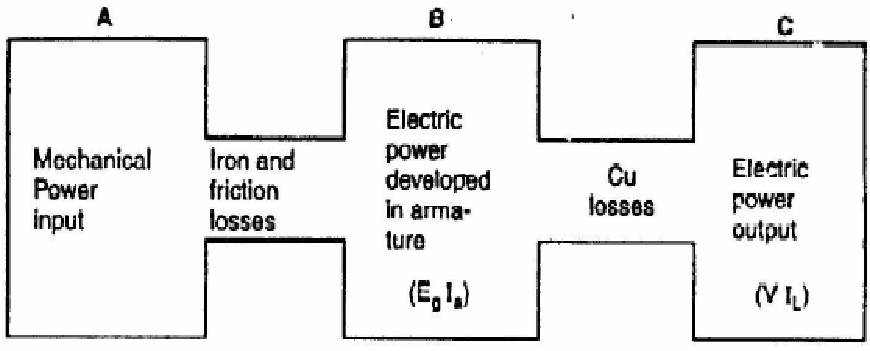

Figure 1.3: Power stages in induction motor

- Rotor I^2R losses
- Friction and windage loss
- Stray load losses

a. Core loss:Core loss represents energy required to magnetize the core material (hysteresis) and includes losses due to creation of eddy currents that flow in the core. Core losses are decreased through the use of improved permeability electromagnetic (silicon) steel and by lengthening the core to reduce magnetic flux densities. Eddy current losses are decreased by using thinner steel laminations.

b. Stator I^2R losses:Stator losses appear as heating due to currents flow Rotor losses appear as I2R heating in the rotor Stray load losses are the result of leakage fluxes (I) through the resistance (R) of the stator winding. This is commonly referred to as an I^2R loss. I^2R losses can be decreased by modifying the stator slot design or by decreasing insulation thickness to increase the volume of wire in the stator.

c. Rotor I^2R losses:Rotor losses amperes as heating I^2R in the rotor winding. Rotor losses can be reduced by increasing the size of the conductive bars and end rings to produce a lower resistance, or by reducing the electrical current.

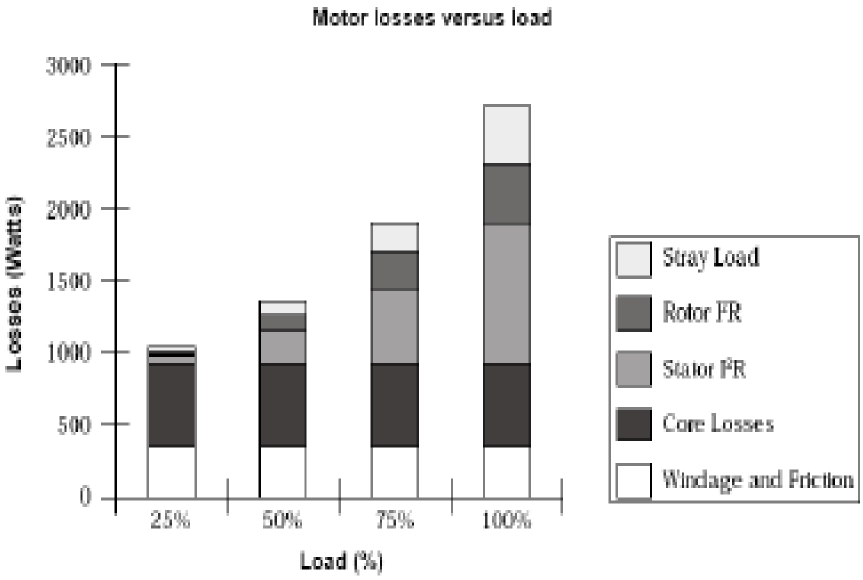

Figure 1.4: motor losses v/s load

d. Friction and windage loss:Friction and windage losses occur due to bearing friction and air resistance. Improved bearing selection, air flow, and fan design are employed to reduce these losses. In an energy-efficient motor, loss minimization results in reduced cooling requirements so a smaller fan can be used.Both core losses and windage and friction losses are independent of motor load.

e. Stray load losses:Stray load losses are the result of leakage fluxes induced by the load currents. Stray load looses stator I^2R losses,rotor I^2R losses increases with load.

Chapter 2

Energy-Efficient Motors

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 and low core loss electrical steel. However, these methods bring cost-rise and need special manufacturing technology.

Induction motors have always played and are still playing a crucial role in the industrial sectors thanks to their high reliability and ruggedness. The motor users and manufacturers have paid much attention to highly efficient motors in an attempts to reduce its manufacturing and operational costs. Higher efficiency in electrical motors can be mainly achieved by improved active materials and optimizing motor design parameters. Obviously, the optimization method is believed to be the most economical approach to improve the motor efficiency and performance.Therefore, it becomes crucial to develop and employ the best and effective optimization techniques for motor design problems.

For many decades the trend of motor design was to minimize the motor size and cost.

This was partly done at the cost of the motor efficiency. With the continuing increase of the cost of electric energy and the pressure caused by the environmental aspects, motor manufactures and consumers have become increasingly concerned with the energy conservation potential of the high-efficiency motors.

EEMs are designed to produce the same output power with less electrical power input. These energy efficient machines contain more copper and iron and have lower friction and windage losses than their standard design counterparts. The result of these design modifications is 1 to 8%-unit increase in efficiency, depending on the size of the motor.The efficiency improvement is greatest for smaller motors, and decreases as the rated power increases.

The benefits of even higher efficiency had long been recognized and a number of manufacturers including ourselves sold energy efficient motor ranges. These usually had losses some 30% lower than standard motors or were about 3% more efficient - but they cost significantly more to manufacture and sold at price premiums of up to 30%.

There are several methods of decreasing the energy consumption in electrical machines, for example: reorganizing the production lines to be more efficient,using adjustable variable speed drives (VSDs),choosing the motor size correctly and reducing the losses of the machines. The first three are mainly dependent on the users decision, but making better motors is a common problem for the manufacturers and the end users.The main barrier to purchasing energy efficiency motors (EEMs) is the higher price. It is well known that the motor buyers set the highest priorities for price, reliability,availability and quick delivery Thus energy efficiency is not ranked to the top of purchaser concerns. Discussions with operating personnel in industry brought up a problem common in large organizations: the users and buyers work in separate units and they have their own budgets. This means that the buyers try to purchase motors as cheaply as possible and the end users to run them as cheaply as possible. Although

EEMs typically cost more than standard motors, the benefit of lower operating costs can often offset the price premium in the first year. Additional benefits of EEMs include longer motor life expectancy,lower noise because of low magnetic saturation and smaller cooling fan, and higher loading capacity. EEMs are designed to produce the same output power with less electrical power input.These energy efficient machines contain more copper and iron and have lower friction and windage losses than their standard design counterparts. The result of these design modifications is a 1-8% unit increase in efficiency, depending on the size of the motor. The efficiency improvement is greatest for smaller motors, and decreases as the rated power increases.

Factors that influence motor efficiency include:

- Age:New motors are more efficient
- Capacity:As with most equipment, motor efficiency increases with the rated capacity
- Speed: Higher speed motors are usually more efficient
- Type:For example, squirrel cage motors are normally more efficient than slip-ring motors
- Temperature: Totally-enclosed fan-cooled (TEFC) motors are more efficient than screen protected drip-proof (SPDP) motors
- Rewinding of motors can result in reduced efficiency
- Load, as described below:
  There is a clear link between the motors efficiency and the load. Manufacturers design motors to operate at a 50-100% load and to be most efficient at a 75% load. But once the load drops below 50% the efficiency decreases rapidly as shown below. Operating motors below 50% of rated loads has a similar, but less significant, impact on the power factor. High motor efficiencies and power

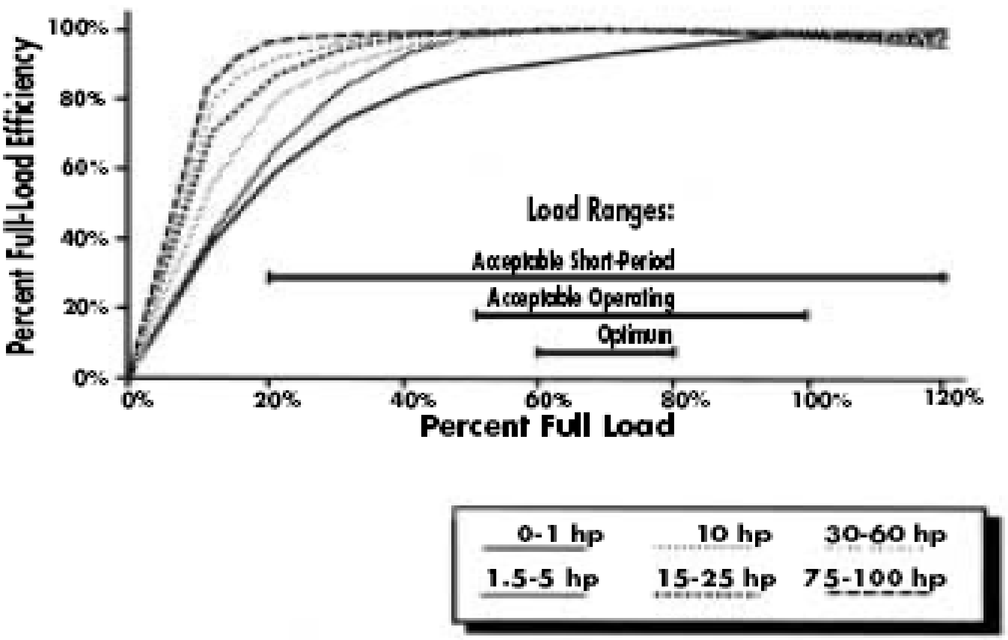

Figure 2.1: Motor Part-load Efficiency (as function of %fullload efficiency)

factor close to 1 are desirable for an efficient operation and for keeping costs down of the entire plant and not just the motor

For this reason, it is useful to determine both the load and efficiency when assessing a motors performance. In most countries it is a requirement for manufacturers to display the full-load efficiency on the motors nameplate. However, when a motor has been in operation for a long time, it is often not possible to determine its efficiency because nameplates of motors are often lost or painted over.

To measure the motors efficiency, it must be disconnected from the load and taken to a test bench for a series of tests. The results of these tests are then compared with the standard motor performance curves which are provided by the manufacturer.

For many decades the trend of motor design was to minimize the motor size and cost. This was partly done at the cost of the motor efficiency With the continuing increase of the cost of electric energy and the pressure caused by the environmental aspects, motor manufactures and consumers have become increasingly concerned with the energy conservation potential of high-efficiency motors.

Motor efficiency can be improved by increasing the volume of the active materials (electrical steel and current conducting material), by using more expensive technologies (better electrical steel, higher copper slot fill-factor, increased amount of the stator and rotor slots, etc.) and by optimizing the motor design with respect to its efficiency.

2.1 Circumstances of Energy Efficient Motor

- When purchasing the new motor.
- In-place of rewinding failed motors.
- Grossly oversized and under-loaded motors must be replaced by EEM.
- As part of an energy management or preventive maintenance program.
- Designing new facilities
- Modifying existing installations or processes.
- Considering rewinding failed motors.
- Replacing oversized motors.
- Setting up an energy management
- For new facilities or when modifications are made to existing installations or processes
- To replace oversized and under loaded motors
- As part of an energy management or preventative maintenance program

- When utility rebates am offered that make high-efficiency motor retrofits even more cost effective.

2.2 Advantages

- It creates a bridge towards higher output coefficients and better use of materials.
- Reduced size - standard efficiency motors could give savings in manufacturing cost and price to both manufacturers and OEMs.
- Manufacturers savings could help fund investment in improved efficiency ranges
- Standard size, improved efficiency ranges.would benefit motor users and the environment
- The new standards structure would eventually encourage development of reduced size improved efficiency ranges.
- Saves money & energy.
- Near uniform efficiency from 50% to 100% of full load even at part load conditions also Short payback period.
- Substantial saving after payback period.
- Longer periods between scheduled actions and fewer forced outrages.
- Accelerated life testing shows longer life expectancy
- 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.
- Design changes, better materials and manufacturing improvements reduces motor losses hence better efficiency.

- Increased bearing life.
- Fewer forced outages.
- Maintenance requirement is same but more reliable.
- Can withstand stalling & overload better compared to standard motors.
- Run quieter.
- 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.
- It also improves power factor.
- Operate with lower no-load losses
- Less sensitive to abnormal conditions such as impaired ventilation, under & over voltage & phase imbalance.
- Have longer service factor in case of hostile environments or poor alignment.
- Green house gas emission reduction.

2.3 Disadvantages

- Higher initial cost(They cost 15-30% more than standard motor).
- Lower starting torque and/or power factor.
- Reduced standardization in the marketplace-at least for a time.

2.4 Efficiency Improvement Techniques

Efficiency improvement techniques are as per following:

- Motor design changes / redesign
- Manufacturing practices changes
- Manufacturing equipment changes
- Material optimization

2.5 High Efficiency Motor Design

The efficiency has been increased by the following improvements:

- Improved steel properties: standard motors use low-carbon laminated steel for the rotor and stator. Such steel typically has electrical losses of 6.6 watt per kg.High efficiency motors are built with high-grade silicon steel, which typically reduces hysteresis and eddy current losses by half,i.e. about 3.3 watt per kg.
- Thinner laminations: reducing lamination thickness in rotor and stator steel also lowers eddy current losses.
- Increasing conductor's volume: standard-efficiency motors employ aluminum or copper conductors of a size no longer than that needed to deliver the required horsepower.High-efficient motors utilize bigger copper conductors to lower the winding resistance with the conductors sized 35 to 40
- Modified slot design: to accommodate the longer volume of copper in the windings and required additional slot insulation, the winding slot cross-sectional area is increased and the stator core is lengthened. A longer core yields an important additional benefit in the form of improved motor power factor.
- Narrowing airgap: when the airgap between stator and rotor decreases, the intensity of the magnetic flux will increase, thereby improving the motor ability to deliver the same torque at a reduced power. Increasing the length of the stator and rotor increases the net flux in the airgap, to the same effect.

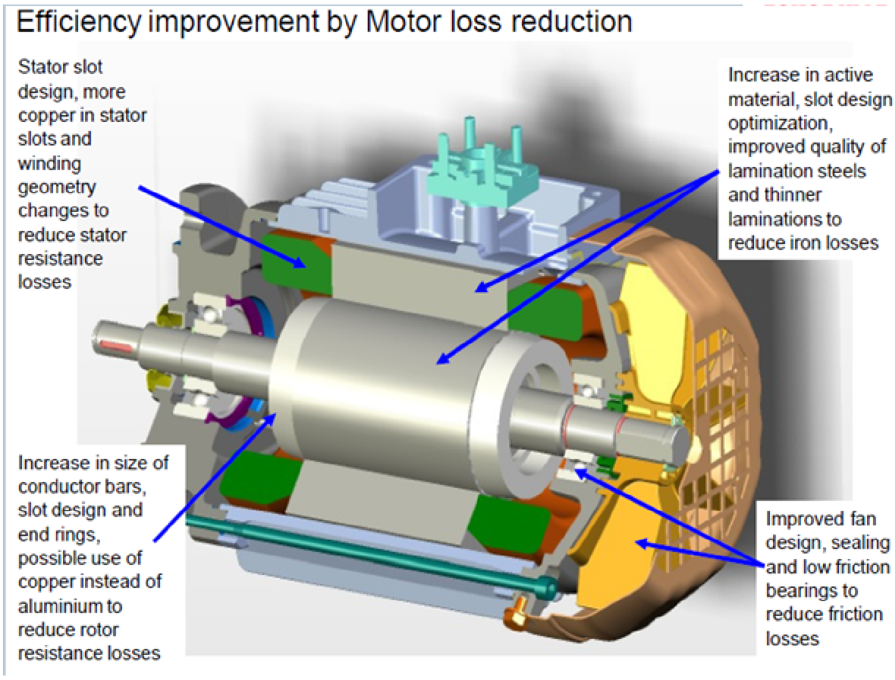

Figure 2.2: Efficiency improvement by motor loss reduction

- Improved rotor insulation: some losses are incurred because of unintentional,spurious condition paths established in the motor manufacturing process. Such a path commonly occurs between rotor bars when the rotor is skewed. Skewing is a normal design practice intended to reduce noise and torque pulses in small motors. In high efficiency motor manufacturing the edges of the rotor slots are treated with high-temperature insulation to reduce these losses.

- More efficient fan design: Because motors designed for high efficiency inherently run cooler than standard types, the design can incorporate a smaller cooling fan, reducing windage losses and resulting in quieter operation.

Motor manufacturers are currently developing new ranges of energy efficiency motors that require accurate motor design, the adoption of new and higher quality materials and innovative technologies. Motor manufacturers typically employ some of the methods outlined below to reduce the energy loss of induction motors.

- Standard motor use lower cost annealed steel, which is more susceptible to temperature and environmental conditions. Newer magnetic steels are capable of operating at higher flux densities. The magnetizing flux needs to be small to minimize the core loss. By increasing the length of the core the loss can also be reduced.

- The largest loss in induction motors is due to the finite resistance of the stator and rotor winding for a given current that produces heat. This loss can be reduced by increasing the cross sectional area of the copper by either increasing the slot fills or by using larger slots in the stator core.

- Cooling fans can be used since energy efficiency motors produce less heat than their standard counter parts. Bearings that have ceramic balls instead of steel balls can be used to further reduce the friction and windage loss.

- Other ways to improve the efficiency are by implementing more accurate manufacturing tolerances and tighter quality control which will reduce the stray load losses. Designer often increase the air gap of the motor to reduce the stray load loss but that may result in lower power factors.

2.6 Efficiency Improvement Techniques

Different losses can be minimized by the following ways:

2.6.1 Copper Losses

To reduce stator copper loss the volume or copper in the stator winding must be increased.If the volume of copper is increased however. the size of the stator slots must also be increased. This reduces the effective volume of the steel laminations. The magnetic flux must bc maintained in order to develop the necessary motor torque. so if the effective volume of the laminations is reduced. The flux density in the steel will increase. This has two detrimental effects. The losses in the steel (so-called iron losses) increase and the current required to magnetize the steel is also increased.Work has been done to reduce the amount of inactive copper in motor end windings to reduce copper losses by changes to layouts and connections.

2.6.2 Iron Losses

Iron loss has three components, hysteresis. classical eddy current and so-called excess loss. Hysteresis loss is caused by domain wall movements in the steel during cyclical magnetization. Classical eddy current loss is due to induced currents in the steel.Excess loss, otherwise known as Stray Load Loss is caused by localized eddy currents generated round moving domain walls in the steel. Each of these losses can be represented by mathematical equations. These give the iron loss for any frequency and waveform, but specified coefficients need to be determined experimentally.

2.6.3 Rotor Slots

The shape and size of the rotor slots in an induction motor has a critical effect on the performance of the machine determining not only the shape of the speed torque characteristic but also the rotor loss.

2.6.4 Magnetic Steel

The development of a new magnetic steel was a major part of the research work. Investigations with the new design program showed that a low cost steel having low losses and high permeability was needed.

2.6.5 Thermal design

The important way to improve efficiency in induction motors is thermal design. Keeping the temperature rise as low as possible and the efficient use of frame materials and airflow was essential to the success of reducing losses.

2.6.6 Fan noise

On larger motors the reduction in fan losses is significant. but for most people the greatest perceived benefit is the reduced noise of the new motors. The noise level of the new range of motors is typically 10 -15 dB (A) lower than the previous range of machines.

2.6.7 Shaft seal losses

Low loss seals were available. but not at prices which would meet cost targets. The apparently simple task of designing and providing a low cost low loss oil seal took the team almost two years and has only recently been solved in co-operation with a major seal manufacturer.

Chapter 3

Rewinding Of Motors

It is common practice in industry to rewind burnt-out motors. The number of rewound motors in some industries exceeds 50% of the total number of motors. Careful rewinding can sometimes maintain motor efficiency at previous levels, but in most cases results in efficiency losses. Rewinding can affect a number of factors that contribute to deteriorated motor efficiency: winding and slot design, winding material, insulation performance, and operating temperature. For example, when heat is applied to strip old windings the insulation between laminations can be damaged, thereby increasing eddy current losses. A change in the air gap may affect power factor and output torque.

However, if proper measures are taken, the motor efficiency can be maintained after rewinding, and in some cases efficiency can even be improved by changing the winding design. Using wires of greater cross section, slot size permitting, would reduce stator losses and thereby increasing efficiency. However, it is recommended to maintain the original design of the motor during the rewind, unless there are specific load-related reasons for redesign.

The impact of rewinding on motor efficiency and power factor can be easily assessed if the no-load losses of a motor are known before and after rewinding. Information of no-load losses and no-load speed can be found in documentation of motors obtained at the time of purchase. An indicator of the success of rewinding is the comparison of no load current and stator resistance per phase of a rewound motor with the original no-load current and stator resistance at the same voltage.

Chapter 4

The Cost Of Improving Efficiency

There is no simple answer to the question How much does increased efficiency cost?. Different motor manufacturers will give different answers which will be influenced both by their investment policies and by the creative thinking (or otherwise) of their design and manufacturing teams.

Energy efficient motor ranges have been offered by a number of manufacturers since the early 1980s. Whilst there was no clear definition of what constituted an energy efficient motor they have typically offered efficiencies some 3% higher than the manufacturers standard ranges and certainly originally this increase was achieved simply by the use of more and better active materials -usually a lower loss (but lower permeability) silicon steel and considerably more copper,particularly in the stator winding. This approach is costly, and energy efficient motors have typically been sold with price premiums of between 20-30%. Although it can be shown quite easily in most cases that this extra cost is recouped in 1-2 years, through reduced running costs, most motors in the range up to 300 kW are sold by the manufacturers to OEMs not users.

The additional active material as a percentage of net selling price in the new higher efficiency motors made by one manufacturer is now only 2% (for an average efficiency gain of just over 3%) compared with over 10% extra material for the same efficiency gain in their older energy efficient range, which was based simply on adding active material to existing motors. This small additional material cost has been offset by reductions in other costs and the new improved or higher efficiency motors (HEMS) are sold at standard prices, thus overcoming the OEM barrier

However, such a policy does require investment both in tooling and training; for the pioneers it also required considerable investment in R&D. Many argue that this investment should be recouped through price premiums, even though it has been shown that because of the structure of the market this would be self defeating. If these improved efficiency motors are to be sold without price premiums and no other financial -incentives are available their introduction must be Phased over the normal replacement cycle of the key tooling. For larger manufacturers this will be a relatively short period, say, 4-5 years, but for some small manufacturers it could be longer.

To summaries:

- Improved efficiency motors can be made by adding active material to existing designs. The policy is unimaginative and costly and will result in a premium priced product with limited customer appeal.

- A holistic approach embracing creative design, new materials and improved manufacturing techniques can reduce the increased material cost almost to zero in many cases, but will require investment in both tooling and training.

- If improved efficiency motors are to be produced by such an approach in the absence of other financial incentives their introduction needs to be phased over the normal replacement cycle for key tooling.

Chapter 5

Comparison Of Std. & Energy-Efficient Motor

5.1 Design Differences

Tables 5.1 and 5.2 provide a comparison of the key design and performance criteria for the above-defined motors. Where the values are limited by codes, standards, or laws, some may vary slightly from manufacturer to manufacturer based on a variety of design techniques, which can be considered a typical representation on the product available to the mill and chemical industry. For the most part, the differences between the electrical designs can be summarized and generalized as shown in Table 5.1.

In most cases, the mechanical structures are made from the same family of parts as shown in Table 5.2.

As motors evolve to higher efficiency levels, the trend will be to optimize the heat transfer capabilities of the mechanical parts. Hence, the frame and brackets will usually have more surface area with improved internal air flow and more effective fan arrangements. It is not likely that the mechanical structures will be weakened, nor

Table 5.1: Comparison Between Standard And Energy-Efficient Motors

TYPE	STANDARD	ENERGY EFFICIENT
Electrical steel	2.5-3.0 watt/lb	1.5-2.0 watt/lb
Lam. Thickness Range	.0185-035”	0.0185”-0.025”
Slot Comb. of Rotor & Stator	Same	Same
Stator slot	Small	Larger
Rotor slot	Single or Double Cage	Single or Double Cage
Rotor skew	Range from 0 to one slot	Range from 0 to one slot
Air Gap	Normal	Same or Slightly Larger
Rotor Construction	Die Cast	Die Cast
Winding	Machine or Hand Wound	Machine or Hand Wound

will the bearing stress be changed in this process.

5.2 Efficiency And Power Factor Tradeoffs

The efficiency and power factor tradeoffs are classical for energy efficient motors. The general rule for a given amount of active material (electrical steel, copper, and aluminum) is to maximize efficiency and correct power factor as a system,if required. Figs. 5.1 and 5.2 show these typical differences.

5.3 Winding Thermal Capacity(Life)

A direct comparison of winding life as impacted by thermal aging is shown in Fig 5.3. These values were derived from the fact that winding insulation life is doubled for every 10C reduction in average operating temperatures.

Fig. 5.4 shows that in the 3-50 hp range there is a significant reduction in the average winding temperatures. Note that in Fig. 5.5 the frame temperatures track closely with the winding temperatures shown in Fig. 5.4.

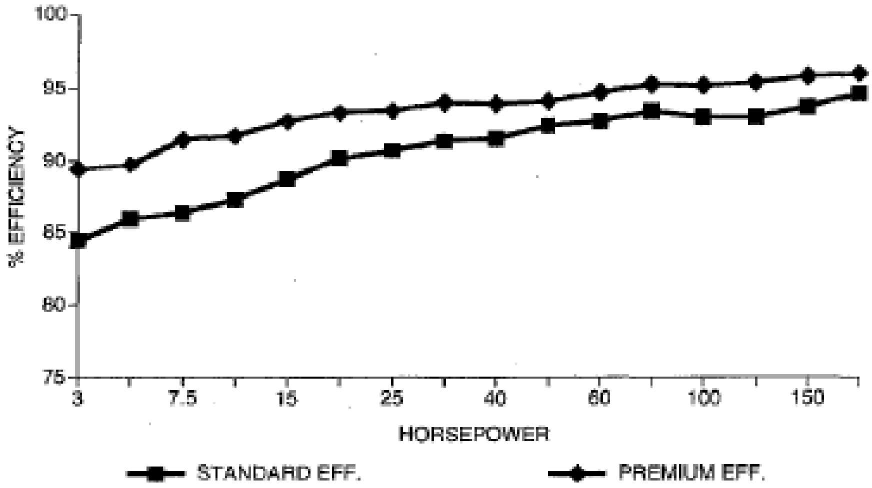

Figure 5.1: Efficiency comparison.

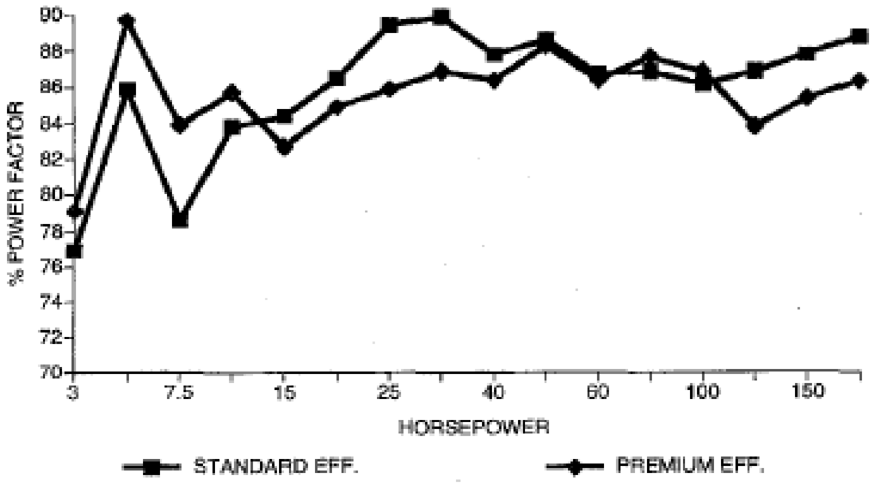

Figure 5.2: Power factor comparison

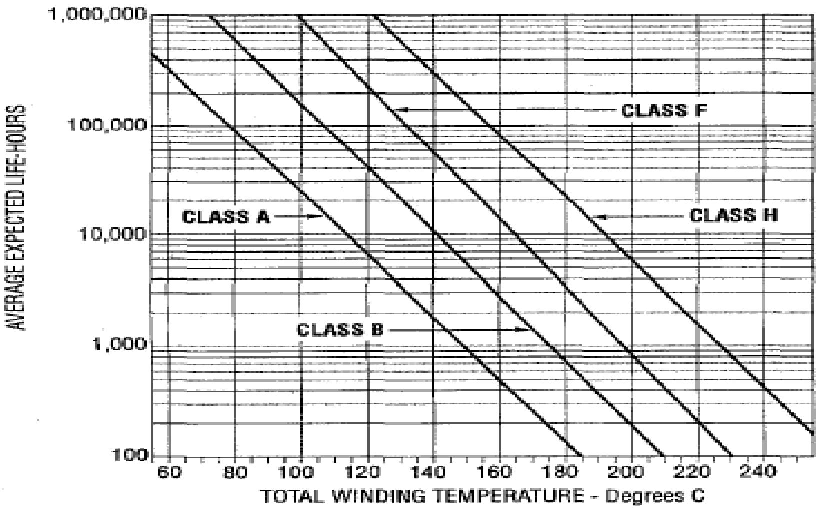

Figure 5.3: Temperature versus life curves for insulation systems (per IEEE Standards 117 and 101).

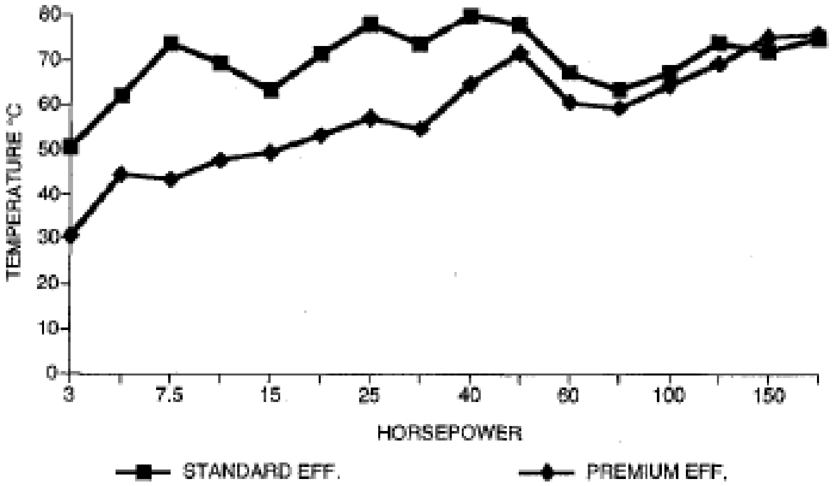

Figure 5.4: Average winding temperature comparison.

Table 5.2: Comparison Between Standard And Energy-Efficient Motors

TYPE	STANDARD	ENERGY EFFICIENT
Frame	Same	Same
Brackets	Same	Same
Fan Cover	Same	Same
Fans	May Be Different	May Be Different
Shaft Seals	Optional	IP54 OR IP55
Outlet Box	Same	Same
Bearings	Usually The Same	Usually The Same
Lubricant	Usually The Same	Usually The Same
Shaft	Same	Same
Bearing Caps	Optional	Required

5.4 Inrush Current

It can be seen from Figs. 5.6 and 5.7 that the locked rotor amps, as described by NEMA, show no significant increase. This is also confirmed in Fig. 5.8, which compares the locked kVA/hp,or code letter. In Fig. 5.9, a comparison was made of the air gap densities. Note that they were actually lower! The last item studied was the ratio of magnetizing-to-air gap current, which is called the saturation factor (Ki). Fig. 5.10 indicates that although the Ki factor is slightly high for many ratings, its only significant impact is associated with lower power factors.Hence, none of the above design comparisons would indicate any depreciation in motor life. Unfortunately, design data is not readily available to confirm or deny any migrations or trend of the above-mentioned parameters over the past 20 years for the large existing population of motors.

5.5 Speed And Torque Characteristics

These two variables are difficult to generate rules for,because there are a variety of ways to achieve the same results. Fig. 5.11 indicates that the torque for the standard and energy efficient motors do not vary significantly. Since there is such a variety

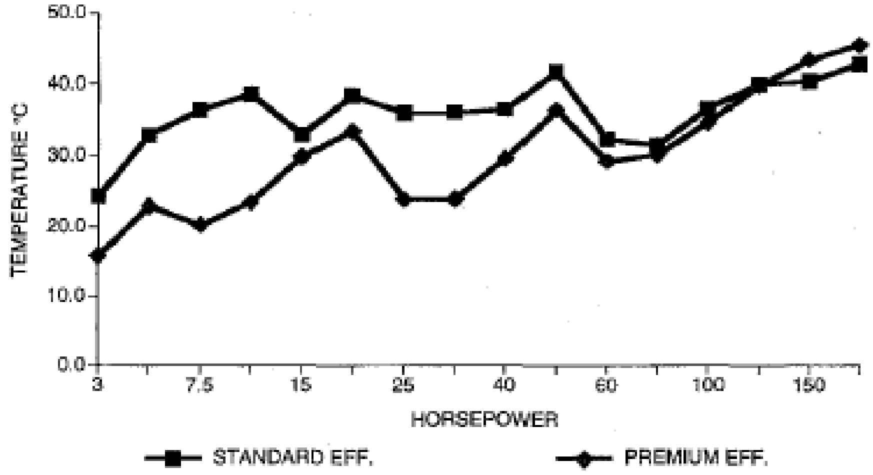

Figure 5.5: Maximum frame temperature comparison

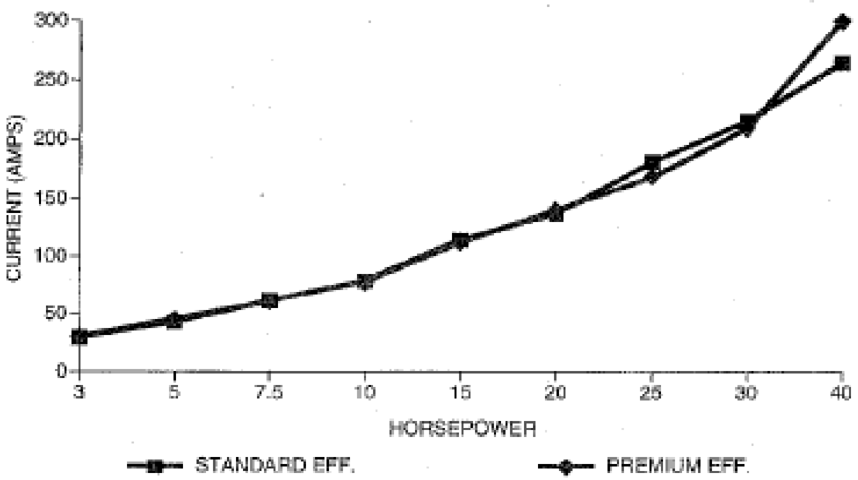

Figure 5.6: Lock amps comparison

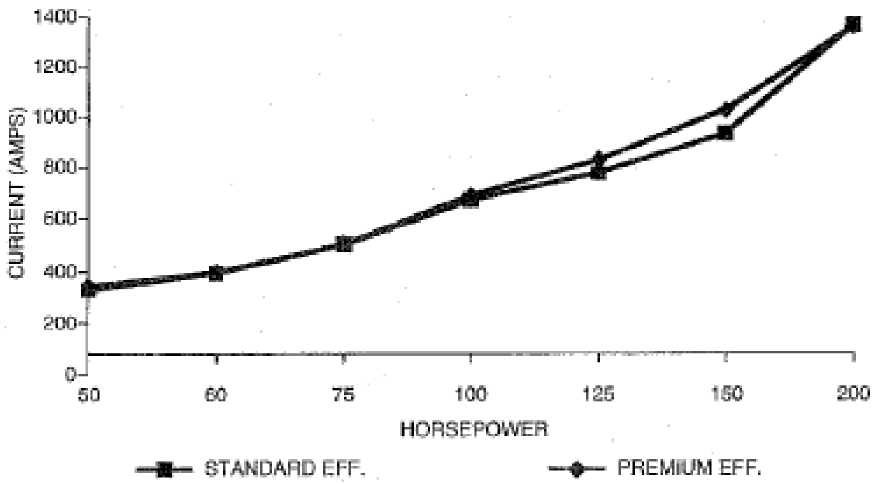

Figure 5.7: Lock amps comparison.

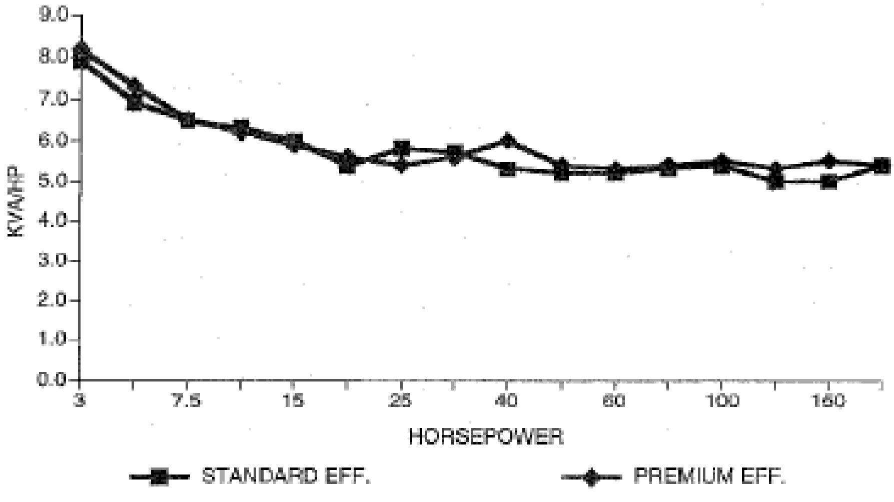

Figure 5.8: Lock kVA/hp comparison

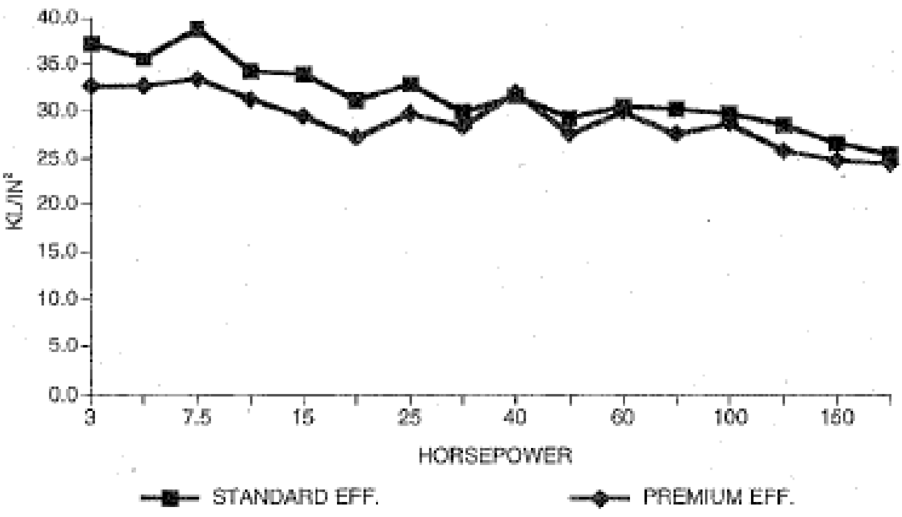

Figure 5.9: Air gap density comparison (kilolines per square inch)

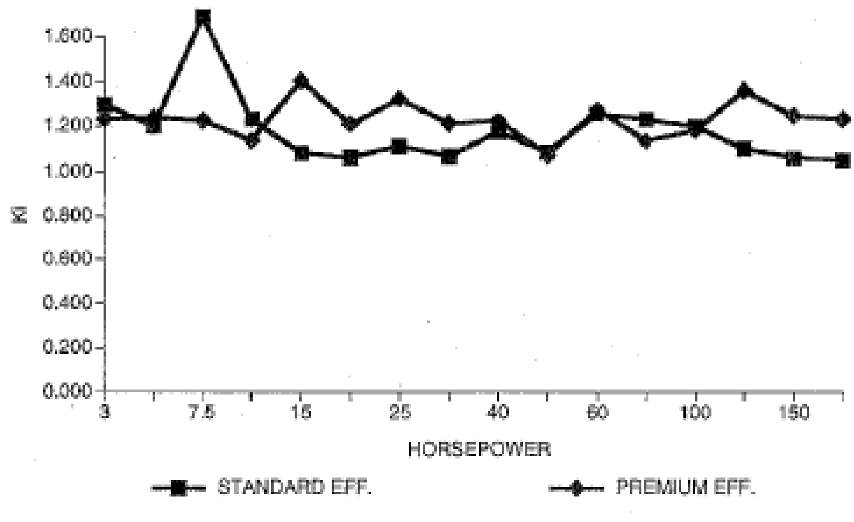

Figure 5.10: Saturation factor (Ki) comparison

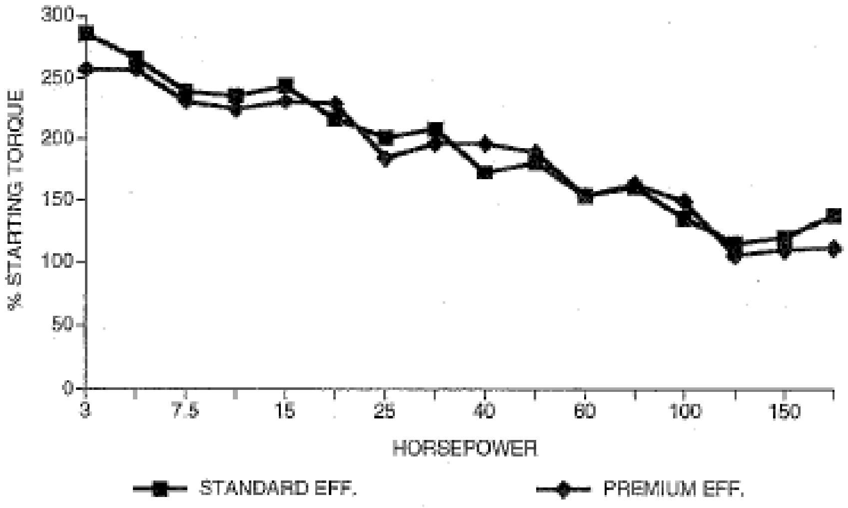

Figure 5.11: Starting torque comparison.

of rotor bar designs available throughout the motor industry, it is very difficult to develop any meaningful rule.However, it is safe to say that the speed-torque characteristics do not reduce the motor life of energy efficient motors.

The full load rpm (slip) as indicated in Fig. 5.12 shows that the smaller energy efficient motors (1-30 hp) do have higher operating rpm or lower slip. These lower slip levels, and the resulting reduction in rotor losses and temperature (see Fig. 5.13), will yield longer rotor and bearing life. In fact, even the stator temperatures are impacted since heat is conducted back across the air gap.

To address the air gap issue briefly, there are contradicting points of view on the best air gap for energy efficient motors. The general rule that the author uses can be stated as follows: Increase the air gap and harvest the resulting reduction in stray load loss until magnetic saturation occurs in the teeth or core of the lamination and the resulting increase in core loss is unacceptable. Hence, as shown in Fig. 5.14, the air gaps are not usually reduced on the energy efficient designs. This rule must be limited to maintaining acceptable power factor levels. Again, the designer is forced to make a tradeoff between efficiency and power factor. Two side benefits for larger

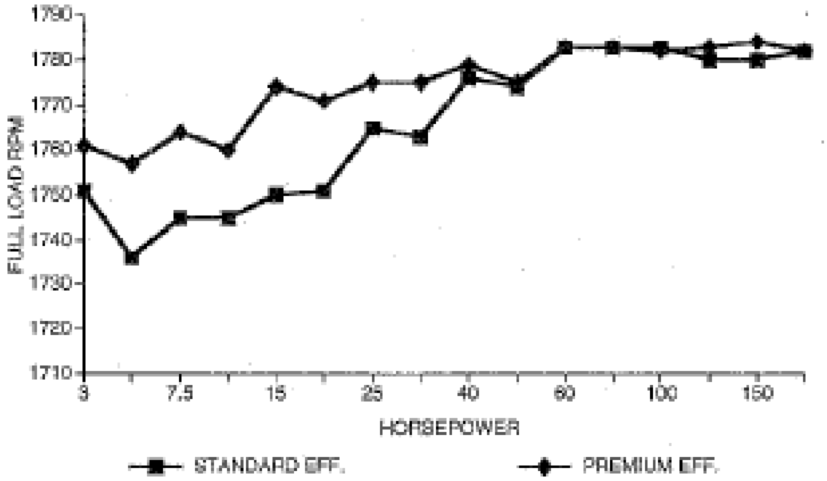

Figure 5.12: Full load RPM comparison.

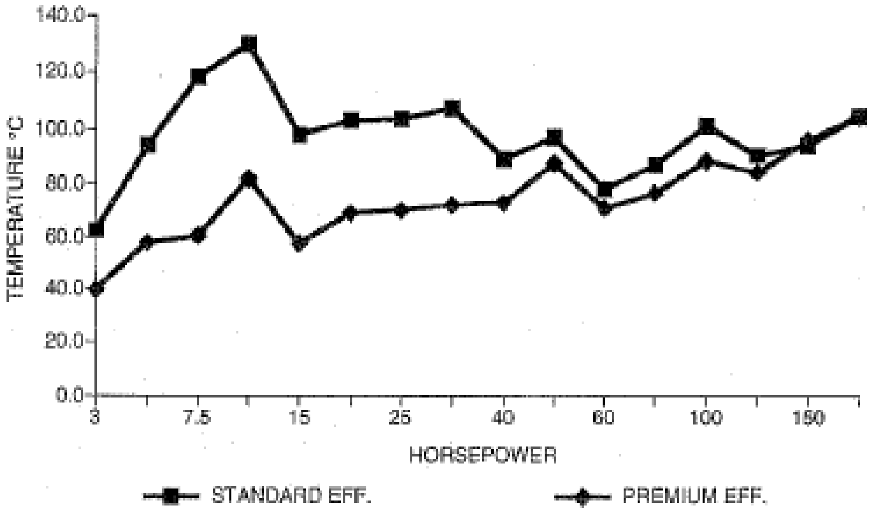

Figure 5.13: Maximum rotor temperature comparison

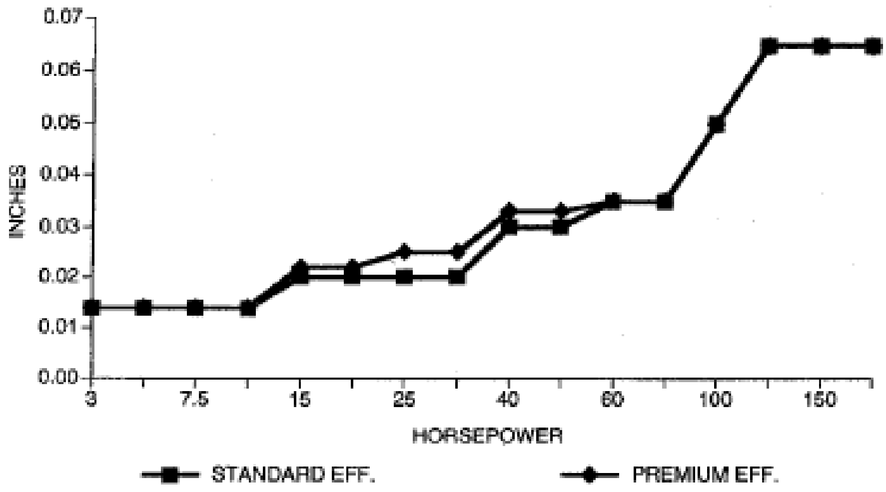

Figure 5.14: Air gap comparison

air gaps, for both types of motors assuming saturation in the magnetic circuit has not occurred, is that they tend to be quieter and have less chance of rotor strikes or pullover.

5.6 Inductive Reactance To Resistance Ratio(X/R)

Recent years, nuisance tripping of the instantaneous circuit breakers used with motors has been associated with the newer generation of motors. Many have assumed that the magnitude of the dc offset (asymmetry) and the X/R ratios have been increasing. As can be seen in Fig. 5.15, the comparison in X/R ratios for standard motors and energy efficient motors show that there is no significant difference up to 100 hp for this particular family of motors.

A more feasible explanation is that the National Electrical Code still only allows instantaneous current setting of 700under way from NEMA to raise the limit to 1700% (Article 430), combined with full-load amp values that have remained the same for over 30 years, but are not adequate for the current generation motors. During this same period, there has been a gradual evolution toward more robust motors with

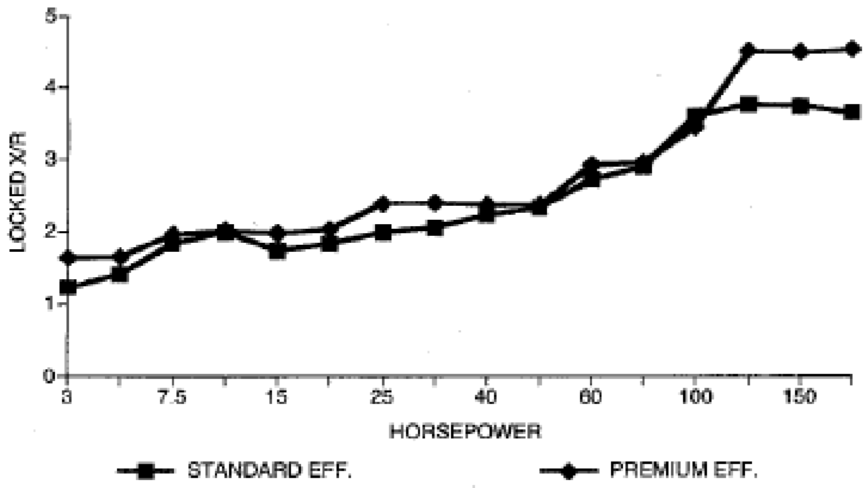

Figure 5.15: Locked X/R ratio comparison.

increased starting torques and inrush current. The slip losses have been reduced to control motor heating, while keeping the X/R ratio relatively constant.

The X/R ratio is basically controlled by the electromagnetic design of the motor. No general conclusions can be drawn regarding X/R ratio of premium efficient versus standard efficiency motors. However, the peak amperes did increase with regard to the locked rotor amperes as the X/R ratio increased. X/R ratios tend to increase with size of the unit and with certain design criteria, such as a low slip design. The higher instantaneous current values are due, in part, to the slower decaying envelope of longer time constraints normally associated with the higher X/R ratios. Compared to other parameters, x/R ratios will generally exhibit a limited effect, except in marginal cases where breaker unlatching may be occurring on the second or third peak cycle.

5.7 Motor Safe Stall Time

Table 5.3 shows the comparison of the temperature rise under a stall or lock condition which indicates that, in most cases, the energy efficient motors have a greater capacity when exposed to this scenario.

Table 5.3: The Comparison Of The Temperature Rise Under A Stall Or Lock Condition

LOCATION	STANDARD	ENERGY	PERC.TEMP
7.5 HP	-	-	-
WINDING HOT SPOT	160	126	127
ROTOR HOT SPOT	217	152	143
25 HP	-	-	-
WINDING HOT SPOT	195	74	260
ROTOR HOT SPOT	207	160	130
30 HP	-	-	-
WINDING HOT SPOT	171	75	230
ROTOR HOT SPOT	212	170	125

5.8 Bearings

For the most part, motor manufacturers do not reduce the load-carrying capability of the bearing system for energy efficient motors. In fact, they usually have the same system. The major difference is that the energy efficient designs tend to run cooler, they may have reduced magnetic side pull due to lower flux densities, and are better sealed because of the IP55 requirement. The fact that some run 10-15 r/m faster has minimal effect on the projected bearing life. Since lubrication life is a key determinant of bearing life for a given rpm,the reduced temperatures more than offset any other factors associated with the design.

Motor manufacturers approach the bearing system design in a variety of ways, but usually yield the same load capacity and life expectations. Some of the major variables include:

- bearing size and type
- sealing methods

- lubricants and lubrication sequence
- fits and clearances
- use of bearing caps,clamping,and preload
- operating temperatures

A review of product differences indicates most manufacturers select the bearing system based on application requirements,not on the required efficiency level.
IEEE Standard 841 specifies bearing life, maximum operating temperature, and sealed capability (i.e., IP54 and IP55), then leave it to the manufacturer to determine how best to comply. This standard was targeted at increasing bearing life over the previous motor generations. Regardless of the motor mounting (horizontal versus vertical), the bearing load is not evenly distributed. One bearing (usually the takeoff end) carries most of the load and the short end serves principally as a guide bearing. Hence, size differences do not usually affect system life.
Table 5.4 shows that the operating temperatures are generally lower or equal to that of previous motor designs. It is the authors opinion that bearing life (for a given motor speed) is not affected as much by the ball speed and type as it is by the quality of the lubricant, which is a function of temperature, mounting, alignment, and vibration of the system.

The following figure 5.15 & 5.16 shows the comparison between standard and energy-efficient motor

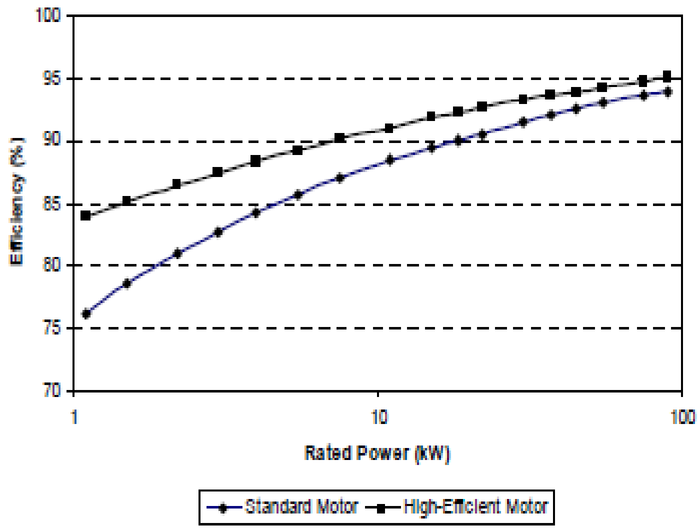

Figure 5.16: Comparison of full load efficiency between standard and high-efficient induction motors (IEC Standard)

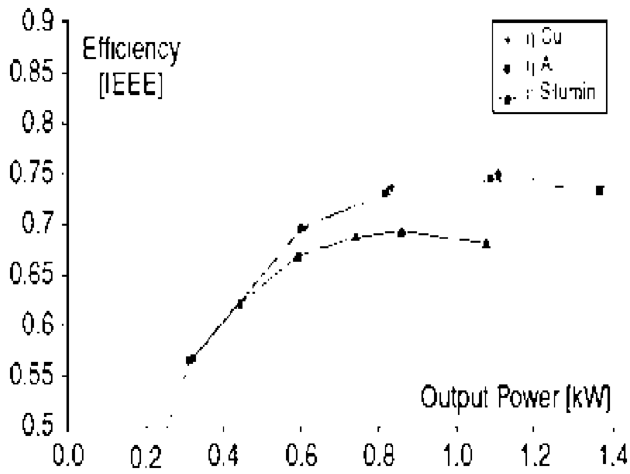

Figure 5.17: Efficiency comparison graph)

Table 5.4: The Comparison Of Operating Temperatures Of Standard and Energy-Efficient Motor

HP	STANDARD	ENERGY	DELTA
3	25	20	-5
5	35	25	-10
7.5	45	25	-20
10	30	30	-15
15	30	30	0
20	40	30	0
25	40	30	-10
30	42	30	-10
40	40	39	-3
50	45	44	-1
60	35	35	0
75	30	35	5
100	35	40	5
125	35	40	5
150	35	40	5
200	45	35	-10

Chapter 6

Optimization of Induction Motor

6.1 Definition of optimization

Aim of design is to determine the dimensions of each part of the machine, material specifications, prepare drawings and furnish to manufacturing units.Design has to be carried out keeping in view the optimizing of the cost, volume & weight and the same time achieving the desired performance as per specification.

The design of electrical machine involves too many variables and also there may be many solutions possible for a design. Optimization of a design means to find out the best possible solutions (design) for a given condition of the machine to be designed. There may be different condition for the machine to be designed like, cheaper machine, machine with low power factor, minimum losses, minimum size, overall good design etc. so when optimization of any design is to be done, the above conditions become the important factor to get the solution of design to suit the given condition. It is clear from the solutions of the design problems given in conventional design chapters for rotating machines that when the variables like length to pole pitch ratio and ampere conductors per meter are changed, the diameter and the length are changed. When diameter is reducing, length becomes more. It has also been discussed in the selection of specific magnetic loading and specific electric loading that the size of the machine can be reduced by selecting the high value of specific electric loadings but the losses will be more and hence temperature rise in the machine will be more with poor efficiency. When specific electric and magnetic loadings are taken lower than the size of machine will increase and hence more material and cost is involved but the performance will be better. When any machine has to be designed for any particular application then compromise between selection of variables and given situation is done to achieve a best possible design.

Modifications to be done in the above program to get optimal design

a. Insert "for" loops for the following parameters to iterate the total program between min and max permissible limits for selecting the feasible design variants:

- No of poles
- St-Wdg current density
- Slots/pole/phase
- Stator conductor thickness
- No. of conductor width-wise

b. Insert also minimum or maximum range of required objective functional values as constraint values, for example

- Efficiency
- Kg/kW
- Temp-rise
- I0/I ratio

c. Run the program to get various possible design variants.

6.2 Performance parameters of induction motor

- Magnetizing current
- Short circuit current
- No load current
- Copper losses
- Iron losses
- Efficiency
- Power factor
- Mechanical loss(friction and windage losses)

6.3 Various objectives to be optimized

- Higher efficiency
- Low losses
- Lower weight
- Less size

Chapter 7

Principles Of Computer Aided Design

In the Design of transformers and other rotating machines, the manual calculations are done to find out the different steps and hence the different dimensions and performance calculations of the machines. It is discussed in the design chapters that the output equations in terms of fundamental values (like voltage and current) are being converted into the output equations in terms of the machine dimensions (like diameter and length in case of rotating machines and window in case of transformers).design of the machine is proceeded with output equation based upon the specifications and other parameters of the machine. The different variables and parameters are interrelated and the variables and performance of the machine have non-liner relationships. The design also depends upon several other factors like mechanical stresses, magnetic forces, temperature rise and cooling medium adopted for the machine.

Taking into consideration the different parameters and operating conditions, the designer has to design a machine which should be best suitable. It should fulfill all the specifications. The machine designed should be rugged, simple, efficient, economic and safe. Designers should have sufficient technical knowledge and able to visualize the simultaneous inter-relationships of all the parameters and their effect. The visu-

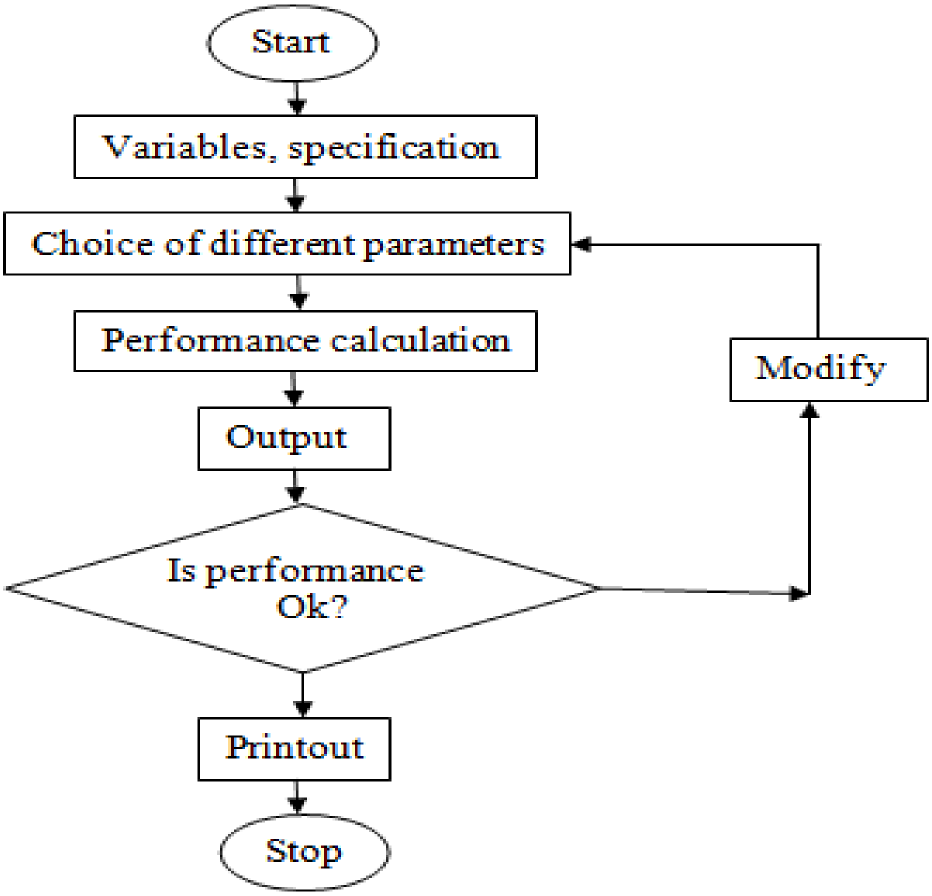

Figure 7.1: flow chart of general induction motor design

alization can be based on wide practical experiences. Some time machine may have to operate in isolation but some time it is used in a system with so many machines.

For a particular application, several set of design of machine may need to be done to find out the optimum designed machines. In finding the optimum design of the machine much iteration may be required to incorporate the changes in parameters till the satisfactory performance design is obtained. These calculations with indefinite iterations are manually not possible. These calculations can be easily done be means of a digital computers. By using computer the data can be easily varied many times to get the optimum design. So the computer has become a powerful and important tool in designing the electrical machines.

7.1 Advantages And Limitations Of Computer Aided Design

7.1.1 Advantages of computer aided design:

The use of digital computers in the design of electrical machines has changed the scene completely. The use of computer reduces the time and money used for the tedious and lengthy hand calculations. This time may be utilized by designer in developing some kind of ideology. Several characteristics of computer aided designs are given below:

- The computer has large memory so it can store maximum data, tables and other information required in the design.
- Computer can do the calculations in short time.
- It takes very less time to take the logical decisions.
- Change in large number of parameters can be modeled, simultaneously using loops in computer aided design
- In manual calculations, there may be errors but there is less chance of error in computer calculations.
- Optimization of design can be obtained by computers hence it reduces the cost on fabrication.
- Due to less error involved in calculation, high speed, fast decisions and better optimization the design becomes accurate, reliable and cost effective. The different steps in iteration can be shown by the flow chart given below.

7.1.2 limitations of CAD:

The use of digital computers involves high initial investment and also a considerable annual expense. The computers may be beneficial for an agency producing large number of machines. It is not suitable for smaller companies due to huge investment. Limitations of CAD are as per following:

- Memory and storage limitations. It makes computer aided design costlier.
- Inter-operability between two computer aided design systems is not available.
- Interface problem between drawing tools and design and analysis tools.
- Verification of feasibility of results obtained by computer aided design difficult.

7.2 Different Approaches For Computer Aided Design

(I)Analysis method of design: In this method, the computer is used only for the purpose of analysis and all the decisions are taken manually by the designer. In analysis method, the choice of basic parameters and types of construction are done by the designer. These are given as input to the computer for estimation of different machine dimensions and performance calculation. The performance calculated by computer is then critically examined by the designer according to the specifications, to be achieved by the machine. If the design is not satisfactory, the designer can make other suitable choice of the parameters to recalculate the performance. This process can be repeated till the performance calculated above is satisfactory.

The program for analysis method is simple, easy to understand and use. It saves much calculation times and can be referred or used in larger and sophisticated design programs. The analysis method gives widely acceptable results. The advantage in this method is that the logical decisions are by the designers and hence the simple programs can be designers and hence the simple programs can be designed.

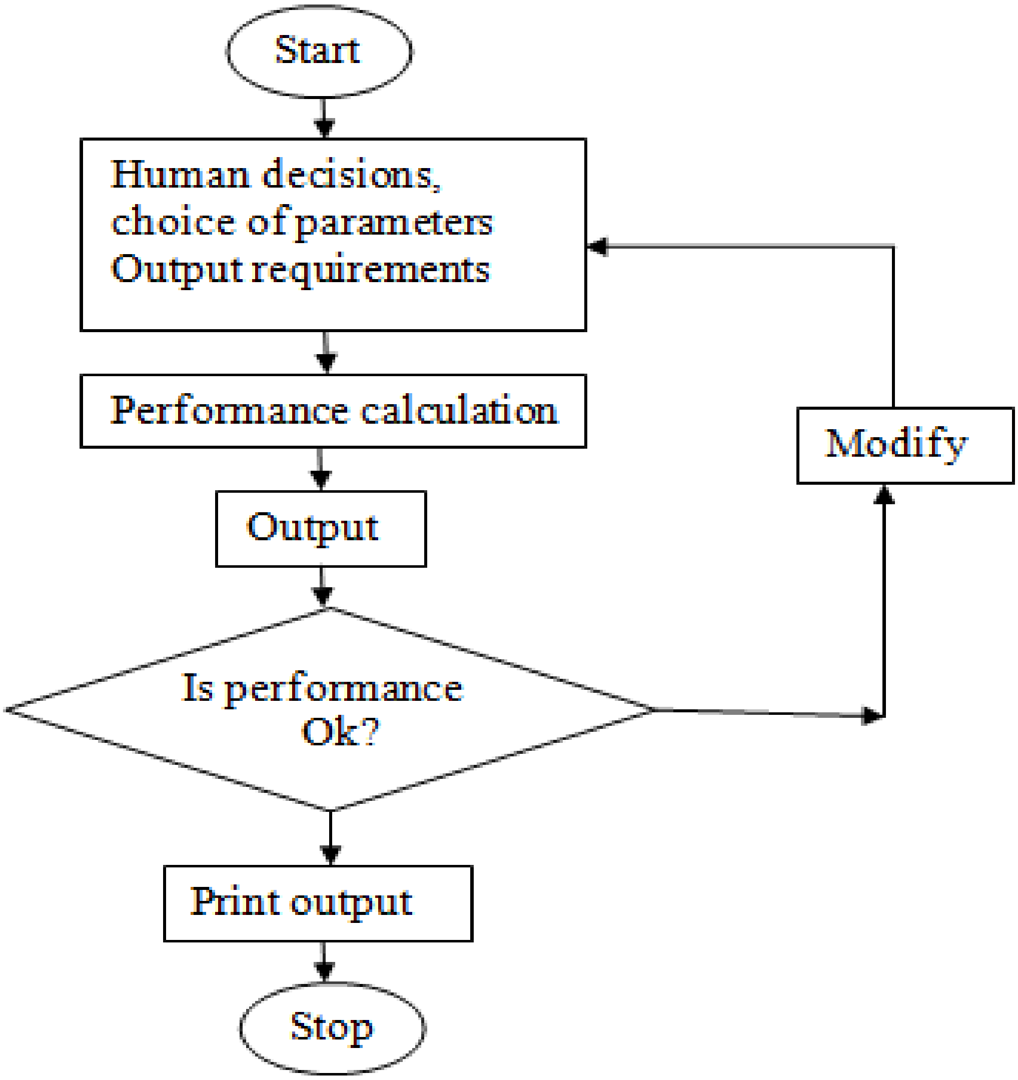

Figure 7.2: analysis method

(II)Synthesis method of design: In analysis method, we have seen that the logical decisions are taken the designers i.e. when the output is not matching with desired specifications then designers select the suitable and again the performance analysis is done.

In synthesis method, the logical decisions are taken by the computers. The logical decisions include the suitable change in parameters to achieve desired design and performance. In synthesis method, the analysis and decision both are done by the computers so the time required in this method is very less. In view of the above aspects, the synthesis method may have several disadvantages:

- Large number of logical decisions to be taken by computers.
- Large number of instructions makes the program complicated and lengthy.
- Complicated and lengthy programs need large computers which require huge investment.
- The programs need changes to incorporate the latest changes in materials and techniques.

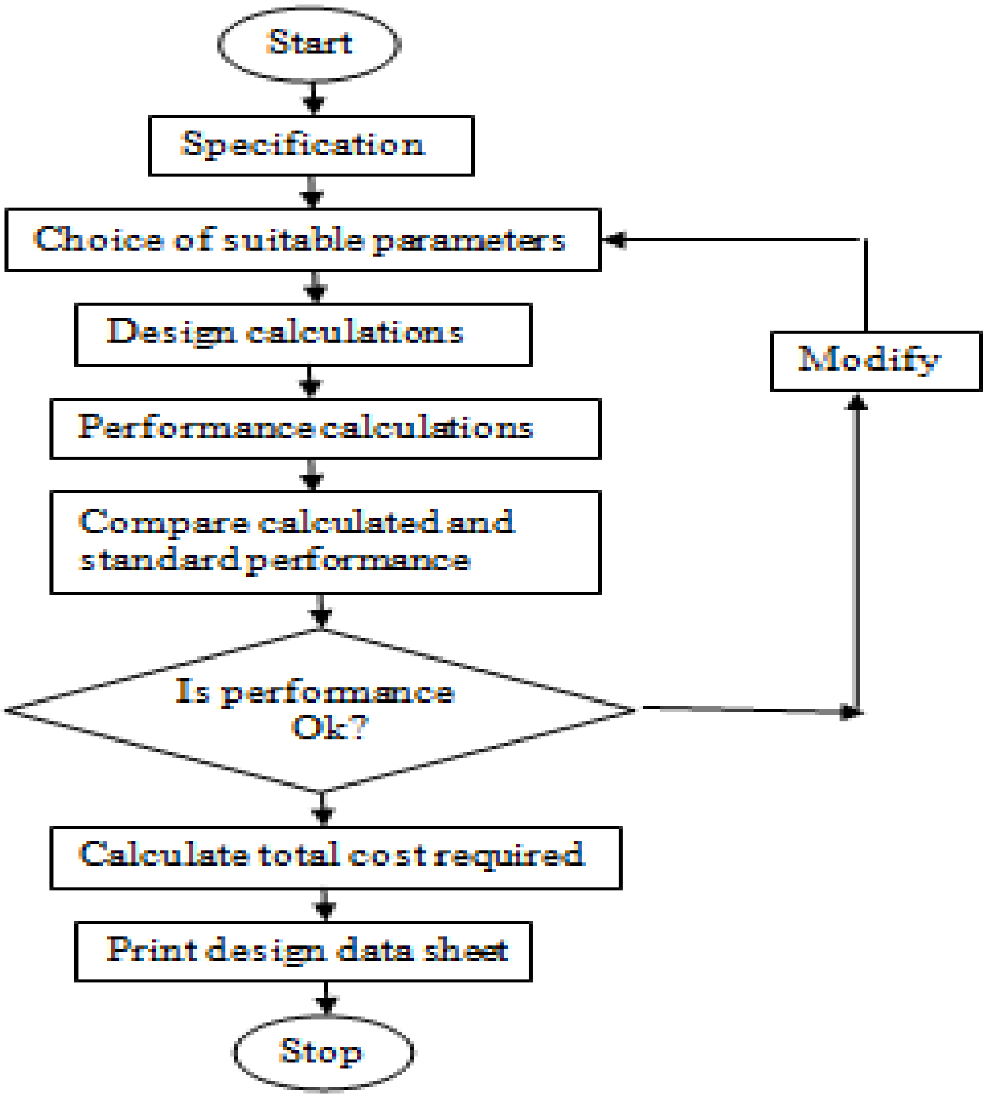

Figure 7.3: synthesis method

Chapter 8

Programming Results

8.1 results of standard motor design

The design data sheet of 3-phase induction motor

Ratings

kW=2.20

line voltage=400

type of connection=delta

frequency=50 Hz

type of rotor=squirrel cage

phase=three

efficiency=75.00

power factor=0.75

number of poles=4

synchronous speed=1500 rpm

KVA Input=4

full load line $current = 6$ amp

specific magnetic $loading = 0.43\ wb/mm^2$

specific electric $loading = 21000$ A/m

output $co-efficient = 95.037$

Main dimensions

diameter D=0.110 m

length=0.138 m

number of ducts Nd=1

net iron length Li=0.11 m

pole pitch Tau=0.09 m

Stator design

Winding

type of lamination=0.5 mm thick lohys

type of winding=single layer mush

type of slot=tapered slot

flux per pole=0.01 wb

stator turns per phase Ts=369

total stator slots=24.0

stator slot pitch yss=14.35 mm

total stator conductors Zs= 24.00

stator conductors per slot Zss=1

angle of chording al=0.52 degree

coil span Cs=5

pitch factor kp=0.97

distribution factor kd=0.97

stator winding factor kws=0.93

Conductor size

stator current per phase Isp=3.26 amp

stator line current Isl=5.65 amp

area of stator conductor as=0.88 mm^2

current density for stator conductors dels= 3.70 A/mm^2

diameter of bare conductor d=1.06 mm

diameter of enameled conductor d1= 0.07 mm

Slot dimensions

area of each slot = 2.21 mm^2

minimum width of stator teeth Wts-min= 0.00 mm

tooth constant width Wts-max=0.01 m

depth of slot dss= 0.00 m

length of mean turn Lmt=0.71 mm

Stator teeth

flux density in stator teeth Bst=1.09 wb/mm^2

Stator core

flux in stator core=0.00 wb

depth of stator core dcs= 0.02 mm

area of stator core Acs=2.16e-003 m^2

flux density in stator core Bcs= 1.18 wb/m^2

outside diameter of stator laminations Do=147.69 mm

Rotor design

Air gap

length of air gap lg=0.30 mm

diameter of rotor Dr=109.08 mm

Rotor slots

number of rotor slots Sr=22.00

rotor slot pitch at the air gap ysr=15.57 mm

Rotor bars

rotor bar current Ib=229.70 amp

area of rotor bar ab=38.50 mm^2

current density for rotor bars dels=5.97 A/mm^2

width of rotor slot Wsr=3.80 mm

depth of rotor slot dsr= 8.30 mm

slot pitch at the bottom of slots ybr= 13.20 mm

tooth width at the rotor Wt=9.40

length of each bar Lb=177.76 mm

resistance of each bar rb=9.70e-005 ohm

total copper loss in bars Prbcu=112.54 w

End ring

end ring current Ie=402.33 amp

current density in end ring dele=4.47 A/mm^2

area of end ring ae=90.00 mm^2

depth of end ring de=5.00 mm

thickness of ring te=18.00 mm

outer diameter of end ring Deo=92.48 mm

inner diameter of end ring Dei=82.48 mm

mean diameter of end ring De=87.48 mm

resistance of each ring re=6.41e-005 ohm

copper loss in two end rings Pecu=20.75 W

total rotor copper loss Pcu=133.29 mm

Rotor core

depth of rotor core dcr=19.00 mm

inner diameter of rotor laminations Dri=54.48 mm

8.2 results of energy-efficient motor design

Design of 2.20KW, 440V, 50Hz, 3-ph sq. cage induction motor

Input data

———

Parameter Values

Rating (KW) 30.0

Volts 440

Poles 4

Hz 50

Interpolated values from curves: Bav=0.484, ac=26802

Eff 0.862

Pf 0.880

Output results:

——

——

Parameter

values

——-

—-

Output co-efficient (C0) 103.34

Sync. Speed (rps) 16.67

D^2L 0.0174

Gross length (mm) 160.0

Net iron length (mm) 128.8

Stator inner dia (mm) 330.0

Peripheral speed (m/s) 17.28

Pole-pitch (mm) 72.8

Length to PP ratio 0.9260

Slots 54

Slot-pitch (mm) 19.199

Cond/slot 18

Turns/ph 162

Flux/pole (wb) 0.01281

Phase current 29.96

Bare strip (w*t) mm 5.0*1.90

Width to thickness ratio 2.63

Area of CS cond (mm^2) 9.186

Current density (A/mm^2) 3.500 Interpolated values of W/kg of stator teeth=23.92 and core=18.32 No. of stripes (width*depth wise) 36

Slot width (mm) 10.6

Slot-height (mm) total 46.0

Stator-tooth-flux-density (1/3) 1.0644

Stator -tooth-flux density-max (T) 1.5997

Length of mean-turn (m) 0.957

Resistance/ph (ohm) 0.3546

Depth of stator core (mm) 39.00

Outer diameter of stator core (mm) 500.0

Stator copper losses (W) 954.6

Wt. of st-teeth+core(kg) 79.51

Iron loss=teeth+core(W) 1602.1

ROTOR

Length of air-gap (mm) 0.6600

No. of rotor slots should NE to 36, 48,42,24,53,52,47,46

No. of rotor slots selected 45

Rotor slot-pitch (mm) 22.9462

Equivalent rotor ct (amp) 25.46

Rotor bar ct (amp) 525.3

Rotor bar CS (mm^2) 88.2000

Bar (w*t) mm 15.06.0

Rotor slot (w*h) mm 6.515.5

Length of bar (m) 210.0

Resistance /bar 0.05000

Losses in rotor bar (W) 620.8

End ring ct (amp) 1254.0

Area of end ring (mm^2) 209.0

Resistance of end-ring 0.0880

Rotor-cu-losses=bars+ end rings (W)=620.8+276.7 897.5

Equivalent rotor res (ohm) 0.461

Rotor (1/3) slot-pitch (mm) 21.50

Rotor (1/3) tooth width (mm) 15.00

Rt-tooth-flux-dens (1/3)(T) 21.50

Rt-tooth flux-dens-max (T) 15.00

Depth of rotor core (mm) 36.84

no-load losses

No-load-losses (W) 1902.1

No-load current (amp) 1.441

magnetizing current

Interpolated values of at/m of st. core= 480.0 and teeth=706.5

Interpolated values of caters co-efficients: k01= 0.663, k02= 0.453, kV=0.700

Stator AT: core+teeth: 38.7+32.5 71.2

Rotor AT: core teeth: 21.9+4.6 26.5

Total AT: stator+rotor+airgap: 71.2+26.5+438.3 536.0

No-load current (A) Iw 1.44

Magnetizing current Im 8.9

No-load current I0 9.0

No-load pf 0.160

I0/Iph ratio 0.300

short-circuit-current

Slot-permeances:stator= 1.987 , rotor=1.019 and rotor referred to stator=1.115

Specific-slot permeance=3.1 Total reactance(X): slot+overhang+zig-zag=1.143+1.140+1.243=3.5

Short-circuit: R=0.82, Z=3.62 and Isc=121.5 at pf=0.225;

Isc/Ifl=4.057

Total losses (Pnl+Pcus+Pcur) =1902.1+954.6+897.5=3754.2

Efficiency =88.88

Slip at full load=2.7

Max. Output (KW) =60.6

Temp-rise (deg-c) =55.6

Total wt (kg) =Wcus+Wt+Wc+Wri+Wcur+Wcue=179.3

Total Wt (kg) =179.3 and kg/kw=5.98

Chapter 9

Conclusion & Future Scope

9.1 Conclusion

- From the programming results,it is shown that efficiency of energy-efficient motor(86%) is higher than standard motor(75%) for the same rating of machine(2.20kW)
- Energy efficient motors have a large saving potential.The most remarkable saving potential is found within the power range below 37 kW. 80% of the total saving potential is in this power range. EE-motors are cost effective in all power ranges. Even if there are high efficiency motors available in the market now new advanced motor materials, improved motor manufacturing processes and design tools still allow a challenge to increase efficiency in an economical way.
- Energy-efficient induction motors are 2 to 8% more efficient than standard motor.
- Use of such motors offer many advantages such as energy and money saving, demand reduction, and green house gas emission reduction. They have generally longer insulation and bearing lives, lower heat output, and less vibration.
- In addition, these motors are often more tolerant of overload conditions and

phase imbalance. This results in low failure rates, which has prompted most manufacturers to offer longer warranties for their energy-efficient lines. Because a motor consumes energy worth 4 to 10 times its own cost each year, energy-efficient motors often make economic sense in a wide variety of applications.

9.2 Future scope

By adding more efficient loops ,one can make standard motor more energy-efficient.

Chapter 10

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Appendix A

Motor design software MATLAB

A.1 standard motor design

```
clear all;
clc;
P=input('enter the rated input power P(watts):');
v=input('enter the rated input voltage v(volts):');
f=input('enter the rated frequency f(hz):');
p=input('enter the no. of poles p:');
N=input('enter the rated speed N(rpm):');
eff=input('enter the motor efficiency eff:');
pf=input('enter the power factor at F.L pf:');
ns=120.*f/p;
wms=ns/60;
disp('Bav :for 50hz m/c=¿b/w 0.3 to 0.6 wb/m.2');
disp('for large O.L. capacity =¿ 0.65 wb/m.2');
disp(' ac :=¿ b/w 5000 to 450000 wb/m.2 );
disp('kw :=¿ about 0.955 assumed ');
Bav=input('enter the magnetic loading Bav:');
```

```
ac=input('enter the electrical loading ac:');
kw=input('enter the winding factor kw:');
c0=11*kw*Bav*ac*(10^-3);
Q=P.*(10.^-3)/(eff.*pf);
disp(':for best power factor =¿ T=aqrt(0.18.*L)');
disp(':for minimum cost =¿ b/w 1.5 to 2.0');
disp(':for good power factor =¿b/w 1.0 to 1.25');
disp(': for good efficiency =¿ 1.5');
disp(':for good overall design =¿1.0');
a=input('enter the L/T ratio');
D=((4.*Q)/(c0.*wms.*a.*pi)).^(1/3);
L=a.*pi.*D./4;
T=pi.*D/p;
disp('provide radial ventilating duct ,if core length exceeds 125mm');
if(L¿0.125)
disp('width of radial ventilating duct is approximately 8 to 10 mm');
nd=input('enter the total no. of ventilating duct nd(mm):');
wd=input('enter the width of ventilating duct wd(mm):');
Li=0.9*(L-(nd*wd.*10.^-3));
else
Li=0.9*L;
end
disp('stator design');
disp('choose your starting connection as mention below');
disp('star-delta starter=¿1');
disp('delta-star starter=¿2');
sd=input('enter the type of connection sd:');
if(sd==1)
Es=v;%Es=stator voltage per phase
```

```
elseif(sd==2)
Es=v./sqrt(3);
end
fym=Bav.*T.*L;%Flux per pole;
Ts=Es./(4.44.*f.*fym.*kw);%stator turns per phase
disp('yss:for open slots=¿b/w 15 to 25 mm');%yss=stator slot pitch;
disp(':for semi enclosed slots =¿ less than 15 mm');
qs=input('enter no. of slots per pole per phase qs:');
if qs¡2
disp('qs can not chosen less than 2,check given input data again');
end
Ss=3.*p.*qs;
yss=(pi. * D. * 10.^-3);
Zs=6.*Ts; %Zs=total stator conductors;
Zss=Zs./Ss; %Zss=stator conductors per slot;
disp('winding selection');
disp('choose mush winding for small induction motors');
disp('choose double layer winding for medium & large sizes induction motors');
disp('mush wdg=1 —— double layer wdg=2');
wdg=input('enter the type of winding wdg:');
if(wdg==1)
cs=Ss./p;%cs=coil span
fprintf('the coil span cs : %f',cs);
disp('coil span should not be even integer for mush winding ,take odd coil span');
disp('for coil span,if even enter 1 and make it odd');
disp('for coil span,if odd remain as it is no change');
Cs=input('enter the coil span is even or odd, enter 1 for even, enter 2 for odd:');
if(Cs==1)
Cs=input('enter new odd coil span Cs:');
```

```
elseif(Cs==2)
Cs=cs;
end
elseif(wdg==2)
Cs=Ss./p;
Cs=cs;
end
alpha=180./cs;%alpha=chording factor
alph=(pi.*alpha./180);
Kp=cos(alph./2);%Kp=pitch factor
Kd=sin(alph./2)./(sin(alph)./(2.*qs));%Kd=distribution factor
Kws=Kd.*Kp;%Kws=stator winding factor
fprintf('the stator wdg factor Kws: %f',Kws);
Kws=0.933;
%conductor size:
Is=P./(3.*Es.*pf.*eff);%Is=stator current per phase
fprintf('give the type of stator connection 1 for delta, 2 for star:');
con=input(' enter the type of connection :');
if(con==1)
Iline=Is.*sqrt(3);%Iline=stator line current
elseif(sd==2)
Iline=Is;
end
disp('current density in stator is between 3 to 5 A/mm2');
delta=input('enter the current density delta (A/mm2)');
as=Is./delta;
d=sqrt(as.*4./pi);
disp('compare diameter of founded with standard from table');
d=input('enter standard diameter value :');
```

as=(pi.*($d.^2$))./4;

delta=Is./as;

%slot dimensions

disp('space factor(sf):between 0.25 to 0.4');

sf=input('enter the space factor sf:');

Aslot=Zss.*as./sf;%Aslot=area of stator slot

Lmt=(2*L)+(2.3*T)+0.24;%Lmt=length of mean turn

%turn(mm),L=length(m),T=toue(m)

disp('flux density in stator teeth between 1.3 to1.7 wb/mm2');

Bmt=input('enter the flux density in tooth Bmt(wb/m2)');

wts=(fym.*p)./(Bmt.*Ss.*Li);%minimum width of stator teeth

%stator teeth

disp('replace the width of stator teeth with standard value');

wts=input('enter the standard value of stator teeth in mm:');

Bts=((p.*fym)./($Ss. * wts. * 10.^3. * Li$)).*(10.^{6});

%stator core

fys=fym./2;%fys=flux in stator in wb

disp('flux density in stator teeth with standard value');

wts=input('enter the standard value of stator teeth in mm:');

Bts=((p.*fym)./($Ss. * wts. * 10.^3. * Li$)).*10^6;

%stator core

fys=fym./2;%fym=flux in stator core in wb;

disp('flux density in stator core(Bcs1) bet 1.2 to 1.4 wb/m2');

Bcs1=input('enter thre flux density Bcs1(wb/m2):');

Acs=fys./Bcs1;%Acs=area stator core

dcs=(Acs./Li).*(10.^{3});%dcs=depth of stator core

```
h=input('enter the height of teeth h(15-25mm):');
wedge=input('enter the wedge(3-8mm):');
lip=input('enter the lip(0.5-2mm):');
dss=h+wedge+lip;%dss=depth of stator slot,lip=1mm,wedge=3mm,slack=1.mm;
Bcs=input('enter the flux density of stator core Bcs:');
D0=(D. * 10^3)+(2*dss)+(2*dcs);
disp('rotor design')
air gap
disp('air gap');
disp('for small m/c:1 —— for large m/c :2—— any :3');
x=input('enter the choice:')
if x==1;
lg=0.2+(2.*sqrt(D.*L));%lg=length of air gap
elseif x==2;
va=(pi.*D.*ns);
lg=0.125+(0.35.*D)+(0.015.*va);
else
lg=(1.6.*sqrt(D))-0.25;
end

disp('if airgap length is very high causes high magnetizing current so replace it');
lg=input('enter the value of air gap length(m):');
Dr=(D.*10.^3)-(2.*lg);%Dr=rotor diameter

%rotor slots
disp('rotor slots');
Sr=Ss-(p./2);%Sr=rotor slots
ysr=pi.*Dr/Sr;%ysr=rotor slot pitch
```

rotor bars

disp('rotor bars');

Ib=(2.*3.*kw.*Ts.*Is.*pf)./Sr;

disp('current density in rotor bars can be taken between 4 to 7 a/mm2');

density=input('enter the value of rotor current density:');

ar=(Ib./density);

disp('compare the result with standard conductor dimensions');

disp('if it is match with standard one than remain the results it is otherwise change it');

ar=input('enter the standard rotor bars area:');

Wsr=input('enter the width of rotor slot:');

Dsr=input('enter the depth of rotor slot:');

disp('checking flux density in the root of rotor teeth that is B11 ');

W11=(pi.*((Dr*10.^{3})-(2.*Dsr)))./Sr;

disp('tooth width at the root');

Wt=W11-Wsr;

disp('flux density at the root of rotor teeth');

B11=(fys.*p)./(Sr.*Li.*($Wt. * 10^-3$));

disp('check this flux density is within limits otherwise modify it');

disp('bars are skewed by one slot pitch');

E1=input('extension of bar beyond the core E1:');

l1=input('enter increase in length due to skewing:');

Lb=125+(2.*E1)+l1;

Rb=(0.021.*(Lb.*10$^-$3))./ar;

Pcu-bars=(Sr.*(Ib.^{2}).*Rb);

end ring

Ie=(Sr.*Ib)./(pi.*p);

disp('current density in end ring should be greater or equal to rotor bars');

dens-endring=input('enter the value of current density in end ring:');

area-endring=(Ie./dens-end ring);

disp('compare founded area of end ring with standard one and if does not match than enter new depth and thickness');

De=input('enter depth of end ring:');

Te=input('enter thickness of end ring:');

ae=(De.*Te);

De-o=((Dr)-(2.*Dsr));

De-i=(De-o)-(2.*De);

Dmean-e=0.5.*(De-o+De-i);

Re=(0.021.*pi.*(Dmean-e.*$10^{-}3$))./ae;

Pcu-endring=(2.*(Ie.^{2}).*Re);

Pcu-total=Pcu-endring+Pcu-bars;

Slip=(Pcu-total)./(P+Pcu-total);

rotor core

Dcr=dcs;

Bcr=input('enter the value of flux density in rotor core Bcr:');

Di=Dr-(2.*Dsr)-(2.*Dcr);

disp('no load current');

magnetizing currnet

air gap

Ws=input('enter the stator width opening:');

Wr=input('enter the rotor width opening:');

Kcs=input('enter the casters co-efficient of stator slot:');

Kcr=input('enter the casters co-efficient of rotor slots:');

Kgss=yss./(yss-(Kcs.*Ws));

Kgsr=ysr./(ysr-(Kcr.*Wr));

Kgs=Kgss*Kgsr;

```
disp('here we are not providing any radial ventilating duct so Kgd=1');
Kgd=1;
Kg=Kgs*Kgd;
Ag=(pi.*D.*L)./Bav;
Bg-60=1.36.*Bav;
lge=Kg.*lg;
ATg=800000.*Bg-60.*lge.*10.^-3;

stator teeth
Ast=(Ss./p).*wts.*10.^3.*Li;
Bts-60=1.36.*Bts;
fprintf('value of Bts-60=%f ',Bts-60);
atst=input('give value of atst corresponding to value of Bts-60:');
ATst=atst.*dss.*10.^-3;

stator core
Acs=Li.*dcs;
Lcs=((pi.*((D.*10.^3)+(2.*dss)+(2.*dcs)))./(3.*p)).*10.^6;
fprintf('value of Bcs=%f',Bcs);
atcs=input('give the value of atcs corresponding to value of Bcs:');
ATcs=atcs.*Lcs;

rotor teeth
Wtr-3=((pi.*(Dr-((4.*Dsr)./3)))./Sr)-Wsr;
Atr=(Sr.*Wtr-3.*10.^3.*Li)./p;
Btr=input('enter the value of flux density in rotor teeth at 1/3rd height:');
Btr-60=1.36.*Btr;
fprintf('value of Btr-60=%f',Btr-60);
atr=input('give the value at atr corresponding to value at Btr-60:');
```

ATtr=atr.*Dsr.*10.^-3;

rotor core

Acr=Li.*Dcr;

fprintf('value of Bcr=%f',Bcr);

atcr=input('give the value of atcr corresponding to value of Bcr:');

Lcr=((Dr-(2.*Dsr)-(2.*Dcr)).*pi)./(3.*p);

ATcr=atcr.*Lcr.*10.^-3;

AT-T=ATg+ATst+ATcs+ATtr+ATcr;

Im=(0.427.*p.*AT-T)./(kw.*Ts);

disp('loss component');

iron losses

Weight-st=input('enter the weight of stator teeth in kg:');

Bts-max=(pi./2).*Bts;

disp('corresponding to max flux density give value of loss per kg from figure');

Loss-st=input('enter the loss per kg of stator teeth:');

Ironloss-st=Loss-st.*Weight-st;

iron loss in stator core

Weight-sc=input('enter the weight of stator core in kg :');

Loss-sc=input('enter the loss/kg of stator core corresponding to Bcs:'); Ironloss-sc=Loss-sc.*Weight-sc;

Ironloss-t=Ironloss-st+Ironloss-sc;

Ironloss-T=2.*Ironloss-t;

friction & windage losses

F-W-Loss=(1.5/100).*P;

No-Load-Loss=Ironloss-T+F-W-Loss;

Il=No-Load-Loss./(p.*v);

I0=sqrt(Im.^{2}+Il.^{2});

I0-pefull=(I0./Is).*100;

PF-noload=(Il./I0);

Phaseangle-noload=acos(PF-noload).*180./pi;

disp('short ckt current');

Xs=input('enter the value of total leakage reactance:');

disp('resistance');

Rs=(0.021.*Ts.*Lmt)./as;

copperloss-stator=3.*Is.^{2}.*Rs;

Pcu-rotor=(Pcu-total)./3;

Rr-s=Pcu-rotor./(Is.^{2}.*pf.^{2});

R-s=Rr-s+Rs;

impedence

Zs=sqrt(R-s.^{2}+Xs.^{2});

Isc=v./Zs;

Pf-sc=R-s./Zs;

fy-sc=cos(Pf-sc).*180./pi;

Total-loss=copperloss-stator+Pcu-total+No-Load-Loss;

P123=P+Total-loss;

Efficiency=(P./(P+Total-loss)).*100;

ph=3;

qr=Sr./(ph.*p);

temperature rise

Pcu-slotportion=(2.*L.*copper loss-stator)./Lmt;

P1=Pcu-slotportion+Ironloss-T;

D12=($pi. * D0. * 10.^3 * L$);

C=input('enter the value of cooling coefficient:');

T12=(D12./C);

D13=(pi.*D.*L);

Va=(pi.*D.*(N./60));

C=0.04./(1+(0.1.*Va));

T13=(D13./C);

Surface-twoends=(pi./2).*((D0.*10.$^-$3.-D.^{2});

Velocity-air=0.1.*Va;

C=(0.15./Velocity-air);

T14=(Surface-two ends)./C;

Totalloss-dissipated=T12+T13+T14;

Temperature-rise=(P1./Total-loss).*100;

disp('design sheet'); fprintf('full load output(watt) :P :=¿%f ',P); fprintf('Line voltage :V :=¿%f ',v); fprintf('Frequency :F :=¿%f ',f); fprintf('phases :ph :=¿%f ',ph); fprintf('efficincy :n :=¿%f ',Efficiency);

fprintf('power factor :pf :=¿%f ',pf);

fprintf('number of poles :P :=¿%f ',p);

fprintf('synchronous speed(rpm) :N :=¿%f ',N);

fprintf('KVA input :Q :=¿%f ',Q);

fprintf('full load line current :Iline:=¿%f ',Iline);

disp('specific loading');

fprintf('specific magnetic loading :Bav :=¿ %f ',Bav);

fprintf('specific electical loading :ac :=¿ %f ', ac);

fprintf('output co-efficient : C0 :=¿ %f ',c0);

disp('main dimensions');

fprintf('staor bore :D:=¿ %f ',D);

fprintf('gross iron length :L:=¿ %f ',L);

if(L¿0.125)

fprintf('no. of ducts :nd:=¿ %f ',nd);

end

fprintf('net iron length :Li:=¿ %f ',Li);

fprintf('pole pitch :T :=¿ %f ',T);

disp('stator parameters')

fprintf('phase voltage : Es :=¿ %f ',v);

fprintf('flux per pole : fym :=¿ %f ',fym);

fprintf('turns per phase :Ts :=¿ %f ',Ts);

fprintf('number of slots :Ss :=¿ %f ',Ss);

fprintf('slots per pole per phase :qs :=¿ %f ',qs);

fprintf('coil span : Cs :=¿ %f ',Cs);

fprintf('distribution factor :Kd :=¿ %f ',Kd);

fprintf('pitch factor : Kp :=¿ %f ',Kp);

fprintf('winding factor :kw :=¿ %f ',kw);

fprintf('slot pitch :yss:=¿ %f ', yss);

fprintf('conductor per slot :Zss:=¿ %f ',Zss);

fprintf('conductor :bare diameter :=¿ %f ',d);

fprintf('conductor :area:=¿ %f ',as);

fprintf('current :density :=¿ %f ',delta);

fprintf('length of mean turn :Lmt :=¿ %f ',Lmt);

fprintf('resistance : R :=¿ %f ',Rs);

fprintf('copper loss at full load :$3Is^2Rs$:=¿ %f ',copperloss-stator);

fprintf('depth of stator core : dcs :=¿ %f ',dcs);

fprintf('outer diameter of stator laminations :Dc :=¿ %f ',D0);

disp('rotor parameter');

fprintf('length of air gap : lg :=¿ %f ',lg);

fprintf('diameter of rotor : Dr :=¿ %f ',Dr);

fprintf('number of slots :Sr:=¿ %f ',Sr);

fprintf('slots per pole per phase :qr:=¿ %f ',qr);

fprintf('conductors per phase :sr :=¿ %f ',1);

fprintf('winding factor :Kw :=¿ %f ',1);

fprintf('slot pitch :ysr:=¿ %f ', ysr);

fprintf('rotor bar current : Ib :=¿ %f ',Ib);

fprintf('rotor bars: cross section :=¿ %f ',7*6.5);

fprintf('rotor bar :area :=¿ %f ',44.6);

fprintf('rotor bar :length :=¿ %f ',Lb);

fprintf('rotor bar: current density :=¿ %f ',density);

fprintf('resistance of each bar :Rb :=¿ %f ',Rb);

fprintf('copper loss in bars :SrIb^{2}Rb :=¿ %f ',Pcu-bars);

fprintf('end ring current :Ie:=¿ %f ',Ie);

fprintf('end ring :cross section :=¿ %f ',10*8);

fprintf('end ring :area :=¿ %f ; ae);

fprintf('end ring :mean diameter :=¿ %f ',Dmean-e);

fprintf('end rinf :current density : :=¿ %f ',dens-end ring);

fprintf('resistance of each ring : Re :=¿ %f ',Re);

fprintf('copper losses in each ring :2Ie^{2}Re :=¿ %f ', Pcu-end ring);

fprintf('total rotor copper loss : Pcu-loss :=¿ %f ',Pcu-total);

fprintf('resistance of rotor refereed to stator : Rrs :=¿ %f ', Rr-s);

fprintf('depth of rotor core :dcr :=¿ %f ',Dcr);

disp('short circuit current');

fprintf('magnetizing mmf per pole : :=¿ %f ',AT-T);

```
fprintf('Phase magnetizing current :Im :=¿ %f ',Im );
fprintf('core losses : :=¿ %f ',Iron loss-T );
fprintf('Friction and windage loss : :=¿ %f ',F-W-Loss );
fprintf('loss component :Il :=¿ %f ', Il);
fprintf('no load current(phase) :Im :=¿ %f ',Im );
fprintf('no load power factor :cos(fy):=¿%f ',fy-sc );

    disp('performance of machine');
disp('AT full load');
fprintf('losses :P-Losses :=¿ %f ',Total-loss );
fprintf('output : output :=¿ %f ',P );
fprintf('input : input :=¿ %f ', P123);
fprintf('efficiency :n :=¿ %f ', Efficiency);
fprintf('power factor :pf :=¿ %f ', pf);
fprintf('temperature rise:Temperature-rise:=¿ %f ', Temperature-rise);
```

Appendix B

Motor design software MATLAB

B.1 energy-efficient motor design

```
close all
clear all
KWa=[0.75,2.2,3.7,7.5,15,25];
na=[0.75,0.75,0.81,0.82,0.85,0.89];
pfa=[0.75,0.82,0.84,0.87,0.89,0.9];
nma=[375,600,750,1000,1500,3000];

aea=[10,20,30,40,50,60,70,80,90,100,110,120,130,140,150,160,170,180,190,200,210,220,230,
240,250,260,270,280,290,300];

dea=[5,5,6,10,10,10,10,10,10,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30];

da=[0.05,0.06,0.071,0.08,0.09,0.1,0.112,0.125,0.132,0.14,0.15,0.16,0.17,0.18,0.195,0.2,0.212,
0.224,0.236,0.250,258,0.265,0.28,0.3,0.307,0.315,0.335,0.355,0.375,0.4,0.425,0.462,0.5,0.53,
0.56,0.6,0.63,0.67,0.71,0.73,0.75,0.8,0.85,0.925,0.95,1.0,1.06,1.12,1.18,1.25,1.32,1.4,1.5,1.6,
1.7,1.8,1.9,2.0,2.12,2.24,2.36,2.5,2.65,2.8,2.9,3.0,3.15,3.25,3.35,3.45,3.55,3.65,3.75,4.0];
```

dla=[0.065,0.078,0.092,0.105,0.115,0.128,0.143,0.159,0.168,0.176,0.186,0.198,0.211,0.223,
0.239,
0.246,0.258,0.272,0.284,0.301,0.309,0.317,0.334,0.54,0.362,0.372,0.393,0.415,0.438
,0.465,0.493,0.531,0.546,0.571,0.602,0.635,0.677,0.707,0.75,0.791,0.811,0.831,0.884,0.935,
1.016,1.041,1.095,1.155,1.215,1.278,1.35,1.42,1.505,1.605,1.71,1.81,1.915,2.015,2.18,
2.241,2.365,2.488,2.63,2.785,2.935,3.04,3.14,3.295,3.395,3.497,3.6,3.7,3.8,3.902,4.155];

aba=[20.1,20.5,20.6,20.7,20.8,21.1,21.3,21.4,21.5,21.6,21.8,21.9,22.0,22.1,22.2,22.5,23.1,23.2,
23.5,23.6,23.7,23.8,23.9,24.0,24.1,1,24.4,24.5,24.7,24.9,25.0,25.5,25.2,25.3,25.4,25.5,25.8,25.9,
26.1,26.2,26.3,26.5,26.6,26.7,26.9,27.0,27.1,27.6,31.7,32.0,32.1,32.5,32.7,32.9,33.1,33.7,33.9,34.1,
34.3,34.5,34.7,34.8,34.9,35.5,39.6,39.7,40.4,40.7,41.1,41.4,41.5,42.2,43.1,43.5,43.9,44.1,44.3,
44.5,44.6,44.7,47.1,47.2,47.5,47.9,48.1,48.6,49.1,49.5,49.9,50.3,51.1,51.6,53.1,53.5,54.1,54.5,
55.1,55.4,55.5,56.7,57.6,59.1,59.5,59.6,61.1,62.0,62.1,63.1,64.1,64.6,65.1,65.5,66.6,69.1,69.5,70.6,
71.1,74.1,74.5,74.5,76.1,77.1,79.1,80.1,81.6,83.1,83.6,86.6,87.1,89.1,90.1,95.1,96.5,96.6,97.1,
98.1,99.1,103,104,107,109,111,112,116,119,120,124,125,127,129,131,134,137,139,142,143,145,149,
153,159,161,164,174,175,179,187,197,199,219,224];

dsra=[6,7,11,14,15,5.5,12,18,7,5,13,6.5,7.5,14,15,12,6,18,8,7,11,20,5.5,22,5,13,10,8,14,18,6.5,15,
16,7.5,13,20,12,6,22,14,9,22,14,9,5.5,15,16,11,7,10,20,9,13,15,6.5,16,6,5.5,10,20,16,18,22,8,16,
6.5,20,13,7.5,15,22,25,12,7,20,6.5,13,14,8,22,16,9,25,7.5,13,7,6.5,14,25,8,20,14,7.5,16,15,7,
25,8,25,16,7.5,7,9,10,20,18,16,8,7.5,12,18,10,22,8,7.5,20,18,13,8,20,11,22,25,14,8,10,10,11,
22,9,20,22,13,12,10,25,11,12,10,18,11,12,13,25,11,10,13,12,15,13,14,11,10,13,14,12,20,14,15,
13,12,22,25,14,16,13,22,14,22,18,16,15,22,16,18,25,22,18,25,22,25,22,25,25];

Wsra=[3.5,3.0,1.9,1.5,1.4,4.0,1.8,1.2,3.2,4.5,1.7,3.5,3.0,1.6,1.5,1.9,4.0,1.3,3.0,3.5,2.2,1.2,
4.5,1.1,5.0,1.9,2.5,3.2,1.8,1.4,4.0,1.7,1.6,3.5,2.0,1.3,2.2,4.5,1.2,1.9,3.0,5.0,1.8,1.7,2.5,
4.0,2.8,1.4,3.2,2.2,1.9,4.5,1.8,5.0,3.0,1.5,1.9,1.7,1.4,4.0,2.0,5.0,1.6,2.5,5.5,3.0,1.5,4.5,
2.8,1.7,1.9,5.0,3.2,2.5,2.2,1.4,5.5,6.0,3.0,1.8,2.8,5.0,2.5,5.5,3.0,1.5,4.5,2.8,1.7,1.9,5.0,

```
3.2,2.5,2.2,2.1,1.4,5.5,6.0,3.0,1.8,2.8,5.0,2.5,1.7,1.5,3.2,5.5,1.9,6.0,3.0,2.8,5.0,1.8,2.5,
4.5,1.6,5.5,3.2,6.0,6.5,3.0,1.7,5.5,2.2,3.2,6.0,8.0,3.0,6.5,1.8,6.0,1.9,3.0,6.5,7.0,5.5,5.0,
2.5,2.8,3.2,6.5,7.0,4.5,3.0,5.5,2.5,7.0,7.5,2.8,3.2,4.5,7.5,3.0,5.5,2.8,2.5,4.5,8.0,6.5,7.0,
6.0,3.0,7.5,3.5,3.2,5.5,6.0,7.5,3.0,7.0,6.5,8.0,4.5,7.5,7.0,6.5,3.5,8.0,9.0,7.0,8.0,6.5,7.5,
7.0,7.5,7.0,9.0,10.0,8.0,7.5,9.0,10.0,8.0,7.5,9.0,5.5,8.0,7.5,9.0,10.0,5.5,5.0,9.0,8.0,10.0
6.0,9.0,5.5,10.0,6.5,8.0,9.0,10.0,9.0,6.5,7.5,7.0,8.0,10.0,7.5,9.0,8.0,10.0,9.0,10.0];
dels1=4;
dele1=5;
delb1=6;
kw=0.955;
Sf=0.9;
qs=2;
sg=(3.14/3);
spf=0.4;
Bcs=1.2;
qb=0.021;
qe=0.021;
h2s=0;
W0s=2;
W0r=1.5;
Wd=1;
h3s=3;
h4s=1;
h3r=1;
W0r=1.5;
h4r=1;
kwr=1;
ms=3;
W0s=2;
```

```
h2r=0;
**************main program***************
fprintf ('\t\t−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−
−−−−−−−−−−−−−−−−−−');
fprintf ('\n\t\tthedesignof3−phinductionmotor');
fprintf ('\nenterthespecificationsof3−phinductionmotor');
fprintf ('\n\t−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−
−−−−−−−−−−−−−−−−');
p=input('enter output power P in kw');
while p¿25
clc
warning on;
warning('enter the value of power rating 25 kw');
p=input('enter again');
end
warning off;
f=50;
fprintf('enterthefrequencyf : 50hz\n');
v=input('enter the rated voltage V in volt:');
while v¿12000
clc
warning on;
warning('enter the value 12000 volts:');
v=input('enter again');
end
warning off
n=1;
o=1;
for m=1:6
```

```
if p¡=KWa(m)
eff=na(n);
n=n+1;
pf=pfa(o);
o=o+1;
break
else
continue
end
end
wdg=input('type of stator winding connection-star/delta: ','s');
wdg1=strcmp(wdg,'star');
xxx=999;
while xxx¡999
if wdg1==1
xxx=999;
u=v/sqrt(3);
Isp=(p*1000)/(3*v*pf*eff);
Isl=Isl*sqrt(3);
break
else
wdg=input('illegal selection-enter proper type again','s');
wdg1=strcmp(wdg,'star');
end
end
nm=input('enter the rated speed of motor(in rpm)');
while nm¿=1500
clc
warning on;
```

```
warning('re enter the speed nm¡1500:');
fprintf('\n');
nm=input('speed of motor(in rpm):');
end
for l=1:7
if nm¡=nma(l)
ns=nma(l);
break;
else
continue;
end
end
po=(120*f)/ns;
Bav=0.3+(0.1744*pf);
ac=10000+(27.5*u);
c0=11*kw*Bav*av*10^-3;
Q=p/(pf*eff);
Slip=((ns-nm)*100)/ns;
fprintf('select the type of machine you want to design:');
fprintf('\n\tselect"c"forminimumcost');
fprintf('\n\tselect"p"forgoodpowerfactor');
fprintf('\n\tselect"e"foegoodefficiency');
fprintf('\n\tselect"o"forgoodoveralldesign');
typ=input('enter the number according to requirement:','s');
while(typ ='c')&(typ ='p')&(typ ='e')&(typ ='o')
typ=input('enter the type according to requirement:','s');
end
switch lower(typ)
case('c')
```

if(p¡=7.5)

LT=1.5;

else

LT=1.9;

end

case('p')

LT=1.15;

case('e')

LT=1.5;

case('o')

LT=1.0;

end

Bst=2;

while(Bst¿1.7)

Va=31;

while Va¿30

LT=LT+0.1;

temp=(Q*po*60)/(3.14*LT*c0*ns);

D=$temp^{0.333}$;

L=3.14*D*LT/po;

T=(3.14*D)/po;

Va=(3.14*D*ns)/60;

end

if (Va¡=30)&(L¡0.125)

Nd=0;

end

clc;

fprintf('the design data sheet of 3-ph induction motor');

fprintf('rating');

fprintf('kW $fprintf('numberofpoles$fprintf('synchronous speed $fprintf('kvainput$fprintf('full load line current $fprintf('loading');$

$fprintf('specificmagneticloading$fprintf('specific electric loading $fprintf('outputco-efficient$fprintf('press "p" to proceed','s');

fprintf('\n');

zzz=input('press "p" to proceed','s');

fprintf('\n');

fprintf('main dimensions');

fprintf(' diameter D $fprintf('lengthL$Nd=(1+((L-0.126)/0.07));

Li=Sf*(L-(Nd*0.01));

fprintf('number of ducts Nd $fprintf('netironlengthLi$fprintf('pole pitch Tau $Phi = (Bav * 3.14 * L * D)/p0;$

$fprintf('statordesign');$

$fprintf('typeoflamination : 0.5mmthickloys');$

$fprintf('typeofwinding : singlelayermush');$

$fprintf('typeofslot : taperedslot');$

$fprintf('fluxperpole$Ts=u/(4.44*f*Phi*kw);

yss=(3.14*D*1000)/Ss;

Zs=6*Ts;

Zss=Zs/Ss;

if mod(Zss,2) =0

Zss=+1;

Zs=Zss*Ss;

end// fprintf('stator turns per phjase Ts $fprintf('totalstatorslots$fprintf('stator slot pitch yss $fprintf('totalstatorconductorsZs$pp=Ss/p0;

Cs=Ss/p0;

if mod(Cs,2)==0

Cs=Cs-1;

al=3.14/(Cs+1);

fprintf('angle of chording al $fprintf('coilspan$else

if mod(Cs,2) =0

al=0;

end

end

kp=cos(al/2);

kd=sin(sg/2)/(qs*sin((sg/(2*qs))));

kws=kp*kd;

fprintf('pitch factor kp $fprintf('distributionfactor$fprintf('stator winding factor kws

$fprintf('press"p"toproceed','s');$

$fprintf('conductorsize');$

$fprintf('statorcurrentperphaseIsp$fprintf('stator line current Isl $as1 = Isp/dels1;$

$dc = sqrt((4 * as1)/3.14);$

$y = 1;$

$forx = 1 : 75$

$ifdc <= da(x)$

$d = da(x);$

$d1 = d1a(y);$

$y = y + 1;$

$else$

$continue$

end

end

$as = (3.14 * d * d)/4;$

$dels = Isp/as;$

$fprintf('areaofstatorconductor$fprintf('current density for stator conductor dels %f',dels);

fprintf('diameter of bare conductor %f',d);

fprintf('diameter of enameled conductor %f',d1);

zzz=input('press "p" to proceed','s');

```
fprintf('slot dimensions');
As=Zss*as;
As1=As/spf;
fprintf('area of each slot %f',Asl);
Wts-min(Phi*po)/(1.7*Ss*Li);
fprintf('minimum width of stator teeth Wts-min %f',Wts-min);
Wts-max=Wts-min+0.0025;
fprintf('tooth constant width Wts-max %f',Wts-max);
W2s=(3.14*(D+0.008))/Ss-(Wts-max);
temp1=W2s*Ss;

   temp2=temp1^2.0;
temp3=(4*As1*Ss*3.14)/1000000;
temp4=temp2+temp3;
W1s=W2s;
temp5=W1s*Ss;
h1s=(sqrt(temp4)-temp5)/(2*3.14);
W3s=W2s+(3.14*2*h1s)/Ss;
dss=h1s+0.004;
fprintf('depth of slot dss %f',dss);
Lmt=(2*L)+(2.3*T)+0.24;
fprintf('length of mean turn Lmt %f',Lmt);
Bst=(Phi*po)/(Ss*Wts-max*Li);
if Bst¡=1.7
break
end
end
zzz=input('press "p" to proceed','s');
fprintf('stator teeth');
```

fprintf('flux density in stator teeth Bst $fprintf('statorcore');$

$Phisc = Phi/2;$

$fprintf('fluxinstatorcore$Ascc=Phisc/Bcs;

dscc=ceil((Acss*1000)/Li);

dcs=dscc/1000;

fprintf('depth of stator core dca $Acs = dcs * Li;$

$fprintf('areaofstatorcoreAcs$Bcs=Phisc/Acs;

fprintf('flux density in stator core Bcs$D0 = (D * 1000) + (2 * dss) + (2 * dcs * 1000);$

$fprintf('outerdiameterofstatorlaminationsD0$lg=0.2+(2*sqrt(D*L));

if lg¿=0.39

lg=0.3;

end

zzz=input($'press"p"toproceed','s');$

fprintf(' rotor design');

fprintf(' air gap');

fprintf('length of air gap lg=$Dr = (D * 1000) - (2 * lg);$

$printf('diameterofrotorDr$fprintf('rotor slots');

Sr=Ss-po/2;

qr=Sr/(3*po);

fprintf('number of rotor slots Sr $ysr = (3.14 * Dr)/Sr;$

$fprintf('rotorslotpitchatairgapysr$Ib=(2*3*kws*Ts*Isp*pf)/Sr;

fprintf('rotor bars');

fprintf('rotor bar current Ib $abc = Ib/delb1;$

$Bt1 = 2;$

$while(Bt1 > 1.7)$

$s = 1;$

$t = 1;$

$forr = 1 : 202$

$ifabc <= aba(r)$

$ab = aba(r);$

$dsr = dsra(s);$

$s = s + 1;$

$Wsr = Wsra(t);$

$t = t + 1;$

$if((dsr/Wsr) > 5)$

$continue$

$else$

$break$

end

end

end

$delb = Ib/ab;$

$fprintf('areaofrotorbarab$fprintf('current density for rotor bars delb $h1r = dsr;$

$Wsr = Wsr + 0.3;$

$dsr = dsr + 2.3;$

$W3r = Wsr;$

$fprintf('widthofrotorslotWsr$fprintf('depth f rotor slot dsr $ysr = (3.14 * (Dr - 2 * dsr))/Sr;$

$fprintf('slotpitchatthebottomofslotsybr$Wt=ybr-Wsr;

fprintf('tooth width at the rotor Wt $ifBt1 <= 1.7$

$break$

$end//end$

$Lb = (L * 1000) + (2 * 15) + 10;$

$fprintf('lengthofeachbarLb$rb=(qb*Lb)/(ab*1000);

fprintf('resistance of each bar rb $Prbcu = Sr * Ib * Ib * rb;$

$fprintf('totalcopperlossinbarsPrbcu$Ie=(Sr*Ib)/(3.14*po);

fprintf('end ring');

fprintf('end ring current Ie $aec = Ie/dele1;$

$forxy = 1 : 30$

$ifaec <= aea(xy)$

$ae = aea(xy);$

$de = dea(yz);$

$break$

end

end

$dele = Ie/ae;$

$te = ae/de;$

$fprintf('currentdensityinendring$fprintf('depth of end ring de $fprintf('thicknessofendringte$D

(2*dsr);

fprintf('outer diameter of end ring De0 $Dei = De0 - (2 * de);$

$fprintf('innerdiameterofendringDei$De=(De0+Dei)/2;

fprintf('mean diameter of end ring De $re = (qe * 3.14 * De)/(a * 1000);$

$fprintf('resistanceofeachringre$Pecu=2*Ie*re;

fprintf('copper loss in two end ring Pecu $Pcu = Prbcu + Pecu;$

$fprintf('totalrotorcopperlossPcu$Bcr=Bcs;

dcr=Phi*1000/(2*Bcr*Li);

zzz=input('press "p" to proceed','s');

fprintf('rotor core');

fprintf('depth of rotor core dcr $Dri = Dr - (2 * (dsr + dcr));$

$fprintf('innerdiameterofrotorlaminationDri$