Induction Motors

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INDUCTION MOTOR-DESIGN

- INTRODUCTION
- CONSTRUCTION
- MOTOR SPEED
- SLIP
- IM & TRANSFORMER
- FREQUENCY
- TORQUE
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- DESIGN OF IM

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EMD-II- Induction Motor Design
VIII Sem Electrical
Introduction

Three-phase induction motors are the most common and frequently encountered machines in industry

- simple design, rugged, low-price, easy maintenance
- wide range of power ratings: fractional horsepower to 10 MW
- run essentially as constant speed from no-load to full load

Its speed depends on the frequency of the power source
- not easy to have variable speed control
- requires a variable-frequency power-electronic drive for optimal speed control
CONSTRUCTIONAL DETAILS OF IM
An induction motor has two main parts:
- A stationary stator
  - consisting of a steel frame that supports a hollow, cylindrical core
  - core, constructed from stacked laminations having a number of evenly spaced slots, providing the space for the stator winding

Stator of IM
Construction

+a revolving rotor

- composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding
- one of two types of rotor windings
- conventional 3-phase windings made of insulated wire (wound-rotor) » similar to the winding on the stator
- aluminum bus bars shorted together at the ends by two aluminum rings, forming a squirrel-cage shaped circuit (squirrel-cage)

Two basic design types depending on the rotor design

+ squirrel-cage: conducting bars laid into slots and shorted at both ends by shorting rings.

+ wound-rotor: complete set of three-phase windings exactly as the stator. Usually Y-connected, the ends of the three rotor wires are connected to 3 slip rings on the rotor shaft. In this way, the rotor circuit is accessible.
Construction

Squirrel cage rotor

Wound rotor

Notice the slip rings
Construction

Cutaway in a typical wound-rotor IM. Notice the brushes and the slip rings.

- Slip rings
- Brushes
- Stator Lamination
- Stator core with smooth yoke
- Stator with ribbed yoke

- Squirrel cage rotor
- Slip ring rotor
Induction motor speed

At what speed will the IM run?

Can the IM run at the synchronous speed, why?

If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed.

When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced.
Induction motor speed

So, the IM will always run at a speed lower than the synchronous speed

The difference between the motor speed and the synchronous speed is called the Slip

\[ n_{\text{slip}} = n_{\text{sync}} - n_m \]

Where \( n_{\text{slip}} \) = slip speed
\( n_{\text{sync}} \) = speed of the magnetic field
\( n_m \) = mechanical shaft speed of the motor
The Slip

Where \( s \) is the *slip*

Notice that: if the rotor runs at synchronous speed

\[
s = 0
\]

if the rotor is stationary

\[
s = 1
\]

Slip may be expressed as a *percentage* by multiplying the above eq. by 100, notice that the slip is a ratio and doesn’t have units
Induction Motors and Transformers

✗ Both IM and transformer works on the principle of induced voltage

✚ Transformer: voltage applied to the primary windings produce an induced voltage in the secondary windings

✚ Induction motor: voltage applied to the stator windings produce an induced voltage in the rotor windings

✚ The difference is that, in the case of the induction motor, the secondary windings can move

✚ Due to the rotation of the rotor (the secondary winding of the IM), the induced voltage in it does not have the same frequency of the stator (the primary) voltage
Frequency

- The frequency of the voltage induced in the rotor is given by

\[ f_r = \frac{P \times n}{120} \]

Where \( f_r \) = the rotor frequency (Hz)

\[ P = \text{number of stator poles} \]

\[ n = \text{slip speed (rpm)} \]

\[ f_r = \frac{P \times (n_s - n_m)}{120} \]

\[ = \frac{P \times s n_s}{120} = s f_e \]
What would be the frequency of the rotor’s induced voltage at any speed $n_m$?

When the rotor is blocked ($s=1$), the frequency of the induced voltage is equal to the supply frequency.

On the other hand, if the rotor runs at synchronous speed ($s = 0$), the frequency will be zero.

$$f_r = s f_e$$
Torque

While the input to the induction motor is electrical power, its output is mechanical power and for that we should know some terms and quantities related to mechanical power.

Any mechanical load applied to the motor shaft will introduce a Torque on the motor shaft. This torque is related to the motor output power and the rotor speed.

\[
\tau_{load} = \frac{P_{out}}{\omega_m} \quad \text{N.m}
\]

and

\[
\omega_m = \frac{2\pi n_m}{60} \quad \text{rad/s}
\]
Horse power

• Another unit used to measure mechanical power is the horse power
• It is used to refer to the mechanical output power of the motor
• Since we, as an electrical engineers, deal with watts as a unit to measure electrical power, there is a relation between horse power and watts

\[ hp = 746 \text{ watts} \]
Power losses in Induction machines

• Copper losses
  – Copper loss in the stator \( (P_{SCl}) = I_1^2R_1 \)
  – Copper loss in the rotor \( (P_{RCl}) = I_2^2R_2 \)

• Core loss \( (P_{core}) \)

• Mechanical power loss due to friction and windage

• How this power flow in the motor?
VARIOUS LOSSES IN IM
Power flow in induction motor

\[ P_{in} = \sqrt{3} V_T I_L \cos \theta \]

\[ P_{AG} \quad P_{conv} \]

Air-gap power

\[ \tau_{ind} \omega_m \]

\[ P_{out} = \tau_{load} \omega_m \]

- \( P_{SCL} \) (Stator copper loss)
- \( P_{core} \) (Core losses)
- \( P_{RCL} \) (Rotor copper loss)
- \( P_{friction and windage} \)
- \( P_{stray} \) (\( P_{misc.} \))
Power relations

\[ P_{in} = \sqrt{3} V_L I_L \cos \theta = 3 V_{ph} I_{ph} \cos \theta \]

\[ P_{SCL} = 3 I_1^2 R_1 \]

\[ P_{AG} = P_{in} - \left( P_{SCL} + P_{core} \right) \]

\[ P_{RCL} = 3 I_2^2 R_2 \]

\[ P_{conv} = P_{AG} - P_{RCL} \]

\[ P_{out} = P_{conv} - \left( P_{f+w} + P_{stray} \right) \]

\[ \tau_{ind} = \frac{P_{conv}}{\omega m} \]
Power relations

\[ P_{in} = \sqrt{3} V_L I_L \cos \theta = 3 V_{ph} I_{ph} \cos \theta \]

\[ P_{SCL} = 3 I_1^2 R_1 \]

\[ P_{AG} = P_{in} - (P_{SCL} + P_{core}) = P_{conv} + P_{RCL} = 3I_2^2 \frac{R_2}{S} = \frac{P_{RCL}}{S} \]

\[ P_{RCL} = 3I_2^2 R_2 \]

\[ P_{conv} = P_{AG} - P_{RCL} = 3I_2^2 \frac{R_2(1-s)}{S} = \frac{P_{RCL}(1-s)}{S} \]

\[ P_{conv} = (1-s)P_{AG} \]

\[ P_{out} = P_{conv} - (P_{f+w} + P_{stray}) \]

\[ \tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{(1-s)P_{AG}}{(1-s)\omega_s} \]
Power relations

\[ P_{AG} : P_{RCL} : P_{conv} = 1 : s : 1-s \]

\[ P_{AG} \rightarrow P_{RCL} \rightarrow P_{conv} \]

1 - s
Torque-speed characteristics

Starting torque

Pullout torque

Full-load torque

Typical torque-speed characteristics of induction motor
Variation of torque and stator current with slip
Performance characteristics
DESIGN OF INDUCTION MOTOR
INDUCTION MOTOR DESIGN

• Dimensions of a machine depend on
  • Torque at a specific speed
  • How intensively the magnetic circuit is used.
  • How intensively the electric circuit is used
  • The type of enclosure
  • Type of cooling
  • The duty cycle of the load
  • The frequency of starting and stopping
PURPOSE OF DESIGNING IM

• The main purpose of designing an induction motor is
• to obtain the complete physical dimensions of all the parts of the machine as mentioned below to satisfy the customer specifications.
• The following design details are required.
• 1. The main dimensions of the stator.
• 2. Details of stator windings.
• 3. Design details of rotor and its windings
• 4. Performance characteristics.
• In order to get the above design details the designer needs the customer specifications
• Rated out put power, rated voltage, number of phases, speed, frequency, connection of stator winding, type of rotor winding, working conditions, shaft extension details etc.
• In addition to the above the designer must have the details regarding design equations based on which the design procedure is initiated, information regarding the various choice of various
• parameters, information regarding the availability of different materials and the limiting values
• of various performance parameters such as iron and copper losses, no load current, power
• factor, temperature rise and efficiency
Output Equation of AC motor

- Let $Q = \text{KVA rating of motor}$
- $E_{ph} = \text{Output voltage per phase}$
- $I_{ph} = \text{Current per phase}$
- $f = \text{Supply Frequency}$
- $\Phi = \text{Flux per pole in Weber}$
- $T_{ph} = \text{Turns per phase}$
- $K_w = \text{Winding factor}$
- $p = \text{No. of poles}$
- $n_s = \text{Synchronous speed}$
- $D = \textbf{Stator Diameter}$
- $L = \text{Core length}$
- $B_{av} = \text{Specific Magnetic loading}$
- $a_c = \text{Specific Electric loading}$
- $I_s = \text{Current in each conductor}$
- $Z = \text{Total armature conductors}$
- $Z_{ss} = \text{Armature conductors per slot}$
- $m = \text{No. of phases}$
- $C_0 = \text{Output Coefficient}$
Consider an m phase motor having one circuit per phase.

- KVA rating of motor

- \( Q = \text{number of phases} \times \text{output voltage per phase} \times \text{current per phase} \times 10^{-3} \)

- \( Q = m \times \text{Eph} \times \text{Iph} \times 10^{-3} \) [1.1]

- Terminal voltage of each phase may be taken equal to the induced emf per phase,

- We have, Induced emf per phase

- \( \text{Eph} = 4.44 f \Phi \text{Tph} \text{Kw} \) [1.2]

- \( \ldots \) .

- \( Q = m \times 4.44 f \Phi \text{Tph} \text{Kw} \text{Iph} \times 10^{-3} \) [1.3]

- But \( f = \frac{\text{pns}}{2} \) [1.4]

- Therefore we can write,

- \( Q = m \times 4.44 \left( \frac{\text{pns}}{2} \right) \Phi \text{Tph} \text{Kw} \text{Iph} \times 10^{-3} \) [1.5]

- \( Q = 1.11 \text{Kw} (p\Phi) (2m \text{Iph} \text{Tph}) \text{ns} \times 10^{-3} \) [1.6]
• Now current in each conductor
• \( I_s = I_{ph} \) (As there is only one circuit per phase).
• Total number of armature conductors
• \( Z = \text{number of phases} \times (2 \text{ turns per phase}) = 2m \ T_{ph} \)
• \( \ldots \) Total electric loading \( (I_s \ Z) = 2m \ I_{ph} \ T_{ph} \)
• Hence, \( Q = 1.11 \text{ Kw (p}\Phi) (I_s \ Z) \text{ ns} \ 10^{-3} \ [1.7] \)
• \( = 1.11 \text{ Kw (total magnetic loading) (total electric loading) (synchronous speed} \ 10^{-3}) \)
• But \( p\Phi = \pi \ D L \ B_{av} \) and \( I_s \ Z = \pi \ D \ a_{c} \)
• Substituting these values in equation \([1.7]\),
• \( Q = 1.11 \text{ Kw (} \pi \ D L \ B_{av} \text{ ) (} \pi \ D \ a_{c} \text{ ) ns} \ 10^{-3} \)
• \( Q = (1.11\pi^2 \ B_{av} \ a_{c} \text{ Kw} \ 10^{-3} \ D^2 \ L \text{ ns} \)
• \( = (11 \ B_{av} \ a_{c} \text{ Kw} \ 10^{-3} \ D^2 \ L \text{ ns} [1.8] \)
• \( Q = C_0 \ D^2 \ L \text{ ns} [1.9] \)
• \( C_0 = 11 \ B_{av} \ a_{c} \text{ Kw} \ 10^{-3} [1.10] \)

• Equation \([1.10]\) is known as the output equation of an a.c. machine. Quantity \( C_0 \) is called the output coefficient
Choice of Specific loadings

- Specific Magnetic loading or Air gap flux density
- Iron losses largely depend upon air gap flux density
- Limitations:
  - Flux density in teeth < 1.8 Tesla
  - Flux density in core 1.3 – 1.5 Tesla
- Advantages of Higher value of Bav
  - Size of the machine reduced
  - Cost of the machine decreases
  - Overload capacity increases
- For 50 Hz machine, 0.35 – 0.6 Tesla. The suitable values of Bav can be selected from design data handbook.
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<th>$\frac{L}{D}$ max.</th>
<th>$\overline{B}$ Wb./m.²</th>
<th>$ac$ amp.-cond./m.</th>
<th>$\delta$ A./mm.²</th>
<th>$\overline{B}$ Wb./m.²</th>
<th>$ac$ amp.-cond./m.</th>
<th>$\delta$ A./mm.²</th>
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Specific Electric loading

• Total armature ampere conductor over the periphery
• Advantages of Higher value of q
  • Reduced size
  • Reduced cost
• Disadvantages of Higher value of q
  • Higher amount of copper
  • More copper losses
  • Increased temperature rise
  • Lower overload capacity
• Normal range 10000 ac/m – 450000 ac/m. The suitable values of q can be selected from design data hand book.
Choice of power factor and efficiency

• Choice of power factor and efficiency under full load conditions will increase with increase in rating of the machine. Percentage magnetizing current and losses will be lower for a larger machine than that of a smaller machine.

• Further the power factor and efficiency will be higher for a high speed machine than the same rated low speed machine because of better cooling conditions. Taking into considerations all these factors the above parameters will vary in a range based on the output of the machine. Similar to Bav and q, efficiency and power factor values can be selected from Design data hand book.
Separation of D and L

- The output equation gives the relation between D2L product and output of the machine.
- To separate D and L for this product a relation has to be assumed or established. Following are the various design considerations based on which a suitable ratio between gross length and pole pitch can be assumed.
  - i. To obtain minimum over all cost 1.5 to 2.0
  - ii. To obtain good efficiency 1.4 to 1.6
  - iii. To obtain good over all design 1.0 to 1.1
  - iv. To obtain good power factor 1.0 to 1.3
FOR BEST POWER FACTOR

• As power factor plays a very important role the performance of induction motors it is advisable to design an induction motor for best power factor unless specified. Hence to obtain the best power factor the following relation will be usually assumed for separation of D and L.

• Pole pitch/ Core length = 0.18/pole pitch
• or \((D/p) / L= 0.18/ (D/p)\)
• i.e \(D = 0.135PL\) where D and L are in meter.
• Using above relation D and L can be separated from \(D2L\) product.
• However the obtained values of D and L have to satisfy the condition imposed on the value of peripheral speed.
Peripheral Speed

• For the normal design of induction motors the calculated diameter of the motor should be such that the peripheral speed must be below 30 m/s.

• In case of specially designed rotor the peripheral speed can be 60 m/s.
Design of Stator

• Stator of an induction motor consists of stator core and stator slots.

• Stator slots: in general two types of stator slots are employed in induction motors viz, open Slots and semi closed slots.

• Operating performance of the induction motors depends upon the shape of the slots and hence it is important to select suitable slot for the stator slots.
Open slots:

• In this type of slots the slot opening will be equal to that of the width of the slots. In such type of slots assembly and repair of winding are easy. However such slots will lead to higher air gap contraction factor and hence poor power factor. Hence these types of slots are rarely used in 3 induction motors.
Semi closed Slots

• In such type of slots, slot opening is much smaller than the width of the slot. Hence in this type of slots assembly of windings is more difficult and takes more time compared to open slots and hence it is costlier.

• However the air gap characteristics are better compared to open type slots.
Tapered slots

• In this type of slots also, opening will be much smaller than the slot width.
• However the slot width will be varying from top of the slot to bottom of the slot with minimum width at the bottom.
Selection of number of stator slots

- Number of stator slots must be properly selected at the design stage as such this number affects the weight, cost and operating characteristics of the motor.

- Though there are no rules for selecting the number of stator slots considering the advantages and disadvantages of selecting higher number slots comprise has to be set for selecting the number of slots.
Following are the advantages and disadvantages of selecting higher number of slots.

- **Advantages:**
  - (i) Reduced leakage reactance.
  - (ii) Reduced tooth pulsation losses.
  - (iii) Higher overload capacity.

- **Disadvantages:**
  - (i) Increased cost
  - (ii) Increased weight
  - (iii) Increased magnetizing current
  - (iv) Increased iron losses
  - (v) Poor cooling
  - (vi) Increased temperature rise
  - (vii) Reduction in efficiency
Based on the above comprise is made and the number of slots/pole/phase may be selected as three or more for integral slot winding. However for fractional slot windings number of slots/pole/phase may be selected as 3.5. So selected number of slots should satisfy the consideration of stator slot pitch at the air gap surface, which should be between 1.5 to 2.5 cm. Stator slot pitch at the air gap surface = \( ss = \frac{D}{S_{ss}} \) where \( S_{ss} \) is the number of stator slots.

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EMD-II- Induction Motor Design
VIII Sem Electrical
Turns per phase

- EMF equation of an induction motor is given by
  \[ Eph = 4.44fTphkw \]
- Hence turns per phase can be obtained from emf equation
  \[ Tph = \frac{Eph}{4.44fkw} \]
- Generally the induced emf can be assumed to be equal to the applied voltage per phase
  - Flux/pole, \( B_{av} \times DL/P \),
- Winding factor \( kw \) may be assumed as 0.955 for full pitch distributed winding unless otherwise specified.
- Number conductors /phase, \( Z_{ph} = 2 \times Tph \), and hence Total number of stator conductors \( Z = 6 \)
- \( Tph \) and conductors /slot \( Z_s = Z/Ss \) or 6 \( Tph/Ss \), where \( Zs \) is an integer for single layer winding and even number for double layer winding.
Conductor cross section

Area of cross section of stator conductors can be estimated from the stator current per phase and suitably assumed value of current density for the stator windings.

- Sectional area of the stator conductor as \( A_s = \frac{I_s}{s} \) where \( s \) is the current density in stator windings
- Stator current per phase \( I_s = \frac{Q}{(3V_{ph} \cos)} \)
- A suitable value of current density has to be assumed considering the advantages and disadvantages.
Advantages & Disadvantages of higher value of current density

- Advantages of higher value of current density:
  - (i) reduction in cross section
  - (ii) reduction in weight
  - (iii) reduction in cost

- Disadvantages of higher value of current density:
  - (i) increase in resistance
  - (ii) increase in cu loss
  - (iii) increase in temperature rise
  - (iv) reduction in efficiency

Hence higher value is assumed for low voltage machines and small machines. Usual value of current density for stator windings is 3 to 5 amps.
Area of stator slot

• Slot area is occupied by the conductors and the insulation.

• Out of which almost more than 25% is the insulation. Once the number of conductors per slot is decided approximate area of the slot can be estimated.

• Slot space factor = Copper area in the slot / Area of each slot

• This slot space factor so obtained will be between 0.25 and 0.4.
Size of the slot

• Normally different types of slots are employed for carrying stator windings of induction motors. Generally full pitched double layer windings are employed for stator windings.

• For double layer windings the conductor per slot will be even.

• slot width should be so selected such that the flux density in tooth is between 1.6 to 1.8 Tesla.
Length of the mean Turn

• Length of the mean turn is calculated using an empirical formula $lmt = 2L + 2.3\ p + 0.24$
• where $L$ is the gross length of the stator
• and $p$ is pole pitch in meter.
Resistance of stator winding

- Resistance of the stator winding per phase is calculated using the formula
- \( R = \frac{0.021 \times l_{mt} \times T_{ph}}{a_s} \)
- where \( l_{mt} \) is in meter
- and \( a_s \) is in mm².
- Using so calculated resistance of stator winding copper losses in stator winding can be calculated as
- Total copper losses in stator winding = 3 \( (I_s)^2 \times R_s \)
AC winding design

• The windings used in rotating electrical machines can be classified as
  • Concentrated Windings
  • All the winding turns are wound together in series to form one multi-turn coil
  • All the turns have the same magnetic axis
  • Examples of concentrated winding are
    • – field windings for salient-pole synchronous machines
    • – D.C. machines
    • – Primary and secondary windings of a transformer
Distributed Windings

• All the winding turns are arranged in several full-pitch or fractional-pitch coils
• These coils are then housed in the slots spread around the air-gap periphery to form phase or commutator winding
• Examples of distributed winding are
  – Stator and rotor of induction machines
  – The armatures of both synchronous and D.C. machines
Closed Windings

• Armature windings, in general, are classified under two main heads, namely, CLOSED WINDINGS

• There is a closed path in the sense that if one starts from any point on the winding and traverses it, one again reaches the starting point from where one had started

• Used only for D.C. machines and A.C. commutator machines
Open Windings

• Open windings terminate at suitable number of slip-rings or terminals
• Used only for A.C. machines, like synchronous machines, induction machines, etc
Some of the terms common to armature windings

1. Conductor. A length of wire which takes active part in the energy-conversion process is called a conductor.
2. Turn. One turn consists of two conductors.
3. Coil. One coil may consist of any number of turns.
4. Coil-side. One coil with any number of turns has two coil-sides.

The number of conductors \((C)\) in any coil-side is equal to the number of turns \((N)\) in that coil.
EXAMPLES
EXAMPLE-1.

• Obtain the following design information for the stator of a 30 kW, 440 V, 3, 6 pole, 50 Hz delta connected, squirrel cage induction motor,

• (i) Main dimension of the stator, (ii) No. of turns/phase (iii) No. of stator slots, (iv) No. of conductors per slot.

• Assume suitable values for the missing design data.
SOLUTION TO EXAMPLE-1:

• Various missing data are assumed from referring to Design data Hand Book or tables in Text Book considering the size, economics and performance

• Specific Magnetic loading, Bav = 0.48 Tesla

• Specific Electric loading, q = 26000 ac/m

• Full load efficiency,  = 0.88

• Full load power factor cos = 0.86

• Winding factor Kw = 0.955
SOLUTION TO EXAMPLE-1:

• (i) Main dimensions

• We have from output equation:

• \( D2L = \frac{Q}{(Co \ ns)} \ m^3 \)

• \( Co = 11 \ Bav \ q \ Kw \ \cos x \ 10^{-3} \)

• \( = 11 \times 0.48 \times 26000 \times 0.955 \times 0.88 \times 0.86 \times 10^{-3} \)

• \( = 99.2 \)

• and \( ns = 16.67 \ \text{rps} \)

• \( D2L = \frac{30}{(99.2 \times 16.67)} \)

• \( = 0.0182 \ m^3 \)
SOLUTION TO EXAMPLE-1:

- Designing the m/c for bets power factor
  - \( D = 0.135PL \)
  - \( = 0.135 \times 6L \)
- Solving for \( D \) and \( L \)
  - \( D = 0.33 \text{ m} \) and \( L = 0.17 \text{ m} \)

- (ii) No. of stator turns
  - \( = (DL/p) \times B_{av} \times 0.48 = 0.141 \text{ wb} \)
- Assuming \( E_{ph} = V_{ph} = 440 \text{ volts} \) (Delta connected IM)

- \( T_{ph} = \frac{E_{ph}}{4.44fkw} = \frac{440}{(4.44 \times 50 \times 0.0141 \times 0.955)} \)
  - \( = 148 \)
SOLUTION TO EXAMPLE-1:

• (iii) No. of stator slots
• Assuming no of slot/pole/phase = 3
• Total no. of slots = 3 x 3 x 6 = 54

• (iv) No of conductors /slot
• Total no of conductors = 148 x 2 = 296
SOLUTION TO EXAMPLE-1:

• No. of conductors /slot = 296/54 = 5.5
• Assuming 76 conductors/ slot
• Total no. of conductors = 54 x 6 = 324
• Revised no. of turns/phase = 162
EXAMPLE-2 HW

• A 15 kW 440m volts 4 pole, 50 Hz, 3 phase induction motor is built with a stator bore of 0.25 m and a core length of 0.16 m. The specific electric loading is 23000 ac/m. Using data of this machine determine the core dimensions, number of slots and number of stator conductors for a 11kW, 460 volts, 6 pole, 50 Hz motor. Assume full load efficiency of 84 % and power factor of 0.82. The winding factor is 0.955.