Design of Electrical Systems

Induction Motor Design

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Induction Motor Design

OUTPUT EQUATION

We have to relate the output of the machine with its main dimensions. Let us use the following nomenclature:

E_{ph} = Induced EMF per phase in volts. (Induced EMF per phase = Applied Voltage per phase)

I_{ph} = Current per phase, A.

T_{ph} = No. of turns per phase.

ϕ = Flux per pole in the air gap.

P = Number of poles

K_w = Winding factor

B_{av} = Average value of flux density in the air-gap

ac = Ampere conductor per meter of the armature periphery

D = armature diameter or Stator bore dia, m.

L = Stator core length, in m

n_s = Synchronous speed in r.ps.

η = Full load Efficiency

Cos ϕ = Full load power factor

τ = Pole pitch = $\pi D/P$

The KVA rating of a three phase induction motor is given by

$$KVA = 3 \times E_{ph} \times I_{ph} \times 10^{-3}$$

or

$$KVA = 3 \times 4.44 \times K_w \times f\phi \times T_{ph} \times I_{ph} \times 10^{-3} \qquad (1)$$

SPECIFIC MAGNETIC LOADING (B_{AV})

It is defined as the average value of flux density over the whole surface of air gap in the machine.

$$B_{av} = \text{total flux in the air gap/area of flux path in the air gap}$$

$$= P\phi/\pi DL \qquad (2)$$

SPECIFIC ELECTRIC LOADING (AC)

It is defined as the rms ampere conductors per metre of armature periphery at the air gap surface.

ac = total armature ampere conductor/armature periphery at the air gap

$$= \frac{3x2xI_{ph}xT_{ph}}{\pi D} \tag{3}$$

Also, we know

$$f = n_s \frac{P}{2} \tag{4}$$

From (2) $\phi = B_{av}x\frac{\pi DL}{P}$

From (3) $I_{ph}xT_{ph}x\frac{acx\pi D}{3x2}$

Rewriting eq (1) and inserting the above values

$$\text{KVA} = 3x4.44xK_wxn_sx\frac{P}{2}xB_{av}x\frac{\pi DL}{P}x\frac{acx\pi D}{3x2}x10^{-3}$$

$$= 1.11x\pi^2K_wB_{av}(ac)(10^{-3})D^2Ln_s \tag{5}$$

$$= C_0D^2Ln_s \tag{6}$$

where $C_0 = 1.11\pi^2K_wB_{av}(ac)(10^{-3})$

Equation (5) or (6) is called as **output equation of an induction motor** and C_0 is called as output coefficient.

FACTORS AFFECTING SIZE OF MACHINE

We know that

$$KVA = C_0D^2Ln_s$$

or $$\frac{KVA}{C_0n_s} = D^2L$$

This equation shows that tor a machine of given rating in KVA, the size or volume of the active parts as given by D^2L depends upon two factors:

- the output coefficient C_0 and
- the speed n_s.

The higher the values of C_0 and n_s, the volume D^2L and therefore the size of the machine decreases. Most usually *speed* is the given specification. Thus to obtain smallest dimensions of the machine the output coefficient C_0 must be selected highest possible. Since C_0 is proportional to B_{av} and ac, we conclude that the size and hence the cost of the machine also decreases if higher values of B_{av} and ac are used. But is it possible to use highest possible values of B_{av} and ac? Now how much high values of B_{av} and ac could be used will obviously be decided by the designer by analysing their effect on important aspects like losses, efficiency, temperature rise, power factor etc. Therefore only such values of B_{av} and ac could be used which give the required specifications, performance characteristics coupled with maximum reliability, good efficiency and minimum cost.

CHOICE OF SP. MAGNETIC LOADING (B_{AV})

The choice of B_{av} directly influences the core loss and magnetising current and thus has an important effect on the power factor. Similarly the flux and therefore the flux-density determines the pull out torque.

- **Power-factor** Higher value of B_{av} means higher value of flux to pass through requiring large magnetising current. Since magnetising current is in quadrature with the applied voltage, the resulting power factor becomes very poor. Therefore from p.f. point of view a small value of B_{av} is selected. The value of B_{av} should be such that there is no saturation in any part of the magnetic circuit. Saturation demands large magnetising current and consequently poor p.f.
- **Core-loss** Both the parts of the core loss i.e. hysteresis and eddy current depends upon flux density. A high value of B_{av} means increased amount of core toss affecting the efficiency.
- **Over load capacity** Higher value of B_{av} means large value of flux per pole. For the given voltage per phase, lesser number of turns per phase are needed, reducing the leakage reactance. Reduced leakage reactance means large dia. of circle diagram and large over load capacity.

Summarizing a small B_{av} gives good p.f. and reduced core toss but a small over load capacity. On the other hand a high B_{av} gives poor p.f. and large amount of core loss but a good over load capacity. Therefore a moderate value of B_{av} is to be selected. For general purpose, it should be 0.3 to 0.55 Tesla.

CHOICE OF SP. ELECTRIC LOADING (AC)

The factors which get directly affected by the choice of ac are discussed below:

- **Temperature rise** A large value of ac leads to increased armature copper losses and ' therefore increased temperature rise.
- **Over load capacity** A large value of ac leads to larger turns per phase and thus Increased leakage reactance This reduces the dia. of the circle diagram resulting in lower value of over load capacity.
- **Voltage** For high voltage motors, insulation space required is larger. Slot space factor is therefore smaller. Now for such motors if higher ac is selected, larger armature diameter is required and hence larger size of the motor. Thus a high value of ac is restricted because of temp, rise, over load capacity and voltage of the winding as discussed above. The value of ac varies between 5000 to 45000 amp. Cond/m depending upon the capacity of the machine and the above factors.

EFFICIENCY AND POWER FACTOR

The capacity of the motor is usually given either in horse power (h.p) or in kW. But this has to be changed in to KVA to use it in the output equation.

$$KVA = \frac{h.p.x0.746}{\eta x \cos\phi}$$

Also $$KVA = \frac{kW}{\eta \cos\phi}$$

Full load p.f. usually varies between 0.82 and 0.92. High p.f. is generally obtained with high speed motors. The full load η is usually varies between 0.82 and 0.93.

CALCULATION OF MAIN DIMENSIONS

The output equation can be written as

$$KVA = [1.11\pi^2 K_w B_{av}(ac)(10^{-3})]\,\mathrm{D}^2\, Ln_s$$

KVA is obtained from H.P. or KW as shown already, n_s is the given specification. We normally assume full pitched winding thus K_w = 0.966. Thus suitably assuming the values of K_w, B_{av}, ac, η and cosϕ the product D^2L could be obtained.

SEPARATION OFF D AND L

The D^2L product obtained as above has to be split up into two components D and L. For normal speeds an approximately square pole can be assumed, Pole-pitch πD/p = L, giving good electrical design particularly as regards leakage reactance. This proportionality can not, however, always be used as the speed and frequency control the number of poles, so that a square pole may result in a diameter excessive for mechanical reasons. The tendency is to use a restricted diameter and greater core length in order to decrease the proportion of inactive copper in the over hang, and to obtain a cheaper motor.

PERIPHERAL VELOCITY (V)

$$v = \pi Dn \text{ m/sec}$$

Where n = r.p.s. The maximum permissible peripheral velocity for normal construction is 30 m/sec. Therefore a check is applied to the diameter D calculated so that the peripheral velocity is within the permissible limit. If it exceeds then either D has to be recalculated or special rotor construction is to be recommended which will definitely make the motor costly. Even for special rotor construction the limit to peripheral velocity is 60 to 75 m/sec.

STATOR WINDING DESIGN

Turns per phase

Flux per pole

$$\phi_m = B_{av}\frac{\pi DL}{P}$$

and stator voltage per phase

$$E_s = 4.44 K_{ws} f \phi_m T_s$$

$\therefore$ Stator winding turns per phase

$$T_s = \frac{E_s}{4.44 K_{ws} f \phi_m}$$

The stator factor K_{ws} may be assumed as 0.955 to start with for a full pitched coil with 60^0 phase spread.

Stator conductor section

Stator current per phase

$$I_s = \frac{KVAx1000}{3E_s}$$

$\therefore$ Cross section area of each conductor

$$a_s = \frac{I_s}{\delta_s}$$

The current density of stator conductor, δ_s is usually assumed between 3 to 5 A/mm^2.

Round conductors would be convenient only if the area of cross-section is well below 8 or 10 mm^2. For conductor area above 10 mm^2 strip conductors are invariably selected.

Stator slot design

Following guide lines will help to select a suitable number of stator slots

1. The number of slots should be so selected to give an integral number of slots per pole per phase. Generally for small and medium size motors the number of slots per pole per phase lie between 3 to 5. The narrow range is 3 to 4.

2. The Slot pitch at gap surface for open slots lies between 15 to 25 mm. However for semi enclosed slots it may become less than 15 mm.

3. The number of conductors per slot must be an even integer for double layer winding.

Let S_s = number of stator slots

$\therefore$ Stator slot pitch

y_{ss} = air gap surface/total number of stator slots

$$= \frac{\pi D}{S_s}$$

Now total number of stator winding conductors = 3 x 2 x T_s

Thus number of conductors per slot

$$Z_{ss} = \frac{3x2xT_s}{S_s}$$

Size of stator slots

Approximate area per slot = copper section per slot/space factor = $Z_{ss}a_s$/space factor

The value of space factor varies from 0.25 to 0.4.

Stator winding resistance

The stator winding resistance per phase

$$r_s = \rho \frac{L_{mts}T_s}{a_s}$$

where L_{mts} = length of mean turn of stator winding.

Length of mean turn of stator winding

It can be calculated from following equation.

$$L_{mts} = 2L + 2.3\tau + 0.24 \text{ m}$$

where L and τ are shown in m. ρ = 0.021 Ω/m length and per mm^2 cross section area at 75^{0}C.

Stator teeth design

The flux density in the stator teeth

$B_{ts} = \phi_m$/tooth area per pole

$= \phi_m$/(no of teeth per pole x net iron length x width of tooth)

$$\therefore \qquad B_{ts} = \frac{\phi_m}{(S_s / P)xLxW_s}$$

The minimum width of stator teeth is over the gap surface. Therefore a minimum width W_{ts} is used to check for B_{ts}. If B_{ts} falls within the required range, it is alright otherwise the slot dimensions are amended to fit B_{ts} within the range.

Depth of stator core

d_{ss} = depth of stator slot

d_{cs} = depth of stator core behind the slot

D_0 = outside diameter of stator core lamination.

The flux through core is half the flux per pole.

∴ Area of cross section of stator core

$$= \frac{\phi_m / 2}{B_{cs}}$$

Where B_s = flux density in the stator core. B_{cs} is normally kept within the range of 1.2 to 1.4 wb/m^2.

Area of cross section of stator core = $L_i d_{cs}$

Thus $$d_{cs} = \frac{\phi_m / 2}{B_{cs} L_i}$$

and $$D_0 = D + 2d_{ss} + 2d_{cs}$$

Example (AMIE W14, S16, 10 marks)

Find the main dimensions, number of stator turns, size of conductor and number of stator slots of a 5 h.p., 400 V, 3-phase, 4-pole squirrel cage induction motor using star-delta starter. Assume the following data:

Average flux density in the air gap = 0.46 Wb/m^2

Ampere conductors per meter of armature periphery = 22 x 10^3

Pull load efficiency - 83 %

Full load p.f. = 0.84 lagging

Winding factor = 0.955

Stacking factor = 0.9

Current density = 4 A/mm^2

No. of slots per poles per phase = 3

L/t = 1.5

Solution

$$KVA = \frac{HPx0.746}{\eta \cos\phi} = \frac{5x0.746}{0.83x0.84} = 5.35\,KVA$$

Assuming winding factor K_w = 0.955

Output coefficient

$C_0 = 1.11 \times \pi^2 \times K_w \times B_{av} \times ac \times 10^{-3}$

$= 1.11 \times \pi^2 \times 0.955 \times 0.46 \times 22000 \times 10^{-3}$

$= 105.88$

Syn rps n_s = 1500/60 = 25

Number of poles = P = 120 x 50/1500 = 4

Finding D and L

$$D^2L = \frac{KVA}{C_o n_s} = \frac{5.35}{105.88x} = 0.00202115 \text{ m}^3 \qquad (1)$$

Choose L/τ = 1.5

Now $$\frac{Lx4}{\pi D} = 1.5 \qquad (2)$$

Solving (1) and (2)

D = 0.12 m and L = 0.14 m

Check for peripheral velocity

v = πDn = π x 0.12 x 25 = 9.42 m/sec

This is less than the permissible limit of 30 seconds.

Net iron length

No radial vent duct is required for a length of 0.14 m.

Assuming a stacking factor of 0.9.

Net iron length

L_i = 0.9 x 0.14 = 0.126 m

Stator turns per phase

Flux per pole

$$\phi_m = B_{av}\frac{\pi DL}{P}$$

$$= 0.46x\frac{\pi x 0.12}{4}x0.14$$

= 6.06955 x 10^{-3} Wb

The machine is to be designed for delta connection because it is started by star delta starter.

∴ Stator voltage per phase = E_s = 400 V

Stator turns per phase

$$T_s = \frac{E_s}{4.44K_{ws}f\phi_m}$$

$$= \frac{400}{4.44x0.955x50x6.06955x10^{-3}} = 311$$

Size of conductor

Stator current per phase

$$I_s = \frac{KVAx1000}{3xE_s}$$

$$= \frac{5.35x1000}{3x400} = 4.4584\,A$$

Assuming a current density

δ_s = 4 A/mm^2

Conductor section

$$A_s = \frac{I_s}{\delta_s} = \frac{4.4584}{4} = 1.1146\,mm^2$$

Number of stator slots

Choosing slots per pole per phase = 3

$\therefore$ Total number of stator slots = 3 x 4 x 3 = 36

Slot pitch

$$= \frac{\pi D}{36} = \frac{\pi x0.12}{36}$$

= 0.01047 m

= 10.47 mm

This is a small motor where semi enclosed slots are to be selected and in such cases the slot pitch could be 10 mm.

Conductor per slot

$$= \frac{311x2x3}{36} = 51.834$$

Taking 52 conductors per slot.

$\therefore$ Actual number of tunes per phase

$$T_s = \frac{52x36}{6} = 312$$

Problem

In the design of a 30 h.p., 3 ph, 440 V, 960 rpm, 50 Hz delta connected induction motor, assume the specific electric loading of 25000 ac/m, specific magnetic loading = 0.46 wb/m^2. Full load efficiency 86%, p.f. 0.87 and estimate the following:

(i) stator core dimensions

(ii) number of stator slots and winding turns.

Answer: D = 0.3054 m; L = 0.16 m; stator turns per phase = 180; slot pitch = 17.45 mm; conductors per slot = 20

Hint: ac = 25000; B_{av} *= 0.46 wb/m*^{2}

Problem (AMIE, Winter 2012, 8 marks)

Determine the main dimensions, number of radial ventilating ducts, number of stator slots and the number of turns per phase of a 3.7 kW, 400 volt, 3 phase, 4 pole, 50 Hz squirrel cage induction motor to be started by a star delta starter. Work out the winding details.

Assume:

Average flux density in the gap = 0.45 wb/m^2

ampere conductors per metre = 23000

efficiency = 0.85 and p.f. = 0.84.

Machines rated at 3.7 kW, 4 pole are sold at a competitive price and therefore choose the main dimensions to give a cheap design.

Assume winding factor = 0.955 and stacking factor = 0.9.

Answer: D = 0.12 m; L = 0.13 m; stator turns per phase = 343; number of stator slots = 36; slot pitch = 10.47 mm; conductors/slot = 57; actual number of turns per phase = 343

Example

A 15 HP, 400 volt, 1430 rpm, 3 phase induction motor with an efficiency of 80% and p.f. 81% has inner diameter of stator 30 cm and length 12 cm. Estimate the diameter and length for a 50 h.p., 406 V, 4 pole, 50 Hz induction motor to be designed for 84% efficiency and 85% p.f.

Solution

Output coefficient C_0

KVA of the motor

$$= \frac{15x0.746}{0.8x0.81} = 17.27\,KVA$$

Since the main dimensions are given hence the output

$$C_0 = \frac{KVA}{D^2 L n_s} = \frac{17.27}{(0.3)^2 x0.12x25} = 63.96$$

Here n_s = 1500/60 = 25 for 1430 rpm motor.

D and L of second motor

C_0 will remain same.

$$KVA = \frac{50x0.746}{0.84x0.85} = 52.24\,KVA$$

Now $$D^2L = \frac{KVA}{C_0 n_s} = \frac{52.24}{63.96x25} = 0.03267\,m^3$$

Here n_s = 25 for a 4 pole, 50 Hz motor.

Now to separate D and L, we can assume the motor to have best power factor, for which

$$\tau = 0.41\sqrt{L}$$

or $$\frac{\pi D}{P} = 0.41\sqrt{L}$$

Solving D = 0.3071 m = 31 cm and L = 34 cm

Problem

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

Answer: D = 0.30 m; L = 0.125 m; stator conductors per phase = 307; total number of stator cond = 1842; cond per slot = 34; using 34 conductors, stator turns/phase = 306

AIR GAP LENGTH

The gap length is determined by the magnetising current, mechanical considerations and other secondary matters such as pulsation losses and cooling from the gap surfaces.

We will look into all these factors on which the air gap length (L_g) depends:

- **Power-factor** This is by far the most important factor. Out of various parts of the magnetic circuit of any rotating electric machine, the air gap generally consumes the maximum amount of mmf to pass the flux through it. Thus greater the air gap, greater will be the amp. turns required to pass the flux through it. This will need large value of magnetizing current. The magnetizing current is a large component of no load current and is in quadrature with the applied voltage (lagging behind by 90°) and tends to lower the power factor of the machine. Therefore to have good power factor the gap length L_g be kept smallest possible.
- **Over load capacity** The Zig-Zag leakage reactance which forms a substantial amount of the total leakage reactance, is reduced with large value of gap length. Reduced leakage reactance means large dia. of the circle diagram giving large value

of over load capacity. So to have large over load capacity, gap length L_g should be large.

- **Pulsation losses and noise** The other important effects of Zig-Zag leakage flux are to introduce pulsation losses and noise. The value of the Zig-Zag leakage flux varies inversely as the air gap length. Therefore to reduce pulsation loss and noise, the tendency would be to have a large air gap-
- **Unbalanced magnetic pull** The complete rotor surface and the stator bore surface have flux crossing the air gap between them and so there will be a force of attraction between the two surfaces. If the rotor is placed exactly at the centre of the stator bore the forces are same in all directions and hence cancel each other. However if the rotor is out of centre may be by a very small amount. There will be a resultant force in one direction. This force is called the unbalanced magnetic pull. With large air gap length the percentage pull would reduce and may not be noticeable. Thus the tendency is to have a large air gap.

Thus for good p.f. the air-gap length (L_g) Should be as small as mechanically possible.

For large overload capacity, less noise, less pulsation loss, less unbalanced magnetic pull, the air gap length should be kept large.

Following relations are used for small machines:

$$L_g = 0.2 + 2\sqrt{DL} \quad \text{mm}$$

$$L_g = 0.125 + 0.35D + L + 0.015v_a \quad \text{mm}$$

$$L_g = 0.2 + D \quad \text{mm}$$

where D and L are expressed in m and v_a = peripheral velocity in m/sec.

For machines with journal bearings

$$L_g = 1.6\sqrt{D} - 0.25 \text{ mm}$$

Example

Estimate the main dimensions, air gap length, no of stator slots, stator turns per phase and cross sectional area of stator conductors for a 3 phase, 20 h.p., 400 V, 6 pole, 50 Hz, 970 r.p.m. induction motor suitable for a star delta starting. Assume magnetic and electric specific loadings as 0.45 wb/m^2 and 23000 ac/m respectively, ratio of core length to pole-pitch 0.85, full load efficiency 0.88 and power factor 0.89.

Solution

KVA = (20 x 0.746)/(0.88 x 0.89) = 19.05 KVA

Syn speed n_s = 1000/60 = 16.667 rps for a 6 pole, 50 Hz machine.

$C_0 = 1.11\ \pi^2 K_w B_{av}(ac)(10^{-3})$

$= 1.11 \times \pi^2 \times 0.955 \times 0.45 \times 23000 \times 10^{-3}$ (assuming $K_w = 0.955$)

$= 108.28$

Now $$D^2L = \frac{KVA}{C_0 n_s} = \frac{19.05}{108.28x16.667} = 0.010557\, m^3$$

Given $L/\tau = 0.85$ or $L \times 6/\pi D = 0.85$

Solving $L = 0.445D$

or $D^3 = 0.02372$ i.e. $D = 0.287$ m = 29 cm

$\therefore$ $L = 12.8$ cm

Air gap length

$L_g = 0.2 + 2\sqrt{DL}$

$= 0.2 + 2\sqrt{(0.29 \times 0.128)}$

$= 0.585$ mm

Flux per pole

$$\phi_m = B_{av} x \frac{\pi DL}{P}$$

$$= 0.45x\frac{\pi x 0.29 x 0.128}{6}$$

$= 8.746 \times 10^{-3}$

$E_s = 4.44 K_w f \phi_m T_s$

or $$T_s = \frac{E_s}{4.44 K_w f \phi_m}$$

$$= \frac{400}{4.44x0.95x50x8.746x10^{-3}}$$

$= 216$

Total conductors = 216 x 2 x 3 = 1296

Full load current

$$I_s = \frac{19.05x1000}{3x400} = 15.875A$$

Conductor cross section

$a_s = I_s/\delta_s$

Choosing a current density

$\delta_s = 4$ A/mm^2

$a_s = 15.875/4 = 3.968$ mm^2

Choosing slots per pole per phase = 3

$\therefore$ Total number of stator slots

$$S_s = 3 \text{ x } 6 \text{ x } 3 = 54$$

Slot pitch

$$y_{ss} = \frac{\pi D}{S_s} = \frac{\pi x 0.29}{5.4} = 16.87\, mm$$

It is within the allowable limit of 15 to 25 mm

$\therefore$ Stator conductors per slot

$$Z_{ss} = 1296/54 = 24$$

DESIGN OF SQUIRREL CAGE ROTOR

Rues for selecting rotor slots

The following general rules should be followed concerning the choice of rotor slots for squirrel cage machines.

- The number of rotor slots should never be equal to stator slots but must either be large or smaller. Satisfactory results are obtained when the number of rotor slots is 15 to 30 per cent larger or smaller than the number of stator slots.
- The difference between stator slots and rotor slots should not be equal to p, 2p or 5p to avoid synchronous cusps.
- The difference between the number of stator and rotor slots should not be equal to 3p for 3 phase machines in order to avoid magnetic locking.
- The difference between number of stator slots and rotor slots should not be equal to, 1.2, (p ± 1) or (p ± 2) to avoid noise and vibrations.

  Summarizing, S_s - S_r should not be equal to

  $$0, \pm p, \pm 2p, \pm 3p, \pm 5p$$

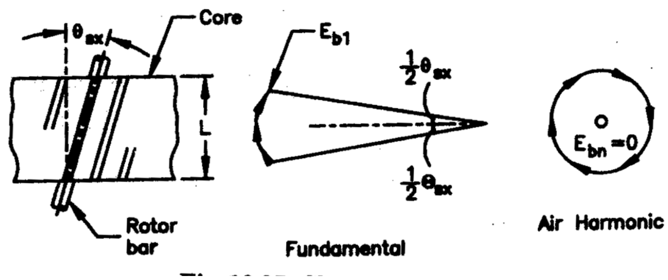
  $$\pm 1, \pm 2, \pm (p \pm 1), \pm (p \pm 2).$$

Reduction of Harmonic Torques

Following are some of the methods used for reduction/elimination of harmonic torques.

- **Chording.** The simplest way to eliminate the harmonic induction torques is to weaken the stator winding mmf harmonics. In order to achieve this, chorded windings with integral number of slots per pole per phase are used.
- **Integral slot windings**. Windings with fractional number of slots per pole per phase create asymmetrical mmf distribution around the air gap and favour the creation of noise in this motor. Therefore, fractional slot windings are not used for induction motor stators and only integral slot windings are used.

- **Skewing**. The motor noise and vibrations, cogging and synchronous cusps can be reduced or even entirely eliminated by skewing either the stator or the rotor. The practice generally followed in India is to skew the rotor (see following figure)



If either stator or rotor slots are skewed, the variations in flux density, magnetic pull, and torque due to the slot openings will be displaced in time phase along the core length, resulting in more uniform torque, less noise, and better voltage waveform. In order to eliminate the effect of any harmonic, the rotor bars should be *skewed* through an angle so that the bars lie under alternate harmonic poles of the same polarity or in other words, bars must be skewed through two pitches.

Design of rotor bars

Current in each bar

$$I_b = \frac{2m_s K_{ws} T_s}{S_r}.I_s \cos\phi$$

For a three phase machine

$$m_s = 3$$

$$\therefore \quad I_b = \frac{6I_s T_s}{S_r} K_{ws} \cos\phi$$

$$= 0.85x\frac{6I_s T_s}{S_r}$$

From this equation we can interpret that rotor mmf is about 85% of stator mmf.

Area of rotor bar

The performance of an induction motor is greatly influenced by the resistance of rotor. A motor designed with high rotor resistance has the advantage that it has a high starting torque. However, a rotor with a high resistance has the disadvantage that its I^2R loss is greater and therefore its efficiency is lower under running conditions.

The value of rotor resistance depends upon the current density used for rotor conductors, the higher the current density, the lower is the conductor area and greater the resistance. Therefore, a rotor designed with a high value of current density results in high starting torque and a lower efficiency for the machine.

The rotor resistance is the *sum of the resistance of the bars and the end rings*. The cross-section of the bars and the end rings must be so selected that a proper value of rotor resistance is obtained i.e. a value of rotor resistance which meets both the requirements of starting torque as well as the efficiency.

It is desirable to have a compromise between a high resistance rotor which gives a good starting torque and a low resistance rotor which gives a high value of efficiency under running conditions.

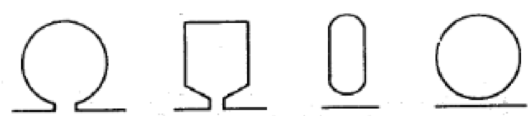
Current density in the rotor bars may be taken between 4 to 7 A/mm^2.

Area of each bar $a_b = I_b/\delta_b$ mm^2

where δ_b is the current density in rotor bars A/mm^2.

Shape and Size of Rotors Slots

The rotor slots for squirrel cage rotor may either be closed or semi-enclosed types as shown in following figure.



Closed slots are preferred for small size machines because the reluctance of the air gap is not large owing to absence of slot openings. This gives a reduced value of magnetizing current. As the surface of the rotor is smooth, the operation of the machine is quieter. The biggest advantage is that the leakage reactance with closed slots is large and therefore the current at starting can be limited. This is very useful in the case of machines which are started with direct on line starters. But the disadvantage is that the increased value of reactance results in reduction of overload capacity. A semi-enclosed slot gives a better overload capacity.

The rectangular shaped bars and slots are generally preferred to circular bars and slots as the higher leakage reactance of the lower part of the rectangular bars, during starting, forces most of the current through the top of the bar. This increases the rotor resistance at starting and improves the starting torque. Deep slots, however, give an increased leakage reactance and a high flux density at the root of the teeth.

Design of end ring

Considering a group of rotor bars under one pole pitch, one half would send current to an end ring in one direction and the other half in the other direction. If the maximum value of the current in each bar is $I_{b(max)}$ and if the current is maximum in all the bars at the same time, then maximum value of the current in the end ring :

$$= \text{(bars per pole/2) x current per bar}$$

$$= \frac{S_r}{2} I_{b(\max)}$$

However, current is not maximum in all the bars under one pole at the same time but varies according to sine law; hence, the maximum value of the current in the end ring is the average of the current of half the bars under one pole.

Maximum value of end ring current

$$I_{e(\max)} = \frac{2}{\pi} x \frac{S_r}{2p} x I_{b(\max)}$$

But the bar current varies sinusoidally.

$\therefore$ $$I_{b(\max)} = \sqrt{2I_b}$$

or $$I_{e(\max)} = \frac{2}{\pi}.\frac{S_r}{2p}.\sqrt{2I_b}$$

The end ring current also varies sinusoidally.

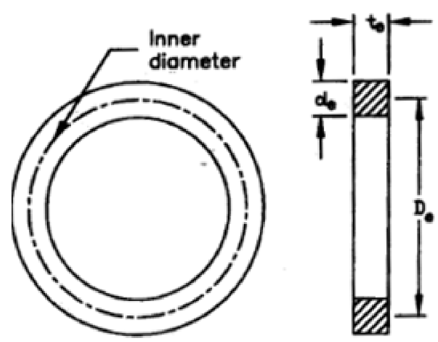
$\therefore$ RMS value of end ring current

$$= I_e = \frac{I_{e(\max)}}{\sqrt{2}} = \frac{1}{\sqrt{2}}.\frac{2}{\pi}.\frac{S_r}{2p}\sqrt{2I_b}$$

$$= \frac{S_r I_b}{\pi p}$$

Area of end ring

The value of current density chosen for the end rings should be such that the desired value of rotor resistance is obtained.



The ventilation is generally better for end rings and therefore a slightly higher value of current density than that obtaining in rotor bars can be taken.

Area of each end ring

$$a_e = \frac{I_e}{S_e} = \frac{S_r I_b}{\pi p S_e} \text{ mm}^2$$

Area of ring

a_e = depth of end ring x thickness of end ring

$= d_e \times t_e$

Full load slip

The value of slip (s) is derived from the following formula

$$\frac{rotor\ copper\ loss}{rotor\ output} = \frac{s}{1-s}$$

where s is per unit slip.

Example

A 11 kW, 3 phase, 6 pole, 50 Hz, 220 V, star connected induction motor has 54 stator slots, each containing 9 conductors. Calculate the values of bar and end ring currents. The number of rotor bars is 64. The machine has an efficiency of 0.86 and a power factor of 0.85. The rotor mmf may be assumed as 85% of stator mm. Also find the bar and end ring sections if the current density is 5 A/mm^2.

Solution

Stator current per phase

$$I_s = \frac{11x1000}{\sqrt{3}x220x0.86x0.85} = 40A$$

Number of stator conductors

$= 54 \times 9$

$= 486.$

∴ Stator turns/phase

$T_s = 486/6 = 81$

Stator mmf

$= 3I_sT_s$

$= 3 \times 40 \times 81$

$= 9720$ A

∴ Rotor mmf = 85% of stator mmf

$= 0.85 \times 9720$

$= 8250$ A

But rotor mmf

$= S_rI_b/2$

$= 32I_b$

∴ $32I_b = 8250$

$\therefore \qquad I_b = 258$ A

End ring current

$$I_s = \frac{S_r I_b}{\pi p}$$

$$= \frac{64x258}{\pi x6} = 883A$$

$\therefore$ Area of each bar

$$a_b = 258/5 = 51.6 \text{ mm}^2$$

and of each end ring

$$a_e = 883/5 = 176.6 \text{ mm}^2$$

Example

The following design data are provided for an induction motor. Calculate (i) no load maximum flux (ii) length of air gap (iii) number of turns per phase (iv) rotor bar current and area (v) end ring current and area and (vi) losses in bars and end rings.

Diameter of stator bore = 15 cm

Length of stator core = 9 cm

Average flux density = 0.45 Tesla

Efficiency = 84%

Power factor = 0.86%

3 phase, 4 pole, 400 V, delta connected, 10 kW

Frequency = 50 Hz

Current density = 5 A/mm^2

Stator slots = 36

Rotor slots = 30

Length of rotor bar = 15 cm

Mean dia of end ring = 12 cm

Solution

No load maximum flux

Average value of flux density in the air gap

$$B_{av} = 0.45 \text{ wb/m}^2$$

$\therefore$ Maximum value of flux density in the air gap

$B_g = 0.45\ (\pi/2)$

$\therefore$ No load maximum flux per pole

$$= B_g \frac{\pi D}{P} L$$

$$= 0.7068 x \frac{\pi x 0.15}{4} x 0.09$$

= 7.49m wb

Length of air gap

$l_g = 0.2 + 2\sqrt{DL}$

$= 0.2 + 2\sqrt{0.15 \text{ x } 0.09}$

= 0.432 mm

Flux per pole

$$\phi = B_{av} x \frac{\pi D}{P} L$$

$$= 0.45 x \pi x \frac{0.15}{4} x 0.09$$

= 4.768 m wb

Turns per phase

$$T_{ph} = \frac{E_{ph}}{4.44 f \phi K_{ws}}$$

$$= \frac{400}{4.44 x 50 x 4.768 \text{ x } 10^{-3} x 0.955}$$

= 396

Stator current per phase

$$I_s = \frac{10 x 1000}{3 x 400 x 0.84 x 0.86}$$

= 1153 A

Assuming rotor mmf = 0.85 stator mmf

Bar current and area

$$I_b = 0.85 x \frac{6 I_s T_s}{S_r}$$

$$= \frac{0.85x6x11.53x396}{30}$$

= 776.2 A

Area of each bar

a_b = 776.2/5 = 155.24 mm^2

End ring current and area

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

$$= \frac{30x776.2}{\pi x4} = 1853A$$

Area of end ring

a_e = 1853/5 = 370.6 mm^2

Losses in bars

Resistance of each bar

$$r_b = \rho \frac{I_b}{a_b}$$

$$= \frac{0.021x0.15}{155.24}$$

= 20.29 x 10^{-6} ohms

∴ Total copper losses in all the bars

= $I_b^2 r_b S_r$

= $(776.2)^2$ x 20.29 x 10^{-6} x 30

= 366.73 Watts

Resistance of each end ring

$$r_e = \frac{0.021x\pi x0.12}{370.6}$$

= 21.36 x 10^{-6} ohms

∴ Total copper loss in both the end rings

= $2I_e^2 r_e$

= 2 $(1853)^2$ x 21.36 x 10^{-6}

= 147.85 watts

∴ Total copper loss in rotor = 366.73 + 147.85 = 514.58 W

Problem

Determine the approximate diameter and length of the stator core, the number of stator slots and the number of conductors for a 11 kW, 400 V, 3 phase, 4 pole, 1425 rpm delta connected induction motor. Adopt a specific magnetic loading of 0.45 wb/m^2 and a specific electric loading of 23000 A/m. Assume full load efficiency and power factor as 0.85 and 0.88 respectively. The ratio of core length to pole pitch is 1. The stator employs a double layer winding.

Answer: D = 0.19 m; L = 0.15 m; slots = 36; conductors = 1080

Problem

Find the values of diameter and length of stator core of a 7.5 kW, 220 V, 50 Hz, 4 pole, 3 phase induction motor for best power factor. Given: specific magnetic loading = 0.4 wb/m^2; specific electric loading = 22000 A/m; efficiency = 0.86; and power factor = 0.87. Also find the main dimensions if the ratio of core length to pole pitch is unity.

Answer: D = 0.18 m; L = 0.12 m; D = 0.172 m; L = 0.136 m

Example (AMIE S06, 16, W14, 10 marks)

Find the current in the bars and end rings of a cage rotor of a 6-pole, 3-phase, induction motor having 72 stator slots with 15 conductors in each slot, if the stator current per phase is 20 A and the rotor slots are 55. Hence, find the suitable size of the cage bars and end rings.

Solution

Given data:

$P = 6$

$S_s = 72$

$Z_s = 15$

$S_r = 55$

Stator current/phase = 20 A

Stator slots

$S_s = 72$

Stator conductors per slot

$Z_s = 15$

Stator's conductors

$= 72 \times 15$

$\therefore$ Stator turns per phase

$$T_{ph} = \frac{72x15}{3x2} = 180$$

$\therefore$ Rotor bar current

$$= 0.85x\frac{6I_sT_s}{S_r}$$

$$= 0.85x\frac{6x20x180}{55} = 333.8\,Amps$$

and end ring current

$$I_s = \frac{S_rI_b}{\pi p} = \frac{55x333.8}{\pi x6}$$

$$= 974 \text{ Amps}$$

MAGNETISING CURRENT

The flux produced by stator mmf turns passes through the following parts:

- air gap
- rotor teeth
- rotor core
- stator teeth
- stator core

In an induction motor the flux is distributed approximately sinusoidally and the mmf varies similarly.

Owing to variations in the permeability of iron, particularly the stator and rotor teeth, a sinusoidal mmf will produce a flat topped flux density distribution curve.

If the value of flux density is calculated for the mean mmf, and a sinusoidal distribution of flux is assumed, the total flux obtained will be larger than true value; or conversely the calculated magnetizing current for a given sinusoidal flux will be smaller than the true value.

If maximum values are taken instead the opposite result is obtained, i.e. flux is too small, or magnetizing current is too large.

Some intermediate position therefore will give a correct value. Though this position may differ somewhat in different motors, a flux tube crossing the air gap at 60° from the interpolar axis will always give a good approximation.

The reason for this is that the flux density distribution curve can be approximated too closely by a sine-wave with a third harmonic. The value of flux density at 60° from the interpolar axis is the same whether the third harmonic is present or not. Thus the calculation of magnetizing mmf should be based upon the value of flux density at 60° from the interpolar axis as far as the gap and teeth are concerned.

Mmf for air gap

$B_{g60} = 1.36B_{av}$

$\therefore$ Mmf for air gap $AT_g = 800{,}000\ B_{g60}K_g l_g$

Mmf for stator teeth

The flux density is uniform in the teeth when they are parallel sided but when parallel sided slots are used, the flux density along the length of teeth is not uniform. The value of mmf for teeth is found out by finding flux density at a section 1/3 height of tooth from narrow end.

Flux density at 1/3 height of tooth from narrow end

$$B_{ts1/3} = \frac{\phi}{(S_g / p)xL_i xW_{ts1/3}}$$

where $W_{ts1/2}$ = width of stator at 1/3 height from narrow end

$$= \frac{\pi(D + 2d_{ss}/3)}{S_4} - W_{ss}$$

The calculation of mmf stator teeth is based upon B_{ts60}.

Where $B_{ts60} = 1.36B_{ts1/3}$

MMF required for stator teeth

$AT_{ts} = \alpha t_{ts} = \alpha t_{ts}\ x\ d_{ss}$

MMF for rotor teeth

Flux density in rotor teeth at 1/3 height from narrow end

$$B_{ts1/3} = \frac{\phi_m}{(S_r / p)xL_i xW_{tr1/3}}$$

and with $\dfrac{\pi(D_r - 4d_{sr}/3)}{S_r} - W_{sr}$

where d_{sr} = depth of rotor slot and W_{sr} = width of rotor slot.

MMF of stator core

Corresponding to flux density in the core, the mmf per metre at_{cs} is found from BH curve. The length of path through the core can be taken as 1/3 pole pitch at the mean core diameter.

Length of path through stator core

$$I_{cs} = \frac{\pi(D + 2d_{ss} + d_{cs})}{3p}$$

MMF for stator core = at_{cr} x l_{cs}

MMF for rotor core

Corresponding to flux density in rotor core mmf per metre at_{cr} is found from BH curve.

Length of flux path in rotor core

$$I_{cr} = \frac{\pi(D_r - 2d_{sr} - d_{cs})}{3p}$$

∴ Total mm for rotor core

$$AT_{cr} = at_{cr} \text{ x } l_{cr}$$

∴ Total magnetising mmf per pole for B_{60}

$$AT_{60} = AT_g + AT_{cs} + AT_{tr} + AT_{cs} + AT_{cr}$$

From following equation

$$I_{ph} = \frac{0.427\,pAT_{60}}{K_{w1}T_{ph}}$$

We get $$I_m = \frac{0.427\,pAT_{60}}{K_{ws}T_s}$$

Example

A 75 kW, 3300 V, 50 Hz, 8 pole, 3 phase star connected induction motor has a magnetising current which is 35% of the full load current. Calculate the value of stator turns per phase if the mmf required for flux density at 30^0 from pole axis is 500 A.

Assuming winding factor = 0.95 and full load efficiency and power factor 0.94 and 0.86 respectively.

Solution

Full load current

$$= \frac{75x1000}{\sqrt{3}x3000x0.94x0.86}$$

= 17.9 A

∴ Magnetizing current

$$I_m = 0.35 \text{ x } 17.9 = 6.26 \text{ A}$$

Now formula for finding magnetizing current is

$$I_m = \frac{0.427\,pAT_{60}}{K_{ws}T_s}$$

Or stator turns per phase

$$T_s = \frac{0.427\,pAT_{60}}{K_{ws}I_m}$$

$$= \frac{0.427x8x500}{0.95x6.28}$$

$$= 288$$

Example

Calculate the equivalent resistance of rotor per phase in terms of stator, current in each bar and end ring and total rotor I^2R loss for the following:

4 pole 3 phase, 50 Hz, 400 V cage motor has 48 slots in stator with 35 conductors per slot. Each conductor carries a current of 10 A. The rotor has 57 slots, each has a bar of 0.12 m length and 50 mm^2 area. The mean diameter of each ring is 0.2 m and area 175 mm^2. Resistivity is 0.02 Ω/m and mm^2 and the power factor is 0.8. The stator winding uses full pitched coils with a phase spread of 60^0.

Solution

The winding factor for an infinitely distributed winding with a phase spread of 60^0 is 0.955.

Equivalent stator current

$$I_r' = I_s\cos\phi = 10 \text{ x } 0.8 = 8 \text{ A}$$

Stator turns per phase

$$T_s = 48 \text{ x } 35/6 = 280$$

Current in each bar

$$I_b = \frac{2m_s K_{ws} T_s}{S_r} x I_r$$

$$= \frac{2x3x0.955x280}{57} x8$$

$$= 226 \text{ A}$$

Current in each ring

$$I_e = \frac{S_r I_b}{\pi p}$$

$$= \frac{57x226}{\pi x4}$$

$$= 1024 \text{ A}$$

Resistance of each bar

$$r_b = 0.02 \text{ x } 0.12/50$$

$$= 48 \text{ x } 10^{-6}\ \Omega$$

I^2R loss in bars

$= 57 \times (226)^2 \times 48 \times 10^{-6}$

$= 140$ W

Resistance of each ring

$= 0.02 \times \pi \times 0.2/175$

$= 72 \times 10^{-6}\ \Omega$

I^2R loss in 2 rings

$= 2\ (1024)^2 \times 72 \times 10^{-6}$

$= 151$ W

Total resistance referred to stator per phase

$r_r' = \text{total rotor } I^2R \text{ loss}/m_s I_r'^2$

$= 298/(3 \times 8^2)$

$= 1.51\ \Omega$

The resistance can be calculated from following formula

$$r_r' = 4 m_s T_s^2 K_{ws}^2 \rho \left[\frac{L_b}{S_r a_b} + \frac{2}{\pi} \frac{D}{p^2 a_e} \right]$$

$$= 4x3x(280)^2 (0.955)^2 (0.02) \left[\frac{0.12}{57x50} + \frac{2}{\pi} x \frac{0.5}{4^2 x175} \right]$$

$= 1.51\ \Omega$

Problem

Calculate the magnetising current of a 415 V, 4 pole, 3 phase, 50 Hz induction motor having the following data:

Stator slots = 36

conductors per stator slot = 30

stator bore = 0.13 m

stator core length = 0.13 m

effective gap length = 1 mm

The winding is full pitch and the phase spread is 60^0. Assume that iron has infinite permeability.

Answer: 4.64 A

Problem

Calculate the equivalent resistance of rotor per phase with respect to stator, the current in each bar and end ring and the total rotor copper loss for a 415 V, 50 Hz, 4 pole, 3 phase induction motor having the following data:

Stator:

Slots = 48

conductor in each slot = 35

current in each conductor = 10 A

Rotor

Slots = 57

length of each bar = 0.12 m

area of each bar = 9.5 x 5.5 mm^2

mean diameter of each ring = 0.2 m

area of each ring = 175 mm^2

resistivity of copper is 0.02 Ω/m and mm^2.

Full load power factor is 0.85.

Answer: 1.49 Ω per phase; 241.5 A; 1095 A; 323 W

COMPARISON BETWEEN WOUND ROTOR MOTOR AND SQUIRREL CAGE MOTOR

Squirrel Cage Induction Motor

- In Squirrel cage induction motors the rotor is simplest and most rugged in construction.
- Cylindrical laminated core rotor with heavy bars or copper or aluminium or alloys are used for conductors.
- Rotor conductors or rotor bars are short circuited with end rings.
- Rotor bars are permanently short circuited and hence it is not possible to connect external resistance in the circuit in series with the rotor conductors.
- Cheaper cost.
- No moving contacts in the rotor.
- Higher efficiency.
- Low starting torque. It is 1.5 time full load torque.
- Speed control by rotor resistance is not possible.

- Starting current is 5 to 7 times the full load.

Slip ring (wound rotor) Induction Motor

- In slip ring induction motors the rotor is wound type. In the motor the slip rings, brushes are provided. Compared to squirrel cage rotor the rotor construction is not simple.
- Cylindrical laminated core rotor is wound for as the number of poles of the stator.
- At starting the 3 phase windings are connected to a star connected rheostat and during running
- condition, the windings is short circuited at the slip rings.
- It is possible to insert additional resistance in the rotor circuit. Therefore it is possible to increase the torque (the additional series resistance is used for starting purposes).
- Cost is slightly higher.
- Carbon brushes, slip rings etc are provided in the rotor circuit.
- comparatively less efficiency.
- High starting torque. It can be obtained by adding external resistance in the rotor circuit.
- Speed control by rotor resistance is possible.
- Less starting current.

CRANE DUTY MOTORS

The operating conditions such as duty cycle, startup, temperature and operating environment are vital considerations in the motor efficiency and reliability. It is absolutely essential to match the motors to their specified operating conditions for minimizing stresses on the motors and to get predetermined performance and life.

One of the areas, in which significant technical requirements are considered lightly or even neglected, is selection of motors for operating various types of cranes and hoists.

These motors are specifically termed as “Crane Duty Motors” and are supplied by all the manufacturers.

Definitions Of Technical Terms

Some technical terms used frequently in intermittent duty drives and hoisting are defined as follows:

- **Duty** Operation of the motor at the declared load(s) including starting, electric braking, no load and rest and de-energised periods to which the motor is subjected, including their durations and sequence in time.

- **Cyclic duration factor** The ratio of the period of loading, including starting and electric braking, to the duration of the one complete duty cycle expressed as percentage. Generally the values for the CDF used are 25%, 40%, 60% and 100%.
- **Starting** The process of energizing a motor to bring it up to rated speed from rest.
- **Jogging or inching** This is an incomplete start during which the motor does not attain more than 25% of the rated speed.
- **Electric braking** A system in which a braking action is applied to an electric motor by causing it to act as a generator.
- **DC Injection braking** A form of braking of an induction motor in which a separate dc supply is used to magnetize the motor.
- **Plug braking** A form of electric braking of an induction motor obtained by reversing the phase sequence of its any two lines.

Duty Type and Class Of Rating

- **Continuous running duty (S1)** The motor works at a constant load round the clock or runs for adequate time to reach thermal equilibrium.
- **Short-time duty (S2)** The motor works at a constant load for a definite time, but not long enough to reach thermal equilibrium. The rest periods are long enough for the motor to cool down to the ambient temperature.
- **Intermittent periodic duty (S3)** The motor works with a sequence of identical duty cycles comprising of period of running at a constant load and rest and de-energized period. Thermal equilibrium is never reached due to these periods being too short. Starting current has little effect on temperature rise.
- **Intermittent periodic duty with starting (S4)** The motor works with a sequence of identical duty cycles, each cycle consisting of significant period of starting, a period of running at a constant load and rest and de-energized period. Thermal equilibrium is never reached due to these periods being too short, but starting current affects temperature rise.
- **Intermittent periodic duty with electric braking (S5)** The motor works with a sequence of identical duty cycles, each cycle consisting of a period of starting, a period of running at a constant load, a period of rapid electric braking and rest and de-energized period. Thermal equilibrium is never attained due to periods of operating, rest and de-energized state being too short
- **Continuous operation periodic duty (S6)** The motor works with a sequence of identical duty cycles, each cycle consisting of a period of running at a constant load and a period of running at no load without rest and de-energized period. Thermal equilibrium is never reached due to operation period at no load is too short.

- **Continuous operation periodic duty with electric braking (S7)** The motor works with a sequence of identical duty cycles, each cycle consisting of a period of starting, a period of running at a constant load and a period of electric braking. Thermal equilibrium is never reached, as rest and de-energized period is not there.
- **Continuous operation with periodic related variations in load and speed (S8)** The motor works with a sequence of identical duty cycles, each cycle consisting of a period of running at a constant load corresponding to a definite speed of rotation, followed by one or more periods of running at other constant loads at different speed. Thermal equilibrium is never reached, as rest and de-energized period is not there.
- **Duty with non-periodic load and speed variations (S9)** The motor works generally at a load and speed, which are varying non-periodically within permissible operating range including frequent application of overloads that may exceed the rating of motor. Thermal equilibrium is never reached, as rest and de-energized period is not there.

Classes of rating

- **Maximum continuous rating** The motor may be operated continuously for unlimited period at the load and service conditions assigned by the manufacturer.
- **Short time rating** Starting at ambient temperature, the motor may be operated continuously for limited period at the load and service conditions assigned by the manufacturer.
- **Equivalent continuous duty** The motor may be operated at the load and service conditions assigned by the manufacturer for the test purposes until thermal equilibrium is attained. This is considered to be equivalent to one of the periodic duty defined in duty type S3 to S8 or to the duty type S9.
- **Periodic duty type rating** The motor may be operated for duty cycles at the load and service conditions assigned by the manufacturer. When applied to the motor, this class of rating corresponds to the periodic duty S3 and S6 types maintaining time of duty cycle 10 minutes and one of the cyclic duration factors (CDF) with values – 15, 25, 40 or 60 percent.
- **Non-periodic duty type rating** The motor may be operated non-periodically for duty cycles having varying loads over varying speed and service conditions, including overloads, assigned by the manufacturer. When applied to the motor, this class of rating corresponds to the non-periodic duty with non-periodic load and speed variations as per duty type S9.

Types of Crane Duty Motors

Following two types of motors are widely used for crane duty applications.

- Squirrel Cage Crane Duty Motors
- Slip ring and Wound Rotor Crane Duty Motors

The crane motors are duty type rated for developing high starting torque with low starting current. The motors are designed to withstand stresses due to frequent starts/stops and reversals. Also, a rapid acceleration is achieved by high pull out torque/rotor inertia ratio.

Generally, the motors assigned duty type S3, S4 and S5 are considered for crane applications.

These motors may also be used for similar applications such as material handling, sluice operation on dams/weirs, lifts of all types and in rolling mills as auxiliary motors or wherever operating drives are required for intermittent services.

Salient technical and constructional features of crane duty motors

The technical and constructional features of crane duty motors as follows are more or less similar to that are found in the standard continuous duty motors.

- Material and construction of stator frame and end shields
- Material and construction of stator and rotor cores
- Bearings at non-drive and drive ends
- Material of construction of shaft
- Earthing to stator frame and terminal box
- Mounting of motor – foot mounted or flange mounted
- Material, construction and position of terminal box

ASSIGNMENT

THEORY

Q.1. (AMIE W13, S15, 15 marks): Describe the method of estimating the magnetising currant of an induction motor.

Q.2. (AMIE W13, S15, 5 marks): Why is a short gap length so important to the operation of an induction motor?

Answer: An increase in air gap length, decreases the harmonic torques. But an increased gap length leads to an increase in no load current and thus make the motor power factor poor. Therefore, only in motors of high reliability, for mechanical reasons, the air gap is made larger than the normal size.

Q.3. (AMIE W13, S15, 10 marks): Show that the end ring current of a squirrel cage induction motor is given by $S_rI_b/\pi P$, where S_r = number of rotor slots, I_b = rotor bar current, and P = number of poles.

Q.4. (AMIE S14, 8 marks): Explain the effect of output coefficient 'G' and D^2L - product on induction motor design, where D = stator bore diameter (m) and L = stator length (m).

Q.5. (AMIE W12, 14, S16, 10 marks): What is meant by specific magnetic and electric loadings of rotating machine? Discuss the factors which affects the choice of specific loadings in an induction motor.

Q.6. (AMIE W14, S16, 10 marks): Show that the output per rpm of a three-phase induction motor is proportional to volume of its stator bore.

Q.7. (AMIE W14, 8 marks): Derive the out put equation of a three-phase induction motor. What are the factors affecting size of induction machine?

Q.8. (AMIE W16, 6 marks): Compare cage and wound rotor induction motor as regards their advantage and disadvantages.

Q.9. (AMIE S17, 5 marks): Justify that leakage reactance plays a very important and significant role in design of induction motor.

Answer: If there are larger number of slots, there are larger number of slots to insulate. Therefore the width of insulation becomes more and this means that the leakage flux has a longer path through air which results in its (leakage flux's) reduction. Therefore with larger number of slots, the leakage flux and hence the leakage reactance is reduced. In fact the slot leakage reactance is inversely proportional to the number of slots/pole/phase. With small values of leakage reactance the diameter of the circle diagram is large and hence the overload capacity increases. Thus, with larger number of slots the machine has a higher overload capacity.

Q.10. (AMIE S17, 5 marks): What are the factors upon which specific electric loading (q) depends in design of an induction motor.

Q.11. (AMIE W14, S16, 8 marks): Why are crane-duty induction motors, generally designed for possible value, i.e., 0.65 Wb/m^2 of specific magnetic loading?

Q.12. (AMIE W17, 10 marks): How do you calculate the following for an induction motor?

(i) Area of stator slots

(ii) Length of mean turn

(iii) Stator teeth

Q.13. (AMIE W17, 10 marks): Discuss the effect on three-phase induction motor with the change of

(i) air gap length

(ii) number of poles

(iii) change of frequency

NUMERICALS

Q.14. (AMIE S12, 20 marks): Find the following for a 30 kW, 440 V, 3 phase, 4 pole, 50 Hz, delta-connected cage induction motor: (i) Main dimensions of stator frame (ii) Number of stator winding turns (iii) Number of stator slots (iv) Number of stator conductors per slot-Assume suitable data.

Q.15. (AMIE S14, 17, 12 marks): Determine the approximate diameter and length of the rotor core, the number of slots and the number of conductors for a 15 h.p. 400 V, 3-phase, 4-pole, 1425 r.p.m. induction motor. Adopt a specific magnetic loading of 0.45 Wb/m^2 and a specific electric loading of 230 ac/cm. Assume that a full load efficiency of 85 percent and a full load power factor of 0.88 will be observed.

Answer: D = 0.19 m; L = 0.152 m; conductors = 638; slots = 36

Q.16. (AMIE S14, 12 marks): A 25 h.p., 400 V. 50 c/s. three-phase wound rotor induction motor has the following data:

Rotor resistance per phase (including connections to starter) = 0.2 ohm

Full load rotor I^{2}R loss (total) = 750 W

Friction and windage losses = 350 W

Assuming that the starting current is not to exceed 1.25 limes full-load current, work out the steps in a 4-step rotor resistance starter for the above motor.

Answer: r_1 = 3.753 Ω; r_2 = 1.749 Ω; r_3 = 0.815 Ω; r_4 = 0.379Ω; r_m = 0.2 Ω

Q.17. (AMIE W15, 12 marks): Determine the approximate air gap diameter, rotor core length and the air gap length for a 3-phase, 20 hp, 400 V, 50 cps, 6-pole induction motor. Adopt specific magnetic loading of 4500 lines/cm^2 and specific electric loading of 230 ac/cm. Assume the ratio (core length)/(pole pitch) to be 0.85, the full load efficiency to be 88 percent and power factor at full-load to be 0.88. Also, assume the motor to be star-delta starting.

Answer: D = 29.8 cm; L = 13.27 cm; air gap length = 0.597 mm

Q.18. (AMIE W06, 16, 14 marks): Find the main dimension of stator frame and number of stator turns per phase of 30 kW, 440 V, 3-phase, 6 pole 50 Hz, delta connected cage induction motor. Assume specific magnetic loading 0.48 T, specific electric loading 26000 Amp cond/m, efficiency 0.88, power factor 0.86.

Answer: D = 33.4 cm; L = 17 cm; Number of stator turns = 155; number of stator slots = 162

Q.19. (AMIE S17, 10 marks): Determine the core and yoke dimensions for a 250 kVA, 50 Hz, l-ϕ, core type transformer. The voltage per turn (V_t) is 15 V/turn. The window space factor is 0.33, current density is 3 Amp/mm^2 and maximum flux density is 1.1 Wb/m^2. Given the distances between the centres of square section core is twice the width of the core.

Q.20. (AMIE W17, 10 marks): Find the main dimensions of a 15 kW, 3-phase, 400 V. 50 Hz, 2810 r.p.m. squirrel cage induction motor having an efficiency of 0.88 and a full load power factor of 0.9.

Assume

specific magnetic loading = 0.5 wb/m^2

specific electric loading = 25000 A/m

Take the rotor peripheral speed as approximately 20 m/s at synchronous speed.

Answer: D = 0.1257 m; L = 0.177 m

Hint: KVA = 15/0.88 x 0.9 = 18.94; round 2810 as 3000 rpm

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