LNCT GROUP OF COLLEGES

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Subject: Electrical Machine Design

Unit: 04

Topic: Design of Three Phase Induction Motors

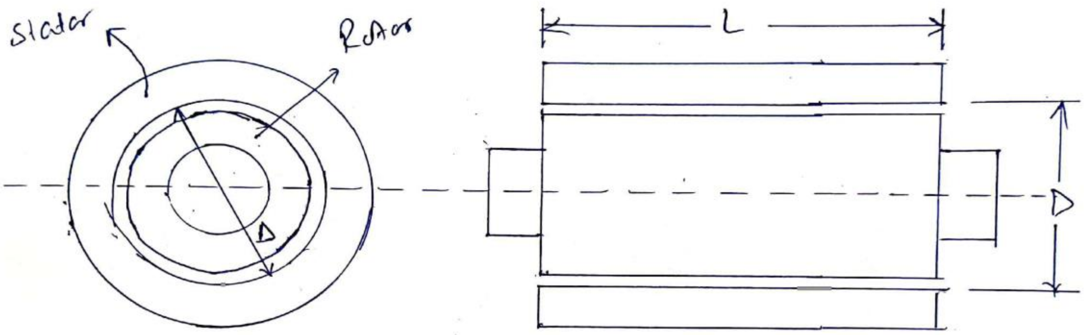
UNIT-04/LECTURE- 01
SUBJECT: ELECTRICAL MACHINE DESIGN
TOPIC: OUTPUT EQUATION OF INDUCTION MOTOR

UNIT – 4

Design of Three-phase Induction motor

Main Dimensions:

The armature diameter (stator bore) D and armature core length L are known as the main dimensions of a rotating machine.



Main dimensions D and L

TOTAL LOADINGS:

> Total magnetic Loading:- The total flux around the armature (or stator) periphery at the air gap is called the total magnetic loading

$$B_{av} = P\phi$$

> Total electric loading:- The total number of ampere conductors around the armature (or stator) periphery is called the total electric loading.

$$ac = I_z Z.$$

* SPECIFIC LOADINGS:-

> **Specific magnetic loading:-** The average flux density over the air gap of a machine is known as specific magnetic loading.

$$B_{av} = \frac{\text{total flux around the air gap}}{\text{area of flux path at the air-gap}} = \frac{P\phi}{\pi DL}$$

> **Specific Electric loading:-** The number of armature (or stator) ampere conductors per meter of armature (or stator) periphery at the air gap is known as specific Electric loading.

$$ac = \frac{\text{total armature ampere Conductors}}{\text{armature periphery at air gap}} = \frac{I_z Z}{\pi D}$$

* OUTPUT EQUATION:-

Let:-

V_{ph} = Phase voltage , I_{ph} = Phase Current

Z_{ph} = No. of Conductors/phase , T_{ph} = No. of turns/Phase

N_s = Synchronous speed in rpm, n_s = synchronous speed in rps

(small) P = No. of poles , B_{av} = Average flux density

ϕ = air gap flux/pole , ac = Specific Electric loading

K_w = Winding factor ; η = efficiency

D = Diameter of the Stator, L = Gross Core length

C_o = output Co-efficient, $\cos\phi$ = Power factor

Consider an 'm' phase machine, with usual notations

output Q in kW = Input $\times$ efficiency

Input to motor = $m\, V_{ph} I_{ph} \cos\phi \times 10^{-3}$ kW

for a $3-\phi$ machine, $m = 3$

Input to motor $= 3 V_{ph} I_{ph} \cos\phi \times 10^{-3}$ kW

Assuming $V_{ph} = E_{ph} = 4.44 f \phi T_{ph} K_w$

$= 2.22 f \phi Z_{ph} K_w$

$\therefore$ output $= 3 \times 2.22 \times \frac{P n_s}{2} \times \phi Z_{ph} K_w \times I_{ph} \eta \cos\phi \times 10^{-3}$ kW

output $= 1.11 \times P\phi \times 3 I_{ph} Z_{ph} \times n_s K_w \eta \cos\phi \times 10^{-3}$ kW

$\because P\phi = B_{av} \pi D L$ and $\frac{3 I_{ph} Z_{ph}}{\pi D} = ac$

Output to motor $= [1.11 \times B_{av} \pi D L \times \pi D ac \times n_s K_w \eta \cos\phi \times 10^{-3}]$ kW

$Q = [(1.11 \pi^2 B_{av} ac K_w \eta \cos\phi \times 10^{-3}) D^2 L n_s]$ kW

$Q = (11 B_{av} ac K_w \eta \cos\phi \times 10^{-3}) D^2 L n_s$ kW

$\therefore$ output $\boxed{Q = C_o D^2 L n_s}$ kW

where $C_o = (11 B_{av} ac K_w \eta \cos\phi \times 10^{-3})$

C_o is called as output co-efficient.

* CHOICE OF SPECIFIC LOADINGS :-

1) Specific magnetic loadings :-

(i) Power factor :- poor power factor for high flux density in air gap.

(ii) Iron loss :- Iron losses Increase with Increase in flux density.

(iii) Overload Capacity :- overload capacity Increase with Increase in flux density

> Limitations :-

(i) flux density in teeth < 1.8 Tesla

(ii) flux density in core - 1.3 – 1.5 Tesla.

* Advantage of the Higher value of B_{av} :-

(i) Size of the machine reduced.

(ii) Cost of the machine decreases.

(iii) Overload capacity Increases.

for 50 Hz machine the value of B_{av} lies between 0.35 - 0.6 Tesla

2) Specific Electric loading :-

(i) Copper loss and temperature rise :

A large value of ac gives higher copper losses and large temperature rise.

(ii) Voltage : for high voltage machine value of ac should be small.

(iii) Overload Capacity: overload capacity decreased with high value of ac.

The value of ac depends upon the size of the motor, voltage of stator winding, type of ventilation and overload capacity desired.

It varies between 5000 - 45000 ampere conductors per meter.

Seperation of D and L :-

The output equation gives the relation between D^2L and output of the machine. To seperate D and L for this product a relation has to be assumed. following are the various design considerations based on which a suitable ratio between gross length and pole pitch (L/τ) assumed.

a) To obtained minimum over all cost - 1.5 to 2.0

b) To obtained good efficiency - 1.4 to 1.6

c) To obtained good over all design - 1.0 to 1.1

d) To obtain good Power factor - 1.0 to 1.3

* Power factor plays a very Important role in the Performance of Induction motors. Hence to obtain the best power factor the following relation will be usually assumed for seperation of D and L

Pole pitch / core length = 0.18 / pole pitch
↳ (for best power factor, $\tau = \sqrt{0.18L}$)

or $(\pi D/p)/L = 0.18(\pi D/p)$

ie $\boxed{D = 0.135\, p\sqrt{L}}$ --- (where D & L are in meter)

* The value of L/τ lies between 0.6 to 2. depending upon the size of machine.

* **Peripheral Speed :-**

> Standard construction = upto 60 m/s
> Special rotor construction = upto 75 m/s

For a normal design, the diameter should be so chosen that the peripheral speed does not exceed about 30 m/s.

* **Turns per phase :-**

flux per pole $\phi_m = B_{av} \times \frac{A}{P}$ --- (A/p = area per pole)

$= B_{av} \times (\pi DL/p)$ ... ($A = \pi DL$) → area

$= B_{av} \times \tau L$ ... ($\because \tau = \pi D/p$)

where, B_{av} : specific magnetic loading

A = area = πDL

P = no. of poles

τ = pole pitch

stator voltage per phase,

$$E_{ph} = 4.44 f \phi_m T_{ph} K_w$$

where,

f = frequency in Hz

ϕ_m : flux per pole

T_{ph} = no. of turns per phase in stator

K_w : winding factor $= K_c \times K_d = 0.955$ (assumed)

$\therefore$ stator turns per phase, T_{ph}

$$\boxed{T_{ph} = \frac{E_{ph}}{4.44 f \phi_m K_w}}$$

#) Area of each stator conductor, $a_s = \dfrac{I_s}{\delta_s}$

> Stator current per phase, $I_s = \dfrac{\text{Input kVA}}{3 E_s}$

> Current density in stator, $\delta_s = 3$ to 5 A/mm.

> Input kVA $Q = \dfrac{kW}{\eta \cos\phi}$

> Input kVA $Q = \dfrac{hp \times 0.746}{\eta \cos\phi}$

> $K_w = 0.955$

Example. Determine the approximate diameter and length of stator core for a 11 KW, 400V, 3-ϕ, 4-pole, 1425 rpm, delta connected induction motor. $B_{av} = 0.45\ Wb/m^2$, ac = 23000 ampere conductors. full load efficiency = 0.85, P.f = 0.88, $L/\tau = 1$.

Given data :

11 KW	delta connected	1425 rpm
3-ϕ	double layer winding	$B_{av} = 0.45\ Wb/m^2$
4-pole	ac = 23000 amp. conductor	PF = 0.88
400 V	$\eta = 0.85$	$L/\tau = 1$

Solution :-

$$\text{KVA Input} = \frac{\text{output}}{\eta \times P.f} = \frac{11}{0.85 \times 0.88} = 14.7\ \text{KVA}$$

Synchronous speed, $n_s = \frac{2f}{P} = \frac{2 \times 50}{4} = 25$ rps.

Let $K_w = 0.955$

$$C_o = 11\ K_w B_{av}\ ac \times 10^{-3}$$

$$= 11 \times 0.955 \times 0.45 \times 23000 \times 10^{-3}$$

$$= 108.72$$

KVA Input, $Q = C_o D^2 L n_s$

$$\therefore D^2 L = \frac{Q}{C_o n_s} = \frac{14.7}{108.72 \times 25} = 0.0054\ m^3$$

$\therefore \; D^2L = 0.0054 \; m^3$

Condition :-

Given that, $L/\tau = 1$

$\therefore \; L = \tau = \frac{\pi D}{p}$

Put, $L = \frac{\pi D}{p}$ in equation for D^2L

$\therefore \; D^2L = \frac{D^2(\pi D)}{p} = 0.0054$

or $D^3 \frac{\pi}{p} = 0.0054$

$\therefore \; D = 0.1902 \; m$

Now, $L = \frac{\pi D}{p} = \frac{\pi \times 0.1902}{4} = 0.1494 \; m$

$\therefore \; \boxed{D = 0.19 \; m \quad \text{and} \quad L = 0.15 \; m}$

STATOR DESIGN

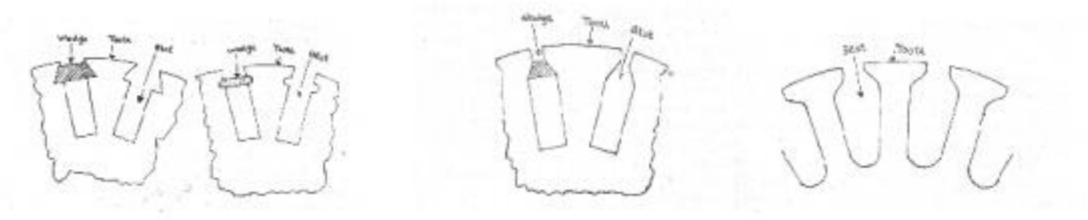
Stator Slots:

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

(i) **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.

(ii) **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.

(iii) **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.



(i) Open type (ii) Semiclosed type (iii) Tapered type

Fig. 10 Different types type slots

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. As there are no rules for selecting the number of stator slots, the advantages and disadvantages of selecting higher number slots help to serve as guidelines in the selection. 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

The number of slots / pole / phase should not be less than 2 otherwise the leakage reactance becomes high. The number of slots should be selected to give an integral number of slots per pole per phase. The stator slotpitch at the air gap surface should be between1.5 to 2.5 cm.

Stator slot pitch at the air gap surface = $\tau_{ss} = \frac{\pi D}{Sss}$

Where S_{ss} is the number of stator slots

Turns per phase:

EMF equation of an induction motor is given by

$$Eph = 4.44\, f\, \Phi\, T_{ph}\, K_w$$

Hence turns per phase can be obtained from emf equation

$$T_{ph} = \frac{Eph}{4.44\, f\, \Phi m\, Kw}$$

Generally the induced emf can be assumed to be equal to the applied voltage per phase

Flux/pole, $\Phi m = \frac{Bav * \pi DL}{p}$

Winding factor K_W may be assumed as 0.955 for full pitch distributed winding unless otherwise specified.

Number conductors / phase, $Z_{ph}= 2xT_{ph}$, and hence Total number of stator conductors $Z=6*T_{ph}$ and conductors/slot $Z_S=Z/S_S$ or $6*T_{ph}/S_S$

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 $a_S=I_S / \delta s$, *where* δs is the current density in stator windings

Stator current per phase, Is=Q / (3VphcosΦ)

A suitable value of current density has to be assumed considering the advantages and disadvantages.

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

- Higher value is assumed for low voltage machines and small machines. Usual value of current density for stator windings is 3 to 5 amps/mm^2.

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.

Length of the mean Turn:

Length of the mean turn is calculated using formula

$$L_{mt} = 2L+2.3\tau+0.24$$

Where L is the gross length of the stator and τ is pole pitch in meter.

Depth of stator core below the slots: There will be certain solid portion below the slots in the stator which is called the depth of the stator core. The flux density in the stator core lies between 1.2 to 1.4 Tesla. The flux passing through the stator core is half of the flux per pole.

Flux in the stator core section, $\Phi c = \frac{\Phi m}{2}$

Area of stator core, $Ac = \frac{\Phi c}{2Bc} = \frac{flux\ through\ core}{Flux\ density\ in\ stator\ core}$

Area of stator core, $Ac = L_i \times d_{cs}$

Hence, depth of the core $(d_{cs}) = \frac{Ac}{Li} = \frac{\Phi c}{2Bc * Li}$

Using the design data obtained so far outer diameter of the stator core can be calculated as

$D_o = D+2(\text{depth of stator slots} + \text{depth of core})$

$D_o = D+2d_{ss}+2d_{cs}$

Length of air gap:

The magnetizing current of the motor depends on the specific magnetic loading and the air gap length of the machine. A large air-gap length leads to higher magnetizing current and poor power factor.

A large air-gap length increases the reluctance of the path of the magnetic flux. The reluctance of the magnetic circuit is similar to the resistance of the electric circuit. The reluctance of a magnetic circuit is;

$$R = MMF/\Phi \quad \text{-----(1)}$$

Also,

$$R = L/\mu A \quad \text{-------(2)}$$

$$MMF = R\Phi$$

$$\Phi = MMF/R$$

$$\Phi = MMF*(\mu A/L) \quad \text{-----(3)}$$

Where,

R = Reluctance of the magnetic circuit

MMF = Magnetomotive force(MMF=NI)

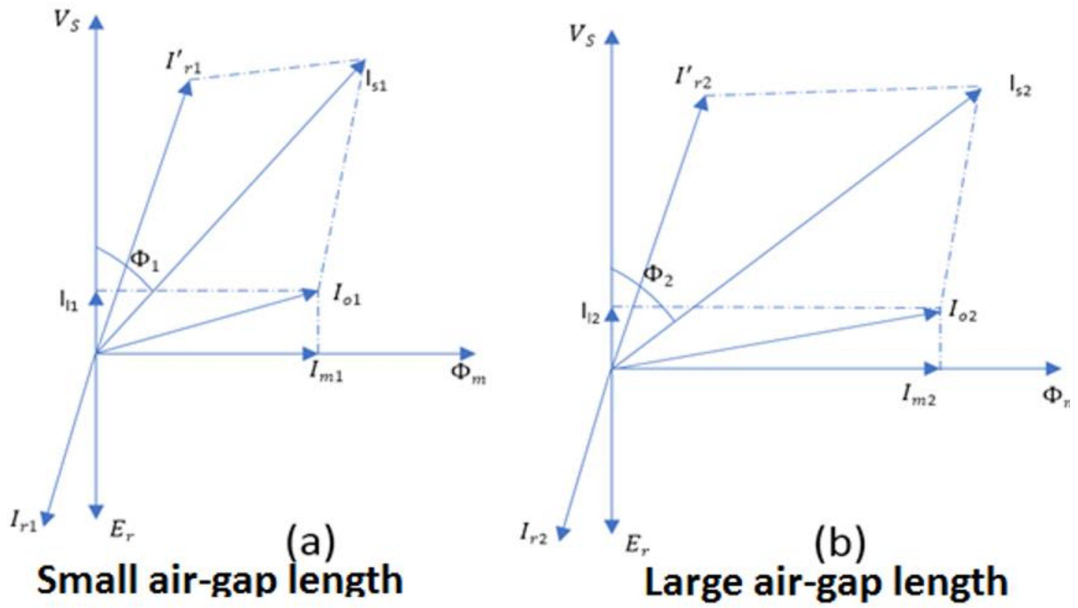
L = length of the air gap

Φ = Flux in the air gap

μ = Permeability of the magnetic material

From equation (3), it is clear that the MMF required for producing and sending the flux through the air gap depends on the flux density and the air-gap length.

If the air gap length is increased, the reluctance of the magnetic circuit will increase. This increase in the reluctance will demand more magneto-motive force to produce the required flux in the motor. To meet the additional requirement of MMF, the stator magnetizing current increases. The power factor of the motor gets worsens with an increase in magnetizing stator current. The phasor diagram of the motor having small and large air gap length is as shown below. The relationship between the air gap length and the power factor can be well understood with the following phasor diagram.



The air gap length in fig (b) is more than the air gap in fig (a). The angle between the applied voltage and the stator current is more in fig (b) than in fig (a).With increase in air gap length, the more magnetizing current is required to produce the rated flux in the magnetic core, and the phase angle between the applied voltage and the magnetizing current increases. As a result, power factor becomes low.

Overload Capacity:

The leakage flux is reduced with an increase in air gap length. The flux produced in the stator winding gets almost fully coupled with the rotor winding if the air gap length is more. Therefore, the overload capacity of a large air gap length motor is more than the overload capacity of the motor that has a small air gap length. With an increase in the air gap length, the leakage reactance decrease and the overload capacity increase.

Cooling:

With large air gap length, the stator and the rotor are separated by large distance so cooling is better. The copper loss (I^2*R Loss) takes place in the stator and rotor winding and, the iron loss takes place in the core. The heat is easily transferred if the motor has large air gap. The insulation of the winding can be used of H class or F class with temperature rise limit to B class if the air gap length is more.

Noise:

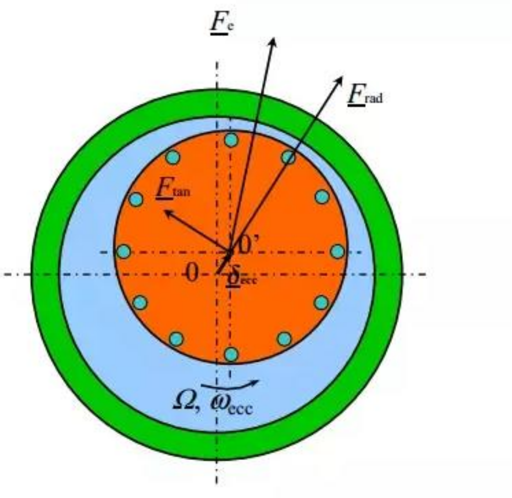
The leakage flux gets reduced with large air gap length. The less noise is generated in the motor that has more air gap length.

Tooth pulsation loss:

The tooth pulsation loss reduces in a large air gap length motor because of small variation in the reactance of air gap.

Unbalanced Magnetic Pull (UMP):

An unequal air gap causes unbalanced magnetic pull. The unbalanced magnetic pull acts in the direction of shortest air gap.



The unbalanced magnetic pull can be minimized by tight tolerances or by making the air gap large within all design constraints.

The motor with small air gap length draws less magnetizing current, and the power factor of the motor is better than the motor having large air gap length.

What should be the optimum air gap length?
Unlike in a transformer, it is impossible to have zero air gap for rotating machine. The rotating machine must have the air gap for its rotation. The optimum air gap of an induction motor can be expressed by the following empirical formula.

lg = 0.2 + 2√ LD mm

Where,

lg = Air gap Length (mm)
L = Stator core Length(Meter)
D = Internal diameter of the Stator core(Meter)

Example:

If the stator core length and diameter is 0.18 meter and 0.34 meter respectively, the air gap length between the stator and the the rotor

$$lg = 0.2 + 2\sqrt{LD} \quad mm$$
$$= 0.2 + 2\sqrt{0.18*0.34}$$
$$= 0.2 + 0.494$$
$$= 0.694 \ mm$$

The designer keeps the minimum air gap length in the ***energy efficient motors*** to improve the power factor and to reduce the no load losses in the motor.

CHOICE OF ROTOR SLOTS FOR SQUIRREL CAGE MACHINES:

With certain combinations of stator and rotor slots, the following problems may develop in the induction motor.

- The motor may refuse to start.
- The motor may crawl at some subsynchronous speed.
- Severe vibrations are developed and so the noise will be excessive.

The above effects are due to harmonic magnetic fields developed in the machine. The harmonic fields are due to winding, slotting, saturation and irregularities in air gap.

The squirrel cage rotor will circulate currents due to any harmonic emf produced by the gap flux except that has a wavelength equal to the pitch of the bars. The effects of space harmonic fields produced by windings are greatly intensified by slotting. The slots introduces steps in the mmf wave and produces further harmonics and also modulates the gap flux. Hence the choice of rotor slots is particularly important in the case of squirrel cage machines. Any bad combination of stator and rotor slots may result in awkward behaviour.

NOTE:

1. **CRAWING**

If the mechanical load on the shaft requires a constant load torque and if the torque developed by the rotor is below this load torque then the motor cannot accelerate upto its full speed but continues to run at a speed little lower than $1/7^{th}$ synchronous speed. This condition of a motor is called crawling.

2. **COGGING**

When the number of rotor slots is equal to the number of stator slots, the speeds of all the harmonics produced by stator slotting coincide with the speed of corresponding rotor harmonics. Thus harmonics of every order would try to exert synchronous torques at their corresponding synchronous speeds and the machine would refuse to start. This is known as cogging.

RULES FOR SELECTING ROTOR SLOTS OF SQUIRREL CAGE MACHINES

Selection of number of rotor slots: The number of rotor slots may be selected using the following guidelines.

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

(ii)To avoid synchronous hooks and cusps in torque speed characteristics $S_s - S_r \neq P, 2P, 5P$.

(iii)To noisy operation $S_s - S_r \neq 1, 2, (P\pm1), (P\pm2)$

Where, S_s = Number of stator slots,

S_r = Number of rotor slots

Rotor Bar Current: Bar current in the rotor of a squirrel cage induction motor may be determined by comparing the mmf developed in rotor and stator. The stator mmf is about 15% higher because of the magnetizing mmf.
Rotor mmf = 0.85*(stator mmf)
Number of rotor bars = N_b = Sr = number of rotor slots
Rotor bar current = I_b

Rotor mmf = $\frac{\text{Ib.Sr}}{2}$

Stator mmf = 3.Is.Ts

Thus $\frac{\text{Ib.Sr}}{2}$ = 0.85*(3.Is.Ts) or I_b = 0.85* $\frac{6*\text{Is}*\text{Ts}}{Sr}$

Cross sectional area of Rotor bar: Sectional area of the rotor conductor can be calculated by rotor bar current and assumed value of current density for rotor bars. As a guideline the rotor bar current density can be assumed between 4 to 7 Amp/mm^2.
Hence sectional area of the rotor bars can be calculated as

$$A_b = I_b/\delta_b \text{ mm}^2$$

Shape and Size of the Rotor slots: Generally semi-closed slots or closed slots with very small or narrow openings are employed for the rotor slots. In case of fully closed slots the rotor bars are force fit into the slots from the sides of the rotor.

The rotors with closed slots are giving better performance to the motor in the following way:

(i) As the rotor is closed the rotor surface is smooth at the air gap and hence the motor draws lower magnetizing current.
(ii) Reduced noise as the air gap characteristics are better.
(iii) Increased leakage reactance.
(iv) Reduced starting current.
(v) Over load capacity is reduced.
(vi) Undesirable and complex air gap characteristics.

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

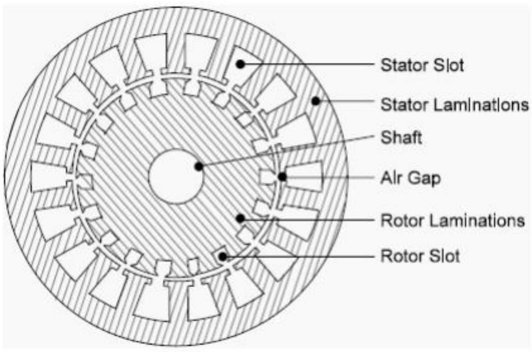


Fig. 11 Semiclosed slots

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

Length of rotor bar lb = L + allowance for skewing

Rotor bar resistance = 0.021 x $\frac{lb}{Ab}$

Copper loss in rotor bars = I_b^2 * r_b * number of rotor bars

End Ring Current: All the rotor bars are short circuited by connecting them to the end rings at both the end rings. As the rotor is a short circuited, there will be current flow because of induced emf in the rotor bars. The distribution of current and end rings are as shown in Fig. Considering the bars under one pole pitch, half of the number of bars and the end ring carry the current in one direction and the other half in the opposite direction. Thus the maximum end ring current may be taken as the sum of the average current in half of the number of bars under one pole.

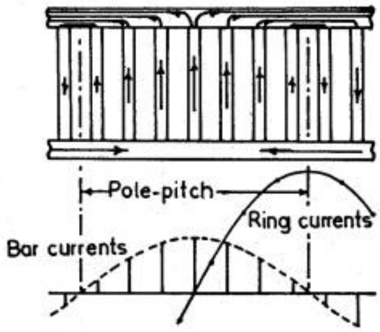


Fig. currents in cage rotor bars and end rings

Maximum end ring current I_e(max) = *(Number of bars over half a pole pitch)* $I_b(av)$

$= \frac{1}{2}$ (Number rotor bars / pole) $I_b(av)$

$= \frac{1}{2}\ \frac{Sr}{P}$ x I_b(av)

Hence the rms value of Ie = $\frac{1}{2\sqrt{2}}$ x $\frac{Sr}{P}$ x $\frac{Ib}{1.11}$ …….. (I_{rms} = 1.11 x I_{avg} & 1.414 x I_{rms} = I_{max})

$= \frac{1}{\pi}$ x $\frac{Sr}{P}$ x $\frac{Ib}{1.11}$

Area of end ring: Knowing the end ring current and assuming suitable value for the Current density in the end rings cross section for the end ring can be calculated. Current density in the end ring may be assumed as 4.5 to 7.5 amp/mm^2.

Area of each end ring, *Ae = Ie/δe mm^2*

Ae = te x de where, te = thickness of end ring and de=depth of end ring

Fig for end ring is shown below:

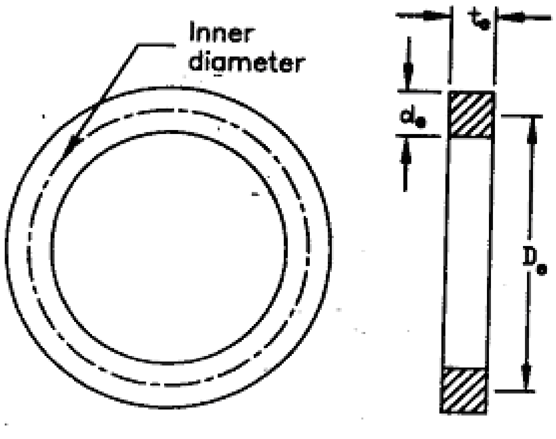


Fig. Dimensions of end ring.

Copper loss in End Rings: Mean diameter of the end ring (*Dme)* is assumed as 4 to 6 cms less than that of the rotor. Mean length of the current path in end ring can be calculated as *lme* = π*Dme*. The resistance of the end ring can be calculated as

$$re = 0.021 \times \frac{lme}{Ae}$$

Total copper loss in end rings = 2 x Ie^2 x *re*

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

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

Design of wound Rotor

These are the types of induction motors where in rotor also carries distributed star connected 3 phase winding. At one end of the rotor there are three slip rings mounted on the shaft. Three ends of the winding are connected to the slip rings. External resistances can be connected to these slip rings at starting, which will be inserted in series with the windings which will help in increasing the torque at starting. Such type of induction motors are employed where high starting torque is required.

Number of rotor slots: The number of rotor slots should never be equal to number of stator slots. Generally for wound rotor motors a suitable value is assumed for number of rotor slots per pole per phase, and then total numbers of rotor slots are calculated. So selected number of slots should be such that tooth width must satisfy the flux density limitation. Semi closed slots are used for rotor slots.

Number of rotor Turns: The voltage between the sliprings on open circuit must be limited to safety values. In general the voltage between the slip rings for low and medium voltage machines must be limited to 400 volts. For motors with higher voltage ratings and large size motors this voltage must be limited to 1000 volts. Based on the assumed voltage between the slip rings comparing the induced voltage ratio in stator and rotor, the number of turns on rotor winding can be calculated:

Voltage ratio, $\frac{Er}{Es} = \frac{Kwr \times Tr}{Kws \times Ts}$

Hence rotor turns per phase, $Tr = \frac{Er}{Es} \times \frac{Kws \times Ts}{Kwr}$

Er = open circuit rotor voltage/phase
Es = stator voltage/phase
Kws = winding factor for stator

Kwr = winding factor for rotor
Ts = Number of stator turns/phase

Rotor Current and conductor section
Assuming rotor mmf = 0.85 * stator mmf
2 x 3 x Ir.Tr = (0.85)2 x 3 x Is.Ts
Rotor current per phase Ir = (0.85)Is.Ts/T
Rotor conductor area Ar = Ir/δr
The current density could be taken as 3 to 5 A/mm^2

Rotor Current

Rotor current can be calculated by comparing the amp-cond on stator and rotor

$$Ir = (Kws \times Ss \times Z's) \times I'r / (Kwr \times Sr \times Z'r);$$

Kws – winding factor for the stator,

Ss – number of stator slots,

Z's – number of conductors / stator slots,

Kwr – winding factor for the rotor,

Sr – number of rotor slots,

Z'r – number of conductors / rotor slots and

I'r – equivalent rotor current in terms of stator current

$I'r = 0.85\, Is$ where *Is* is stator current per phase

Area of Rotor Conductor: Area of rotor conductor can be calculated based on the assumed value for the current density in rotor conductor and calculated rotor current. Current density rotor conductor can be assumed between 4 to 6 Amp/mm^2

$$Ar = Ir / \delta r \qquad mm2$$

Ar< 5mm2 use circular conductor, else rectangular conductor, for rectangular conductor width to thickness ratio = 2.5 to 4. Then the standard conductor size can be selected similar to that of stator conductor.

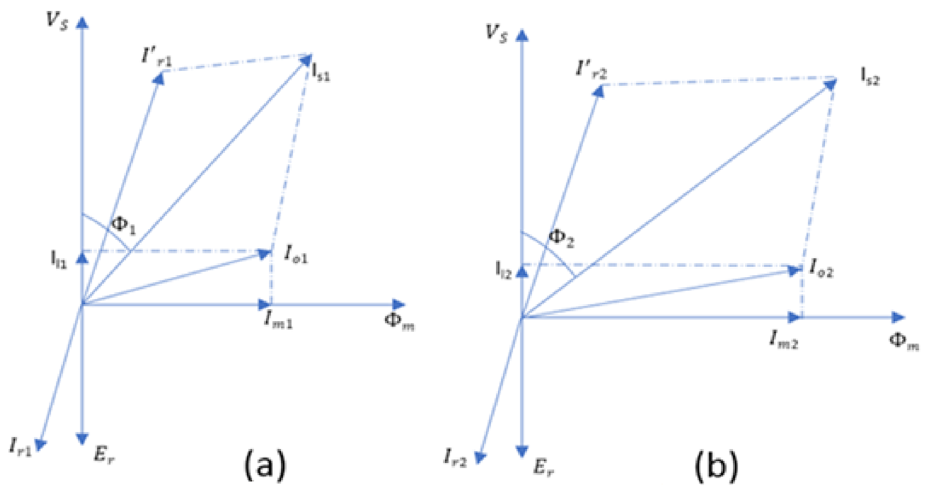
Size of Rotor slot: Mostly Semi closed rectangular slots employed for the rotors. Based on conductor size, number conductors per slot and arrangement of conductors similar to that of stator, dimension of rotor slots can be estimated. Size of the slot must be such that the ratio of depth to width of slot must be between 3 and 4.

Total copper loss: Length of the mean Turn can be calculated from the empirical formula,

$$l_{mt} = 2L + 2.3\ \tau_p + 0.08 \text{ m}$$

Resistance of rotor winding is given by Rr = (0.021 x l_{mt} x Tr) / Ar Total copper loss = 3 Ir^2 Rr Watts

No load current of Induction motor:



As seen from the figure, no load current of an induction motor has two components magnetizing component, Im and iron loss component, Iw.

Thus the no load current, $I_0 = \sqrt{(Im)^2+(Iw)^2}$ amps

Magnetizing current:

Magnetizing current of an induction motor is responsible for producing the required amount of flux in the different parts of the machine. Hence this current can be calculated from all the magnetic circuits of the machine. Based on the total ampere turns of the magnetic circuit the magnetizing current can be calculated as

$$\text{Magnetizing current, } I_m = pAT_{30} / (1.17\ k_w\ T_{ph})$$

Where, p – no. of pairs of poles, AT_{30} = Total ampere turns of the magnetic circuit at 30^o from the centre of the pole, T_{ph} – Number of stator turns per phase.

Iron loss component of current:

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

$$\text{Iron loss component of current, } I_w = \text{Total no load losses} / (3 \times \text{phase voltage})$$

No load Power Factor:

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

$$\text{No load power factor } \cos\Phi_o = I_w / I_o$$

Leakage reactance:

Leakage factor or Leakage coefficient LC.

All the flux produced by the pole will not pass through the desired path i.e., air gap. Some of the flux produced by the pole will be leaking away from the air gap. The flux that passes through the air gap and cut by the armature conductors is the useful flux and that flux that leaks away from the desired path is the leakage flux

Thus $\phi_p = \phi + \phi_l$

As leakage flux is generally around (15 to 25) % of ϕ,

$$\phi_p = \phi + (0.15 \text{ to } 0.25)\ \phi$$
$$= LC \times \phi$$

where LC is the Leakage factor or Leakage coefficient and lies between (1.15 to 1.25). Magnitude of flux in different parts of the magnetic circuit.