

#### 4.7 Computer program: Design of slip-ring rotor

##### Problem:

Design a 30HP, 3 phase, 440V, 960 r.p.m, 50Hz, delta connected squirrel cage induction motor. Assume specific electric loading 25000, specific magnetic loading .46 Wb /m<sup>2</sup>full load efficiency 86% power factor = 0.87 calculate the following

- i) Stator core dimension D and L
- ii) Number of stator slots and winding turns

##### Solution:

$$P_o = 30\text{HP} = 30 \times .746\text{kW}$$

$$\text{eff} = 86\% = 0.86$$

$$\text{p.f.} = .87$$

$$\text{therefore input k.V.A} = 30 \times .746 / (.86 \times .87) = 29.92\text{k.V.A}$$

We also have  $a_c = 25000$

$$B_{av} = .46\text{Wb}$$

$$K_w = .9 \text{ as always}$$

$$C_o = 1.11 \times \pi^2 \times B_{av} \times a_c \times K_w \times 10^{-3} = 1.11 \times 3.14 \times 3.14 \times .46 \times 25000 \times .9 \times 10^{-3} = 120.3$$

$$\text{Now as } N = 960\text{r.p.m so } N_s = N/60 = 16.67 \text{ r.p.s}$$

$$\text{So number of poles} = 2f/N_s = 6$$

$$\text{kVA} = C_o \times N_s \times D^2 \times L$$

$$\text{so } D^2L = 29.91 / (120.3 \times 16.67) = .015\text{m}^3$$

$L/\tau = 1$  considering a good overall design

$$\text{where } \tau = \pi \times D / \text{Pole}$$

$$L \times \text{Pole} / (\pi \times D) = 1$$

Substituting  $L = .015/D^2$  and rearranging

we have  $D^3 = .015 \cdot 6 / 3.14 = .028 \text{m}^3$

So  $D = .3 \text{m}$

hence  $L = .015 / D^2 = .16 \text{m}$

So we get peripheral speed  $V_a = \pi \cdot D \cdot N_s = 3.14 \cdot .3 \cdot 16.67 = 15.6 \text{m/sec}$

so as  $V_a$  is less than  $30 \text{m/sec}$  hence these dimensions are permissible.

Now  $B_{av} = \text{Pole} \cdot \Phi_m / (\pi \cdot D \cdot L)$  giving us

$\Phi_m = B_{av} \cdot \pi \cdot D \cdot L / \text{Pole} = .46 \cdot 3.14 \cdot .16 \cdot 3 / 6$

$\Phi_m = .0115 \text{Wb}$

Number of stator turns  $T_s = E_s / (4.44 \cdot f \cdot \Phi_m \cdot K_{ws}) = 440 / (4.44 \cdot 50 \cdot .0115 \cdot .955)$  so  $T_s = 180$

Total number of stator pole per phase per pole  $S_s = 3 \cdot \text{pole} \cdot \text{phase} = 3 \cdot 6 \cdot 3 = 54$

Slot pitch =  $Y_{ss} = \pi \cdot D / S_s = 3.14 \cdot .3 / 54 = .017$

So  $Z_{ss} = 6 \cdot T_{ph} = 1080$

Number of slot =  $1080 / 54 = 20$

**Program:**

function design\_squirrel\_cage\_induction\_motor

$P_o = 30 \cdot .746$ ; %kw

$V_{in} = 440$ ;

$N = 960$ ;

$N_s = N / 60$ ;

$f = 50$ ;

$B_{av} = .46$ ;

$\text{pf} = .87$ ;

eff = .86;

ac = 25000;

Kws = .955;

phase = 3;

%rating in kVA

Q = Po/(eff\*pf);

Kw = .9;

fprintf('\nProgram to design squirrel cage induction motor'); fprintf('\n—————  
—————');

Co = 1.11\*pi\*pi\*Bav\*ac\*Kw\*(10^-3);

%number of poles

pole = (2\*f)/Ns;

%Q = Co\*Ns\*D2L

fprintf('\nInput power or rating power = ');

disp(Q);

D2L = Q/(Co\*Ns);

%for good overall design

%L/tow = 1

%L\*pole/pi\*D

D3 = (Q\*pole)/(Co\*Ns\*pi);

D = D3^(1/3);

fprintf('\nHence Diameter D = ');

disp(D);

```
fprintf('\nHence Length L = ');  
  
L = pi*D/(pole);  
  
disp(L);  
  
%peripheral speed Va  
  
Va = pi*D*Ns;  
  
fprintf('\nPeripheral speed = ');  
  
disp(Va);  
  
if(Va<30)  
  
fprintf('\nAs Peripheral speed is less than 30m/secs so dimensions are permissable');  
  
else  
  
fprintf('\nAs Peripheral speed is not less than 30m/sec the dimensions are not  
permissable. But still the dimensions will be');  
  
end  
  
phim = Bav*pi*D*L/pole;  
fprintf('\nFlux density phim = ');  
disp(phim);  
  
%number of stator turns Ts  
  
Ts = Vin/(4.44*f*phim*Kws);  
  
fprintf('\nNumber of stator turns Ts = ');  
  
disp(round(Ts));  
  
%total number of stator slot per phase per pole Ss  
  
Ss = 3*pole*phase;  
  
fprintf('\nTotal number of stator slot per phase per pole Ss');
```

```
disp(Ss);  
fprintf('\nSlot pitch Yss = ');  
Yss = pi*D/Ss;  
disp(Yss);  
Zss = 6*round(Ts);  
fprintf('\nTotal Coconductors Zss = ');  
disp(Zss);  
fprintf('\nNumber of Slots = ');  
noofslots = Zss/Ss;  
disp(noofslots);  
end
```

**Output:**

Input power or rating power = 29.9118

Hence Diameter  $D = 0.3201$

Hence Length  $L = 0.1609$

Peripheral speed = 16.0904

As Peripheral speed is less than 30m/secs so dimensions are permissible

Flux density  $\phi_{im} = 0.0119$

Number of stator turns  $T_s = 174$

Total number of stator slot per phase per pole  $S_s = 56.2500$

Slot pitch  $Y_{ss} = 0.0179$

Total Coconductors  $Z_{ss} = 1044$

Number of Slots = 18.5600

## 4.5 Magnetic leakage calculations & Operating characteristics

### Magnetic leakage calculations

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

$$\phi_P = \phi + \phi_l$$

As the leakage flux is generally around (15 to 25)% of  $\phi$ ,

$$\phi_P = \phi + (0.15 \text{ to } 0.25)\phi$$

$$\phi_P = \phi * LC$$

and that flux that leaks away from the desired path is the leakage flux 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.

### Leakage reactance of polyphase machines:

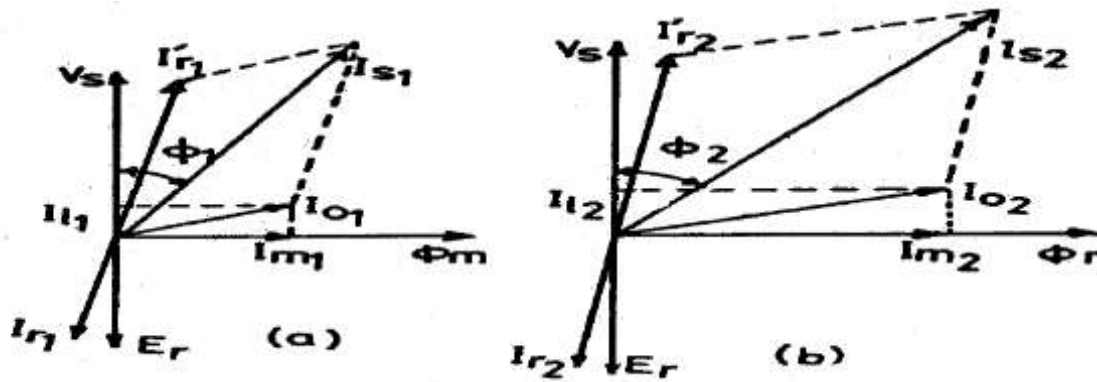
$$\text{Leakage reactance} = 2\pi f \times \text{inductance} = 2\pi f \times \text{Flux linkage} / \text{current}$$

Note:

1. Useful flux: It is the flux that links with both primary and secondary windings and is responsible in transferring the energy Electro-magnetically from primary to secondary side. The path of the useful flux is in the magnetic core.
2. Leakage flux: It is the flux that links only with the primary or secondary winding and is responsible in imparting inductance to the windings. The path of the leakage flux depends on the geometrical configuration of the coils and the neighboring iron masses.

### Magnetizing current:

Effect of magnetizing current and its effect on the power factor can be understood from the phasor diagram of the induction motor shown in Fig.



**Figure 4.5.1 Phasor diagram of induction motor**

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-10.48]

Magnetizing current and power factor being very important parameters in deciding the performance of induction motors, the induction motors are designed for optimum value of air gap or minimum air gap possible. Hence in designing the length of the air gap following empirical formula is employed.

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### 4.3 Choice of specific loadings

#### Specific magnetic loading:

Following are the factors which influences the performance of the machine.

**(i) Iron loss:**

A high value of flux density in the air gap leads to higher value of flux in the iron parts of the machine which results in increased iron losses and reduced efficiency.

**(ii) Voltage:**

When the machine is designed for higher voltage space occupied by the insulation becomes more thus making the teeth smaller and hence higher flux density in teeth and core.

**(iii) Transient short circuit current:**

A high value of gap density results in decrease in leakage reactance and hence increased value of armature current under short circuit conditions.

**(iv) Stability:**

The maximum power output of a machine under steady state condition is indirectly proportional to synchronous reactance. If higher value of flux density is used it leads to smaller number of turns per phase in armature winding. This results in reduced value of leakage reactance and hence increased value of power and hence increased steady state stability.

**(v) Parallel operation:**

The satisfactory parallel operation of synchronous generators depends on the synchronizing power. Higher the synchronizing power higher will be the ability of the machine to operate in synchronism. The synchronizing power is inversely proportional to the synchronous reactance and hence the machines designed with higher value air gap flux density will have better ability to operate in parallel with other machines.



### **Specific Electric Loading:**

Following are the some of the factors which influence the choice of specific electric loadings.

**(i) Copper loss:**

Higher the value of  $q$  larger will be the number of armature of conductors which results in higher copper loss. This will result in higher temperature rise and reduction in efficiency.

**(ii) Voltage:**

A higher value of  $q$  can be used for low voltage machines since the space required for the insulation will be smaller.

**(iii) Synchronous reactance:**

High value of  $q$  leads to higher value of leakage reactance and armature reaction and hence higher value of synchronous reactance. Such machines will have poor voltage regulation, lower value of current under short circuit condition and low value of steady state stability limit and small value of synchronizing power.

**(iv) Stray load losses:**

With increase of  $q$  stray load losses will increase. Values of specific magnetic and specific electric loading can be selected from Design Data Hand Book for salient and non-salient pole machines.

### **Separation of D and L:**

Inner diameter and gross length of the stator can be calculated from  $D^2L$  product obtained from the output equation. To separate suitable relations are assumed between  $D$  and  $L$  depending upon the type of the generator. Salient pole machines: In case of salient pole machines either round or rectangular pole construction is employed. In these types of machines, the diameter of the machine will be quite larger than the axial length.

## 4.6 Circle Diagram for Three Phase Induction Motors

### Tests Required

#### No-load Test

Run the induction motor on no-load at rated supply voltage. Observe the supply line voltage  $V_0$ , No-load line current  $I_0$  and no-load power  $P_0$ .

$$\text{Phase angle for no-load condition } \Phi_0 = \cos^{-1} \left( \frac{P_0}{\sqrt{3} V_0 I_0} \right)$$

#### Blocked Rotor Test

Block the rotor firmly and apply a reduced voltage to obtain rated current at the motor terminals. Observe the supply line voltage  $V_{SC}$ , No-load line current  $I_{SC}$  and no-load power  $P_{SC}$ .

$$\text{Phase angle for blocked rotor condition } \Phi_{SC} = \cos^{-1} \left( \frac{P_{SC}}{\sqrt{3} V_{SC} I_{SC}} \right)$$

Current drawn if rated voltage is applied at blocked rotor condition  $I_{SN} = I_{SC}$

#### Resistance Test

By voltmeter-ammeter method determine per phase equivalent stator resistance,  $R_1$ .

If the machine is wound rotor type, find the equivalent rotor resistance  $R_2'$  also after measuring rotor resistance and required transformations are applied.

## Construction of Circle Diagram

1. Draw horizontal axis OX and vertical axis OY. Here the vertical axis represents the voltage reference.
2. With suitable scale, draw phasor OA with length corresponding to  $I_0$  at an angle  $\Phi_0$  from the vertical axis. Draw a horizontal line AB.
3. Draw OS equal to  $I_{SN}$  at an angle  $\Phi_{SC}$  and join AS.
4. Draw the perpendicular bisector to AS to meet the horizontal line AB at C.
5. With C as centre, draw a semi circle passing through A and S. This forms the circle diagram which is the locus of the input current.
6. From point S, draw a vertical line SL to meet the line AB.
7. Fix the point K as below.

- For wound rotor machines where equivalent rotor resistance  $R_2'$  can be found out: Divide SL at point K so that SK:KL = equivalent rotor resistance : stator resistance.

- For squirrel cage rotor machines:

Find Stator copper loss using  $I_{SN}$  and stator winding resistance  $R_1$ .

Rotor copper loss = total copper loss – stator copper loss.

Divide SL at point K so that SK : KL = rotor copper loss : stator copper loss

*Note:* If data for separating stator copper loss and rotor copper loss is not available then assume that stator copper loss is equal to rotor copper loss. So divide SL at point K so that SK= KL

8. For a given operating point P, draw a vertical line PEF GD as shown.

Then, PD = input power, PE = output power, EF = rotor copper loss, FG = stator copper loss, GD = constant loss (iron loss + mechanical loss)

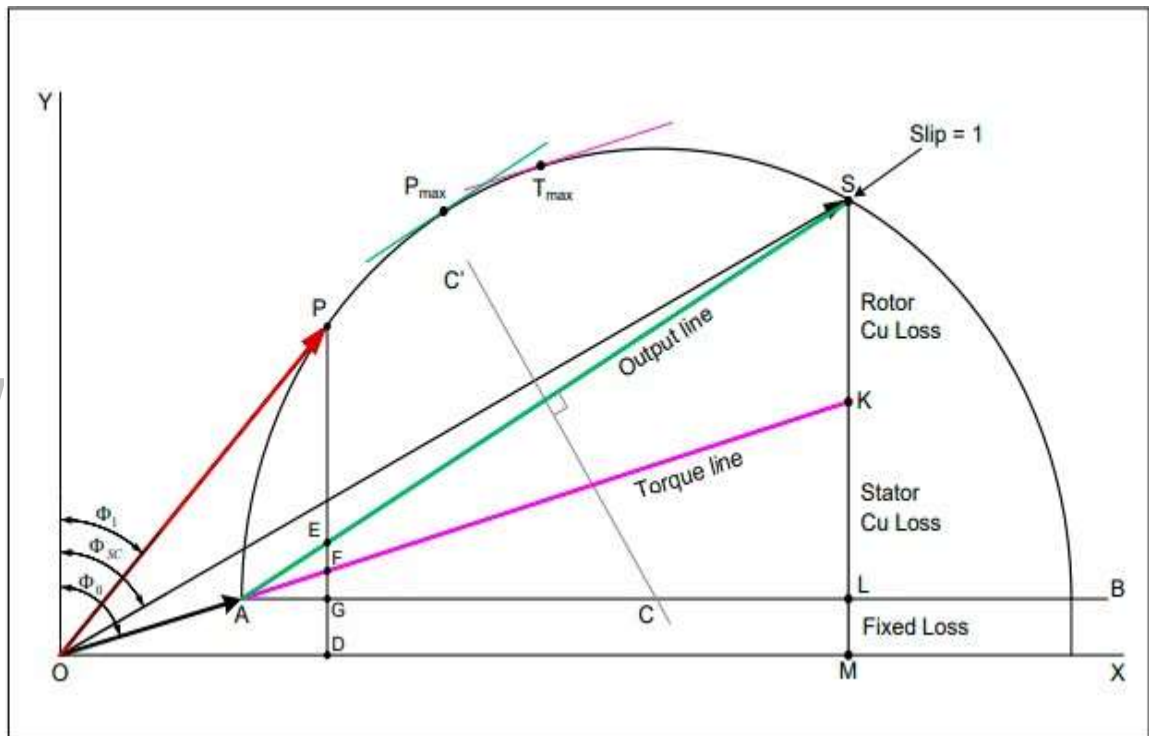
9. Efficiency of the machine at the operating point P, =  $\frac{PE}{PD}$

10. Power factor of the machine at operating point P =  $\cos \phi_1$

11. Slip of the machine at the operating point P,  $s = \frac{EF}{PF}$

12. Starting torque at rated voltage (in syn. watts) = SK

13. To find the operating points corresponding to maximum power and maximum torque, draw tangents to the circle diagram parallel to the output line and torque line respectively. The points at which these tangents touch the circle are respectively the maximum power point ( $P_{max}$ ) and maximum torque point ( $P_{max}$ ).



**Figure 4.6.1 Circle diagram**

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-10.54]

## 4.1 Construction of Induction Machine

### Construction of Stator

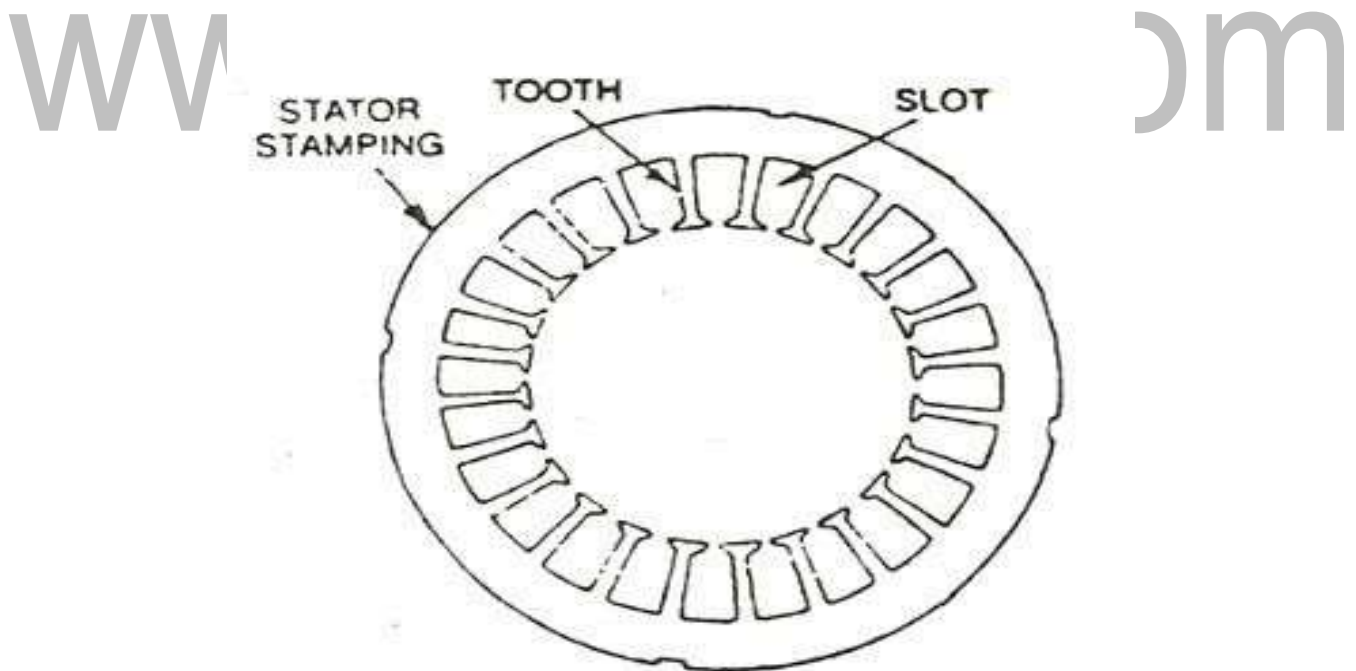
The stator is built up of high-grade alloy steel laminations to reduce eddy current losses. It has three main parts, namely outer frame, the stator core and a stator winding.

#### Outer frame

It is the outer body of the motor. Its main function is to support the stator core and to protect the inner parts of the machine. For small machines, the outer frame is casted, but for the large machine, it is fabricated. The figure below shows the stator construction.

#### Stator Core

The stator core is built of high-grade silicon steel stampings. Its main function is to carry the alternating magnetic field which produces hysteresis and eddy current losses. The stampings are fixed to the stator frame. Each stamping are insulated from the other with a thin varnish layer. The thickness of the stamping usually varies from 0.3 to 0.5 mm. Slots are punched on the inner side of the stampings as shown in the figure below.



**Figure 4.1.1 Stator stamping**

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-10.1]

## Stator windings

The core of the stator carries three phase windings which are usually supplied from a three-phase supply system. The six terminals of the windings (two of each phase) are connected in the terminal box of the machine. The stator of the motor is wound for a definite number of poles, depending on the speed of the motor. If the number of poles is greater, the speed of the motor will be less and if the number of poles is less than the speed will be high. As the relationship between the speed and the pole of the motor is given as

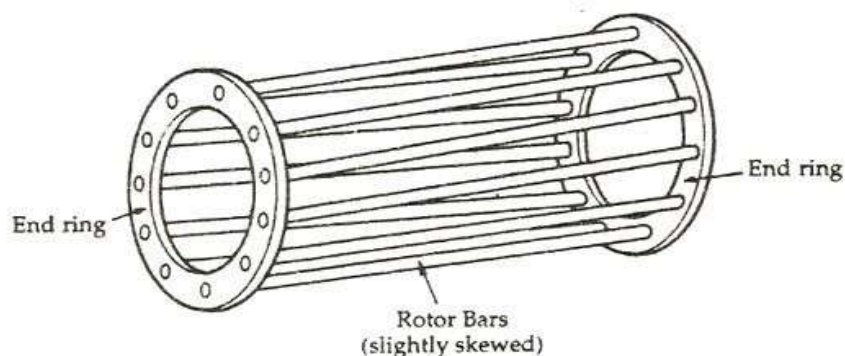
$$N_s = \frac{120f}{p}$$

## Construction of Rotor

The rotor is also built of thin laminations of the same material as the stator. The laminated cylindrical core is mounted directly on the shaft. These laminations are slotted on the outer side to receive the conductors. There are two types of rotor.

### Squirrel Cage Rotor

A squirrel cage rotor consists of a laminated cylindrical core. The circular slots at the outer periphery are semi-closed. Each slot contains uninsulated bar conductor of aluminum or copper. At the end of the rotor the conductors are short-circuited by a heavy ring of copper or aluminum. The diagram of the cage rotor is shown below.



**Figure 4.1.2 Squirrel cage rotor**

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-10.2]

The rotor slots are usually not parallel to the shaft but are skewed. The skewing of the rotor conductors has the following advantages given below.

- It reduces humming and provide smooth and noise free operation.
- It results in a uniform torque curve for different positions of the rotor.
- The locking tendency of the rotor is reduced. As the teeth of the rotor and the stator attract each other and lock.
- It increases the rotor resistance due to the increased length of the rotor bar conductors.

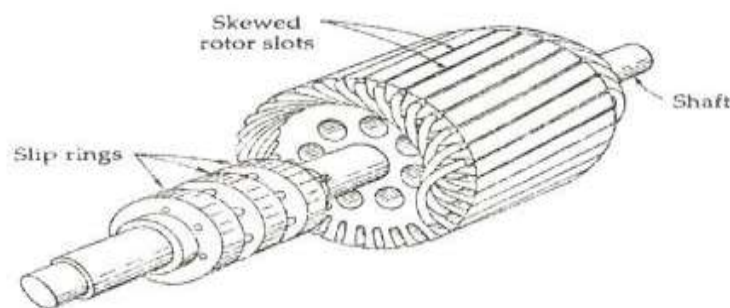
### **Advantages of Squirrel Cage Rotor**

The following advantages of the cage rotor are given below.

- The cage rotor is cheaper, and the construction is robust.
- The absence of the brushes reduces the risk of sparking.
- Its Maintenance is less.
- The power factor is higher
- The efficiency of the cage rotor is higher.

### **Phase Wound Rotor**

The Phase wound rotor is also called as Slip Ring Rotor. It consists of a cylindrical core which is laminated. The outer periphery of the rotor has a semi-closed slot which carries a 3 phase insulated windings. The rotor windings are connected in star. The slip ring induction motor is shown in the figure below.



**Figure 4.1.3 Slip-ring rotor**

[Source: "A Course in Electrical Machine Design" by A.K.Sawhney, page-10.2]

The slip rings are mounted on the shaft with brushes resting on them. The brushes are connected to the variable resistor. The function of the slip rings and the brushes is to provide a means of connecting external resistors in the rotor circuit. The resistor enables the variation of each rotor phase resistance to serve the following purposes given below.

- It increases the starting torque and decreases the starting current.
- It is used to control the speed of the motor.

In this type also, the rotor is skewed. A mild steel shaft is passed through the center of the rotor and is fixed to it. The purpose of the shaft is to transfer mechanical power.

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#### 4.4 Design of squirrel cage rotor and wound rotor

- Number of stator slots should not be equal to rotor slots satisfactory results are obtained when  $S_r$  is 15 to 30% larger or smaller than  $S_s$ .
- The difference ( $S_s - S_r$ ) should not be equal to  $+ \text{ or } - p$ ,  $+ \text{ or } - 2p$  or  $+ \text{ or } - 5 p$  to avoid synchronous cusps.
- The difference ( $S_s - S_r$ ) should not be equal to  $+ \text{ or } - 1$ ,  $+ \text{ or } - 2$ ,  $+ \text{ or } - (p+1)$  or  $+ \text{ or } - (p+2)$  to avoid noise and vibrations.

#### Design of rotor bars & slots

There are two types of rotor construction. One is the squirrel cage rotor and the other is the slip ring rotor. Most of the induction motor are squirrel cage type. These are having the advantage of rugged and simple in construction and comparatively cheaper. However they have the disadvantage of lower starting torque. In this type, the rotor consists of bars of copper or aluminum accommodated in rotor slots. In case slip ring induction motors the rotor complex in construction and costlier with the advantage that they have the better starting torque. This type of rotor consists of star connected distributed three phase windings. Between stator and rotor is the air gap which is a very critical part. The performance parameters of the motor like magnetizing current, power factor, over load capacity, cooling and noise are affected by length of the air gap. Hence length of the air gap is selected considering the advantages and disadvantages of larger air gap length.

#### Advantages:

- (i) Increased overload capacity
- (ii) Increased cooling
- (iii) Reduced unbalanced magnetic pull
- (iv) Reduced in tooth pulsation

## **Disadvantages**

- (i) Increased Magnetising current
- (ii) Reduced power factor

## **Number of slots:**

Proper numbers of rotor slots are to be selected in relation to number of stator slots otherwise undesirable effects will be found at the starting of the motor. Cogging and Crawling are the two phenomena which are observed due to wrong combination of number of rotor and stator slots. In addition, induction motor may develop unpredictable hooks and cusps in torque speed characteristics or the motor may run with lot of noise. Let us discuss Cogging and Crawling phenomena in induction motors.

## **Crawling:**

The rotating magnetic field produced in the air gap of the will be usually non-sinusoidal and generally contains odd harmonics of the order 3rd, 5th and 7th. The third harmonic flux will produce the three times the magnetic poles compared to that of the fundamental. Similarly, the 5th and 7th harmonics will produce the poles five and seven times the fundamental respectively. The presence of harmonics in the flux wave affects the torque speed characteristics. The Fig. below shows the effect of 7th harmonics on the torque speed characteristics of three phase induction motor. The motor with presence of 7th harmonics is to have a tendency to run the motor at one seventh of its normal speed. The 7th harmonics will produce a dip in torque speed characteristics at one seventh of its normal speed as shown in torque speed characteristics.

## **Cogging:**

In some cases, where in the number of rotor slots are not proper in relation to number of stator slots the machine refuses to run and remains stationary. Under such conditions there will be a locking tendency between the rotor and stator. Such a phenomenon is called cogging. Hence in order to avoid such bad effects a proper number of rotor slots are to be selected in relation to number of stator slots. In addition, rotor slots will be skewed by one slot pitch to minimize the tendency of cogging, torque defects like synchronous hooks and cusps and noisy operation while running. Effect of skewing will

slightly increase the rotor resistance and increases the starting torque. However, this will increase the leakage reactance and hence reduces the starting current and power factor.

### **Selection of number of rotor slots:**

The number of rotor slots may be selected using the following guide lines.

- (i) To avoid cogging and crawling: (a)  $S_s \neq S_r$  (b)  $S_s - S_r \neq \pm 3P$
- (ii) To avoid synchronous hooks and cusps in torque speed characteristics  $\neq P, \neq 2P, \neq 5P$ .
- (iii) To noisy operation  $S_s - S_r \neq \pm 1, \neq 2, (\neq P \pm 1), (\neq P \pm 2)$

### **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. Hence the current per rotor bar is given by

$$I_b = (K_{ws} \times S_s \times Z'_s) \times I_r / (K_{wr} \times S_r \times Z'_r) ;$$

where

$K_{ws}$  – winding factor for the stator,

$S_s$  – number of stator slots,

$Z'_s$  – number of conductors / stator slots,

$K_{wr}$  – winding factor for the rotor,

$S_r$  – number of rotor slots,

$Z'_r$  – number of conductors / rotor slots and

$I_r$  – equivalent rotor current in terms of stator current and is given by  $I_r = 0.85 I_s$  where  $I_s$  stator current per phase.

### **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 cooling conditions are better for the rotor than the stator higher current density can be assumed. Higher current density will lead to reduced sectional area and hence increased resistance, rotor cu losses and reduced efficiency. With increased rotor resistance starting torque will increase. As a guide line

the rotor bar current density can be assumed between 4 to 7 Amp/mm<sup>2</sup> or may be selected from design data Hand Book.

Hence sectional area of the rotor bars can be calculated as  $A_b = I_b / b$  mm<sup>2</sup>. Once the cross sectional area is known the size of the conductor may be selected from standard table given in data hand book.

### **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 and
- (iv) reduced starting current.
- (iv) Over load capacity is reduced
- (v) Undesirable and complex air gap characteristics.

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

### **Copper loss in rotor bars:**

Knowing the length of the rotor bars and resistance of the rotor bars cu losses in the rotor bars can be calculated. Length of rotor bar  $l_b = L +$  allowance for skewing

$$\text{Rotor bar resistance} = 0.021 \times l_b / A_b$$

$$\text{Copper loss in rotor bars} = I_b \times r_b \times \text{number of rotor bars.}$$

### **End Ring Current:**

All the rotor bars are short circuited by connecting them to the end rings at both the end rings. The rotating magnetic field produced will induce an emf in the rotor bars which will be sinusoidal over one pole pitch. As the rotor is a short circuited body, there will be current flow because of this EMF induced. The distribution of current and end rings are as shown in Fig. below. Referring to the figure 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.

### **Area of end ring:**

Knowing the end ring current and assuming suitable value for the current density in the end rings cross section for the end ring can be calculated as

Area of each end ring  $A_e = I_{e} / \delta_e \text{ mm}^2$ , current density in the end ring may be assume as 4.5 to 7.5 amp/mm<sup>2</sup>.

### **Copper loss in End Rings:**

Mean diameter of the end ring ( $D_{me}$ ) 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  $l_{me} = D_{me}$ .

The resistance of the end ring can be calculated as  $r_e = 0.021 \times l_{me} / A_e$

Total copper loss in end rings =  $2 \times I_e^2 \times r_e$

### **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:**

As mentioned earlier 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 number of rotor slots are calculated. So selected number of slots should be such that tooth width must satisfy the flux density limitation. Semiclosed slots are used for rotor slots.

### **Number of rotor Turns:**

Number of rotor turns are decided based on the safety consideration of the personal working with the induction motors. The volatge between the slip rings 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.

$$\text{Voltage ratio } E_r / E_s = (K_{wr} \times T_r) / (K_{ws} \times T_s)$$

$$\text{Hence rotor turns per phase } T_r = (E_r / E_s) (K_{ws} / K_{wr}) T_s$$

$E_r$  = open circuit rotor voltage/phase

$E_s$  = stator voltage /phase

$K_{ws}$  = winding factor for stator

$K_{wr}$  = winding factor for rotor

$T_s$  = Number of stator turns/phase

### **Rotor Current:**

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

$$I_r = (K_{ws} \times S_s \times Z'_s) \times I'_r / (K_{wr} \times S_r \times Z'_r) ;$$

$K_{ws}$  – winding factor for the stator,  $S_s$  – number of stator slots,

$Z'_s$  – number of conductors / stator slots,  $K_{wr}$  – winding factor for the rotor,

$S_r$  – number of rotor slots,

$Z'_r$  – number of conductors / rotor slots and

$I'_r$  – equivalent rotor current in terms of stator current  $I'_r = 0.85 I_s$  where  $I_s$  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<sup>2</sup>

$$A_r = I_r / r \text{ mm}^2$$

$A_r < 5 \text{ mm}^2$  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  $l_{mt} = 2L + 2.3 p + 0.08m$  Resistance of rotor winding is given by  $R_r = (0.021 \times l_{mt} \times Tr) / Ar$

Total copper loss =  $3 I_r^2 R_r$  Watts

### Flux density in rotor tooth:

It is required that the dimension of the slot is alright from the flux density consideration. Flux density has to be calculated at 1/3rd height from the root of the teeth. This flux density has to be limited to 1.8 Tesla. If not the width of the tooth has to be increased and width of the slot has to be reduced such that the above flux density limitation is satisfied. The flux density in rotor can be calculated by as shown below.

Diameter at 1/3rd height  $D_{r'} = D - 2/3 \times h_{tr} \times 2$

Slot pitch at 1/3rd height =  $r = \pi D_{r'} / S_r$

Tooth width at this section =  $b_{tr} = r - b_{sr}$

Area of one rotor tooth =  $a_{tr} = b_{tr} \times l_i$

Iron length of the rotor  $l_i = (L - w_d \times n_d) k_i$ ,

$k_i$  = iron space factor Area of all the rotor tooth / pole  $A_{tr} = b_{tr} \times l_i \times S_r / P$

Mean flux density in rotor teeth  $B_{tr} = \phi / A_{tr}$

Maximum flux density in the rotor teeth  $< 1.5$  times  $B_{tr}$

### Depth of stator core below the slots:

Below rotor slots there is certain solid portion which is called depth of the core below slots. This depth is calculated based on the flux density and flux in the rotor core. Flux density in the rotor core can be assumed to be between 1.2 to 1.4 Tesla. Then depth of the core can be found as follows.

Flux in the rotor core section  $\phi = c \times A_{cr}$

Area of stator core  $A_{cr} = \phi / c$

Area of stator core  $A_{cr} = l_i \times d_{cr}$

Hence, depth of the core  $d_{cr} = A_{cr} / l_i$

Inner diameter of the rotor can be calculated as follows

Inner diameter of rotor =  $D - 2l_g - 2h_{tr} - 2d_{cr}$

## 4.2 Output equation of Induction motor

Output equation is the mathematical expression which gives the relation between the various physical and electrical parameters of the electrical machine.

In an induction motor the output equation can be obtained as follows Consider an 'm' phase machine, with usual notations

Output Q in kW = Input x efficiency

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

For a 3  $\Phi$  machine  $m = 3$ ,

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

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

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

$$f = PN_s/120 = Pn_s/2,$$

$$\text{Output} = 3 \times 2.22 \times Pn_s/2 \times \Phi Z_{ph} K_w I_{ph} \eta \cos \Phi \times 10^{-3} \text{ kW}$$

$$\text{Output} = 1.11 \times P \Phi \times 3 I_{ph} Z_{ph} \times n_s K_w \eta \cos \Phi \times 10^{-3} \text{ kW},$$

$$P \Phi = B_{av} \pi D L, \text{ and } 3 I_{ph} Z_{ph} / \pi D = q$$

$$\text{Output to motor} = 1.11 \times B_{av} \pi D L \times \pi D q \times n_s K_w \eta \cos \Phi \times 10^{-3} \text{ kW}$$

$$Q = (1.11 \pi^2 B_{av} q K_w \eta \cos \Phi \times 10^{-3}) D^2 L n_s \text{ kW}$$

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

$$\text{Output } Q = C_o D^2 L n_s \text{ kW}$$

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

$V_{ph}$  = 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

$p$  = no of poles,

$q$  = Specific electric loading

$\Phi$  = air gap flux/pole;

$B_{av}$  = Average flux density

$k_w$  = winding factor.

$\eta$  = efficiency

$\cos\Phi$  = power factor

$D$  = Diameter of the stator,

$L$  = Gross core length

$C_o$  = Output coefficient

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