UNIT I

# *Basic Principles of Machine Design*

Consists of

1. Introduction
2. Constructional Elements of Transformer
3. Constructional Elements of Rotating Machines
4. Classification of design problems
5. Magnetic loading
6. Electrical loading
7. Output Equation
8. Standard Specifications

## *1.Introduction*

- The problem of design and manufacture of electrical machinery is to build as economically as possible, a machine which fulfils a certain set of specifications and guarantees.
- The major considerations to evolve good design are

  1. Cost

  2. Durability

  3. Compliance with performance criteria as laid down in specifications

## *2. Constructional Elements of Transformer*

- 1.Iron Core
- 2.Primary and Secondary Winding
- 3.Transformer Tank
- 4.Cooling Tubes

## *3. Constructional elements of rotating machines*

- 1.Stator
- 2.Rotor
- 3.Others

3.(a)DC Machine

1. Stator:

   Yoke,Field Pole, Pole Shoe, Field Winding, Interpole

2. Rotor:

   Armature Core, Armature Winding , Commutator

3. Others:

    Brush and Brush holder

3.(b)Squirrel cage induction motor

1. Stator:

    Frame, stator core and stator winding

2. Rotor:

    Rotor core, rotor bars and Endrings

***4. Classification of design problems***

- 1. Electromagnetic Design
- 2. Mechanical Design
- 3. Thermal Design
- 4. Dielectric Design

***5. Magnetic loading***

- 1. Total Magnetic Loading (TML)

    TML=Total flux entering and leaving the armature

    TML=pØ

    2. Specific Magnetic Loading (SML)

    SML=(Flux per pole)/Area Under a pole      SML=(pØ)/(¶DL)

***6. Electric Loading***

- 1. Total Electric Loading (TEL)

    TEL=sum of currents in all the conductors on the armature

    TEL=IzZ

2. Specific Electric Loading (SEL)

    SEL=(Total Armature ampere conductors)

    Armatue periphery at airgap

    SEL=(IzZ)/¶D

***7. Output Equation***

- The output of a machine can be expressed in terms of its main dimensions, specific magnetic and electric loadings and speed.
- Pa=CoD2Ln

Where Output coefficient Co=¶2Bavac*10-3

***8. Standard Specifications***

- The standard specifications of electrical machines are

- 1. Standard ratings of machines
- 2. Types of enclosure
- 3. Standard dimensions of conductors to be used
- 4. Method of marking ratings and name plate details
- 5. Performance specifications to be met
- 6. Types of insulation and permissible temperature loss
- 7. Permissible loss and range of efficiency
- 8. Procedure for testing of machine parts and machines
- 9. Auxiliary equipments

***Name Plate Details***

- KW or KVA rating of machine
- Rated working voltage
- Operating speed
- Full load current
- Class of insulation
- Frame size
- Manufacturers name
- Serial number of the machine

***ISO numbers with year***

- IS 325-1966 : Specifications for 3ph induction motor
- IS 4029-1967 : Guide for testing 3ph induction motor
- IS12615-1986 : Specifications for energy efficient induction motor
- IS13555-1993 : Guide for selection & application of 3ph induction motor for different types of driven equipment
- IS8789-1996 : Values of performance characteristics for 3ph induction motor
- IS 12066-1986: 3ph induction motors for machine tools

UNIT II

## *DC Machines*

Consists of

- Constructional Elements
- Output Equation
- Choice of specific loadings
- Selection of number of poles
- Length of airgap
- Armature design
- Field system design
- Commutator and brushes
- Efficiency and Losses

### *1. Constructional Elements*

(i) Armature

(1) winding

(2) core

(3) commutator

(ii) Field

(1) winding

(2) core

(3) pole shoe

(iii) Frame

### *2. Output equation*

The output of a machine can be expressed in terms of its main dimensions, specific magnetic and electric loadings and speed.

$Pa=CoD^2Ln$

Where Output coefficient $Co=¶^2Bavac*10^{-3}$

### *3. Choice of specific loading*

3.1 Choice of specific magnetic loading

Depends on, 1. Flux density in teeth

2. Frequency of flux reversal

3. Size of machine

(i) Flux density

Large values of Bav in teeth increases field mmf.

Higher mmf results in increase of iron loss, cu loss & cost of cu.

Bav does not exceed $2.2 wb/m^2$

(ii) Frequency of flux reversal

If f is high then iron losses in arm. Core & teeth would be high.

So high value of Bav is not used.

(iii) Size of machine

If size increases Bav also increases.

As the dia increases the width of the tooth also increases, permitting increased value of Bg without saturation.

Bg bet 0.55 to 1.15Wb/m2 & Bav 0.4 to0.8 wb/m2

3.2 Choice of specific electric loading

Depends on, 1. Temperature rise

2. Speed of machine

3. Voltage

4. Size of machine

5. Armature reaction

6. Commutation

(i) Temperature rise

Higher ac results in high temp rise of wdgs.

Temp rise depends on type of enclosure & cooling techniques employed.

Ex. In m/cs. Using class F insulation which can withstand a temp. of 155'c, the value of ac can be approx. 40% higher than that used in m/cs. Designed for class A insulation which can withstand a temp. of only 105'c.

(ii) Speed of machine

If N is high, ventilation of the machine is better & therefore greater losses can be dissipated. Thus higher ac can be used for high N.

(iii) Voltage

In high V m/cs large space is reqd. for insulation & therefore less space for conductors.

Ie. Space left for conductors is less & therefore we should use a small value of ac.

(iv) Size of m/c

In large size m/cs it is easier to find space for accommodating conductors. Hence ac can be increased with increase in dimensions.

(v) Armature reaction

With high ac, arm. Reaction will be severe. To counter this the field mmf is increased & so cost goes high.

(vi) Commutation

$$Ac = \frac{Iz*Z}{D*\Pi}$$

High value of ac will have either (i) Large Z OR

(ii) small dia D

(i) M/c have large Z having large no. of turns; L is proportional to square of no. of turns; so large ac

(ii) If small dia, it is not possible to use wide slots because otherwise the space left for teeth will become smaller giving rise to high B in them. Only way is us ting deeper slots to use. But the deeper slots increases the L value.

Increased L increases reactance voltage which delays the commutation.

High ac worsens the commutation condition in m/cs.

From commutation point of view small ac is desirable.

Ac lies bet. 15,000 to 50,000amp.cond/m

## ***4. Selection of no. of poles***

The aim of the designer to select the main dimensions as will result in the minimum cost and yet at the same time meet the desired specifications.

As for as the magnetic circuit is concerned it is necessary to choose a suitable no. of poles and to suitably proportion them. A proper design of the electric circuit requires suitable dimensions which result in satisfactory arrangements for wdg and commutator.

For choice of no. of poles let us assume D,L,Bav & ac are const.P only variable.

(i) Frequency

F=pn/2

If p is high then f also increases which may lead to excessive iron losses in arm. Teeth and core.

In case of high speed turbo alternators the no. of poles used is 2 oterwise the frequency will become high giving rise to excessive iron losses.

(ii) Weight of iron parts

No. of poles effects the no. of parts in magnetic circuit

(a) Yoke area

For 2 pole m/c

Total flux around the airgap is const.=ØT

Flux per pole = ØT/2

At yoke the flux further divided into 2 parts & therefore

Yoke has to carry a flux of ØT/4

For 4 pole m/c

Flux per pole = ØT/4

At yoke the flux further divided into 2 parts & therefore

Yoke has to carry a flux of ØT/8

Thus if the no. of poles is doubled, the flux carried by yoke is halved. The flux carried by yoke is inversely proportional to no. of poles. Therefore by using no. of poles, the area of cross section of yoke is proportionately decreased.

(b) Armature core area

The flux per pole divides itself in 2 paths in the armature core.

For 2 pole m/c

Flux in the arm. = ØT/4

For 4 pole m/c

Flux in the arm. = ØT/8

Thus we can safely use a large no. of poles so as to reduce the wt of iron in the yoke.But increase in no. of poles would result in higher iron loss in arm. Core owing to increased frequency of flux reversals.

We can examine this here.

For 2 pole m/c

Eddy ct loss in arm. Core $\alpha$ $Bc^2f^2$ $\alpha$ $Bc^2(pn/2)^2$

s $\alpha$ $(ØT/4A2)^2*(2*n/2)^2$

$\alpha$ $(ØT^2n^2)/16A2^2$

For 4 pole m/c

Eddy ct loss in arm. Core α Bc2f2 α Bc2(pn/2)2

s α (ØT/8A4)2*(4*n/2)2

α (ØT2n2)/16ª42

## ***5. Length of airgap***

A small gap is provided between the rotor and stator to avoid the friction

between the stationary and rotating parts.

A large value of airgap results in

1. Lesser noise
2. better cooling
3. Reduced pole face losses
4. Reduced circulating losses
5. Less distortion of field form
6. Higher field mmf which reduces armature reaction

$$\text{Length of airgap (lg)} = \frac{(0.5 \text{ to } 0.7)*ac*\Gamma}{1,600,000*Bg*Kg}$$

## ***6. Armature Design***

The armature of a dc machine consists of core and winding.

The armature core is cylindrical in shape with slots on the outer periphery of the armature. The core is formed with circular laminations of thickness 0.5mm. The winding is placed on the slots in the armature core. The design of armature core involves the design of main dimensions D & L, number of slots, slot dimensions and depth of core.

(i) Number of armature slots

The factors to be considered for selection of number of armature slots are

(i) slot width

(ii) cooling of armature conductors

(iii) flux pulsations

(iv) commutation

(v) cost

(ii) Slot dimensions

The dimensions of the slot are slot width and depth. Usually the slot area is estimated from the knowledge of conductor area and slot space factor. The slot factor lies in the range of 0.25 to 0.4 & the value depends on the thickness of insulation.

Slot area = (Conductor Area)/(Slot space factor)

The following factors can be considered before finalising the slot dimensions.

1. Flux density in tooth
2. Flux pulsations
3. Eddy current loss in conductors
4. Reactance voltage
5. Fabrication difficulties

(iii) Depth of armature core

The depth of armature cannot be independently designed, because it depends on the

(1) diameter of armature

(2) inner diameter of armature

(3) depth of slot

Depth of core = (1/2)*( Ø/Li*Bc)

Where

Ø = flux per pole

Li= Net iron length of the armature

Bc= flux density in the core

***7. Field system design***

The field system consist of

(i) poles

(ii) poloe shoes

(iii) field winding

The two types of the field winding are

(i) shunt field winding

(ii) series field winding

The shunt field winding consists of large number of turns made of thin conductors, because the current carried by them is very low. The series field winding is designed to carry heavy current and so it is made of thick conductors.

7.1 Design of shunt field winding

The design of shunt field winding involves the determination of the following

(i) Dimensions of the main field pole
(ii) Dimensions of the field coil
(iii) Dimensions of the field conductor
(iv) Current in the shunt field winding
(v) Resistance of the field coil
(vi) Number of turns in the field coil
(vii) Losses in the field coil

(i) Dimensions of the main field pole

The dimensions of the rectangular field pole are

(1) Area of cross-section
(2) Length
(3) Width
(4) Height of pole body

For cylindrical poles the dimensions has to be estimated instead of length and width.

(ii) Dimensions of field coil

The field coils are former wound & placed on the poles. The field coils may have rectangular or circular cross-section, depending on the type of poles. The dimensions of the field coil are depth, height & length of mean turn of field coil.

(iii) Current in the shunt field winding

The shunt field current can be estimated from the knowledge of voltage across field coil and the resistance of field coil. Each pole of a dc machine carries one field coil and all the field coils are connected in series to form shunt field winding. Hence the voltage across each field coil is given by

$$\text{voltage across each field coil, } E_f = \frac{\text{voltage across shunt field winding}}{\text{Number of poles}}$$

field current= Ef/Rf

(iv) Resistance of field coil

The resistance of the field coil can be estimated from the knowledge of resistivity of copper, length of mean turn of field coil and area of cross section of field conductor.

(v) Dimensions of field conductor

The dimensions of the are area of cross section and diameter. The area of cross section of the field conductor can be estimated from the knowledge of field current (If) & current density (δf). The usual range of current density in the field conductor is 1.2 to 3.5 A/mm2.

(vi) Number of turns in field coil

When the ampere turns to be developed by the field coil is known the turns can be estimated from the knowledge of field current.

(vii) Power loss in the field coil

The power loss in the field coil is copper loss which depends on resistance and current. Heat developed in the field coil due to this loss and heat is dissipated through the surface of the coil. If there is no sufficient surface for heat dissipation then heat accumulates, which may lead to damage(or burning) of the coil. In field coil design the loss dissipated per unit surface area is specified and from which the required surface area can be estimated. The surface area of field coil depends on length of mean turn, depth and height of field coil. Usually the length of mean turn is estimated in order to provide the required surface area.

The heat can be dissipated from all the 4 sides of a coil ie., inner, outer, top & bottom surface of the coil.

***8. Design of commutator and brushes***

The commutator and brush arrangement are used to convert the bidirectional internal current to unidirectional external current or viceversa. The current flows through the brushes mounted on the commutator surface. The brushes are located at the magnetic neutral axis which is midway between adjacent poles.

When a armature conductor pass through the magnetic neutral axis, the current in the conductor reverses from one direction to the other. Since the brushes are mounted on magnetic neutral axis, the coil undergoing current reversal is short circuited by carbon brush. During this short circuit period, the current must be reduced from its original value to zero and then built up to an equal value in the opposite direction. This process is called the time of commutation.

The process of commutation is classified into

(i) Resistance commutation

(ii) Retarted commutation

(iii) Accelerated commutation

(iv) Sinusoidal commutation

***9. Efficiency and losses***

Efficiency of a machine is defined as the ratio of output of the machine to the input supplied to the machine.

Losses in the dc machine are given as follows

(i) Iron loss

(ii) Copper loss

(iii) Windage and friction loss

# *UNIT III*

## *Transformers*

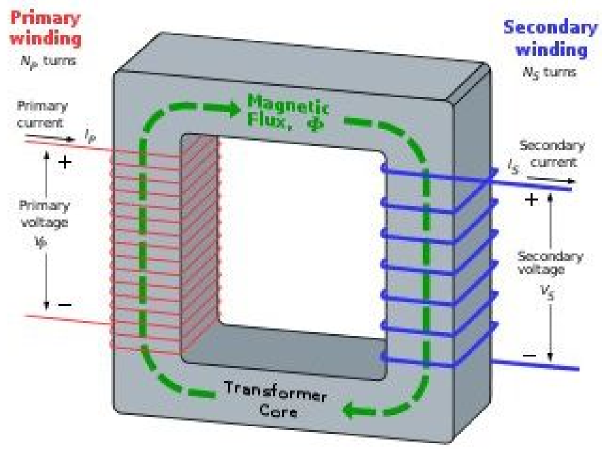
This unit consists of

- Introduction
- Types
- Output equation
- Design of cores
- Overall dimensions
- Design of winding
- Design of tank with cooling tubes
- Efficiency and losses

## *1. Introduction*

The transformer is based on two principles: first, that an electric current can produce a magnetic field (electromagnetism), and, second that a changing magnetic field within a coil of wire induces a voltage across the ends of the coil (electromagnetic induction). Changing the current in the primary coil changes the magnetic flux that is developed. The changing magnetic flux induces a voltage in the secondary coil.

An ideal transformer is shown in the adjacent figure. Current passing through the primary coil creates a magnetic field. The primary and secondary coils are wrapped around a core of very high magnetic permeability, such as iron, so that most of the magnetic flux passes through both the primary and secondary coils.




## Induction law

The voltage induced across the secondary coil may be calculated from Faraday's law of induction, which states that:

$$V_s = N_s \frac{d\Phi}{dt},$$

where $V_s$ is the instantaneous voltage, $N_s$ is the number of turns in the secondary coil and Φ is the magnetic flux through one turn of the coil. If the turns of the coil are oriented perpendicular to the magnetic field lines, the flux is the product of the magnetic flux density $B$ and the area $A$ through which it cuts. The area is constant, being equal to the cross-sectional area of the transformer core, whereas the magnetic field varies with time according to the excitation of the primary. Since the same magnetic flux passes through both the primary and secondary coils in an ideal transformer, the instantaneous voltage across the primary winding equals

$$V_p = N_p \frac{d\Phi}{dt}.$$

Taking the ratio of the two equations for $V_s$ and $V_p$ gives the basic equation for stepping up or stepping down the voltage

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}.$$

## 2. *Types*

(i) Core

(ii) Shell

(i) Core

The iron core is made of thin laminated silicon steel (2-3 % silicon) Pre-cut insulated sheets are cut or pressed in form and placed on the top of each other .The sheets are overlap each others to avoid (reduce) air gaps.

1. Easy in design
2. Has low mechanical strength due to non bracing of windings
3. reduction of leakage reactance is not easily dismantled.
4. The assembly can be easily dismantled for repair work.
5. Better heat dissipation from windings.
6. Has longer mean length of core and shorter mean length of coil turn. Hence best suited for Extra High voltage(EHV) requirements.

**(ii) Shell**

1. Comparatively complex
2. High mechanical strength
3. Reduction of leakage reactance is highly possible
4. It cannot be easily dismantled for repair work.
5. Heat is not easily dissipated from windings since it is surrounded by core
6. It is not suitable for EHV requirements.

### 3. *Output Equation*

The equation which relates the rated KVA output of a transformer to the area of core & window is called output equation.

In transformers the output KVA depends on flux density and ampere turns.

The flux density is related to core area & the ampere turns is related to window area.

The low voltage winding is placed nearer to the core in order to reduce the insulation requirement. The space inside the core is called window & it is the space available for accommodating the primary and secondary winding. The window area is shared between the winding and their insulations.

Induced emf in a transformer $E=4.44f\phi mT$ volts

Window space factor $K_w = A_c/A_w$

Where $A_c$ = Conductor area in window

$A_w$ = Total area of window

Current density $= I_p/a_p=I_s/a_s$;

Where $a_p$ = area of cross-section of primary conductor

$a_s$ = area of cross-section of secondary conductor

Ampere turns $AT = I_pT_p=I_sT_s$

Where $T_p,T_s$ = Number of turns in primary & secondary

Total copper Area in window, $A_c= 2AT/\delta$;

KVA rating $Q = V_p*I_p*10^{-3}$

$Q = 2.22*f*B_m*A_i*A_w*K_w*\delta*10^{-3}$

## ***3.1Output equation of 3 phase Transformer***

Induced emf in a transformer $E=4.44f\phi mT$ volts

Window space factor $K_w = A_c/A_w$

Where $A_c$ = Conductor area in window

$A_w$ = Total area of window

Current density $= I_p/a_p=I_s/a_s$;

Where $a_p$ = area of cross-section of primary conductor

$a_s$ = area of cross-section of secondary conductor

Ampere turns $AT = I_pT_p=I_sT_s$

Where $T_p,T_s$ = Number of turns in primary & secondary

Total copper Area in window, $A_c= 4AT/\delta$;

KVA rating $Q = 3*V_p*I_p*10^{-3}$

$Q = 3.33*f*B_m*A_i*A_w*K_w*\delta*10^{-3}$

## 4. *Design of cores*

For core type transformer the cross-section may be

(i) Rectangular

(ii) Square

(iii) Stepped

When circular coils are required for distribution and power transformers, the square and stepped cores are used.

For shell type transformer the cross-section may be

Rectangular

When rectangular cores are used the coils are also rectangular in shape.

The rectangular core is suitable for small and low voltage transformers.

In square cores the diameter of the circumscribing circle is larger than the diameter of stepped cores of same area of cross-section. Thus when stepped cores are used the length of mean turn of winding is reduced with cosequent reduction in both cost of copper & copper loss. However with a large number of steps a large number of different sizes of laminations have to be used. This results in higher labour charges for shearing and assembling different types of laminations.

| Ratio | Square core | Cruciform core | 3-stepped core | 4stepped core |
|---|---|---|---|---|
| Agi/Area of circumscribing circle | 0.64 | 0.79 | 0.84 | 0.87 |
| Ai/Area of circumscribing circle | 0.58 | 0.71 | 0.75 | 0.78 |
| Core area factor, $Kc = Ai/d^2$ | 0.45 | 0.56 | 0.6 | 0.62 |

Where Agi = Gross core area

Ai = Net core area

## 5. ***Overall Dimensions***

The main dimensions of the transformer are

(i) Height of window(Hw)

(ii) Width of the window(Ww)

The other important dimensions of the transformer are

(i) width of largest stamping(a)

(ii) diameter of circumscribing circle

(iii) distance between core centres(D)

(iv) height of yoke(Hy)

(v) depth of yoke(Dy)

(vi) overall height of transformer frame(H)

(vii) overall width of transformer frame(W)

## *6. Design of winding*

The transformer has one low voltage winding and one high voltage Winding. The design of winding involves the determination of number of Turns & area of cross-section of the conductor used for winding. The number Of turns is estimated using voltage rating & emf per turns. The area of cross-section is estimated using rated current & current density.

Usually the number of turns of low voltage winding is estimated first using the given data & it is corrected to nearest integer. Then the number of turns of high voltage winding are chosen to satisfy the voltage rating of the transformer.

Number of turns in low voltage winding , T1=V1/Et=AT/I1

Number of turns in high voltage winding , T2=T1*V2/V1

V1,V2 = Voltage in low & high values

Rated current in a winding = (KVA per phase*$10^{-3}$)/Voltage rating of the winding

## *7.Design of Tank with cooling Tubes*

The transformers are provided with cooling tubes to increase the heat dissipating area. The tubes are mounted on the vertical sides of the transformer tank.

But the increase in dissipation of heat is not proportional increase in area, because the tubes would screen some of the tank surface preventing radiations from the screened surface. On the other hand the tubes will improve the circulation of oil. This improves the dissipation of loss by convection. The circulation of oil is due to more effective pressure heads produced by columns of oil in tubes.

The improvement in loss dissipation by convection is equivalent to loss dissipated by 35% of tube surface area. Hence to account for this improvement in



dissipation of loss by convection an additional 35% tube area is added to actual tube surface area or specific heat dissipation due to convection is taken as 35% more than that without tubes.

Dissipating surface of tank = St

Dissipating surface of tubes = XSt

Total area of walls & tubes = St(1+X)

Loss dissipated per area of Surface = Total loss dissipated/Total area

= (12.5+8.8X)/(1+X)

Total loss = Pi+Pc

Total Area of cooling tubes = (1/8.8)*[(Pi+Pc/Θ)-12.5St]

Total number of tubes = Total Area of tubes/Area of each tube

8. ***<u>Efficiency and losses</u>***

In an ideal transformer, the power in the secondary windings is exactly equal to the power in the primary windings. This is true for transformers with a coefficient of coupling of 1.0 (complete coupling) and no internal losses. In real transformers, however, losses lead to secondary power being less than the primary

power. The degree to which a real transformer approaches the ideal

conditions is called the efficiency of the transformer:

*Efficiency* = *Pout/Pin*100%*

where $P_{out}$ and $P_{in}$ are the real output and the input powers. Apparent and reactive

powers are not used in efficiency calculations.

Losses in a transformer are

(i) Core losses

(ii) Copper losses

There are no rotating parts in the transformer so there are no rotational

losses.

# ***UNIT – IV***

## ***INDUCTION MOTOR***

Consists of

- Construction
- Output equation
- Choice of loadings
- Main dimensions
- Stator winding
- Stator core
- Length of airgap
- Choice of rotor slots
- Design of Squirrel cage rotor
- Design of Wound rotor

### ***1. Construction***

Consists of two major parts

(i) Stator

(ii) Rotor

Stator consists of

(i) Core

(ii) Winding

Rotor is of two types

(i) Squirrel cage
(ii) Wound rotor

Squirrel cage rotor consists of

(i) core
(ii) copper or aluminium bars
(iii) end rings

Wound rotor consists of

(i) core
(ii) winding
(iii) slip rings & brushes

## 2. ***Output Equation***

Output equation of ac machine is relation of KVA rating of the machine to the specific loadings and main dimensions.

KVA = $Co*D^2*L*ns$

Output coefficient = $11Kws*Bav*ac*10^{-3}$

The rating of an induction motor is sometimes given in horse power(HP) . This rating refers to the power output at the shaft of the motor. The KVA input for the motor can be calculated from the following formula.

KVA = $(HP*0.746)/(\eta*\cos\phi)$

$\cos\phi$ = Power Factor

$\eta$ = Efficiency

Squirrel cage Induction motor

$\eta$ varies from 72% to 91%

Power factor varies from 0.66 to 0.9

Slip Ring Induction motor

$\eta$ varies from 84% to 91%

Power factor varies from 0.7 to 0.92

## 3. ***Choice of specific loadings***

The value of output coefficient depends upon the choice of specific electric loading(ac) & specific magnetic loading(Bav).

Choice of specific electric loading depends on

1. copper loss
2. Temperature rise
3. voltage rating
4. overload capacity

Choice of specific magnetic loading depends on

1. Power factor
2. iron loss
3. overload capacity

3.1 Choice of specific electric loading

A large value of 'ac' results in higher copper losses & higher temperature rise. For machines with high voltage rating smaller values of 'ac' should be prepared. Since for high voltage machines the space required for insulation is large.

For high overload capacity, lower values of 'ac' should be selected. Since large values of 'ac' results in large number of turns per phase, leakage reactance will be high. Large values of leakage reactances results in reduced overload capacity.

3.2 Choice of specific magnetic loading

With large values of Bav, the magnetizing current will be high, which results in poor power factor. However in induction motors the flux density in the airgap should be such that there is no saturation in any part of the magnetic circuit.

A large value of Bav results in increased iron loss & decresed efficiency. With higher values of Bav higher values of over load capacity can be obtained. Since the higher Bav provides large values of flux per pole, the turns per phase, will be less & so the leakage reactance will be less. Lower value of leakage reactance results in higher over load capacity.

## *4. Main Dimensions*

The main dimensions of induction motor are the diameter of stator bore,D & the length of stator core,L.

In induction motors most of the operating characteristics are decided by L/ ζ ratio of the motor.

| | L/ ζ ratio |
|---|---|
| For minimum cost | 1.5 to 2 |
| For good power factor | 1 to 1.25 |
| For good efficiency | 1.5 |
| For good overall design | 1 |

## *5.Stator winding*

For small motors upto 5HP, single layer windings like mush Winding, whole coil concentric winding & bifurcated concentric winding are employed.

For large capacity machines, double layer windings(either lap or wave winding) are employed with diamond shaped coils.

5.1 Stator turns per phase

The turns per phase Ts, can be estimated from stator phase voltage and maximum flux in the core. The maximum flux(ϕm) in the core can be estimated from Bav,D,L and p.

Bav = pϕm/ЛDL

Stator turns per phase = Es/(4.44*Kws*f*ϕm)

Es = Stator phase voltage

5.2 Length of mean turn

The Length of mean turn for voltage upto 650 Vcan be calculated by

Length of mean turn = 2L+2.3 ζ +0.24

5.3 Stator conductors

The area of cross section (as) of stator conductors can be estimated from the knowledge of current density, KVA rating of the machine & stator phase voltage.

Stator phase current,Is= Q/(3Es*10-3)

$$as=Is/\delta s$$

$$as=Л\mathrm{ds}^2/4$$

## ***6. Stator Core***

The design of stator core involves selection of number of slots, estimation of dimensions of teeth and depth of stator core.

6.1 Stator slots

Different types of slots are

1. open slots
2. semi enclosed slots

When open slots are used the winding coils can be formed and fully insulated before installing & it is easier to replace the individual coils. Another advantage is that we can avoid excessive slot leakage thereby reducing the leakage reactance.

When semienclosed slots are used the coils must be taped & insulated after they are placed in the slots. The advantages of semienclosed slots are less airgap contraction factor giving a small value of magnetising current, low tooth pulsation loss & much quieter operation.

In small motors round conductors are used and in large & medium size mototrs strip conductors are used.

6.2 Choice of stator slot

Number stator slots depends on

1. tooth pulsation loss
2. leakage reactance
3. ventilation

4. magnetizing current
5. iron loss
6. cost

stator slot pitch,yss = Gap surface/Total no. of stator slots

Total no. of stator slots = Ss

Gap surface = ЛD

Total no. of stator slots = No. of phases*Conductors per phase

= 3*2Ts

Conductors per slot,Zss = Total no. of stator slots/Ss

6.3 Area of stator slot

Area of each slot = Copper area per slot/space factor

= Zss*as/ space factor

After obtaining the area of the slot, the dimensions of the slot should be adjusted. The slot should not be too wide to give a thin tooth.

6.4 Stator teeth

Minimum teeth area per pole = ϕm/1.7

Teeth area per pole = (Ss/p)*Li*Wts

Minimum width of teeth, Wts= ϕm/(1.7*Ss/p*Li)

The minimum width of stator tooth is either near the gap surface or at one third height of tooth from slot opening.

6.5 Depth of stator core

The Depth of stator core depends on the flux density in the core.

Depth of stator core = ϕm/(2*Bcs*Li)

Bcs = Flux desity in stator core

## *7.Length of air gap*

Length of air gap is decided by

1. Power Factor
2. Pulsation loss
3. cooling
4. Over load capacity

5. Unbalanced magnetic pull
6. Noise

## ***8. Choice of rotor slots***

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

1. The motor may refuse to start
2. The motor may crawl at some subsynchronous speed
3. Severe vibrations are developed & 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

1. winding
2. slotting
3. saturation
4. irregularities in air gap

The harmonic fields are superposed upon the fundamental sine wave field & induce emfs in the rotor windings & thus circulate harmonic currents. These harmonic currents in turn interact with the harmonic fields to produce harmonic torques.

Harmonic induction torque

Harmonic induction torques are torques produced by harmonic fields due to stator winding and slots.

Harmonic synchronous torque

Harmonic synchronous torques are torques produced by the combined effect of same order of stator & rotor harmonic fields.

Crawling

Crawling is a phenomena in which the induction motor runs at a speed lesser than subsynchronous speed.

Cogging

Cogging is a phenomena in which the induction motor refuse to start.

Synchronous Cusps

Synchronous Cusps are the synchronous torques produced due to harmonic synchronous speeds. Due to Synchronous Cusps the machine will crawl.

Vibration & Noise

The teeth being cantilevers respond to varying forces and set into vibrations. Thus noise is produced.

## *9. Design of squirrel cage rotor*

It consists of

1. laminated core
2. Rotor bars
3. End rings

Diameter of rotor,Dr = D-2lg;

lg-length of air gap

Design of rotor bars & slots

Rotor bar current is given by

$$Ib = (6*Is*Ts*Kws*Cos\phi)/Sr$$

Area of each rotor bar is given by

$$ab = Ib/\delta b \text{ in mm2}$$

Advantages of closed slots

1. Low reluctance
2. less magnetising current
3. Queiter operation
4. Large leakage reactance & so starting current is limited

Disadvantages of closed slots

Reduced over load capacity

Design of end rings

It can be shown that if flux distribution is sinusoidal then the bar current & end ring current will also be sinusoidal.

Maximum value of end ring current,Ie(max) = (Sr*Ib(max))/2*p

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 endring is the average value of the current of half the bars under one pole.

Maximum value of end ring current,Ie(max) = (Sr*Ib(ave))/2*p

RMS value of end ring current,Ie = Ie(max)/1.414

Area of cross section of end ring ae= Ie/δe in mm2

Also

Area of cross section of end ring ae = de*te;

de - depth of end ring;

te - Thickness of endring

## ***10. Design of wound rotor***

The wound rotor has the facility of adding external resistance to rotor circuit in order to improve the torque developed by the motor. The rotor consists of laminated core with semi-enclosed slots and carries a 3 phase winding.

10.1 Rotor windings

For small motors mush windings are employed.

For large motors double layer bar type wave windings are employed.

10.2 Number of rotor turns

Number of rotor turns can be calculated by

Number of rotor turns,Tr = (Kws*Ts*Er)/(Kwr*Es)

Ts - Number of stator turns

Rotor current , Ir = (0.85*Is*Ts)/Tr

Area of rotor conductor,ar = Ir/δr

10.3 Number of rotor slots

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

1. The motor may refuse to start
2. The motor may crawl at some subsynchronous speed

3. Severe vibrations are developed & 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

1. winding
2. slotting
3. saturation
4. irregularities in air gap

10.4 Rotor teeth

Minimum teeth area per pole = ϕm/1.7

Teeth area per pole = (Sr/p)*Li*Wtr

Minimum width of teeth, Wtr= ϕm/(1.7*Sr/p*Li)

Minimum width of teeth, Wtr=[Л(Dr-2dsr)/Sr]-Wsr

10.5 Rotor core

Depth of rotor core dcr = ϕm/(2*Bcr*Li)

Where

Bcr= Flux density in the rotor core

Inner diameter of rotor lamination, Di = Dr-2(dsr+dcr)

Where dcr = depth of rotor core

10.6 Slip rings & brushes

The wound rotor consists of 3 slip rings mounted on the shaft but insulated from it. The rings are made of either brass or phosphor bronze.

The brushes are made up of metal graphite. The brush dimensions are decided by assuming a current density of 0.1 to 0.2 $A/mm^2$

# UNIT –V

## *Synchronous Machine*

Consists of

- Introduction
- Output equation
- Choice of specific magnetic loadings
- Choice of specific electric loadings
- Short Circuit Ratio
- Length of airgap
- Number of stator slots
- Field design
- Computer Aided Design of Electrical Machines

### *1. Introduction*

The synchronous machines may be classified into

(i) Salient pole machines

(ii) Cylindrical rotor machines

(i) Salient pole machines

These are driven by water wheels or diesel engines. They operate at low speeds and so large number of poles is required to produce desired frequency. This type of machine has projecting poles and field coils are mounted on the poles.

(ii) Cylindrical rotor machines

These are driven by steam turbines and gas turbines which run at very high speeds. They have slots on the periphery of smooth cylindrical rotor. The field conductors are placed on these slots.

### *2. Output Equation*

Output equation of ac machine is relation of KVA rating of the machine to the specific loadings and main dimensions.

KVA ,Q $= Co*D^2*L*ns$

Output coefficient,Co $= 11Kws*Bav*ac*10^{-3}$

## 3. *Choice of Specific magnetic loading*

The choice of Bav depend on

(i) Iron loss

(ii) Stability

(iii) Voltage rating

(iv) Parallel operation

(v) Transient short circuit current

i) High $B_{ave}$ which results in high flux density in the teeth and core which results in high iron loss gives higher temperature rise.

ii) high $B_{ave}$ which results in low $T_{ph}$ which results in low leakage reactance ($X_l$) gives high short circuit current

iii) In high voltage machines slot width required is more to accommodate thicker insulation which results in smaller tooth width which results in small allowable $B_{ave}$

iv) stability : $P_{max} = V*E/X_s$. Since high $B_{ave}$ gives low $T_{ph}$ and hence low $X_l$ $P_{max}$ increases and improves stability.

v) Parallel operation : $P_s = (VE \sin\delta)/X_s$ ; where δ is the torque angle. So low $X_s$ gives higher value for the synchronizing power leading stable parallel operation of synchronous generators.

Guide lines : Non-salient pole alternator : 0.54 – 0.65 $Wb/m^2$

Salient – pole alternator : 0.52 – 0.65 $Wb/m^2$

## *4. Choice of specific Electric loading (ac)*

It depends on the following

(i) Copper loss

(ii) temperature rise

(iii) Operating voltage

(iv) Synchronous reactance

(v) Stray load losses

i) Copper loss and temperature rise: High value of ac Copper loss and temperature rise higher copper loss leading high temperature rise. So choice of depends on the cooling method used.

ii) Operating voltage : High voltage machines require large insulation and so the slot space available for conductors is reduced. So a lower value for ac has to be chosen.

iii) Synchronous reactance ($X_s$) : High value of ac results in high value of $X_s$ , and this leads to a) poor voltage regulation b) low steady state stability limit.

iv) Stray load losses increase with increase in ac.

Guide lines : Non-salient pole alternators : 50, 000 – 75,000 A/m
Salient pole alternators : 20,000 – 40,000 A/m

## *5. Short Circuit Ratio (SCR)*

$$SCR = \frac{\text{Field current required to produce rated voltage on opencircuit}}{\text{Field current required to produce rated current on short circuit}}$$

$$= 1/\text{ direct axis synchronous reactance} = 1/X_d$$

Thus SCR is the reciprocal of $X_d$ , if $X_d$ is defined in p.u.value for rated voltage and rated current. But $X_d$ for a given load is affected by saturation conditions that then exists, while SCR is specific and univalued for a given machine.
Non-salient pole alternators : 1- 1.5 ; Salient pole alternators : 0.5 – 0.7

Effect of SCR on machine performance

i) Voltage regulation : A low SCR high $X_d$ which results in large voltage drop which results in poor voltage regulation..

ii) Parallel operation : A low SCR which results in high $X_d$ which results in low synchronizing power which results in parallel operation becomes difficult.

iii) Short circuit current : A low SCR which results in high $X_d$ which results in low short circuit current. But short circuit current can be limited by other means not necessarily by keeping a low value of SCR.

iv) self excitation : Alternators feeding long transmission lines should not be designed with small SCR as this would lead to large terminal voltage on open circuit due to large capacitance currents.

Summarizing ,high value of SCR leads to

i) high stability limit
ii) low voltage regulation
iii) high short circuit current
iv) large air gap

The present trend is to design machines with low value of SCR, this is due to the recent development in fast acting control and excitation systems.

## ***6. Length of airgap***

The length of air gap very much influences the performance of a synchronous machine. A large airgap offers a large reluctance to the path of the flux produced by the armature MMF and thus reduces the effct of armature reaction. Thus a machine with large airgap has a small $X_d$ and so has i)small regulation

ii) high stability limit

iii) high synchronizing power which makes the machine less sensitive to load variations

iv) better cooling at the gap surface

v) low magnetic noise and smaller unbalanced magnetic pull.

But as the airgap length increases, a large value of Field MMF is required resulting in increased cost of the machine.

## *7. Number of stator slots*

Factors to be considered in the selection of number of slots :

1. Balanced 3-phase winding to be obtained
2. With large number of slots
   i) which results in large number of coils gives increased labour cost
   ii) cooling is improved
   iii) tooth ripples are less
   iv) Flux density in the iron increases due to decreased tooth width.

Guide lines : Slot pitch ($y_s$) $\leq$ 25 mm for low voltage machines;
$\leq$ 40 mm for machines upto 6 kV ;
$\leq$ 60 mm for machines upto 15 kV.

### 7.1. Methods of Eliminating Harmonics

By using

i) distributed windings

ii) fractional coil pitch

iii) fractional slot windings

iv) skewing

v) large airgap

Further calculations needed after determining D and L :

i) Flux per pole = $\Phi$ = Bave ($\pi$ DL/p )

ii) $T_{ph}$ is calculated from the EMF equation taking $E_{ph} = V_{ph}$

iii) $I_{ph}$ = (Qx $10^3$ ) / √ 3 $V_L$

iv) Armature MMF/pole = $At_a$ = 2.7 $I_{ph}$ $T_{ph}$ $K_w$ /p

v) Effective area per pole = 0.6 – 0.65 times actual area

## 8. ***Field Design (Salient poles)***

Data needed for the design of the Field winding:

i) Flux density in the pole core
ii) Winding depth ($d_f$)
iii) Leakage factor (pole flux/gap flux)
iv) Field winding space factor ($S_f$)
v) Power dissipation ($q_f$) in W/m$^2$
vi) The ratio of field MMF to armature MMF
vii) Allow about 30 mm for insulation , flanges and height of the pole shoe.

MMF per unit height of the winding = $10^4$ Sqrt ($S_f$ $d_f$ $q_f$ )

## 9. ***Computer Aided Design of Electrical Machines***

The process of design any electrical may be broadly divided into three major aspects:

i) Electrical design
ii) Mechanical design
iii) Thermal design. Even though, these problems can be solved separately, there are many inter- related features.

The advantages of computer aided design are :

i) The computer can handle large volume of data to make a number of trial designs.

ii) Speed and accuracy of calculations are very high.

iii) It can be programmed to satisfying take logical decisions

iv) An optimized design with least cost and the required performance can be easily obtained.

Generally any design method can be

i) Analysis method

ii) Synthesis method

iii) Hybrid method

In the analysis method of design , a preliminary design is made by the designer regarding the machine dimensions, materials and other constructional features and these are given as input data to the computer and the performance quantities are calculated. The designer examines the performance and accordingly alters the input data and then feed them to the computer again. The computer calculates the new performance with the revised data. This process is repeated till the required performance is achieved.

In the synthesis method, the required performance values are also given to the computer as input. The computer through an iterative process alters the dimensions till the required performance is obtained.

In the hybrid method, by some human intervention, a combination of analysis and synthesis methods are adopted.

The method of design optimization using computers **:**

i) Choice of independent variables
ii) Variable transformation
iii) Forming the constraint functions for the performance
iv) Forming the objective function (OBJ)
v) Applying the minimization technique till the OBJ becomes with in the chosen tolerance.

Example of Design of optimization of Induction Motors

The independent variables which has a significant effect on the performance are

stator core diameter, stator core length , stator core depth, stator slot depth, stator slot width, rotor slot depth, rotor slot width, end ring depth, end ring width, . airgap length and airgap flux density.

The other variables in the design are either taken as constants dased on the voltage and power rating of the machine or they are in some way related to the above 11 variables.

During the course of optimization when the variables undergo incrementing or decrementing, they should also be constrained to be with in practical ranges. This is obtained by variable transformation. For example for airgap $X_{act} = X_{tran} + Lg_{min}$ ; where they respectively denote actual and transformed values and $Lg_{min}$ = minimum airgap required.

Performance Specifications:

1. Starting torque
2. maximum torque
3. Full- load power factor

4. full -load efficiency
5. full load slip
6. tooth and core flux densities
7. starting current
8. temperature rise
9. cost of the machine.

Objective function

The objective function is formed by comparing the specified and calculated values of the performance quantities at each iteration. Objective function minimization can be carried out either using conventional methods such as Powel's algorithm or Rosenbrock method or the recent techniques such as Genetic algorithm.

It should be noted that the independent variables or the performance specifications vary with the type of machine and its application.