Chapter 1

BASIC PRINCIPLES OF ELECTRICAL MACHINE DESIGN

List of symbols

Symbol	Meaning	Unit
a	Number of parallel paths in armature winding	-
a_z	Area of cross section of conductor	*mm^2*
ac	Specific electric loading	*amp.cond./m*
B_{av}	Specific magnetic loading	*Wb/m^2 or Tesla*
B_{gm}	Maximum air-gap flux density under load conditions	*Wb/m^2 or Tesla*
b	Pole arc	*m*
b_p	Width of the pole body	*m*
C_o	Output coefficient	*kVA/m^3 - rps*
c	Cooling coefficient	*°C $W\text{-}m^2$*
D	Armature diameter or stator bore	*m*
d_s	Depth of slot	*mm*
E	Generated emf or back emf	*V*
E_{cm}	Maximum voltage between adjacent segments	*V*
E_{ph}	Induced emf per phase	*V*
f	Frequency	*Hz*
I	Rated current	*A*
I_a	Armature current	*A*
I_z	Current in each conductor	*A*
I_{ph}	Current per phase	*A*
L	Armature length or stator core length	*m*
N	Speed	*rpm*
n	Speed	*rps*
n_s	Synchronous speed	*rps*
P	Rating of machine (Rated output power)	*kW*
P_a	Power developed by armature	*kW*

Symbol	Meaning	Unit
Q	kVA rating of machine	*kVA*
Q_l	Loss dissipated	*kW*
q	Loss dissipated per unit area	kW/m^2
R	Resistance	Ω
S	Dissipating surface	m^2
T_c	Turns per coil	-
T_{ph}	Turns per phase	-
V_a	Peripheral speed	*m/sec*
w_s	Width of the slot	*mm*
y_s	Slot pitch	*mm*
Z	Total number of armature or stator conductors	-
ϕ	Magnetic flux	*Wb*
Ψ	Ratio of pole arc to pole pitch	-
τ	Pole pitch	*m*
η	Efficiency	-
θ	Temperature rise	*°C*
δ	Current density	A/mm^2
ρ	Resistivity	Ω-*m*

1.1 INTRODUCTION

Electrical machine design involves application of science and technology to produce cost-effective, durable, quality and efficient machines. Also the machines should be designed as per standard specifications. The requirements like low cost and high quality will be conflicting in nature and so a compromise should be made between them.

The electrical machines can be classified into static and dynamic machines. The transformer is a static (stationary) machine. The motors and generators are dynamic (rotating) machines. The transformer converts electrical energy from one voltage level to another voltage level. The rotating machines converts electrical energy to mechanical energy or vice-versa.

The conversion in any electrical machine takes place through magnetic field. The required magnetic field is produced by an electromagnet which requires a core and winding. The basic principle of operation of all electrical machine is governed by Faraday's law of electromagnetic induction.

1.1.1 Constructional Elements of Transformer

The transformer is a static electromagnetic device used to transfer electrical energy from a high potential (voltage) circuit to low potential (voltage) circuit or vice-versa. It consists of two or more windings which link with a common magnetic field. An iron core serves as a path for magnetic flux.

The constructional elements of the transformer are windings, core, tank and cooling tubes or radiators. A simple transformer has two windings and they are called high voltage winding and low voltage winding. One of the winding is connected to supply and it is called ***primary***. The other winding is connected to load and it is called ***secondary***.

The two different types of transformer constructions are core type and shell type. In core type transformer the windings surround the core and in shell type transformer the core surround the windings. The core and winding assembly is housed in the tank. Cooling tubes or radiators are provided around the tank surface in order to increase the effective cooling surface.

1.1.2 Constructional Elements of Rotating Machines

The rotating electrical machines converts electrical energy to mechanical energy or vice-versa. The energy conversion takes place through magnetic field. Every rotating machine have the following three quantities. The presence of any two quantities, will produce the third quantity.

1. Magnetic field - I (Field)
2. Magnetic field - II (Armature)
3. Mechanical force

In generator, the armature is rotated by a mechanical force inside a magnetic field or the magnetic field is rotated by keeping armature stationary. By Faraday's law of induction, an emf is induced in the armature. When the generator is loaded, the armature current flows, which produce another magnetic field (armature magnetic field). Hence in a generator, by the presence of a magnetic field and mechanical force, an another magnetic field is produced.

The mechanical force developed by the motor is due to the reaction of two magnetic fields. A current carrying conductor has a magnetic field around it. When it is placed in another magnetic field it experiences a mechanical force due to the reaction of two magnetic field. Hence in a motor by the presence of two magnetic fields a mechanical force is developed.

From the above discussion it is clear that any rotating machine requires two magnetic field and one of the field is rotating. Hence a rotating machine will have a stationary and rotating electromagnet, each consisting of a core and winding. The stationary electromagnet is called ***stator*** and the rotating electromagnet is called ***rotor***.

The basic constructional elements of a rotating electrical machine are stator and rotor. In DC machines the stator consists of field core and winding. The rotor comprises of armature core and winding. In AC machines the stator has armature core and winding. The rotor consists of field core and winding. The constructional elements of various electrical machines are listed here.

Constructional elements of DC machine

Stator	-	Yoke or Frame	**Rotor**	-	Armature core
	-	Field pole		-	Armature winding
	-	Pole shoe		-	Commutator
	-	Field winding	**Others**	-	Brush
	-	Interpole		-	Brush holder

Constructional elements of salient pole synchronous machine

Stator	-	Frame	**Rotor**	-	Field pole
	-	Armature core		-	Pole shoe
	-	Armature winding		-	Field winding
				-	Damper winding

Constructional elements of cylindrical rotor synchronous machine

Stator	- Frame	**Rotor**	- Solid rotor
	- Armature core		- Field conductors or bars
	- Armature winding		

Constructional elements of squirrel cage induction motor

Stator	- Frame	**Rotor**	- Rotor core
	- Stator core		- Rotor bars
	- Stator winding		- End ring

Constructional elements of slip ring induction motor

Stator	- Frame	**Rotor**	- Rotor core
	- Stator core		- Rotor winding
	- Stator winding		- Slip rings

1.1.3 Classification of Design Problems

The design of an electrical machine involves solution of many complex and diverse engineering problems. The design problems may be classified under the following four major headings.

1. Electromagnetic design
2. Mechanical design
3. Thermal design
4. Dielectric design

Each major problem may be solved separately and the results are combined to give overall solution. Each major problem may be further divided into simple problems and solutions of individual problem are combined to give the solution of a major design problem.

The electromagnetic design problem in rotating machines involves the design of stator and rotor core dimensions, stator and rotor teeth dimensions, air-gap length, stator and rotor windings. In transformer it is the problem of designing the core and the windings.

The mechanical design in rotating machine involves the design of frame (enclosure), shaft and bearings. In transformer it is the design of tank (i.e., housing for core and winding assembly).

The thermal design in rotating machine involves the design of cooling ducts in core and cooling fans. In case of large machines coolants like air or hydrogen may be forced to circulate in the ducts and air-gap. In transformer it involves the design of cooling tubes or radiators.

Another important design problem, that may require great attention in the design of insulations (dielectric design). Dielectric materials are used to insulate one conductor from other and also the windings from the core. The dielectric materials are designed to withstand high voltage stresses. The breakdown of dielectric materials may lead to failure of machine.

1.1.4 Standard Specifications *(AU, Apr'17, 8 M)*

Every country has a standards organisation to fix standard specifications for the manufacturers. The specifications are guidelines for the manufacturers to produce economic products without compromising quality. The manufacturers who are compiling with the standards will be issued a certification for their products. The quality of the certified products will be periodically monitored by the standards organisation.

The standard specifications issued for electrical machines includes the following,

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 rise
7. Permissible loss and range of efficiency
8. Procedure for testing of machine parts and machines
9 Auxiliary equipments to be provided
10. Cooling methods to be adopted.

In India, Indian Standards Institution (ISI) was started in the year 1947 to lay down specification for various products. ISI was renamed as Bureau of Indian Standards (BIS) in the year 1986.

The standard specifications of a product (or part of a product) will be framed and released with a prefix IS (Indian standard) followed by number and year of publication.

The standards will be amended time to time, in order to include the latest developments in technology. Recently they have released revised standards ISO 9002, to comply with international standards.

The name plate of a rotating machine has to bear the following details as per ISI specifications.

1. kW or kVA rating of machine
2. Rated working voltage
3. Operating speed
4. Full load current
5. Class of insulation
6. Frame size
7. Manufacturers name
8. Serial number of the product

Some of the Indian standard specifications numbers along with year of issue for electrical machines are listed here.

IS 325-1966:	Specifications of three-phase induction motor.
IS 1231-1974:	Specifications of foot mounted induction motor.
IS 4029-1967:	Guide for testing three-phase induction motor.
IS 996-1979:	Specifications of single-phase AC and universal motor.
IS 1885-1993:	Specifications of electric and magnetic circuits.
IS 9499-1980:	Conventions concerning electric and magnetic circuits.
IS 7538-1996:	Specifications of three-phase induction motor for centrifugal pumps and agricultural applications.
IS 12615-1986:	Specifications of energy efficient induction motor.
IS 9320-1979:	Guide for testing DC machines.
IS 4722-1992:	Specifications of rotating electrical machines.

IS 12802-1989:	Temperature rise measurement of rotating electrical machines.
IS 4889-1968:	Method of determination of efficiency of rotating electrical machines.
IS 13555-1993:	Guide for selection and application of three-phase induction motor for different types of driven equipment.
IS 7132-1973:	Guide for testing synchronous machines.
IS 5422-1996:	Specifications of turbine type generators.
IS 7572-1974:	Guide for testing single-phase AC and universal motors.
IS 8789-1996:	Values of performance characteristics for three-phase induction motors.
IS 12066-1986:	Specifications of three-phase induction motors for machine tools.
IS 1180-1989:	Specifications of outdoor 3-phase distribution transformer upto 100 kVA. (Sealed and Non-sealed type)
IS 2026-1994:	Specifications of power transformers.
IS 11171-1985:	Specifications of dry type power transformers.
IS 5142-1969:	Continuously variable voltage auto transformers.
IS 10028-1985:	Code of practice for selection, installation and maintenance of transformers.
IS 10561-1983:	Application guide for power transformers.
IS 13956-1994:	Testing transformers.
IS 9678-1980:	Methods of measuring temperature rise of electrical equipment.
IS 12063-1987:	Classification of degree of protections provided by enclosures of electrical equipment.
IS 3855-1966:	Standard dimensions of rectangular enamelled copper conductor.
IS 449-1962:	Standard dimensions of enamelled round copper conductor (oleo resinous enamel).
IS 1595-1960:	Standard dimensions of enamelled round copper conductor (synthetic enamel).
IS 1897-1962:	Standard dimensions of bare copper strip.
IS 1666-1961:	Standard dimensions of paper covered rectangular copper conductor for transformer windings.
IS 2068-1962:	Standard dimensions of cotton covered rectangular copper conductor for transformer windings.
IS 3454-1966:	Standard dimensions of paper covered round conductors used for transformer windings.
IS 450-1964:	Standard dimensions of cotton covered round conductors used for transformer windings.

1.1.5 Major Considerations in Electrical Machine Design *(AU, Apr' 17, 8 M)*

The major considerations in electrical machine design are the following,

1. Cost
2. Durability
3. Performance as per specifications.

Most of the design aspects will be oriented towards reducing the cost of a machine but sometimes the low cost and durability cannot be achieved easily. Generally, a compromise is made between low cost and durability. The cost of a machine can be greatly reduced by choosing low cost materials without compromising performance specifications.

In rotating electrical machines, the volume of active part (and hence size of machine) is inversely proportional to speed for a specified output. Therefore, the machine can be designed to operate at the highest permissible speed so that the volume of active part will be less which results in low cost. Similarly, in transformers the volume of core is inversely proportional to flux density. Therefore, transformers can be designed to operate at higher flux densities so that the volume of core will be less which results in low cost.

The durability of a machine can be enhanced by choosing good quality materials and adapting latest design techniques and this naturally leads to higher cost. Mostly electrical machines are designed for longer life (typically more than 20 years) and continuous running.

The components of electrical machines are designed to have satisfactory performance as per specifications. The major components of rotating electrical machines are stator, rotor and windings. The major components of transformers are core and windings. The major components are designed to meet specifications like voltage, current and power rating, power factor, losses and efficiency and temperature rise.

1.2 GENERAL DESIGN PROCEDURE

In general any electrical machine has two windings. The transformer has primary and secondary winding. The DC machine and synchronous machine has armature and field winding. The induction machine has stator and rotor winding. The basic principle of operation of all electrical machine is governed by Faraday's law of induction. Also in every electrical machine the energy is transferred through the magnetic field. Hence a general design procedure can be developed for the design of electrical machines.

The general design procedure is to relate the main dimensions of the machine to its rated power output. An electrical machine is designed to deliver a certain amount of power called rated power. The rated power output of a machine is defined as the maximum power that can be delivered by the machine safely. In DC machine the power rating is expressed in *kW* and in AC machine in *kVA*. In case of motor the output power is expressed in *HP*.

In electrical machines the core and winding of the machine are together called ***active part*** (because the energy conversion takes place only in the active part of the machine). The active part of rotating machine is cylindrical in shape. If L is length and D is diameter of active part then volume of active part is $D^2 L$. A general output equation can be developed for DC machine which relates the power output to volume of active part ($D^2 L$), speed, magnetic and electric loading. Similarly a general output equation can be developed for AC machine which relates kVA rating to volume of active part ($D^2 L$), speed, magnetic and electric loading.

1.2.1 Main Dimensions of Rotating Machines *(PTU, May'19, 2 M)*

In rotating machines the active part is cylindrical in shape. The volume of the cylinder is given by the product of area of cross section and length. If D is the diameter and L is the length of cylinder, then the volume is given by $\pi D^2 L/4$. Therefore D and L are specified as main dimensions.

In case of DC machine, D represent the diameter of armature and L represent the length of armature. The Fig. 1.1 shows the main dimensions of DC machine.

Here, D = Diameter of armature

l_g = Length of air-gap

L = Length of armature

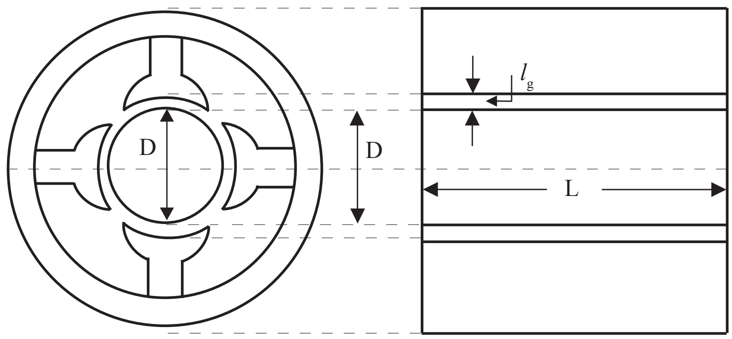

Fig. a: *Main dimensions of DC machines.*

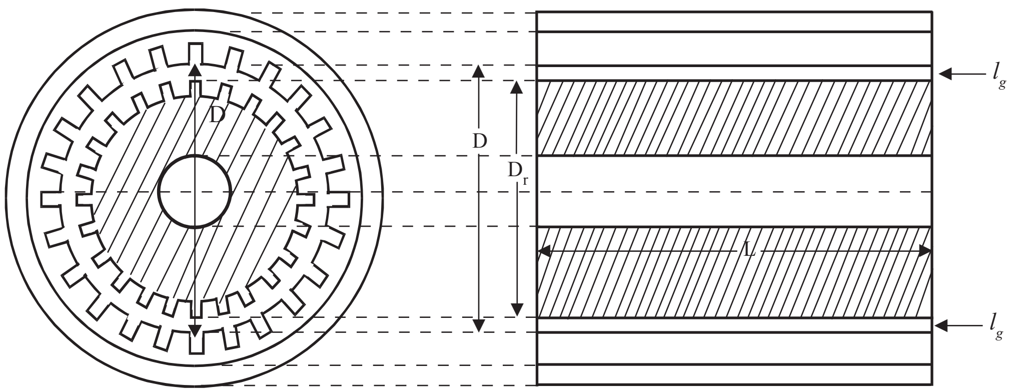

Fig. b: *Main dimensions of AC machines.*

Fig. 1.1: *Main dimensions of rotating machines.*

1.3 MAGNETIC AND ELECTRIC LOADINGS

Consider a conductor of length L, carrying a current of I_z amperes. If the conductor is moved in a uniform magnetic field of flux density, B_{av} Wb/m^2 then the work done in moving the conductor through a distance X is given by,

$$\text{Work} = X\, B_{av}\, L\, I_z \qquad .....(1.1)$$

When the conductor is moved through a distance X, the conductor cuts through a magnetic flux of $\phi = X\, B_{av} L$ webers.

$$\therefore\ \text{Work} = \phi\, I_z$$

In rotating machines the conductors are placed in armature. In one revolution of the armature, each conductor moves through a total flux of $p\phi$ webers, where ϕ is flux per pole and p is number of poles. If Z is the total number of armature conductors then the work done in one revolution is given by,

$$\text{Work} = p\,\phi \times I_z\, Z \qquad .....(1.2)$$

In equation (1.2) the term $p\phi$ represent the total flux entering and leaving the armature and so it is called ***total magnetic loading*** (or total flux). The term $I_z Z$ represents the sum of currents in all the conductors on the armature and so it is called ***total electric loading*** (or total current volume or total ampere conductors on the armature).

$$\therefore \text{ Total magnetic loading } = p\phi \qquad .....(1.3)$$

$$\text{Total electric loading } = I_z Z \qquad .....(1.4)$$

Therefore we can say that the work done in one complete revolution is given by the product of total magnetic loading and total electric loading.

The ***total magnetic loading*** is defined as the total flux around the armature periphery at the air-gap. The ***total electric loading*** is defined as the total number of ampere conductors around the armature periphery.

1.3.1 Specific Magnetic Loading

(PU, Nov'19, 8 M)

Each unit area of armature surface is capable of receiving a certain magnetic flux. Hence the flux per unit area is an important parameter to estimate the intensity of magnetic loading and it is also a criterion to decide the volume of active material. This flux per unit area is expressed as the average value of the flux density at the armature surface or specific magnetic loading (by assuming that the armature is smooth). It is denoted by B_{av} .

The ***specific magnetic loading*** or average flux density, B_{av} is given by the ratio of flux per pole and area under a pole.

$$\therefore \text{ Specific magnetic loading, } B_{av} = \frac{\text{Flux per pole}}{\text{Area under a pole}} = \frac{\text{Flux per pole}}{\text{Pole pitch} \times \text{Length of armature}}$$

$$= \frac{\phi}{\frac{\pi D}{p} \times L} = \frac{p\phi}{\pi DL} \qquad .....(1.5)$$

From equation (1.5) we can say that the ***specific magnetic loading*** is also given by the ratio of total flux around the air-gap and the area of flux path at the air-gap.

$$\therefore \text{ Specific magnetic loading, } B_{av} = \frac{\text{Total flux around the air-gap}}{\text{Area of flux path at the air-gap}} = \frac{p\phi}{\pi DL} \qquad .....(1.6)$$

The typical values of specific magnetic loading for various types of rotating machines are listed in Table 1.1.

1.3.2 Choice of Specific Magnetic Loading

(HTU, Dec'18, 10 M)

The specific magnetic loading is determined by,

1. Maximum flux density in iron parts of machine
2. Magnetizing current
3. Core losses.

Maximum flux density in iron

The maximum flux density in any iron part of machine must be below a certain limiting value. The maximum flux density occurs in the teeth of the armature (or stator core). [Teeth are the portion of the core in between slots].

The flux density in the teeth is directly proportional to specific magnetic loading. Hence the choice of specific magnetic loading should be such that the maximum value of flux density in the teeth is not exceeded. The maximum value of flux density in the teeth is between 1.7 to 2.2 Wb/m^2.

Magnetizing Current

The magnetizing current of a machine is directly proportional to mmf. The mmf is directly proportional to specific magnetic loading. Hence a large value of specific magnetic loading results in increased values of magnetizing mmf and magnetizing current.

The value of magnetizing current is not usually a serious design consideration in dc machines. But in induction motors an increased value of magnetizing current results in low power factor. Hence specific magnetic loading in induction motors is lower than in DC machines. For synchronous machines the magnetizing current is not so critical and the value of specific magnetic loading is intermediate between that of DC and induction machines.

Core loss

The core loss in any part of the magnetic circuit is directly proportional to flux density for which it is going to be designed. The flux density is directly proportional to the specific magnetic loading. Hence the core loss in a machine varies directly as the specific magnetic loading. Thus a large value of specific magnetic loading results in increased core loss and consequently a decreased efficiency and an increased temperature rise.

With a given specific magnetic loading, the core loss increases as the frequency of flux reversals is increased. This is because the hysteresis loss is directly proportional to the frequency and eddy current loss is proportional to the square of the frequency. It follows that for high speed dc machines, or high frequency AC machines, specific magnetic loadings must be reduced in order to achieve lower iron loss.

1.3.3 Specific Electric Loading

Every section of armature is capable of carrying certain amount of current. Hence ampere-turn per unit section of armature periphery (circumference) is an important parameter to estimate the intensity of electric loading and it is also a criterion to decide the volume of active material. This ampere-turn per unit section of armature periphery is expressed as the specific electric loading. It is denoted by **ac**.

The ***specific electric loading*** is given by the ratio of total armature ampere conductors and armature periphery (circumference) at air-gap.

$$\therefore \text{ Specific electric loading, } \mathbf{ac} = \frac{\text{Total armature conductors}}{\text{Armature periphery at air-gap}} = \frac{I_z Z}{\pi D} \qquad .....(1.7)$$

The value of specific electric loading for various types of rotating machines are listed in Table 1.1.

Table 1.1: Specific Magnetic and Electric Loadings

Machine	Specific magnetic loading B_{av} in Wb/m²	Specific electric loading ac in amp.cond./m
DC machine	0.4 to 0.8	15000 to 50000
Induction motor	0.3 to 0.6	5000 to 45000
Synchronous machine	0.52 to 0.65	20000 to 40000
Turbo alternator	0.52 to 0.65	50000 to 75000

1.3.4 Choice of Specific Electric Loading

The choice of specific electric loading depends on,

1. Permissible temperature rise
2. Voltage rating of machine
3. Size of machine
4. Current density

Permissible temperature rise

Let, θ = Temperature rise; c = Cooling Coefficient

S = Dissipating surface; δ = Current density

Q_l = Loss dissipated; ρ = Resistivity

$$\left.\begin{array}{r}\text{Loss dissipated per unit area}\\ \text{of armature surface}\end{array}\right\} q = \frac{(\text{Current})^2 \times \text{No.of conductors} \times \text{Resistance}}{\text{Surface area of armature}}$$

$$= \frac{I_z^2 \times Z \times \rho\, L/a_z}{\pi\, D\, L} = \frac{I_z Z}{\pi D} \times \frac{I_z}{a_z} \times \rho = \mathbf{ac}\, \delta\, \rho \qquad .....(1.8)$$

where, $\delta = I_z / a_z$

Also, $q = Q_l / S$ .....(1.9)

The temperature rise, $\theta = \frac{Q/c}{S} = qc$ .....(1.10)

From equation (1.10), $q = \theta/c$ .....(1.11)

On equating the equations (1.8) and (1.11),

$$\mathbf{ac}\, \delta\, \rho = \frac{\theta}{c}$$

$\therefore$ Maximum allowable specific electric loading, $\mathbf{ac} = \frac{\theta}{\rho\, \delta\, c}$ .....(1.12)

From equation (1.8) it can be inferred that the heat dissipated per unit area of armature is proportional to specific electric loading.

From equation (1.12) it is clear that allowable specific electric loading is fixed by allowable temperature rise and the cooling coefficient. A high value of **ac** can be used in a machine when a high temperature rise is allowed. The maximum allowable temperature rise of a machine is determined by the type of insulating materials used in it. When better quality insulating materials which can withstand high temperature rises are used in the machines, increased values of specific electric loading can be used. This results in reduction in the size of the machine.

A high value of electric loading may be used if the cooling coefficient of the machine is small. The value of cooling coefficient depends upon the ventilation conditions in the machine. High speed machines will have better ventilation and so higher value of **ac** can be used.

Voltage

Let, w_s = Width of the slot y_s = Slot pitch
d_s = Depth of the slot δ = Current density
S_f = Slot space factor

The specific electric loading can be related to the above terms by the equation,

$$\mathbf{ac} = d_s\,(w_s/y_s)\,\delta\,S_f \qquad .....(1.13)$$

From equation (1.13) it is clear that the specific electric loading is directly proportional to slot space factor S_f. In high voltage machines, greater insulation thickness is required and therefore the space factor for these machines is lower. Hence an increase in voltage will, in general, necessitate a reduction in specific electric loading **ac**.

Size of machine

From the equation (1.13) it is clear that **ac** depends on the dimension of the slot. For large machines the depth of the slot will be greater and so higher values of **ac** can be used. Actually if the current density and the slot space factor are assumed constant, then specific electric loading is proportional to the diameter as slot depth usually depends upon the diameter.

Current density

From the equation, $q = \mathbf{ac}\,\delta\,\rho$ it is clear that a higher value of specific electric loading can be used in a machine which employs lower current density in its conductors. (because $\mathbf{ac} = q/\delta\,\rho$).

Typical values of current density are in the range of 2 to 5 A/mm^2. The temperature rise is usually 40°C (above ambient) for normal applications and cooling coefficient is between 0.02 and 0.035°C $W\text{-}m^2$.

1.4 OUTPUT EQUATION

The output of a machine can be expressed in terms of its main dimensions, specific magnetic and electric loadings and speed. The equation which relates the power output to D, L, B_{av}, **ac** and n of the machine is known as output equation.

Output equation and Output coefficient of DC machine

The following equations are used to derive the output equation.

Induced emf in armature, $$E = \frac{\phi ZN}{60}\,\frac{p}{a} \quad \Rightarrow \quad E = \frac{\phi Znp}{a} \qquad \boxed{n = \frac{N}{60}} \qquad .....(1.14)$$

Current through each conductor, $$I_z = \frac{I_a}{a} \quad \Rightarrow \quad I_a = a\,I_z \qquad .....(1.15)$$

Specific magnetic loading, $B_{av} = \dfrac{p\phi}{\pi DL} \quad \Rightarrow \quad p\phi = \pi DL\, B_{av}$ .....(1.16)

Specific electric loading, $\mathbf{ac} = \dfrac{I_z Z}{\pi D} \quad \Rightarrow \quad I_z Z = \pi D\, \mathbf{ac}$ .....(1.17)

where,
- n = Speed in rps
- I_a = Armature current
- p = Number of poles
- a = Number of parallel paths
- Z = Number of armature conductors
- D = Diameter of rotor
- L = Length of rotor
- ϕ = Flux per pole

In DC generator the electrical power generated in the armature is given by the product of induced emf and armature current. In case of DC motor the mechanical equivalent of electrical power in armature is given by the product of induced emf (back emf) and armature current.

$\therefore$ Power developed in armature, $P_a = E\, I_a \times 10^{-3}$ in *kW* .....(1.18)

$$= \frac{\phi Znp}{a} \times aI_z \times 10^{-3}$$ Using equations (1.14) and (1.15)

$$= p\phi \times I_z Z \times n \times 10^{-3}$$

$$= \pi DL\, B_{av} \times \pi D\, \mathbf{ac} \times n \times 10^{-3}$$ Using equations (1.16) and (1.17)

$$= \pi^2 B_{av}\, \mathbf{ac} \times 10^{-3} \times D^2 L\, n$$

$$= C_o\, D^2 L\, n \qquad .....(1.19)$$

where, $C_o = \pi^2 B_{av}\, \mathbf{ac} \times 10^{-3}$ .....(1.20)

The equation, $P_a = C_o\, D^2\, Ln$ is called output equation of DC machine and the term C_o is called ***output coefficient*** of DC machine.

The output coefficient, C_o in terms of maximum gap density, B_g is given by,

$$C_o = \pi^2\, \psi B_g\, \mathbf{ac} \times 10^{-3} \qquad .....(1.21)$$

where, $B_g = \dfrac{B_{av}}{\psi}$ .....(1.22)

$\psi = \dfrac{b}{\tau}$ = Ratio of pole arc to pole pitch .....(1.23)

The term $D^2 L$ in the output equation is proportional to volume of active part. Therefore if C_o is constant then we can say the power output is directly proportional to the product of volume of active part and speed.

i.e., $P_a \;\alpha\;$ Volume of active part × Speed

If C_o is varied then power output is directly proportional to the four quantities and they are B_{av}, **ac**, volume of active part and speed.

i.e., $P_a \;\alpha\; B_{av} \times \mathbf{ac} \times$ Volume of active part × Speed.

Power developed by the armature, P_a is different from the rated power output P, of the machine. The relationship between the two are,

$$P_a = \frac{P}{\eta} \quad \text{- For DC generator} \qquad .....(1.24)$$

$$P_a = P \quad \text{- For DC motors} \qquad .....(1.25)$$

where, η = Efficiency of DC generator

Alternative expression for power developed in armature

Consider the equation (1.20), $P_a = p\phi \times I_z Z \times n \times 10^{-3}$.

Here $p\phi$ = Total magnetic loading

$I_z Z$ = Total electric loading

n = Speed in rps

Hence power developed in the armature can be expressed as shown in equation (1.26)

$$\left.\begin{matrix}\text{Power developed in} \\ \text{armature in KW}\end{matrix}\right\} = \begin{pmatrix}\text{Total} \\ \text{Magnetic} \\ \text{loading}\end{pmatrix} \times \begin{pmatrix}\text{Total} \\ \text{electric} \\ \text{loading}\end{pmatrix} \times \begin{pmatrix}\text{Speed} \\ \text{in} \\ \text{rps}\end{pmatrix} \times 10^{-3} \qquad .....(1.26)$$

In DC generator the power developed in armature has to supply for copper losses and load. Therefore the power developed in the armature of DC generator can also be expresseds shown in equation (1.27).

$$\left.\begin{matrix}\text{Power developed by} \\ \text{armature of a DC} \\ \text{generator}\end{matrix}\right\} = \begin{pmatrix}\text{Output} \\ \text{power}\end{pmatrix} + \begin{pmatrix}\text{Armature} \\ \text{copper loss}\end{pmatrix} + \begin{pmatrix}\text{Field} \\ \text{copper loss}\end{pmatrix} \qquad .....(1.27)$$

If we consider the input mechanical power from the prime mover then the electrical power developed in the armature of DC generator can be expressed as shown in equation (1.28).

$$\left.\begin{matrix}\text{Power developed by} \\ \text{armature of a DC} \\ \text{generator}\end{matrix}\right\} = \begin{pmatrix}\text{Input} \\ \text{power}\end{pmatrix} - \begin{pmatrix}\text{Friction, Windage and} \\ \text{Iron losses}\end{pmatrix} \qquad .....(1.28)$$

If P = output, η = efficiency then, input power = P/η

In DC motor the power developed in armature has to supply for constant losses and the remaining power is delivered to load.

$$\left.\begin{matrix}\text{Power developed by} \\ \text{armature of a DC motor}\end{matrix}\right\} = \begin{pmatrix}\text{Output} \\ \text{power}\end{pmatrix} + \begin{pmatrix}\text{Friction, Windage and} \\ \text{Iron losses}\end{pmatrix} \qquad .....(1.29)$$

In case of large machines the friction, windage and iron losses can be neglected.

$\therefore$ $P_a = P/\eta$ for generators and $P_a = P$ for motors

In case of small machines the friction, windage and iron losses can be taken as one-third of total losses.

$$\text{Total losses} = \begin{pmatrix}\text{Input} \\ \text{power}\end{pmatrix} - \begin{pmatrix}\text{Output} \\ \text{power}\end{pmatrix} = \frac{p}{\eta} - p = p\left(\frac{1-\eta}{\eta}\right) \qquad .....(1.30)$$

$$\left.\begin{array}{l}\text{Power developed by}\\ \text{armature of a DC motor}\\ \text{(small motor)}\end{array}\right\} = \begin{pmatrix}\text{Output}\\ \text{power}\end{pmatrix} + \begin{pmatrix}\text{Friction, Windage and}\\ \text{Iron losses}\end{pmatrix}$$

$$= P + \frac{1}{3} P\left(\frac{1-\eta}{\eta}\right) = P\left[\frac{3\eta + 1 - \eta}{3\eta}\right] = P\left(\frac{1+2\eta}{3\eta}\right) \qquad .....(1.31)$$

$$\left.\begin{array}{l}\text{Power developed by}\\ \text{armature of a DC generator}\\ \text{(small generator)}\end{array}\right\} = \begin{pmatrix}\text{Input}\\ \text{power}\end{pmatrix} - \begin{pmatrix}\text{Friction, Windage and}\\ \text{Iron losses}\end{pmatrix}$$

$$= \frac{P}{\eta} - \frac{1}{3} P\left(\frac{1-\eta}{\eta}\right) = P\left[\frac{3 - 1 + \eta}{3\eta}\right] = P\left(\frac{2+\eta}{3\eta}\right) \qquad .....(1.32)$$

Output equation and output coefficient of AC machine

The equations of induced emf, frequency, current through each conductor and total number of armature conductors of an AC machine are given below. These equations are obtained from the knowledge of machine theory.

Induced emf per phase, $E_{ph} = 4.44\ f\ \phi\ T_{ph}\ K_{ws}$ .....(1.33)

The frequency of induced emf, $f = \dfrac{pn_s}{2}$ .....(1.34)

Current through each conductor, $I_z = \dfrac{I_{ph}}{a}$ .....(1.35)

where, I_{ph} = Current per phase

and a = Number of parallel circuits or paths per phase.

Total number of armature conductors, Z = Number of phases $\times\ 2\ T_{ph}$

$= 3 \times 2\ T_{ph} = 6\ T_{ph}$ .....(1.36)

Consider a 3-phase machine having one circuit (one parallel path) per phase. The volt-ampere rating of one phase is given by the product of voltage per phase and current per phase. Hence the kVA rating of 3-phase AC machine can be written as shown in equation (1.37).

kVA rating of 3-phase machine, $Q = 3\ E_{ph}\ I_{ph} \times 10^{-3}$ .....(1.37)

On substituting for E_{ph}, I_{ph} and f from equations (1.33), (1.35) and (1.34) respectively in equation (1.37) we get,

$$Q = 3 \times 4.44\ f\ \phi\ T_{ph}\ K_{ws} \times I_z \times 10^{-3} = 3 \times 4.44 \times \frac{p\ n_s}{2} \times \phi\ T_{ph}\ K_{ws}\ I_z \times 10^{-3}$$

$$= 6.66\ p\ n_s\ \phi\ T_{ph}\ K_{ws}\ I_z \times 10^{-3} \qquad .....(1.38)$$

$$= 1.11 \times p\phi \times I_z\ 6\ T_{ph} \times n_s \times K_{ws} \times 10^{-3}$$

On substituting for $6T_{ph}$ from equation (1.36) in equation (1.38) we get,

$$Q = 1.11 \times p\phi \times I_z Z \times n_s \times K_{ws} \times 10^{-3} \qquad .....(1.39)$$

On substituting for $p\phi$ and $I_z Z$ from equations (1.16) and (1.17) in equation (1.40) we get,

$$Q = 1.11 \times \pi\, D\, \mathbf{ac} \times n_s \times K_{ws} \times 10^{-3}$$

$$= 1.11\, \pi^2\, B_{av}\, \mathbf{ac}\, K_{ws} \times 10^{-3} \times L\, n_s$$

$$= 11\, B_{av}\, \mathbf{ac}\, K_{ws} \times 10^{-3} \times D^2\, L\, n_s$$

$$= C_o\, D^2\, L\, n_s \qquad .....(1.40)$$

where, $C_o = 11\, B_{av}\, \mathbf{ac}\, K_{ws} \times 10^{-3}$ .....(1.41)

The equation, $Q = C_o\, D^2\, L\, n_s$ is called ***output equation*** and C_o is called ***output coefficient***. The term D^2 L in the output equation is proportional to volume of active part. Therefore, if C_o is constant then we can say that the kVA rating is directly proportional to the product of volume of active part and speed.

i.e. Q α Volume of active part × Speed

If C_o is varied then power output is directly proportional to the four quantities : B_{av}, **ac**, volume of active part and speed.

i.e. Q α B_{av} × **ac** × Volume of active part × Speed

1.5 SEPARATION OF D AND L

From equations (1.19) and (1.40) we can say that the output of a rotating electrical machine is directly proportional to the term D^2 L. The active part of the rotating electrical machine is cylindrical in shape and the volume of cylinder is πD^2 L. Hence the term D^2 L is related to volume of active part. The seperation of D and L refers to the selection of an appropriate values for D and L for a given volume of active part.

For a given volume of active part there are various choice of D and L. The choice of D and L and the ratio between them depends on a number of factors in various types of rotating machines. In the following sections a brief discussion about various factors that decides the choice of D and L in various types of rotating machines are presented. In general a ratio of L/τ or L/D is assumed where τ = pole pitch = $\pi D/p$. Using the output equation and from the knowledge of kW or kVA rating, specific loadings and speed, the value of D^2 L is estimated. Then by solving the two equations (i.e., the equation of L/τ or L/D and D^2 L) the values of D and L are estimated.

1.5.1 Separation of D and L for DC Machines

In DC machines the separation of D and L depends on,

1. Pole proportions
2. Peripheral speed
3. Moment of inertia
4. Voltage between adjacent commutator segments

Pole proportions

The dimensions of the machine are decided by the square pole criterion. This states that for a given flux and cross-section area of pole, the length of mean turn of field winding is minimum, when the periphery forms a square. This means that the length, L must be approximately equal to pole arc or $\mathbf{L = b = \psi\, \tau}$. The value of Ψ is usually between 0.64 to 0.72. ($\therefore$ The ratio L/τ = 0.64 to 0.72). However in practice L is slightly greater than pole arc, b and L/τ is usually between 0.7 to 0.9. For square pole criterion choose L/τ as 0.7.

b_p = Width of pole body

b = Pole arc

L = Core length

τ = Pole pitch = $\pi D/p$

Ψ = b/τ = Ratio of pole arc to Pole pitch

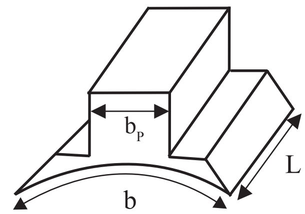

Fig. 1.2: *Pole Dimensions.*

Peripheral speed

The peripheral speed of armature (V_a) is sometimes a limiting factor to the value of diameter. The peripheral speed should not exceed about 30 *m/s*.

Maximum peripheral of armature, V_{am} = 30 *m/s*

Moment of inertia

For machines used in control systems, a small moment of inertia is desirable. For low moment of inertia the diameter should be made as small as possible. Conversely a high inertia machine may be required for impact load applications and such machines are designed with larger diameter.

Voltage between adjacent commutator segments

The maximum core length is fixed by the maximum voltage that can be allowed between adjacent segments. It can be shown that the maximum voltage between adjacent commutator segments in DC machines is given by equation (1.42) (using equations (3.47) and (3.50) of section 3.6.5).

Maximum voltage between adjacent segments, $E_{cm} = 2\, B_{gm}\, L\, V_a\, T_c$ .....(1.42)

where, B_{gm} = Maximum air-gap flux density under load conditions.

T_c = Turns per coil

The limiting values of B_{gm}, V_a, E_{cm} are B_{gm} = 1.2 Wb/m^2, V_{am} = 30 *m/s*, E_{cm} = 30 *V*. With these limiting values, for T_c = 1, L $\approx$ 0.4 *m*. This is only an indication of limiting value of core length, but it must be clear that large DC machines should have large diameters rather than large core lengths.

1.5.2 Separation of D and L for Induction Motors

The operating characteristics of an induction motor are mainly influenced by the ratio L/τ. The ratio of L/τ for various design features are listed below.

For minimum cost,	L/τ = 1.5 to 2
For good power factor,	L/τ = 1.0 to 1.25
For good efficiency,	L/τ = 1.5
For good overall design,	L/τ = 1.0

Generally L/τ lies between 0.6 to 2. It can be shown that for best power factor the pole τ pitch is given by the equation, $\tau = \sqrt{0.18\, L}$.

1.5.3 Separation of D and L for Synchronous Machines

In synchronous machines the separation of D and L depends on,

1. Pole proportions
2. Peripheral speed
3. Number of poles
4. Short circuit ratio.

Pole proportions

In salient pole synchronous machines the choice of diameter (D) depends on the type of pole and the permissible peripheral speed. The two-types of poles used in salient pole machines are round poles and rectangular poles.

When round poles are used the ratio of L/τ is between 0.6 to 0.7, where τ = pole pitch = $\pi D/p$. When rectangular poles are employed the ratio of L/τ is between 1 to 5.

Peripheral speed

For large high speed machines D is fixed by the limiting peripheral speed. The output equation for synchronous machine can be expressed in terms of peripheral speed (V_a) as shown below.

The output equation is, $Q = C_o D^2 L n_s$

where, $C_o = 11 B_{av}\, ac\, K_{ws} \times 10^{-3}$

But $V_a = \pi D n_s$; $\quad \therefore \quad D = \dfrac{V_a}{\pi n_s}$ $\left[\begin{array}{c}\text{Here length of air - gap } (l_g) \\ \text{is neglected.}\end{array}\right]$

On substituting the expression for C_o and D in the output equation,

$$Q = 11 B_{av}\, ac\, K_{ws} \times 10^{-3} \left(\frac{V_a}{\pi n_s}\right)^2 L n_s$$

$$Q = 1.11 B_{av}\, \mathbf{ac}\, K_{ws} \times 10^{-3} \frac{V_a^2 L}{n_s} \qquad .....(1.43)$$

From equation (1.43) we can say that an increase in machine rating will necessitate an increase in V_a which in turn is achieved by increasing D, until the maximum permissible peripheral speed is reached. Once this happens, the value of D cannot be increased further and the only way to get increased output is to increase the length L. In general the value of D is calculated using the limiting value of peripheral speed V_a for cylindrical rotor synchronous machines. Then using the values of D^2 L and D, the value of L is estimated.

Number of poles

The small diameter and large number of poles results in the small pole pitch and so less space for field coils. Hence a large diameter is advisable for machines having large number of poles. The empirical relationship used to decide the number of poles is

$$\tau/L = 0.5 + (6/p) \qquad .....(1.44)$$

Short circuit ratio

A major factor influencing the design of synchronous machines is their short circuit ratio (SCR).

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

Higher values of SCR results in higher stability limit and a low value of inherent regulation. For high values of SCR, the length of core (L) should be large.

1.6 FACTORS AFFECTING THE SIZE OF ROTATING MACHINES

The factors affecting the size of rotating machines are speed and output coefficient. The output coefficient in turn depends on specific electric and magnetic loadings.

Speed

The power developed in armature of a rotating machine is directly proportional to speed. Also the speed is inversely proportional to volume of active parts.

Power developed in armature, $P_a = C_o D^2 L n$

$\therefore$ Power, $P_a \propto n$ (Provided C_o and D^2L is constant)

Speed, $n \propto \frac{P_a}{D^2 L}$ (Provided C_o is constant)

Since D^2L is propotional to volume of active parts, for same volume with increase in speed the output will increase. For a given output, a high speed machine will have less volume and costs less. Therefore for reducing the cost highest possible speed may be selected. The maximum speed is limited by mechanical stresses of the rotating parts.

Output coefficient

The power developed in armature of rotating machine is directly proportional to output coefficient. Also the volume of active parts is inversely proportional to output coefficient.

Power developed in armature, $P_a = C_o D^2 L n_s$

$\therefore P_a \propto C_o$ (Provided D^2L and n are constant)

$C_o \propto \frac{1}{D^2 L}$ (Provided P_a and n are constant)

Hence higher value of C_o results in higher output. With high C_o, the volume of active parts decreases and the machine costs less.

The output coefficient, C_o depends on specific loadings, B_{av} and **ac**. Hence for higher C_o, higher specific loadings are chosen.

$$C_o = \pi^2 B_{av} \, \mathbf{ac} \times 10^{-3}$$

$$\therefore C_o \propto B_{av} \, \mathbf{ac}$$

The high values of specific loadings may affect some of the performance characteristics of the machines like temperature rise, efficiency, commutation conditions, etc. So, specific loadings are chosen such that they give best performance and minimum cost.

1.7 VARIATION OF OUTPUT AND LOSSES WITH LINEAR DIMENSIONS

Consider two machines of the same type with all their linear dimensions in the ratio x :1 and having the same speed, flux density and current density. Let the machine with linear dimensions x times be called A and the other machine B.

Output

$$\text{Output} = C_o D^2 Ln$$

$$= \pi^2 B_{av}\,\mathbf{ac}\,D^2 Ln \times 10^{-3}$$

Using equations (1.19) and (1.20)

Let, B_{av} and n are constants,

$\therefore$ Output $\propto$ **ac** D^2 L

$$\mathbf{ac} = \frac{I_z Z}{\pi D} = \frac{\delta\, a_z\, Z}{\pi D}$$

$$\delta = \frac{I_z}{a_z}$$

Since δ, Z and π are constants,

$$\mathbf{ac} \propto \frac{a_z}{D}$$

Here, $a_z \propto x^2$ and $D \propto x$

$$\therefore\ \mathbf{ac} \propto \frac{x^2}{x}$$

$$\therefore\ \mathbf{ac} \propto \mathbf{x}$$

Here, $D^2 \propto x^2$ and $L \propto x$

Since, Output $\propto$ **ac** D^2 L,

Output $\propto x\, x^2\, x$

$\therefore$ **Output** $\propto x^4$

Therefore the output of machine A is x^4 times the output of machine B.

Losses

I^2 R loss = Number of conductors × Copper loss in each conductor

$$= Z I_z^2 \left(\rho \frac{L}{a_z}\right)$$

$$\frac{\rho l}{a} = \text{Resistance}$$

$$\therefore\ I^2 R \text{ loss} = Z(\delta\, a_z)^2 \frac{\rho L}{a_z} = \delta^2 \rho \times (Z a_z L)$$

$$\delta = \frac{I_z}{a_z}$$

$$= \delta^2 \rho \times \text{Volume of active portion of conductors}$$

$\therefore I^2$ R loss α Volume of active portion of conductors

$\therefore I^2$ R loss α x^3

Thus the copper loss of machine A is x^3 times those of B.

Total iron loss = Loss per unit volume × Volume of iron

$\therefore$ Total iron loss $\propto x^3$

Both I^2 R loss and iron losses vary as the third power of linear dimensions. **Hence total losses of machine A is x^3 times those of B.**

Efficiency

The efficiency increases with increase in x.

$$\text{Efficiency, } \eta = \frac{\text{Output}}{\text{Output + Losses}}$$

$$\therefore \ \eta \propto \frac{x^4}{x^4 + k\,x^3} = \frac{1}{1 + k/x}$$

With increase in x (i.e., as the size of machine increases) the term k/x becomes smaller and smaller. Hence the efficiency increases, with increase in the linear dimensions of the machine.

1.8 LIMITATIONS IN DESIGN

(VTU, Dec' 19, 6 M)

The specifications imposed by consumers and standards organisation are major limitations in design. Some of the specifications to be met are allowable temperature rise, losses, efficiency, power factor, voltage rating, torque requirement, etc.

The following factors impose limitations on design of electrical machines.

1. Saturation
2. Temperature rise
3. Stress on insulation
4. Efficiency
5. Stress and strain on rotating parts and bearings
6. Mechanical precision of air-gap
7. Commutation
8. Power factor
9. Specifications.

For maximum utilization of active material the specific magnetic and electric loading can be kept as high as possible. The value of specific magnetic loading is limited by the saturation of magnetic materials used in the machine.

The value of specific electric loadings is limited by the allowable temperature rise in the machine, which in turn depends on the insulating material. If an insulating material is subjected to temperatures above its limit, then its life is drastically reduced.

The heat developed in the electrical machines (due to losses) impose thermal stress on the insulating materials. The operating voltage impose electrical stress on the insulating materials. The short circuit currents that may flow in the windings create mechanical stresses on the insulating materials. The type of insulating material is decided by the operating temperature and the size (dimension) of insulation is decided by the electrical and mechanical stresses.

The capital and running cost of machine depends on efficiency. If the losses in the machine are low then running cost will be less. In order to keep the electric and magnetic losses to a low value, the specific electric and magnetic loadings should be as low as possible. This requires larger volume of active material (iron and copper/aluminium) which results in higher capital cost. Hence, for a machine with high value of efficiency the capital cost will be higher and running cost will be lesser.

The dimension of rotor and the central shaft are limited by the mechanical stress and strain on them. In general the rotor should be stiff and there should not be any significant deflection due to strain. In high speed machines the rotor slot dimensions are selected such that the mechanical stresses at the bottom of rotor teeth do not exceed the limit.

The type of bearings to be used in rotating machines are decided by the rotor weight, external loads, forces due to unbalanced rotors and unbalanced magnetic pull.

In induction motors, the length of air-gap is kept as small possible for high power factor. The length of air-gap is mainly limited by the precision (accuracy) of mechanical fabrication technology. By employing modern CNC machines and dynamic balancing of rotors smaller air-gaps can be achieved.

The commutation conditions in DC machines limit the maximum power output that can be delivered by the machine. The maximum power output that can be obtained from a single DC machine is 10 *MW*.

In general the power factor should be high in order to reduce the current level for the same power. For high value of power factor, the specific magnetic loading should be less and the length of air-gap should be as small as possible. These requirements will increase the cost of the machine. (Because when magnetic loading is reduced the volume of active material has to be increased and for small values of air-gap the fabrication cost will be high).

1.9 MODERN MACHINES MANUFACTURING TECHNIQUES

The modern electrical machines are characterized by a very wide range of power outputs. The power range varies from a fraction of a watt to several hundreds of megawatts. The range of rotational speeds of electrical machines is also very wide. The range of speed may vary from few revolutions per second to several thousand revolutions per second. The large varied fields of applications and wide range of both power output and speed of operation of electrical machines has led to a variety of types of construction. The type of construction to be adopted in mostly influenced by the operating speed of the machine.

Some of the modern trend in electrical machine manufacturing techniques are given below:

1. Low-speed machines (below 250 rpm) are built with large diameter and small axial length and high-speed machines (3000 rpm and above) with small diameter and a long core length.

2. The size machine is designed as small in size as possible. This leads to use of lesser material with same efficiency and overload capacity. The increase in power ratings using smaller size coupled with good overall performance has been possible due to technology advancement in loss reduction techniques and design of better cooling systems.

3. Use of magnetic materials having permeability, a low iron loss and a high mechanical strength. These characteristics permit use of the high values of flux density and therefore result in reduction in the size of the machine and help to achieve higher power output.

4. The modern trend is to use improved insulating materials and high quality newer insulating materials that can withstand much higher temperatures. This leads to design small size machines with higher power output.

5. Modern machine manufacturing techniques are equipped with use of higher electro-magnetic loadings for active parts and increased mechanical loadings for construction materials.

6. The modern trend is to analyze and improve the design of individual parts for better performance and cost reduction.

7. Also, modern design trend takes care of satisfactory operation under the desired environmental conditions.

1.10 MODERN TRENDS IN DESIGN OF ELECTRIC MACHINES *(JNTKU, Apr'19, 6 M)*

The modern trend in electrical machine design is considering all types of electrical machine as electromechanical energy network and use optimization technique to search best design for a specified objective like low cost, small size, highly efficient, etc.

Another, modern trend is to design a series of machines having different ratings to fit into a single frame size. In this case, the finished designs of machines are in groups, in which all designs within a group are interdependent. This again is an optimization problem because frame sizes have to be optimum giving due weightage to designs of all the machines in a series or a group.

The design of electrical machines by optimization techniques is an iterative process in which the assumed data may have to be varied a number of times to arrive at the desired design. Therefore the final design data to meet the specified optimum criteria is a matter of long and tedious iterations, This fact has led to the application of fast digital computers to the design of electrical machines.

The digital computer has completely revolutionized the field of electrical machine design. The computer aided design has the advantages of eliminating tedious and time-consuming hand calculations thereby allowing the designer to concentrate on physical and logical ideas.

Also, the use of computer makes possible more trial designs and enables sophisticated calculations to be made with in tolerable limits in lesser time. When computers are used it is easy to check data at every design stage, easy to handles non-linearities and incorporates the designer's ideas. Computer aided design permits implementation of more detailed and precise functional relationships which give rise to possibility of new and comprehensive design procedures.

1.11 COMPUTER AIDED DESIGN OF ELECTRICAL MACHINES *(KTU, Feb'18, 4 M)* *(AKTU, Dec'19, 5 M)*

The various computer aided design techniques available for electrical machine design can be broadly classified into Analysis method and Synthesis method. In the analysis method the design will be finalized by human and computer interactions, whereas in synthesis method the design is finalized by computer itself by employing optimization techniques to fit the design for a specified performance.

1.11.1 Analysis Method of Design of Electrical Machines *(UTU, Dec'13, 5 M)*

The various steps in analysis method of electrical machine design are shown as a flowchart in Fig. 1.3. In analysis method the human or a designer select the choice of dimensions, materials and types of construction to be employed and input these details as input data to a computer program. The computer does all the design calculations and then using the design data the computer estimate the performance of the machine. The design data and estimated performance of the machine are given as output to the designer. The designer examines the performance and if the performance is not satisfactory then the designer modifies the input design parameters and make another run of the computer program with modified data and this process is repeated until a satisfactory design is achieved. The design is finalized by the designer.

The analysis method of design is good for a beginner using digital computers for the design of electrical machines and in fact most of the designer engineers initially start machine design by analysis method.

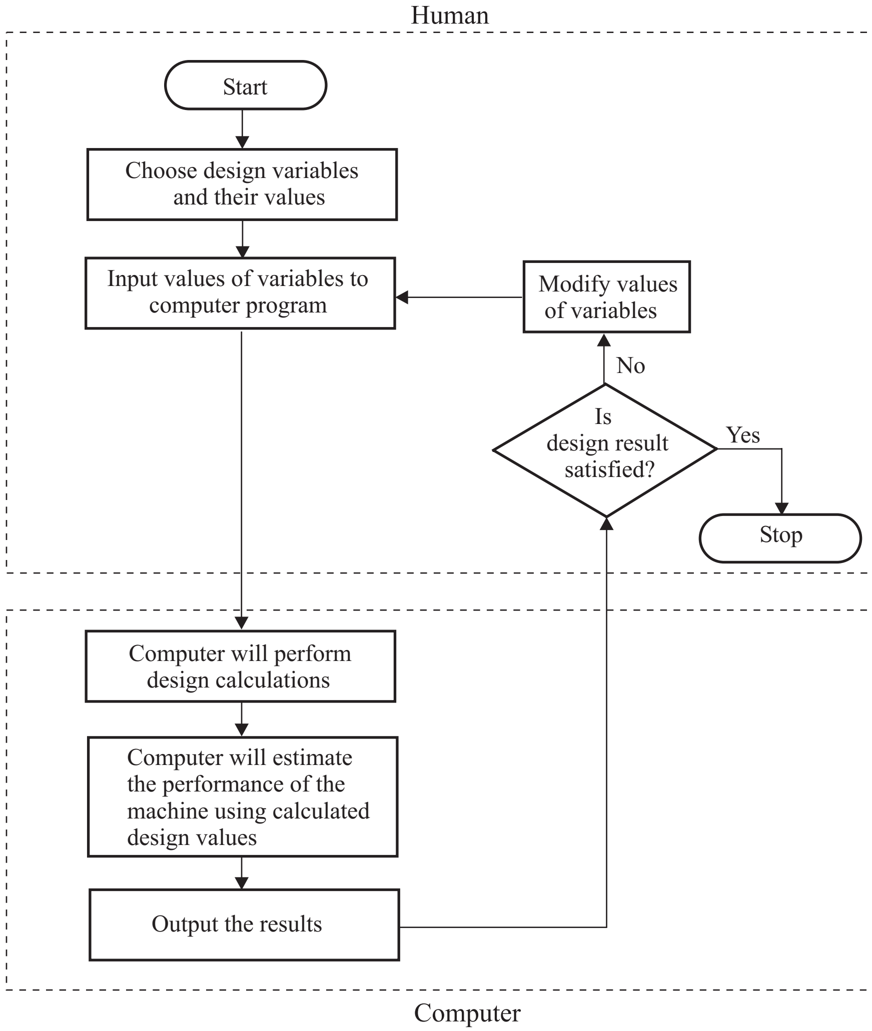

Fig. 1.3: *Analysis method of computer aided design of electrical machines.*

The advantages of analysis method are,

1. It is easy and straight forward to program the design equations.
2. It results in considerable time saving in performing calculations.
3. Analysis method programs are simple and they become the foundations for later larger and sophisticated programs.
4. The interaction of designer and computer yields highly acceptable results.

1.11.2 Synthesis Method of Design of Electrical Machines

(AKTU, Dec'19, 7 M)
(UTU, Dec'13, 5 M)

The various steps in synthesis method of electrical machine design are shown as a flowchart in Fig. 1.4. The major difference between analysis and synthesis method is that the desired performance is also given as input along with design variables and data to the computer. The logical decisions required to modify the variables to achieve the desired performance are implemented in the program as a set of instructions or an algorithm. Therefore, human or designer interaction is not necessary in synthesis method and the computer itself will decide the final design. Most of the synthesis method employ an optimization algorithm to achieve a best design. Sometimes, the design is carried by different optimization algorithms and the results of various optimization techniques are compared to choose better design.

Synthesis method of design is designing a machine that satisfies a set of specifications or performance indices. A large number of solutions are possible for a given set of specifications and it will be difficult to choose a particular design. Therefore, the synthesis design includes optimum design techniques with an objective for good design. It will be very difficult to arrive at final design in synthesis method without optimization technique.

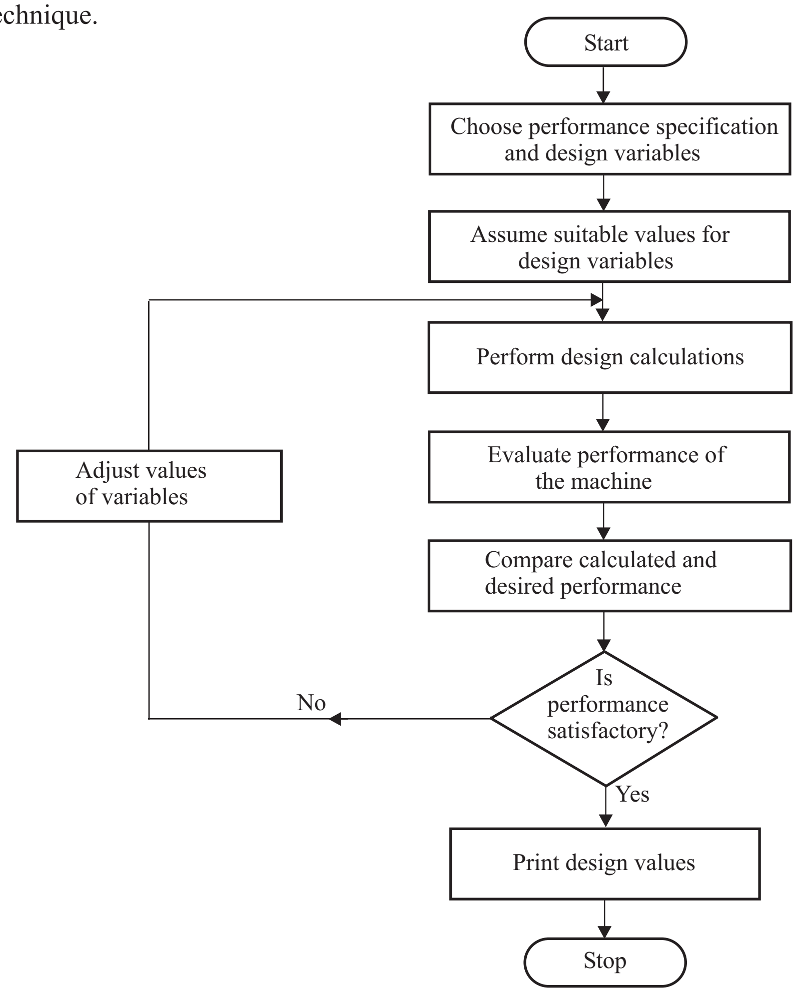

***Fig. 1.4:** Synthesis method of computer aided design of electrical machine.*

The advantages of synthesis method of design is the savings in time and in engineering man hours due to the decision making left to the computer.

The disadvantages in synthesis method of design are,

1. The synthesis method involves too much of logic and before incorporating these logical decisions in the program they have to be accepted by team of design engineers. In a team, different members may give different suggestions to produce an optimum design and it becomes really hard to formulate an unique logical decisions.

2. The synthesis method programs are too complex which lead to high software development cost and require computers with high configurations involving huge expenditure.

3. The synthesis program developed at high cost needs periodic updating to incorporate latest development in materials, manufacturing techniques, performance standards, costs of materials and market conditions. Also, require changes in the design logic itself. Therefore, a synthesis program requires both additional effort and cost.

1.11.3 Hybrid Method of Design of Electrical Machines

Hybrid method incorporates both the analysis as well as the synthesis method in the program. Normally a machine design includes design of number parts of the machine. In hybrid method of design some parts are designed by analysis method and other parts are designed by synthesis method. Since the synthesis methods involve greater cost, a classification is needed to decide the parts to be designed by analysis method and parts to be designed by synthesis method.

The advantages of hybrid method are,

1. The results of hybrid method will be more appropriate, due to combination of designer involvement in finalizing design and optimization of vital parts.

2. The cost of hybrid systems will be lesser than synthesis systems, due to design of non vital parts by analysis method.

3. Since the design of some parts are carried by analysis method, the time required for design will also be lesser than synthesis method.

1.11.4 Optimization Techniques in Electrical Machine Design *(UTU, Dec'13, 10 M)*

The aim of optimization in the design of electrical machine is to achieve a best design solution for a given set of specifications by satisfying the performance requirements and constraints.

The optimization process, involves possible range of values of varies variables and a logic to change the values of variables in order to satisfy all limitations or restraints imposed on the performance of the machine. Therefore, optimization is a process of finding a best solution for a given set of conditions.

In order to achieve the best possible solution, it is necessary to define the objective of optimization process. The objective may vary from one problem to another and in general the objective may be either economical or technical. In electrical machine design, some of the objectives are low cost, small size, high efficiency, etc.

The design problem of electrical machines has conflicting conditions or constraints. For example, the cost of active materials in induction motors can be reduced by using high values of specific electric and magnetic loadings but these high values of specific loadings will result in unsatisfactory performance like high temperature rise and poor power factor. The choice of low values of specific loading has the undesirable effect of high cost and better performance. Therefore, the cost and performance are conflicting in nature. The best design can be obtained by making a compromise between cost and performance.

1.11.5 General Procedure for Optimization in Design of Electrical Machines

1. Choose a design problem and define an objective for the design problem under consideration. For example, design of small DC motor with high efficiency. In this example design of small DC motor is design problem and high efficiency is objective.

2. Determine the restrictions or constraints in design the problem. For example, limitation in speed, maximum values of main dimensions, etc.

3. Identify the physical system of the design problem and examine the structure of the system and the inter-relationship of the system elements. In design of small DC motor, physical system is DC machine and components of DC machine are system elements.

5. Construct a mathematical model of the system using design equations and variables.

6. Determine the range of system variables. Also, define the various restrictions imposed on the system variables.

7. Choose an optimization algorithm and develop software codes in a programming language to perform design calculations and estimate the performance.

8. The optimization involves a number of iterations or repetitions of design calculations and performance estimation to achieve the objective.

9. In each iteration the estimated performance is compared with specified objective and difference is estimated. In next iteration the variables are modified and algorithm is applied to get next best solution. This process is repeated until we get a solution very close to specified and estimated performance.

1.12 SUMMARY OF DESIGN EQUATIONS

1. Total magnetic loading = $p\phi$
2. Total electric loading = $I_z Z$
3. Specific magnetic loading, $B_{av} = \dfrac{p\phi}{\pi DL}$
4. Specific electric loading, **ac** $= \dfrac{I_z Z}{\pi D}$
5. Power developed in the armature of DC machine, $P_a = C_o D^2 L n$
6. Output coefficient of DC machine, $C_o = \pi^2 B_{av}$ **ac** $\times 10^{-3}$
7. kVA rating of 3-phase AC machine, $Q = C_o D^2 L n_s$
8. Output coefficient of AC machine, $C_o = 11 B_{av}$ **ac** $K_{ws} \times 10^{-3}$
9. Pole pitch, $\tau = \pi D/p$
10. Choice of L/τ for DC machines
    i) In general, $L/\tau = 0.7$ to 0.9
    ii) For square pole criterion, $L/\tau = 0.7$

11. Choice of L/τ for induction motors
    i) For minimum cost, $L/\tau = 1.5$ to 2
    ii) For good power factor, $L/\tau = 1.0$ to 1.25
    iii) For good efficiency, $L/\tau = 1.5$
    iv) For good overall design, $L/\tau = 1.0$
    v) For best power factor, $\tau = \sqrt{0.18\,L}$
12. Choice of L/τ for salient pole synchronous machines
    i) When round poles are employed, $L/\tau = 0.6$ to 0.7
    ii) When rectangular poles are employed, $L/\tau = 1$ to 5
13. In cylindrical rotor synchronous machines,
    i) Diameter of rotor, $D_r = \dfrac{V_a}{\pi n_s}$
    ii) Stator inner diameter, $D = D_r + 2\,l_g$

> ***Note :*** *If l_g (length of air-gap) is neglected then $D = D_r$*

14. Maximum allowable specific electric loading, **ac** = $\dfrac{\theta}{\rho\,\delta\,c}$

1.13 SOLVED PROBLEMS

(KTU, Feb' 18, 10 M) (AU, Apr' 18, 8 M)

EXAMPLE 1.1

A 350 *kW*, 500 *V*, 450 *rpm*, 6 pole DC generator is built with an armature diameter of 0.87 *m* and core length of 0.32 *m*. The lap wound armature has 660 conductors. Calculate the specific electric and magnetic loadings.

GIVEN DATA

P = 350 *kW*	D = 0.87 *m*	V = 500 *V*	L = 0.32 *m*
n = 450/60 *rps*	Z = 660	p = 6	Lap wound

SOLUTION

Specific electric loading, **ac** = $\dfrac{I_z Z}{\pi D}$

Specific magnetic loading, $B_{av} = \dfrac{p\phi}{\pi DL}$

Power output of the generator, $P = VI \times 10^{-3}$ in *kW*

Full load current, $I = \dfrac{P}{V \times 10^{-3}} = \dfrac{350}{500 \times 10^{-3}} = 700\ A$

Current through each armature conductor $\Big\}\ I_z = \dfrac{\text{Armature current}}{\text{Number of parallel paths}} = \dfrac{I_a}{a}$

$$= \frac{700}{6} = 116.67\ A$$

Specific electric loading, **ac** = $\dfrac{I_z Z}{\pi D} = \dfrac{116.67 \times 660}{\pi \times 0.87} = 28173$ *amp.cond./m*

Induced emf in DC generator, $E = \phi Z n \frac{p}{a} = \phi Z n$

Flux per pole, $\phi = \frac{E}{Z n} \approx \frac{V}{Z n} = \frac{500}{660 \times 450/60} = 0.101\ Wb$

Specific magnetic loading, $B_{av} = \frac{p\phi}{\pi DL} = \frac{6 \times 0.101}{\pi \times 0.87 \times 0.32} = 0.6929\ Wb/m^2$

RESULT

Specific electric loading, **ac** = 28173 *amp.cond./m*

Specific magnetic loading, B_{av} = 0.6929 Wb/m^2.

EXAMPLE 1.2

The output coefficient of 1250 *kVA*, 300 *rpm*, synchronous generator is 200 kVA/m^3*-rps*.

Determine the main dimensions D and L for following three cases.

Case (i): The ratio of length to diameter is 0.2.

Case (ii) : Specific loadings are decreased by 10% each with speed remaining the same as in case (a).

Case (iii): Speed is decreased to 150 *rpm* with specific loadings remaining the same as in case (a).

Assume the same ratio of length to diameter in all the three cases. Comment upon the results.

GIVEN DATA

C_o = 200 kVA/m^3*-rps* Q = 1250 *kVA*

$\frac{L}{D}$ = 0.2 N_s = 300 *rpm*

SOLUTION

Case (i)

Given that, $\frac{L}{D} = 0.2$

$\therefore$ Length of stator core, L = 0.2 D .....(1)

Synchronous speed, $n_s = \frac{300}{60} = 5\ rps$

kVA rating, $Q = C_o D^2 L n_s$

$$\therefore D^2 L = \frac{Q}{C_o n_s} = \frac{1250}{200 \times 5} = 1.25\ m^3$$

$\therefore$ $D^2 L = 1.25$

$D^2 (0.2D) = 1.25$ | Using equation (1) |

$\therefore$ Diameter of stator bore, $D = \left(\frac{1.25}{0.2}\right)^{1/3} = 1.842\ m$

| Using equation (1) |

$\therefore$ Length of stator core, L = 0.2 D = 0.2 × 1.842 = 0.368 *m*

Case (ii)

Let, Output coefficient of machine-II, $C_{o2} = \pi^2 B_{av2}\, \mathbf{ac}_2 \times 10^{-3}$

In case (ii) the specific loadings are reduced (decreased) by 10%.

$\therefore B_{av2} = 0.9\, B_{av}$ and $\mathbf{ac}_2 = 0.9\, \mathbf{ac}$

$$\left.\begin{array}{l}\therefore \text{Output coefficient} \\ \text{of machine} - \text{II}\end{array}\right\} C_{o2} = 11\, B_{av2}\, \mathbf{ac}_2 \times 10^{-3}$$

$$= 11 \times 0.9\, B_{av} \times 0.9\, \mathbf{ac} \times 10^{-3}$$

$$= 0.9 \times 0.9 \times (11\, B_{av}\, \mathbf{ac} \times 10^{-3}) = 0.9 \times 0.9 \times C_o$$

$$= 0.9 \times 0.9 \times 200 = 162\ kVA/m^3\text{-}rps$$

kVA rating of machine–II, $Q_2 = C_{o2}\, D_2^2\, L_2\, n_s$

$$\therefore D_2^2\, L_2 = \frac{Q_2}{C_{o2}\, n_s}$$

$$= \frac{1250}{162 \times 5} = 1.543\ m^3$$

$\boxed{Q_2 = 1250\ kVA \text{ (same as case (a))}}$

$\therefore D_2^2 L_2 = 1.543$

$D_2^2\ (0.2\, D_2) = 1.543$

$\boxed{\begin{array}{l}\text{Using equation (1)} \\ L_2 = 0.2\, D_2\end{array}}$

$\therefore$ Diameter of stator bore, $D_2 = \left(\frac{1.543}{0.2}\right)^{1/3} = 1.976\ m$

$\therefore$ Lenght of stator core, $L_2 = 0.2\, D_2 = 0.2 \times 1.976 = 0.395\ m$

Comment : Here $D_2^2\, L_2 = 1.543\ m^3$ but $D^2\, L = 1.25\ m^3$, therefore volume of machine-II is more than machine-I and so the size of the machine increases with decrease in specific loadings.

Case (iii)

In case (iii) the speed is reduced to 150 *rpm*.

$\therefore$ Synchronous speed in rps, $n_{s3} = \frac{150}{60} = 2.5\ rps$

kVA rating of machine-III, $Q_3 = C_o\, D_3^2\, L_3\, n_{s3}$

$\boxed{\begin{array}{l}\text{Q and } C_o \text{ same as case (a)} \\ \therefore Q_3 = 1250\ kVA \text{ and} \\ \therefore C_o = 200\ kVA/m^3\text{-}rps.\end{array}}$

$$\therefore D_3^2\, L_3 = \frac{Q_3}{C_o\, n_{s3}} = \frac{1250}{200 \times 2.5} = 2.5\ m^3$$

$\therefore D_3^2\, L_3 = 2.5$

$\boxed{\begin{array}{l}\text{Using equation (1)} \\ L_3 = 0.2\, D_3\end{array}}$

$D_3^2\, (0.2\, L_3) = 2.5$

$\therefore$ Diameter of stator bore, $D_3 = \left(\frac{2.5}{0.2}\right)^{1/3} = 2.32\ m$

$\therefore$ Length of stator core, $L_3 = 0.2\, D_3 = 0.2 \times 2.32 = 0.464\ m$

Comment : Here $D_3^2\, L_3 = 2.5\ m^3$ but $D^2\, L = 1.25\ m^3$, therefore volume of machine-III is more than machine-I and so the size of machine increases with decrease in operating speed.

RESULT

Case (i)	Case (ii)	Case (iii)
D = 1.842 *m*	D_2 = 1.976 *m*	D_3 = 2.32 *m*
L = 0.368 *m*	L_2 = 0.395 *m*	L_3 = 0.464 *m*.

EXAMPLE 1.3

A 20 *HP*, 440 *V*, 4 pole, 50 *Hz*, 3-phase induction motor is built with a stator bore of 0.25 *m* and core length of 0.16 *m*. The specific electric loading is 23000 *amp. cond./m*. Find the specific magnetic loading of the machine. Assume full load efficiency of 84% and a power factor of 0.82. Using the data of the above machine determine the main dimensions, number of stator slots and stator conductors for a 15 *HP*, 460 *V*, 6 pole, 50 *Hz* motor. Take K_{ws} = 0.955.

GIVEN DATA

Machine-I		Machine-II
20 *HP*	4 pole	15 *HP*
440 *V*	50 *Hz*	460 *V*
D = 0.25 *m*	3-phase	50 *Hz*
L = 0.16 *m*		6 pole
ac = 23000 *amp.cond./m*		K_{ws} = 0.955

SOLUTION

Machine-I

$$\text{kVA input, } Q_1 = \frac{HP_1 \times 0.746}{\eta \times pf} = \frac{20 \times 0.746}{0.84 \times 0.82} = 21.66\ kVA$$

$$\text{Synchronous speed, } n_{s1} = \frac{2f}{p} = \frac{2 \times 50}{4} = 25\ rps$$

Also, kVA input, $Q_1 = C_o D^2 L n_s$,

where, $C_o = 11\, B_{av}\, \mathbf{ac}\, K_{ws} \times 10^{-3}$

$$\therefore Q_1 = 11\, B_{av}\, \mathbf{ac}\, K_{ws} \times 10^{-3} D^2 L n_s$$

$$\therefore B_{av} = \frac{Q_1}{11\, \mathbf{ac}\, K_{ws} \times 10^{-3} D^2 L n_s}$$

$\boxed{K_{ws} = 0.955}$

$$= \frac{21.66}{11 \times 23000 \times 0.955 \times 10^{-3} \times 0.25^2 \times 0.16 \times 25} = 0.3586\ Wb/m^2$$

Machine-II

$$\text{kVA input, } Q_2 = \frac{HP_2 \times 0.746}{\eta \times pf} = \frac{15 \times 0.746}{0.84 \times 0.82} = 16.246\ kVA$$

$$\text{Synchronous speed, } n_{s2} = \frac{2f}{p} = \frac{2 \times 50}{6} = 16.667\ rps$$

The value of **ac** (specific electric loading) decreases when voltage rating is increased. Hence the ratio of specific electric loading can be expressed as shown below.

$$\frac{\mathbf{ac}_2}{\mathbf{ac}_1} = \frac{V_{L2}}{V_{L1}}$$

The ratio of voltage rating = $\frac{V_{L2}}{V_{L1}} = \frac{460}{440} = 1.0455$

$$\therefore \mathbf{ac}_2 = \mathbf{ac}_1 \times \frac{V_1}{V_2} = \frac{\mathbf{ac}_1}{V_2 / V_1}$$

$$= \frac{\mathbf{ac}_1}{1.0455} = \frac{23000}{1.0455} = 21999.044 \approx 22000 \; amp.cond./m$$

Let us assume same L/τ ratio for both the machines.

For machine-I, $\frac{L_1}{\tau_1} = \frac{L_1}{\frac{\pi D_1}{p_1}} = \frac{L_1 \, p_1}{\pi \, D_1} = \frac{0.16 \times 4}{\pi \times 0.25} = 0.8149$

For machine-II, $\frac{L_2}{\tau_2} = 0.8149$

$$\therefore L_2 = 0.8142 \;\; \tau_2 = 0.8149 \times \frac{\pi D_2}{p_2} = \frac{0.8149 \times \pi}{6} D_2 = 0.4267 \, D_2$$

$\boxed{\tau = \frac{\pi D}{p}}$

$\therefore$ Length of stator core, $L_2 = 0.4267 \, D_2$ .....(1)

kVA input, $Q_2 = C_{o2} \, D_2^2 \, L_2 \, n_{s2}$

where, $C_{o2} = 11 \, B_{av} \, \mathbf{ac}_2 \, K_{ws} \times 10^{-3}$

$\boxed{\text{Taking same } B_{av} \text{ for both machines.}}$

$$\therefore Q_2 = 11 \, B_{av} \, \mathbf{ac}_2 \, K_{ws} \times 10^{-3} \times D_2^2 \, L_2 \, n_{s2}$$

$$\therefore D_2^2 \; L_2 = \frac{Q_2}{11 \, B_{av} \, \mathbf{ac}_2 \, K_{ws} \times 10^{-3} \, n_{s2}}$$

$\boxed{K_{ws} = 0.955}$

$$= \frac{16.246}{11 \times 0.3586 \times 22000 \times 0.955 \times 10^{-3} \times 16.667} = 0.0118 \; m^3$$

$$\therefore D_2^2 \, L_2 = 0.0118 \; m^3$$

$\boxed{\text{Using equation (1)}}$

$$D_2^2 \, (0.4267 \, D_2) = 0.0118$$

$\therefore$ Diameter of stator bore, $D_2 = \left(\frac{0.0118}{0.4267}\right)^{1/3} = 0.3024 \; m = 0.3 \; m$

$\therefore$ Length of stator core, $L_2 = 0.4267 \times 0.3 = 0.128 \; m$

Maximum flux per pole, $\phi_m = \frac{B_{av} \, \pi \, D_2 \, L_2}{p}$

$$= \frac{0.3586 \times \pi \times 0.3 \times 0.128}{4} = 0.011 \; Wb$$

Stator turns per phase, $T_s = \frac{E_s}{4.44 \, f \, \phi_m \, K_{ws}}$

$\boxed{\text{Delta connected motor.} \; \therefore E_s = V_L}$

$$= \frac{440}{4.44 \times 50 \times 0.011 \times 0.955} = 188$$

The stator slot pitch should be lie between 15 *mm* to 25 *mm*.

Stator slot, $S_s = \frac{\pi D}{y_{SS}}$

When, y_{ss} = 15 *mm*, $S_s = \frac{\pi \times 0.3}{15 \times 10^{-3}} = 62$

When, y_{ss} = 25 *mm*, $S_s = \frac{\pi \times 0.3}{25 \times 10^{-3}} = 38$

The stator slot should be lie between 38 to 62.

The stator slot be multiple of q, where q is slots per pole per phase.

Stator slot, S_s = Number of phase × Poles × q = 3 p q

When, q = 2 $S_s = 3 \times 4 \times 2 = 24$

When, q = 3 $S_s = 3 \times 4 \times 3 = 36$

When, q = 4 $S_s = 3 \times 4 \times 4 = 48$

The S_s value of 48 lie in the range of 38 to 64.

Conductors per slot, $Z_{ss} = \frac{6\,T_S}{S_S}$

$$= \frac{6 \times 188}{48} = 23.5 \simeq 24$$

$\therefore$ Total stator conductors, $Z = S_s \times Z_{ss} = 48 \times 24 = 1152$

$\therefore$ New value of turns per phase, $T_s = \frac{Z_{SS} \times S_S}{6}$

$$= \frac{48 \times 24}{6} = 192$$

RESULT

Machine-I	Specific magnetic loading,	B_{av}	= 0.3586 *Wb/m²*
Machine-II	Diameter of stator bore,	D_2	= 0.2972 *m*
	Length of stator core,	L_2	= 0.127 *m*
	Conductors per slot,	Z_{ss}	= 24
	Stator slot,	S_s	= 48
	Total stator conductors,	Z	= 1152
	Stator turns per phase,	T_s	= 192

EXAMPLE 1.4

Calculate the main dimensions of a 20 *HP*, 1000 *rpm*, 400 *V*, DC motor. Given that, B_{av} = 0.37 *Wb/m²* and **ac** = 16000 *amp.cond./m*. Assume an efficiency of 90%.

GIVEN DATA

P = 20 *HP*	B_{av} = 0.37 *Wb/m²*	N = 1000 *rpm*
V = 400 *V*	**ac** = 16000 *amp.cond./m*	η = 90%

SOLUTION

Power input, $P_i = \frac{P}{\eta} = \frac{20 \times 0.746}{0.9} = 16.58\ kW$

Also power input, $P_i = VI \times 10^{-3}$

$\therefore$ Load current, $I = \frac{P_i}{V \times 10^{-3}} = \frac{16.58}{400 \times 10^{-3}} = 41.45\ A$

Armature current, $I_a \approx I = 41.45\ A$

Since the armature current is less than 200 *A*, the current per parallel path will not exceed the upper limit of 200 *A*.

Let, $p = 2, \quad f = \frac{pN}{120} = \frac{2 \times 1000}{120} = 16.67\ Hz$

$p = 4, \quad f = \frac{pN}{120} = \frac{4 \times 1000}{120} = 33.33\ Hz$

$p = 6, \quad f = \frac{pN}{120} = \frac{6 \times 1000}{120} = 50\ Hz$

The frequency of flux reversals should lie in the range of 25 to 50 *Hz*. For minimum cost the highest possible choice of poles should be chosen.

Hence, the number of poles, p = 6

Let us assume a square pole face.

For square pole face, $\frac{L}{\tau} = 0.7$

$\therefore L = 0.7\ \tau = 0.7 \times \frac{\pi D}{p} = \frac{0.7 \times \pi}{6} \times D = 0.3665\ D$ $\quad \boxed{\tau = \frac{\pi D}{p}}$

$\therefore$ Length of armature, L = 0.3665 D .....(1)

Output coefficient, $C_o = \pi^2 B_{av}\ \mathbf{ac} \times 10^{-3}$

$= \pi^2 \times 0.37 \times 16000 \times 10^{-3}$

$= 58.428\ kW/m^3\text{-}rps$

For DC motor, power developed in armature $\Big\}\ P_a \approx P = 20\ HP = 20 \times 0.746 = 14.92\ kW$

Also, power developed in armature, $P_a = C_o D^2 L n$

$$\therefore D^2 L = \frac{P_a}{C_o n}$$

$$= \frac{14.92}{58.428 \times (1000/60)} = 0.0153\ m^3$$

$\therefore D^2 L = 0.0153$

$D^2 (0.3665D) = 0.0153$

$\therefore$ Diameter of armature, $D = \left(\frac{0.0153}{0.3665}\right)^{1/3} = 0.3469\ m \approx 0.35\ m$

$\therefore$ Length of armature, L = 0.3665 D = 0.3665 × 0.35 = 0.128 *m* $\quad$ Using equation (1)

RESULT

Diameter of armature, D = 0.35 *m*

Length of armature, L = 0.128 *m*.

EXAMPLE 1.5

A 600 *rpm*, 50 *Hz*, 10000 *V*, 3-phase, synchronous generator has the following design data. B_{av} = 0.48 *Wb/m²*, δ = 2.7 *A/mm²*, slot space factor = 0.35, number of slots = 144, slot size = 120 × 20 *mm*, D = 1.92 *m* and L = 0.4 *m*. Determine the kVA rating of the machine.

GIVEN DATA

3-phase	B_{av} = 0.48 *Wb/m²*	D = 1.92 *m*
600 *rpm*	δ = 2.7 *A/mm²*	L = 0.4 *m*
10000 *V*	Slots = 144	Slot size = 120 × 20 *mm*
		Slot space factor = 0.35

SOLUTION

We know that,

Current density, $\delta = \dfrac{I_Z}{a_Z}$

∴ Current in each armature conductor, $I_z = \delta\, a_z$ .....(1)

Conductors area in a slot = Slot area × Slot space factor = 120 × 20 × 0.35 = 840 *mm²*

$$\left.\begin{array}{l}\text{Total number of armature}\\ \text{conductors}\end{array}\right\} Z = \frac{\text{Conductors area in a slot} \times \text{Number of slots}}{\text{Area of cross-section of each conductor}}$$

$$= \frac{840 \times 144}{a_Z} \quad .....(2)$$

Specific electric loading, $\mathbf{ac} = \dfrac{I_Z\, Z}{\pi D}$

Using equations (1) and (2).

$$= \frac{\delta\, a_Z \dfrac{840 \times 144}{a_Z}}{\pi D} = \frac{\delta \times 840 \times 144}{\pi D}$$

$$= \frac{2.7 \times 840 \times 144}{\pi \times 1.92} = 54144 \ amp.cond./m$$

kVA rating, $Q = C_o D^2 L n_s$

$C_o = 11\, B_{av}\, K_{ws} \times 10^{-3}$

$= 11\, B_{av}\, \mathbf{ac}\, K_{ws} \times 10^{-3}\, D^2\, L\, n_s$

$= 11 \times 0.48 \times 54144 \times 0.955 \times 10^{-3} \times 1.92^2 \times 0.4 \times \dfrac{600}{60}$

= 4025 *kVA*

RESULT

kVA rating, Q = 4025 *kVA.*

1.14 SHORT-ANSWER QUESTIONS

Q1.1 What are the constructional elements of a transformer?

The constructional elements of a transformer are core, high and low voltage windings, cooling tubes or radiators and tank.

Q1.2 List the constructional elements of a DC machine.

The major constructional elements of a DC machine are stator, rotor, brushes and brush holders. The various parts of stator and rotor are listed below,

Stator	- Yoke (or) Frame	**Rotor**	- Armature core
	- Field pole		- Armature winding
	- Pole shoe		- Commutator
	- Field winding	**Others**	- Brush
	- Interpole		- Brush holder

Q1.3 List the constructional elements of salient pole synchronous machine.

The various constructional elements of salient pole synchronous machine are,

Stator	- Frame	**Rotor**	- Field pole
	- Armature core		- Pole shoe
	- Armature winding		- Field winding
			- Damper winding

Q1.4 What are the constructional elements of cylindrical rotor synchronous machine?

The constructional elements of cylindrical rotor synchronous machine are,

Stator	- Frame	**Rotor**	- Solid rotor
	- Armature core		- Field conductors or bars
	- Armature winding		

Q1.5 List the constructional elements of squirrel cage induction motor.

The constructional elements of squirrel cage induction motor are,

Stator	- Frame	**Rotor**	- Rotor core
	- Stator core		- Rotor bars
	- Stator winding		- End ring

Q1.6 List the constructional elements of slip ring induction motor.

The constructional elements of slip ring induction motor are,

Stator	- Frame	**Rotor**	- Rotor core
	- Stator core		- Rotor winding
	- Stator winding		- Slip rings

Q1.7 How the design problems of an electrical machine can be classified?

The design problems of electrical machine can be classified as,

1. Electromagnetic design
2. Mechanical design
3. Thermal design
4. Dielectric design.

Q1.8 What are the major considerations to evolve a good design of electrical machines? *(AU, Apr' 18, 2 M)*

The major consideration to achieve a good electrical machine are,

1. Cost
2. Durability
3. Performance as per specifications.

Q1.9 Write a short note on standard specifications.

The standard specifications are the specifications issued by the standards organisation of a country. The standard specifications serve as guideline for the manufacturers to produce quality products at economical prices. The standard specifications for electrical machines include ratings, types of enclosure, dimensions of conductors, name plate details, performance indices, permissible temperature rise, permissible loss, efficiency, etc.

Q1.10 What are the items to be mentioned in the rating plates of rotating machinery?

The name plate of a rotating machine has to bear the following details as per ISI specifications.

1. kW or kVA rating of machine
2. Rated working voltage
3. Operating speed
4. Full load current
5. Class of insulation.
6. Frame size
7. ISI specification number
8. Manufacturers name
9. Serial number of product

Q1.11 List the Indian Standard specifications for transformer. *(AU, Nov' 17, 2 M)*

i) IS 1180 - 1989: Specifications for out door 3-phase distribution transformer upto 100 *kVA*.

ii) IS 2026 - 1972: Specifications of power transformers.

Q1.12 List the Indian Standard Specifications for induction motor.

i) IS 325 - 1966: Specifications of three-phase induction motor.

ii) IS 1231 - 1974: Specifications of foot mounted induction motor.

iii) IS 4029 - 1967: Guide for testing three-phase induction motor.

iv) IS 996 - 1979: Specifications of single-phase AC and universal motor.

Q1.13 What is meant by general design procedure?

The general design procedure is to relate the main dimensions of the machine to its rated power output. A general output equation can be developed for electrical machines which relates the power output to volume of active part (D^2L), speed, magnetic and electric loadings.

Q1.14 What is active part?

In electrical machines the core and winding of the machine are together called active part. Because, the energy conversion takes place only in the active part of the machine.

Q1.15 What are the main dimensions of a rotating machine?

The main dimensions of a rotating machine are the armature diameter or stator bore, D and armature or stator core length, L.

Q1.16 Define total magnetic loading.

The total magnetic loading is defined as the total flux around the armature (or stator inner) periphery at the air-gap.

Total magnetic loading = $p\phi$

where p = Number of poles ; ϕ = Flux per pole

Q1.17 Define total electric loading.

The total electric loading is defined as the total number of ampere conductors around the armature (or stator) periphery.

Total electric loading = $I_z Z$

where I_z = Current through one armature conductor ; Z = Total number of armature conductors.

Q1.18 Define specific magnetic loading. ***(VTU, Dec'19, 8 M)***

The specific magnetic loading is defined as the average flux density over the air-gap of a machine.

$$\text{Specific magnetic loading, } B_{av} = \frac{\text{Total flux around the air-gap}}{\text{Area of flux path at the air-gap}} = \frac{p\phi}{\pi DL}$$

Q1.19 Define specific electric loading.

The specific electric loading is defined as the number of armature (or stator) ampere conductors per metre of armature (or stator) periphery at the air-gap.

$$\text{Specific electric loading, } \mathbf{ac} = \frac{\text{Total armature ampere conductors}}{\text{Armature periphery at air-gap}} = \frac{I_Z Z}{\pi D}$$

Q1.20 Why total loadings are not used to determine the output of a rotating machine?

Each unit area of armature surface is capable of receiving a certain magnetic flux. Similarly every section of armature is capable of carrying certain amount of current. Hence specific loadings indicates the intensity of loading and the utility of active materials. Therefore specific loadings are used to determine the output rather than total loadings.

Q1.21 Give typical values of specific electric and magnetic loading.

Machine	**Specific magnetic loading, B_{av} in Wb/m^2**	**Specific electric loading, ac in amp.cond./m.**
DC machine	0.4 to 0.8	15000 to 50000
Induction motor	0.3 to 0.6	5000 to 45000
Synchronous machine	0.52 to 0.65	20000 to 40000
Turbo-alternator	0.52 to 0.65	50000 to 75000

Q1.22 What is output equation.

The equation which relates the kVA input to the main dimensions (D and L), Specific loadings (B_{av} and **ac**) and speed (n) of a machine is known as output equation.

The output equation of DC machine is, $P_a = C_o D^2 L n$, in *kW*
The output equation of AC machine is, $Q = C_o D^2 L n_s$, in *kVA*

where, P_a = Power developed in armature of DC machine.
Q = kVA rating of AC machine.
C_o = Output coefficient.

Q1.23 Write the expression for output coefficient.

For DC machine, Output coefficient, $C_o = \pi^2 B_{av}$ **ac** $\times 10^{-3}$, in *kW/m^3- rps*

For AC machine, Output coefficient, $C_o = 11 \; B_{av}$ **ac** $K_{ws} \times 10^{-3}$, *in kVA/m^3- rps.*

Q1.24 How the power developed by armature is taken for a generator and for a motor?

Let P = Rated power output of a DC machine

η = Efficiency.

P_a = Power developed by the armature of DC machine.

Now, $P_a = P/\eta$ for DC generators

$P_a = P$ for DC motors

Note : *The above concepts are applicable for large DC machines (above 1 kW), because in these machines the friction, windage and iron losses can be neglected.*

Q1.25 How fixed losses are accounted in small DC machines?

The fixed losses in dc machines includes the friction, windage and iron losses. For design purpose, the fixed losses can be taken as one-third of total losses.

Q1.26 What are the factors that can be varied to vary the power output of a rotating electrical machine?

The power output of a rotating electrical machine depends of specific electric loading, specific magnetic loading, volume of active part and speed. Hence by varying these four quantities the power output of a machine can be varied.

Q1.27 Give the expression for the torque developed by a DC motor in terms of main dimensions of armature.

Let, T_a = Torque developed in the armature

We know that,

Power = Torque × Angular velocity $\Rightarrow$ $P_a = T_a \times 2\pi n$

$$\boxed{\begin{aligned} P_a &= C_o D^2 L n \\ &= \pi^2 B_{av} \, \mathbf{ac} \times 10^{-3} D^2 \times L n \end{aligned}}$$

$$\therefore \text{Torque, } T_a = \frac{1}{2\pi n} P_a$$

$$= \frac{1}{2\pi n} \pi^2 B_{av} \, \mathbf{ac} \times 10^{-3} D^2 L n$$

$$= \frac{\pi}{2} B_{av} \, \mathbf{ac} \, D^2 L \times 10^{-3}$$

Q1.28 Calculate the main dimensions for a 500 kW, 1kV, 600 rpm, 6 pole DC machine. Take L/τ = 1 and C_o = 220 kW/m³-rps.

Solution

Given that, $L / \tau = 1$,

$$\therefore L = \tau = \frac{\pi D}{p} = \frac{\pi}{6} D = 0.5236 \, D \qquad .....(1)$$

We know that, $P_a = C_O D^2 L n$

$$\therefore D^2 L = \frac{P_a}{C_o n} = \frac{500}{220 \times 600 / 60} = 0.2273 \, m^3$$

$$\therefore D^2 L = 0.2273$$

$$\therefore D^2 (0.5236 \, D) = 0.2273 \qquad \boxed{\text{Using equation (1)}}$$

$$\therefore D = \left(\frac{0.2273}{0.5236}\right)^{1/3} = 0.76 \, m$$

$$\therefore L = 0.5236 \, D = 0.5236 \times 0.76 = 0.4 \, m$$

Q1.29 How to separate D and L for rotating machines?

The seperation of D and L refers to the selection of an appropriate values for D and L for a given volume of active part. There are various choice of D and L for a given volume of active part.

In general a ratio of L/τ or L/D is assumed to form an equation relating D and L, where τ = pole pitch = $\pi D/p$.

Using the output equation and from the knowledge of *kW/ kVA* rating, specific loadings and speed, the value of $D^2 L$ is estimated which gives another equation relating D and L. Then by solving the two equations the values of D and L are estimated.

Q1.30 What is the significance of the ratio of core length and pole pitch in induction motor?

In induction motors the operating characteristics are mainly influenced by the ratio of core length and pole pitch, L/τ. The factors influencing this choice are,

For minimum cost,	L/τ = 1.5 to 2	For good efficiency,	L/τ = 1.5
For good power factor,	L/τ = 1.0 to 1.25	For good overall design,	L/τ = 1.0

Q1.31 List the factors that influences the separation of D and L of a DC machine.

In DC machines the separation of D and L depends on,

1. Pole proportions
2. Peripheral speed
3. Moment of inertia
4. Voltage between adjacent commutator segments

Q1.32 What is square pole criterion?

The square pole criterion states that for a given flux and cross section area of pole, the length of mean turn of field winding is minimum, when the periphery forms a square. This implies that the length L must be approximately equal to pole arc b, i.e. $\mathbf{L = b = \psi \tau}$.

Q1.33 In a DC machine, What are the limiting values of armature peripheral speed and voltage between adjacent commutator segments?

Maximum armature peripheral speed, $V_{a\,max}$ = 30 *m/sec*.

Maximum voltage between commutator segments, E_{cm} = 30 *V*.

Q1.34 List the various values of L/τ used for separation of D and L in induction motor.

The operating characteristics of an induction motor are mainly influenced by the ratio L/τ. The various values of L/τ used are listed here.

For minimum cost, $L/\tau = 1.5$ to 2

For good power factor, $L/\tau = 1.0$ to 1.25

For good efficiency, $L/\tau = 1.5$

For overall design, $L/\tau = 1.0$

Q1.35 What is the factor that is used to design an induction motor for best power factor?

For best power factor the separation of D and L is performed using the equation,

$$\text{Pole pitch, } \tau = \sqrt{0.18\,L}$$

where $\tau = \pi D/p$.

Q1.36 What are the factors to be considered for the separation of D and L of synchronous machine?

In synchronous machine the separation of D and L depends on pole proportions peripheral speed, number of poles and short circuit ratio.

Q1.37 List the various values of L/τ used for separation of D and L in synchronous machine.

In salient pole synchronous machines, when round poles are used the ratio of L/τ is between 0.6 to 0.7, and when rectangular poles are employed the ratio of L/τ is between 1 to 5.

Note : *In cylindrical rotor synchronous machines, the ratio L/τ is not used for separation of D and L. In this type of machine, the permissible peripheral speed is used to calculate D. Then L is estimated using output equation and this value of D.*

Q1.38 What is peripheral speed? Write the expression for peripheral speed of a rotating machine.

The peripheral speed is a translational speed that may exist at the surface of the rotor, while it is rotating. (It is a translational speed equivalent to the angular speed at the surface of the rotor).

Peripheral speed, $V_a = \pi D_r n$ in *m/sec*

where, D_r = Diameter of rotor ; n = Speed of the rotor.

Q1.39 High speed alternators have very long armature. Why?

In high speed alternators, the peripheral speed will be high and so the diameter has to be kept low to limit the peripheral speed. For a given volume of active part, if the diameter is kept low then the length has to be increased. Therefore the high speed alternators have very long armature.

Q1.40 What are the factors that affect the size of rotating machine?

The factors affecting the size of rotating machines are speed and output coefficient. The output coefficient in turn depends on specific electric and magnetic loadings.

Q1.41 What is the effect of speed on the size of the machine?

For a given output power the speed is inversely proportional to volume of active parts. Hence for a given output a high speed machine will have less volume and costs less. Therefore for reducing the cost highest possible speed may be selected. The maximum speed is limited by mechanical stresses of the rotating parts.

Q1.42 What is the importance of output coefficient?

The power output of a machine is directly proportional to output coefficient. Hence higher value of C_o results in higher power output.

For a given power output and speed, the volume of active part is inversely proportional to output coefficient. Hence with high values of C_o, the volume of active parts decreases and the machine costs less.

Q1.43 Why the output coefficient changes with size and type of machines?

For a given power output and speed, the volume of active part is inversely proportional to output coefficient. Hence if the output coefficient is higher then size of the machine will be small and vice versa.

The output coefficient is directly proportional to specific electric and magnetic loadings. Therefore for high values of C_o, high values of specific loadings are chosen, which affects the performance characteristics like temperature rise, efficiency, commutation conditions, etc. The type of machine (for e.g., forced air cooled) is decided by the performance requirements and so by output coefficient.

Q1.44 What are the factors that decide the choice of specific magnetic loading?

The value of magnetic loading is determined by

1. Maximum flux density in iron parts of machine
2. Magnetizing current and
3. Core losses.

Q1.45 The effect of magnetizing current is considered as important in case of induction motor. Why?

In induction motor the magnetizing current decides the power factor of the motor. When the magnetizing current is high, the power factor is low and vice versa. If power factor is low, then to deliver the same power output the current rating will be higher, which increases the cost of winding and motor.

Q1.46 Give the relation between core losses and frequency.

The hysteresis and eddy current losses are called core losses. The hysteresis loss is directly proportional to the frequency and eddy current loss is proportional to the square of the frequency.

Q1.47 What are the factors that decide the choice of specific electric loading?

The choice of specific electric loading depends on the following factors

1. Permissible temperature rise
2. Size of machine
3. Voltage rating of machine
4. Current density

Q1.48 Calculate the maximum allowable ac (specific electric loading), given that maximum allowable temperature rise = 55°C, resistivity = 2.7 ×10⁻⁸ Ω-m, current density = 2.75 A/mm² and cooling coefficient = 0.025.

Solution

$$\left.\begin{array}{l}\text{Maximum allowable specific}\\ \text{electric loading}\end{array}\right\}\ \mathbf{ac} = \frac{\theta}{\rho\,\delta\,c} = \frac{55}{2.7\times10^{-8}\times2.75\times10^{6}\times0.025}$$

$$= 29629.6 \approx 29630\ \textit{amp.cond./m}$$

Q1.49 Give the typical values of current density, temperature rise and cooling coefficient for the best choice of specific electric loading.

For the best choice of specific electric loading the current density can be in the range of 2 to 5 A/mm^2, the temperature rise can be in the range of 40° to 60°C above ambient and cooling coefficient can be in the range of 0.02 to 0.035 °C $W\text{-}m^2$.

Q1.50 Give typical values for specific electric and magnetic loading for a 3.7 kW, 1440 rpm squirrel cage induction motor.

One of the typical choice of specific loadings for a 3.7 *kW*, 1440 *rpm* squirrel cage induction motor are,

Specific electric loading = 28,000 *amp.cond./m* ; Specific magnetic loading = 0.56 Wb/m^2.

Q1.51 Smaller machines have low specific magnetic loadings. Why?

A higher value of specific magnetic loading results in increased core loss and higher temperature rise. Consequently the efficiency of the machine will be low. In small machines, the losses has to be kept low in order to get higher power output and so a low value of specific magnetic loading is preferred in small machines.

Q1.52 In 2 DC machines running at same speed and having same number of poles, the physical dimensions are in the ratio 105 : 1. Compare their output.

Let linear dimensions are in the ratio 105 : 1 = x : 1

The output of dc machine, $P_a = C_o D^2 L n$

The output coefficient, $C_o = \pi^2 B_{av}\, \mathbf{ac} \times 10^{-3}$

$\therefore$ Output, $P_a = \pi^2 B_{av}\, \mathbf{ac} \times 10^{-3} D^2 L n$

Here B_{av} and n are constants.

$$\mathbf{ac} = \frac{I_z Z}{\pi D} = \frac{\delta\, a_z Z}{\pi D}$$

$a_z \propto x^2$ and $D \propto x$

$\therefore \mathbf{ac} \propto \frac{x^2}{x} \propto x$

Also $D^2 \propto x$ and $L \propto x$

$\therefore$ Output $\propto x\ x^2\ x$

Output $\propto x^4$

Since x = 105, Output $\propto 105^4$

Q1.53 To what value the output of rotating machine will be reduced if the dimensions are scaled down to 75% of their original values?

If x is the linear dimension of the rotating machine, then the output of a rotating machine is proportional to x^4. The linear dimensions are reduced to 0.75 (i.e., 75%). Let the linear dimensions of original machine be 1(100%). The ratio of linear dimensions is 1 : 0.75. Hence the ratio of output is $1^4 : 0.75^4$.

$$0.75^4 = 0.3164 \Rightarrow 31.64\ \%$$

The output of the machine reduces by 31.64% if the linear dimensions are reduced by 75%.

Q1.54 Prove that large machines are more efficient than small machines. ***(PTU, May'19, 2 M)***

If x is the linear dimension of a machine then we can show that the output is proportional to x^4 and total loss is proportional to x^3.

$$\text{Efficiency, } \eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output + Total losses}}$$

$$\therefore \eta \ \alpha \ \frac{x^4}{x^4 + k\,x^3} \quad \Rightarrow \quad \eta \ \alpha \frac{1}{1 + k / x}$$

where, k is a constant.

With increase in x (i.e., as the size of machine increases) the term k/x becomes smaller and smaller. Hence the efficiency increases, with increase in the linear dimensions of the machine. Therefore, large machines are more efficient than small machines.

Q1.55 What are the factors that impose technical limitations on the design?

The factors that impose technical limitations on design of electrical machines are

1. Saturation
2. Temperature rise
3. Stress on insulation
4. Efficiency
5. Stress and strain on rotating parts and bearings
6. Mechanical precision of air-gap
7. Commutation
8. Power factor
9. Specifications

Q1.56 Write approximate efficiency of static and dynamic devices.

The efficiency of static devices will be in the range of 90 to 98%. The efficiency of dynamic devices will be in the range of 85 to 95%. The static electrical devices will have copper and iron losses, and there is no friction losses. Hence the efficiency of static devices will be more than that of dynamic devices.

Q1.57 How does power factor influence the design aspect?

For same power output when power factor is less, the current level will be high. The higher current rating is achieved by increasing the specific electric loading which increases the size of conductor and so the cost of winding and machine.

On the other hand, if power factor is high then the current level will be less. The higher power factor is achieved by decreasing the specific magnetic loading. For low value of specific magnetic loading the volume of active material should be large or the air-gap should be as small as possible. These requirements will increase the cost of the machine.

Q1.58 What are the various methods of computer aided design of electrical machines?

The methods of computer aided design for electrical machines are,

1. Analysis method
2. Synthesis method
3. Hybrid method.

Q1.59 What are the advantages of analysis method of computer aided design?

The advantages of analysis method are,

1. It is easy and straight forward to program the design equations.
2. It results in considerable time saving in performing calculations.
3. Analysis method programs are simple and they become the foundations for later larger and sophisticated programs.
4. The interaction of designer and computer yields highly acceptable results.

Q1.60 Give any two disadvantages of synthesis method of computer aided design.

1. The synthesis method involves too much of logic and before incorporating these logical decisions in the program they have to be accepted by team of design engineers. In a team, different members may give different suggestions to produce an optimum design and it becomes really hard to formulate an unique logical decisions.
2. The synthesis method programs are too complex which lead to high software development cost and require computers with high configurations involving huge expenditure.

Q1.61 Mention the advantages of hybrid method of computer aided design. ***(AKTU, Dec' 19, 3 M)***

The advantages of hybrid method are,

1. The results of hybrid method will be more appropriate, due to combination of designer involvement in finalizing design and optimization of vital parts.
2. The cost of hybrid systems will be lesser than synthesis systems, due to design of non vital parts by analysis method.
3. Since the design of some parts are carried by analysis method, the time required for design will also be lesser than synthesis method.

1.15 EXERCISES

I. Fill in the blanks

1. The electrical machines can be classified into .... and .... machines.
2. The basic constructional elements of a rotating electrical machine are .... and ....
3. The general design procedure is to relate the .... of the machine to its rated ....
4. In electrical machines the core and the winding of the machine are together called ....
5. The .... is defined as the total flux around the armature periphery.
6. The .... is defined as the total number of ampere conductors around the armature periphery.
7. The .... and .... of armature are called main dimensions.
8. The unit of output coefficient is ....
9. In small DC machines, the friction, windage and iron losses are approximately equal to .... of the ....

10. In large DC machines, if P is the *kW* rating of the machine and η is efficiency then the power developed in the armature of generator is .... and that of motor is ....
11. The main dimensions of a machine .... with .... in speed and output coefficient.
12. In induction motors, low power factor is due to .... in the value of magnetizing current.
13. The value of specific magnetic loading in synchronous machines is .... than DC machines and .... than induction machines.
14. If specific magnetic loading is increased then the core loss .... and efficiency ....
15. Space factor is the ratio of .... to total slot area.
16. In high .... machines, the space factor is less due to .... thickness of insulation.
17. The organic and inorganic insulating materials can withstand the temperatures of .... and .... respectively.
18. In rotating machines if .... is the linear dimension then the output is proportional to ....
19. In rotating machines, if .... is the linear dimension then the losses are proportional to ....
20. The .... loss is proportional to frequency and .... loss is proportional to the square of the frequency.

Answers

1.	static, dynamic	11.	decreases, increase
2.	stator, rotor	12.	increase
3.	main dimensions, power output	13.	lower, higher
4.	active part	14.	increases, decreases
5.	total magnetic loading	15.	bare conductor area
6.	total electric loading	16.	voltage, higher
7.	diameter, length	17.	105°C, 180°C
8.	kW/m^3-*rps* or kVA/m^3-*rps*	18.	x, x^4
9.	one-third, total losses	19.	x, x^3
10.	P/η, P	20.	hysteresis, eddy current

II. State whether the following statements are True/False

1. The basic principle of operation of all electrical machine is Faraday's law of electromagnetic induction.
2. In DC machines the power rating is expressed in *kVA* and in AC machines in *kW*.
3. The work done per revolution is given by the product of total electric and magnetic loading.
4. Total loadings are used to determine the output of a machine.
5. The winding factor is accounted only for AC machines.
6. Specific electric and magnetic loadings are directly proportional to each other.
7. In small DC machines the friction, windage and iron losses are very small, hence they can be neglected.
8. In a rotating machine, the volume of active part is inversely proportional to speed.
9. The size and cost of the machine increases with increase in output coefficient.
10. Two machines having different speed, can have same output power.
11. The maximum flux density occurs in the teeth.
12. In general a ratio of L/τ is assumed for separation of D and L.

13. In induction machines, higher value of magnetizing current is preferred in order to achieve good power factor.
14. Core loss is observed only when the iron parts are subjected to alternating magnetization.
15. Air-gap flux density is directly proportional to frequency of flux reversals.
16. Higher values of **ac** are used for machines having round conductors, because space factor is less for them.

Answers

1.	True	5.	True	9.	False	13.	False
2.	False	6.	False	10.	True	14.	True
3.	True	7.	False	11.	True	15.	False
4.	False	8.	True	12.	True	16.	False

III. Unsolved problems

E1.1 Estimate the main dimensions of a 4-pole, 100 *kW*, 1500 *rpm* DC generator assuming specific electric and magnetic loadings as 19000 *amp.conductors per metre* and 0.4 T respectively. Assume that the length of armature is equal to the pole pitch.

(D = 0.41 *m* ; L = 0.32 *m*)

E1.2 Find the suitable values for number of poles, diameter and length of armature core of a 400 *kW*, 500 *V*, 180 *rpm* DC generator. Assume B_{av} = 0.6 Wb/m^2 and **ac** = 35000. Choose L/τ = 1.2.

(p = 20 ; D = 1.5 *m* ; L = 0.28 *m*)

E1.3 Determine the main dimensions of a DC shunt generator with the following specifications: 5 *kW*, 220 *V*, 1500 *rpm*, 4-pole, **ac** = 200 *amp.cond./cm*, B_{av} = 0.6 T, η = 90% and pole arc = 0.7τ. Choose $L=\tau$.

(D = 0.15 *m* ; L = 0.08 *m*)

E1. 4 A 400 *kW*, 440 *V*, 600 *rpm*, 6 pole DC generator is built with an armature diameter of 0.9 *m* and core length of 0.45 *m*. The lap wound armature has 660 conductors. Calculate the specific electric and magnetic loadings.

(**ac** = 35364 *amp.cond./m,* B_{av} = 0.3159 Wb/m^2)

E1. 5 Calculate the main dimensions of a 40 *HP*, 1400 *rpm*, 500 *V*, DC motor. Given that, B_{av} = 0.5 Wb/m^2 and **ac** = 18000 *amp.cond./m*. Assume an efficiency of 90%.

(D = 0.34 *m*, L = 0.125 *m*)

E1. 6 A 400 *rpm*, 50 *Hz*, 8000 *V*, 3-phase, synchronous generator has the following design data. B_{av} = 0.32 Wb/m^2, δ = 1.9 A/mm^2, slot space factor = 0.18, number of slots = 36, slot size = 120 × 20 *mm*, D = 1.12 *m* and L = 0.2 *m*. Determine the kVA rating of the machine.

(Q = 47 *kVA*)