UNIT –II
DC MACHINES

Electric Machine

- Electric machines can be used as motors and generators
- Electric motor and generators are rotating energy-transfer electromechanical motion devices
- Electric motors convert electrical energy to mechanical energy
- Generators convert mechanical energy to electrical energy

Electric Machine

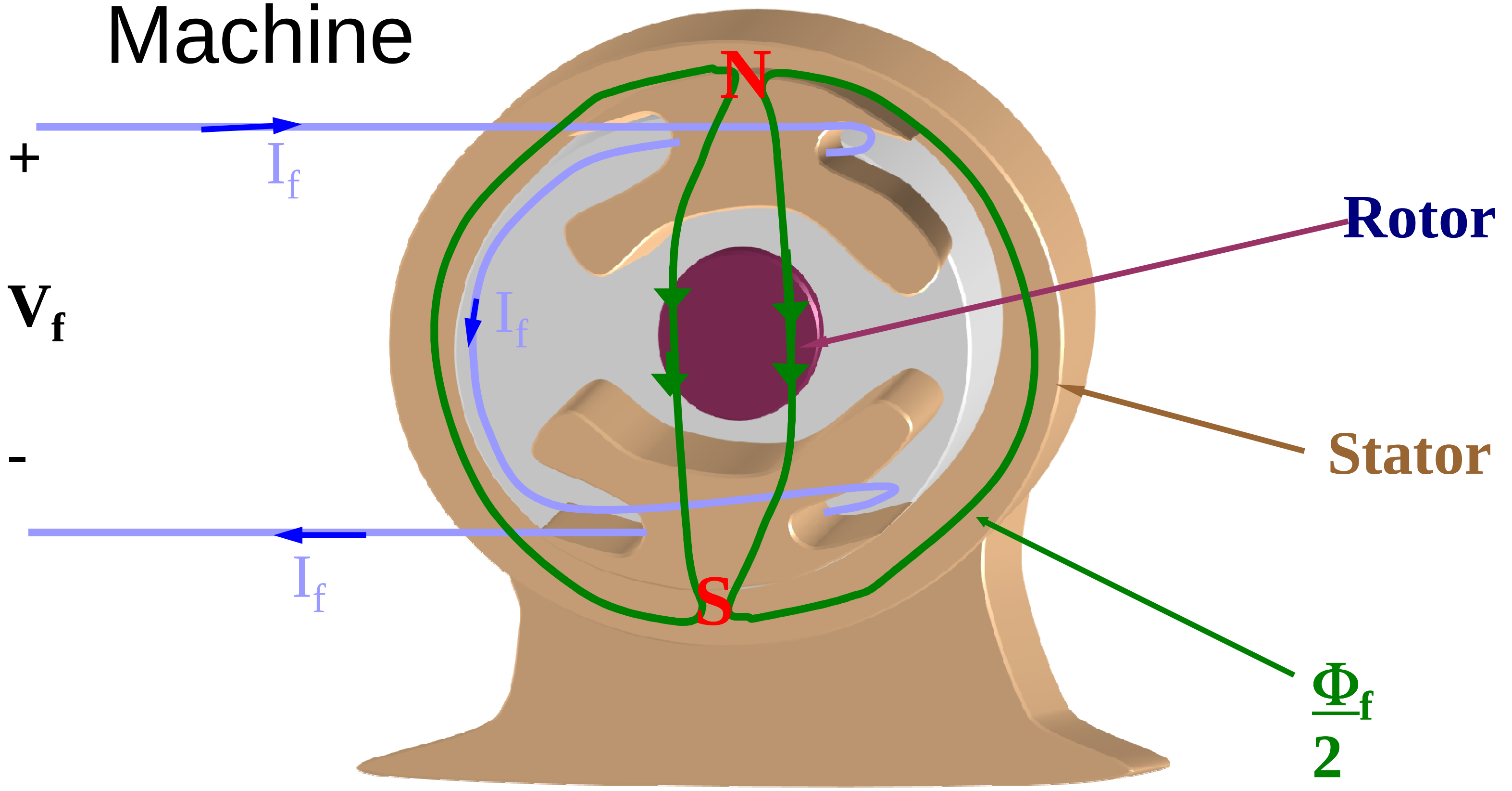
- Electric machines can be divided into 2 types:
    - AC machines
    - DC machines
- Several types DC machines
    - Separately excited
    - Shunt connected
    - Series connected
    - Compound connected
    - Permanent magnet

Electric Machine

- All Electric machines have:
  - Stationary members (stator)
  - rotating members (rotor)
  - Air gap which is separating stator and rotor
- The rotor and stator are coupled magnetically

DC Machines

- Schematic representation of a DC Machine

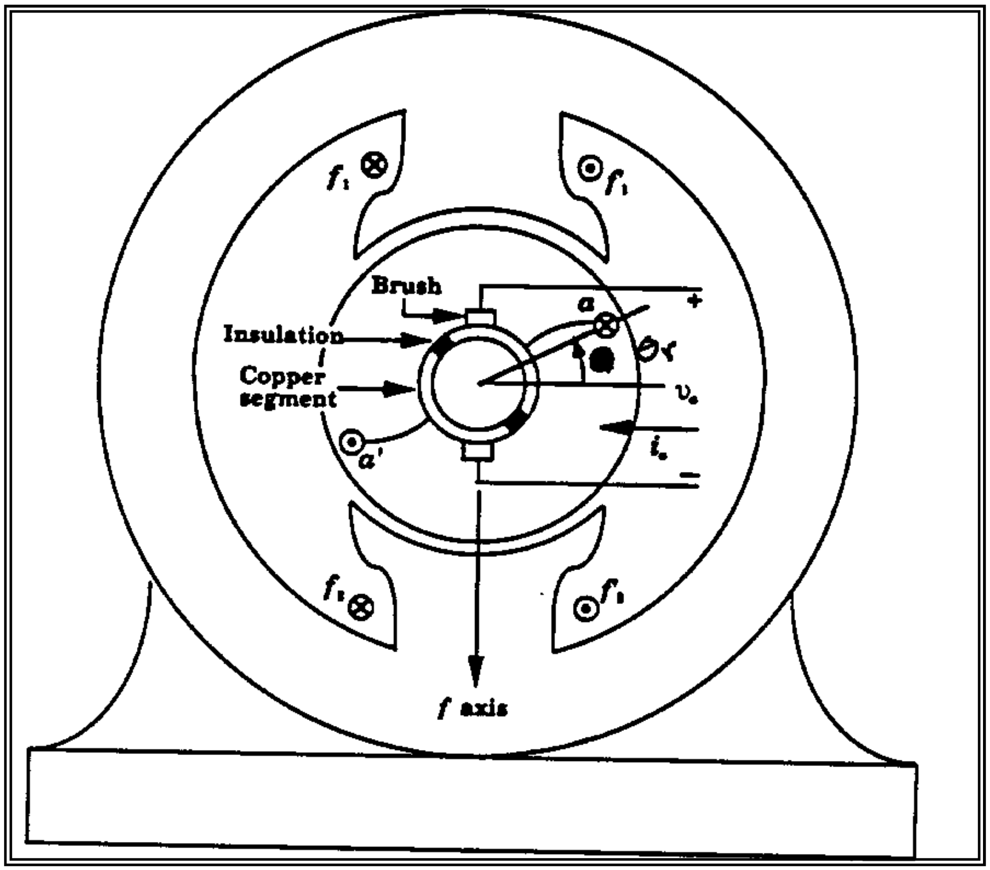


Electric Machine

- The armature winding is placed in the rotor slot and connected to rotating commutator which rectifies the induced voltage
- The brushes which are connected to the armature winding, ride on commutator

DC Machines

- Elementary two-pole DC Machine

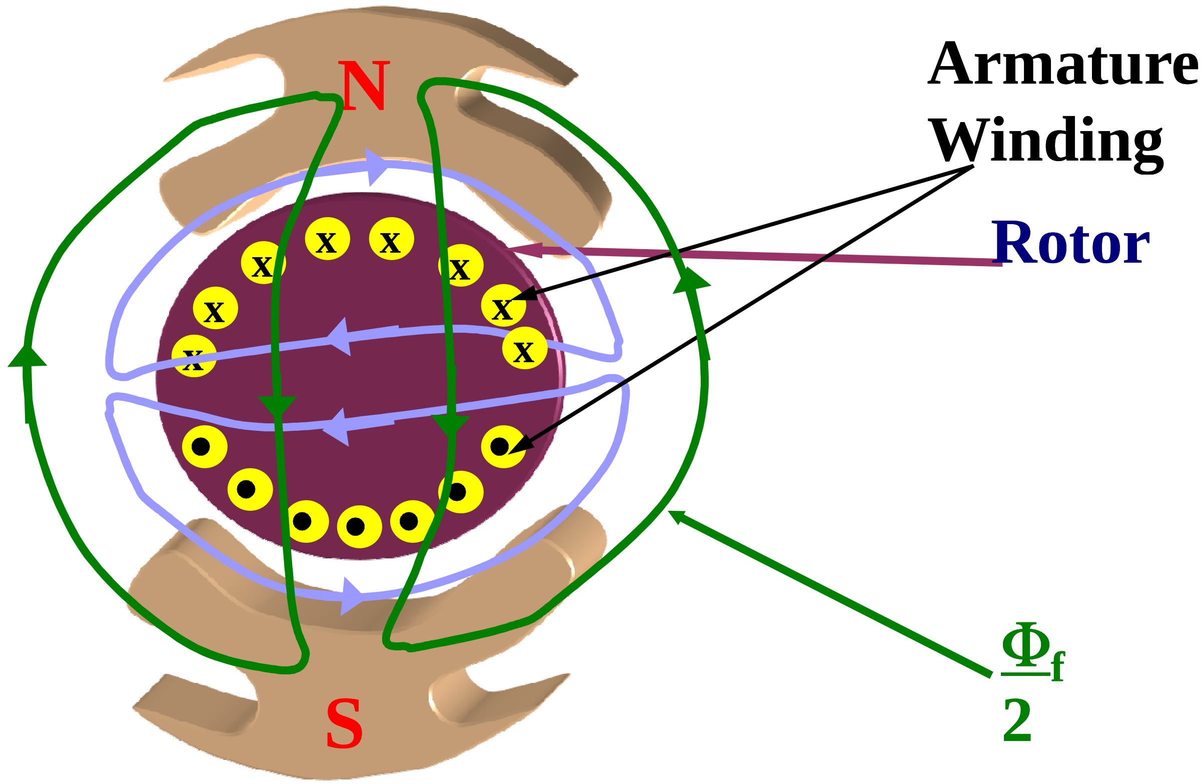


Electric Machine

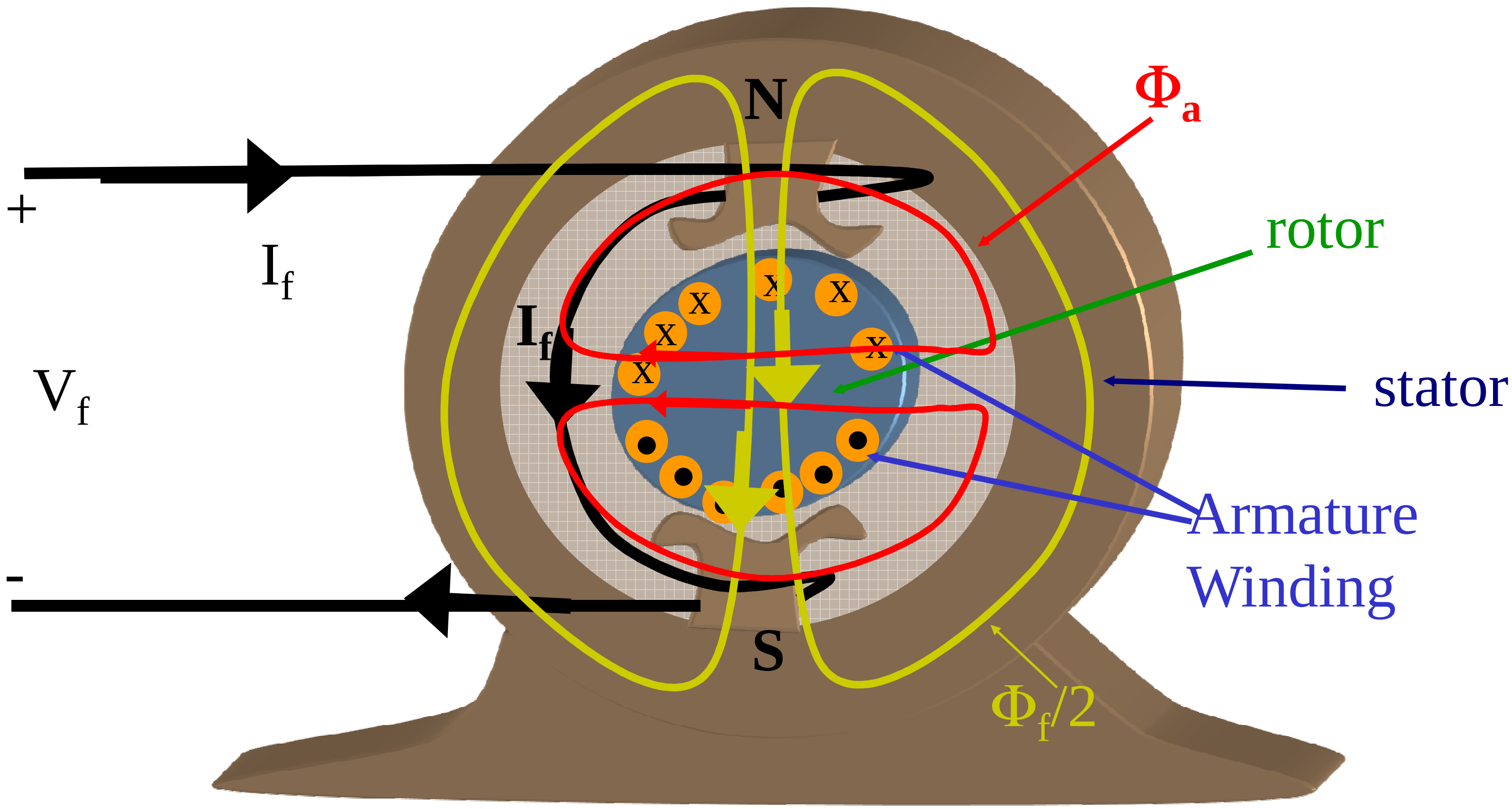
- The armature winding consists of identical coils carried in slots that are uniformly distributed around the periphery of the rotor
- Conventional DC machines are excited by direct current, in particular if a voltage-fed converter is used a dc voltage uf is supplied to the stationary field winding
- Hence the excitation magnetic field is produced by the field coils
- Due to the commutator, armature and field windings produce stationary magnetomotive forces that are displaced by 90 electrical degrees

DC Machines

- The field winding is placed on the stator and supplied from a DC Source.



Magnetic Flux in DC machines



DC Machines

- The current is induced in the **Rotor Winding** (**i.e.** the **Armature Winding**) since it is placed in the field (***Flux Lines***) of the Field Winding.

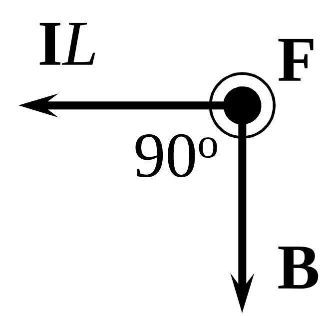
Orthogonality of Magnetic Fields in DC Machines

- mmf produced by the armature and mmf produced by the field winding are orthogonal.

$$\mathbf{F} = \mathbf{I}L \times \mathbf{B} = ILB\sin\left(90^o\right)$$

$\mathbf{B}$: Magnetic field due to field winding

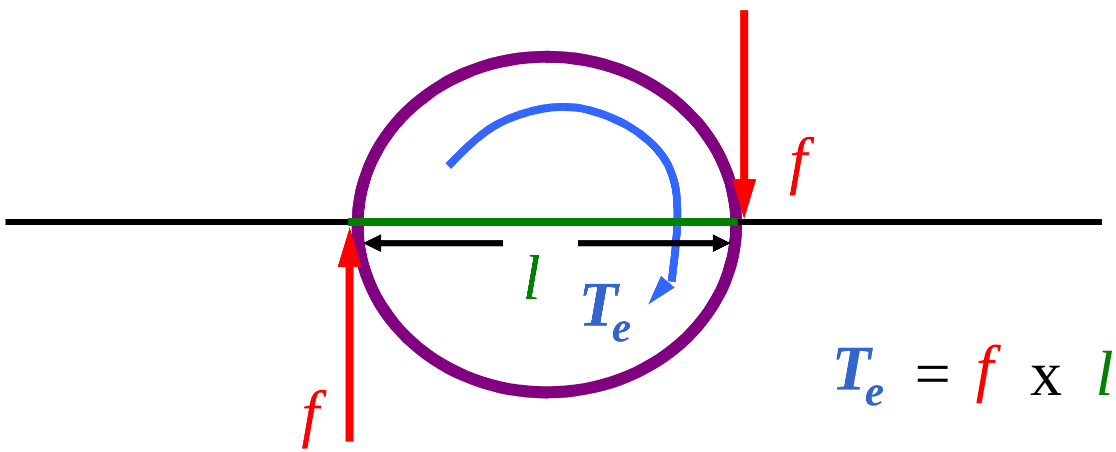
$\mathbf{I}L$: Magnetic field due to armature winding



DC Machines

- The force acting on the rotor, is expressed as

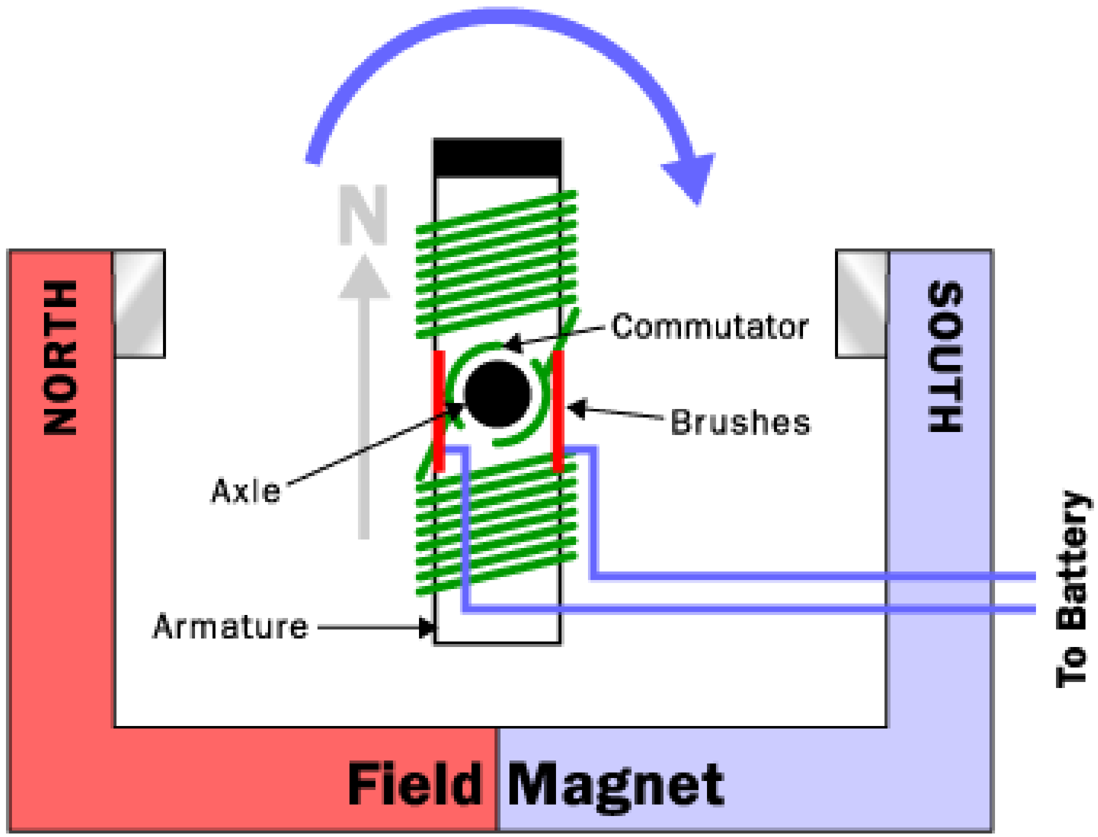
$$f = \underbrace{I\,L}_{\text{Due to the Armature}} \times \underbrace{B}_{\text{Due to the Field}}$$

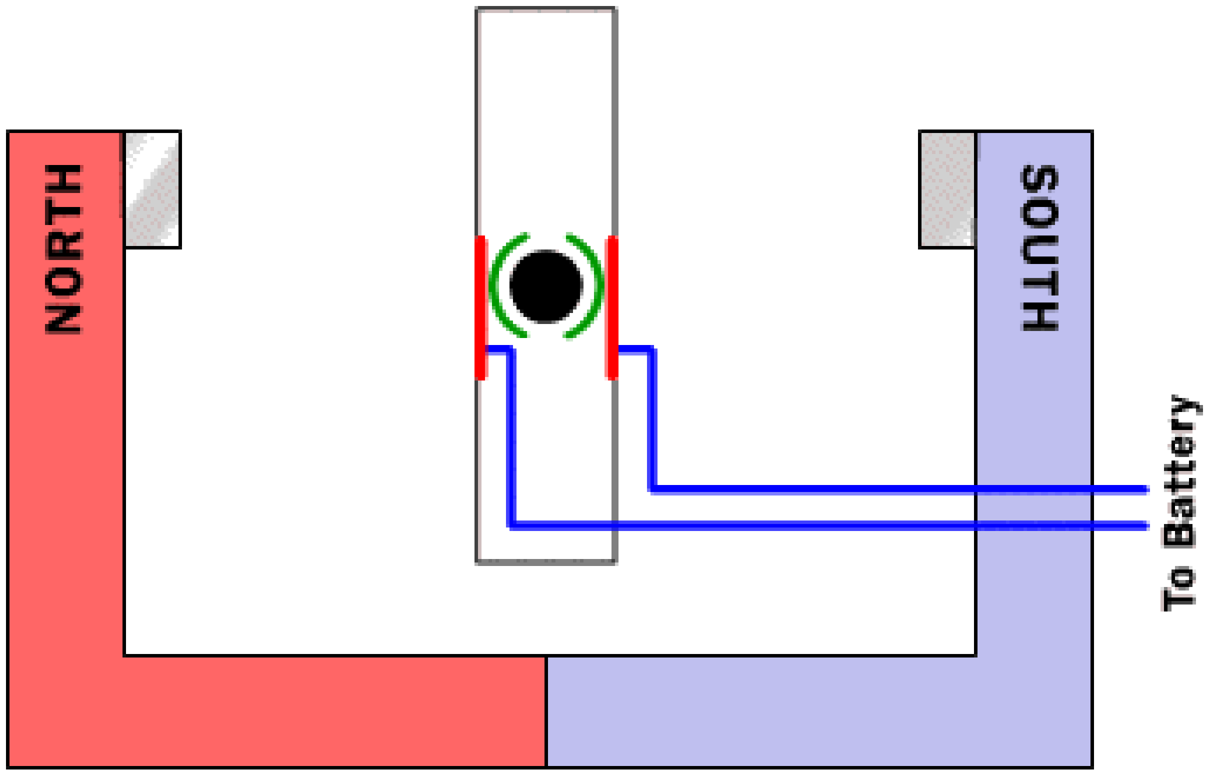


$$T_e = f \text{ x } l$$

DC Machines

- The Field winding is placed on the stator and the current (voltage) is induced in the rotor winding which is referred also as the armature winding.
- In DC Machines, the ***mmf*** produced by the field winding and the ***mmf*** produced by the armature winding are at right-angle with respect to each other.
- The torque is produced from the interaction of these two fields.


N
NORTH
SOUTH
Commutator
Brushes
Axle
Armature
To Battery
Field Magnet


NORTH
SOUTH
To Battery

8.1 DC Motor

- The direct current (dc) machine can be used as a motor or as a generator.
- DC Machine is most often used for a motor.
- The major advantages of dc machines are the easy speed and torque regulation.
- However, their application is limited to mills, mines and trains. As examples, trolleys and underground subway cars may use dc motors.
- In the past, automobiles were equipped with dc dynamos to charge their batteries.

8.1 DC Motor

- Even today the starter is a series dc motor
- However, the recent development of power electronics has reduced the use of dc motors and generators.
- The electronically controlled ac drives are gradually replacing the dc motor drives in factories.
- Nevertheless, a large number of dc motors are still used by industry and several thousand are sold annually.

8.1 Construction

DC Machine Construction

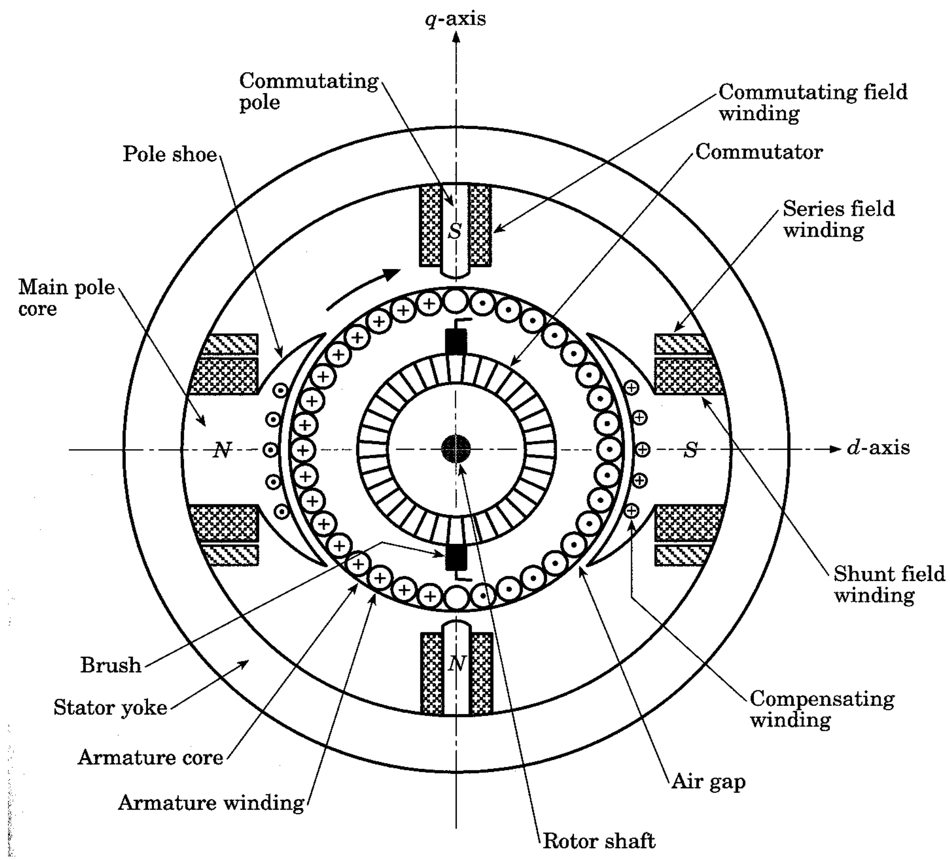
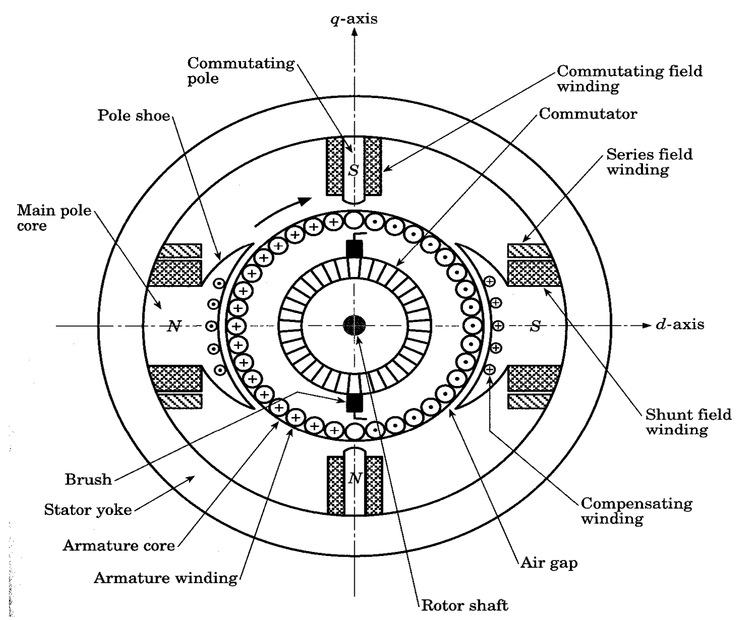


Figure 8.1 General arrangement of a dc machine

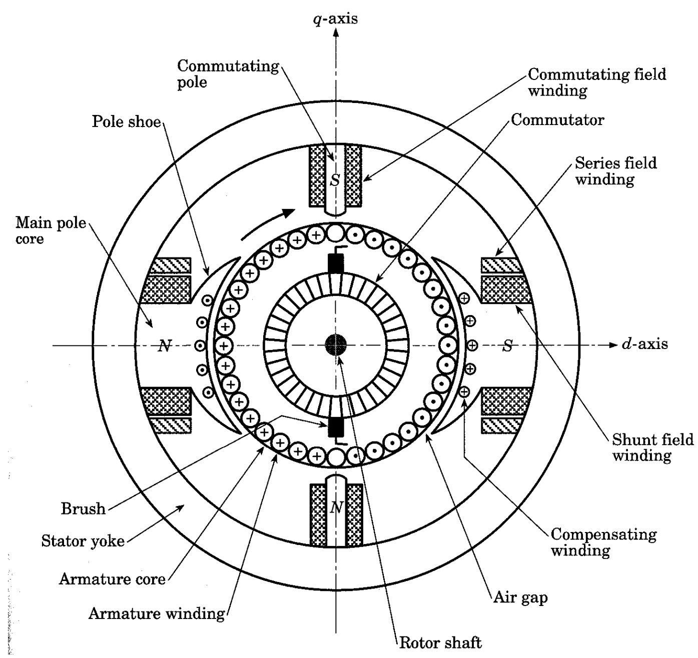
DC Machines

- The stator of the dc motor has poles, which are excited by dc current to produce magnetic fields.
- In the neutral zone, in the middle between the poles, commutating poles are placed to reduce sparking of the commutator. The commutating poles are supplied by dc current.
- Compensating windings are mounted on the main poles. These short-circuited windings damp rotor oscillations. .



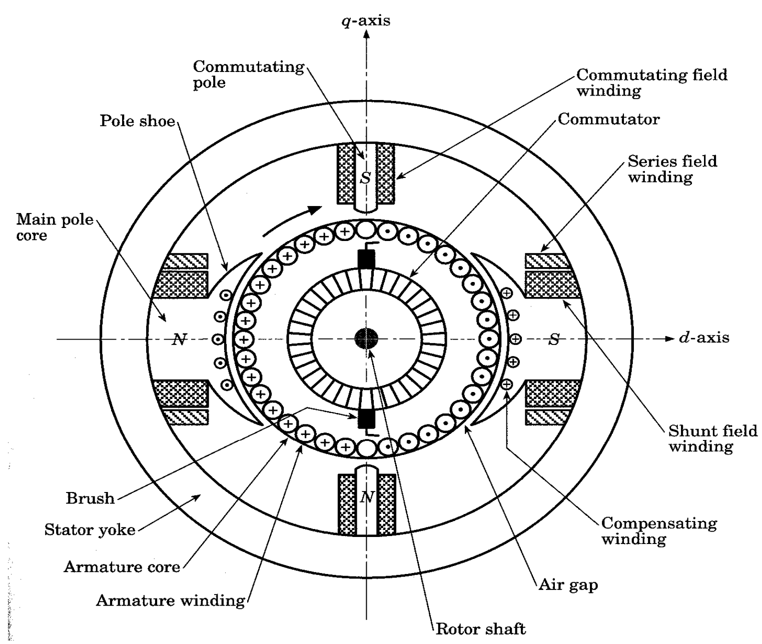
DC Machines

- The poles are mounted on an iron core that provides a closed magnetic circuit.
- **The motor housing supports the iron core, the brushes and the bearings.**
- **The rotor has a ring-shaped laminated iron core with slots.**
- **Coils with several turns are placed in the slots. The distance between the two legs of the coil is about 180 electric degrees.**



DC Machines

- The coils are connected in series through the commutator segments.
- The ends of each coil are connected to a commutator segment.
- The commutator consists of insulated copper segments mounted on an insulated tube.
- Two brushes are pressed to the commutator to permit current flow.
- The brushes are placed in the neutral zone, where the magnetic field is close to zero, to reduce arcing.



DC Machines

- The rotor has a ring-shaped laminated iron core with slots.
- The commutator consists of insulated copper segments mounted on an insulated tube.
- Two brushes are pressed to the commutator to permit current flow.
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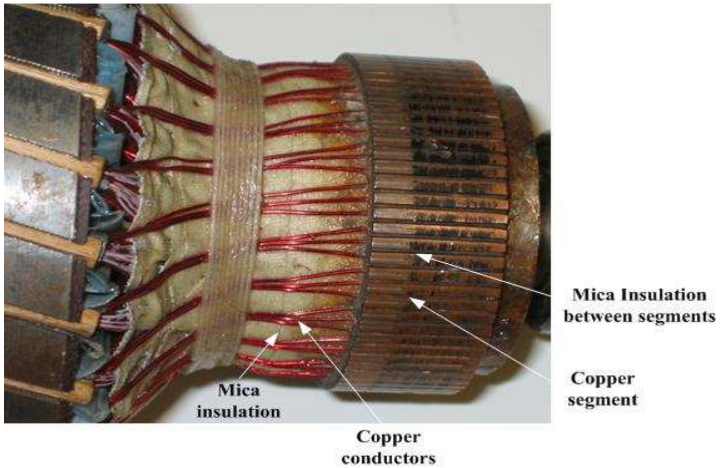
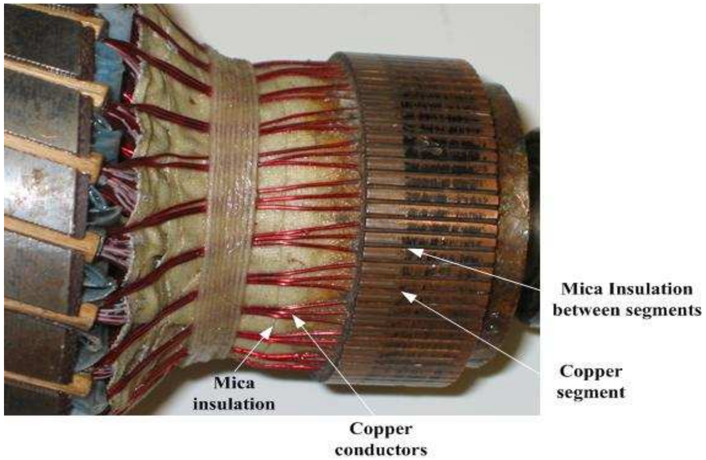


DC Machines

- The *commutator* switches the current from one rotor coil to the adjacent coil,
- The switching requires the interruption of the coil current.
- The sudden interruption of an inductive current generates high voltages .
- The high voltage produces flashover and arcing between the commutator segment and the brush.



DC Machine Construction

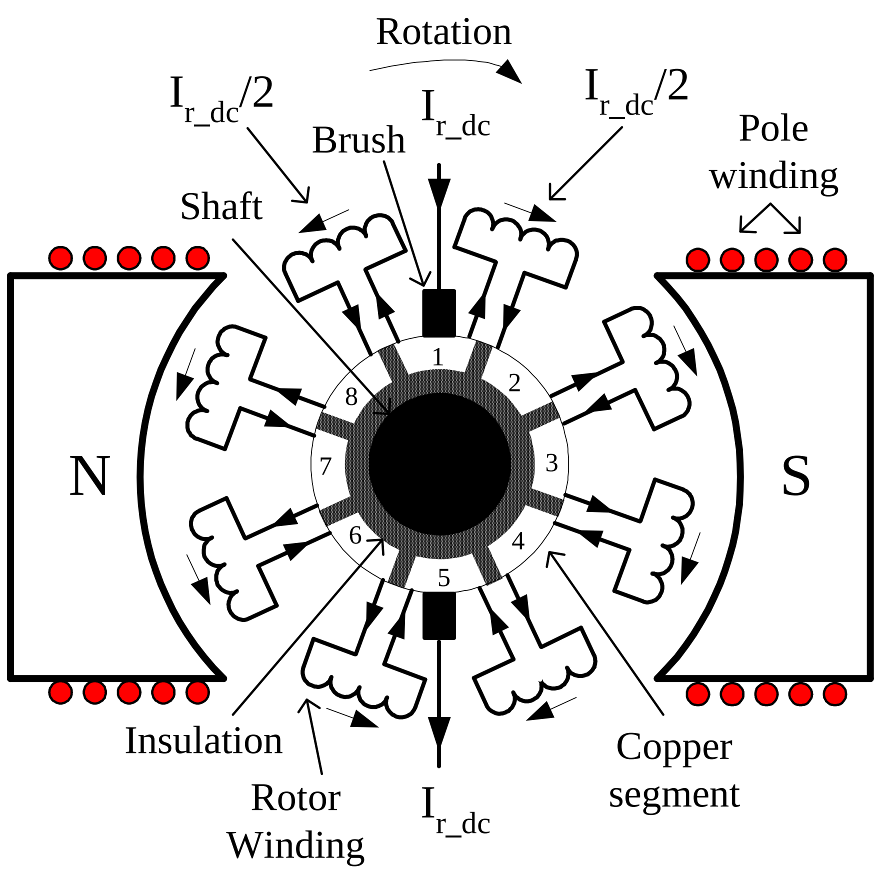


Figure 8.2 Commutator with the rotor coils connections.

DC Machine Construction

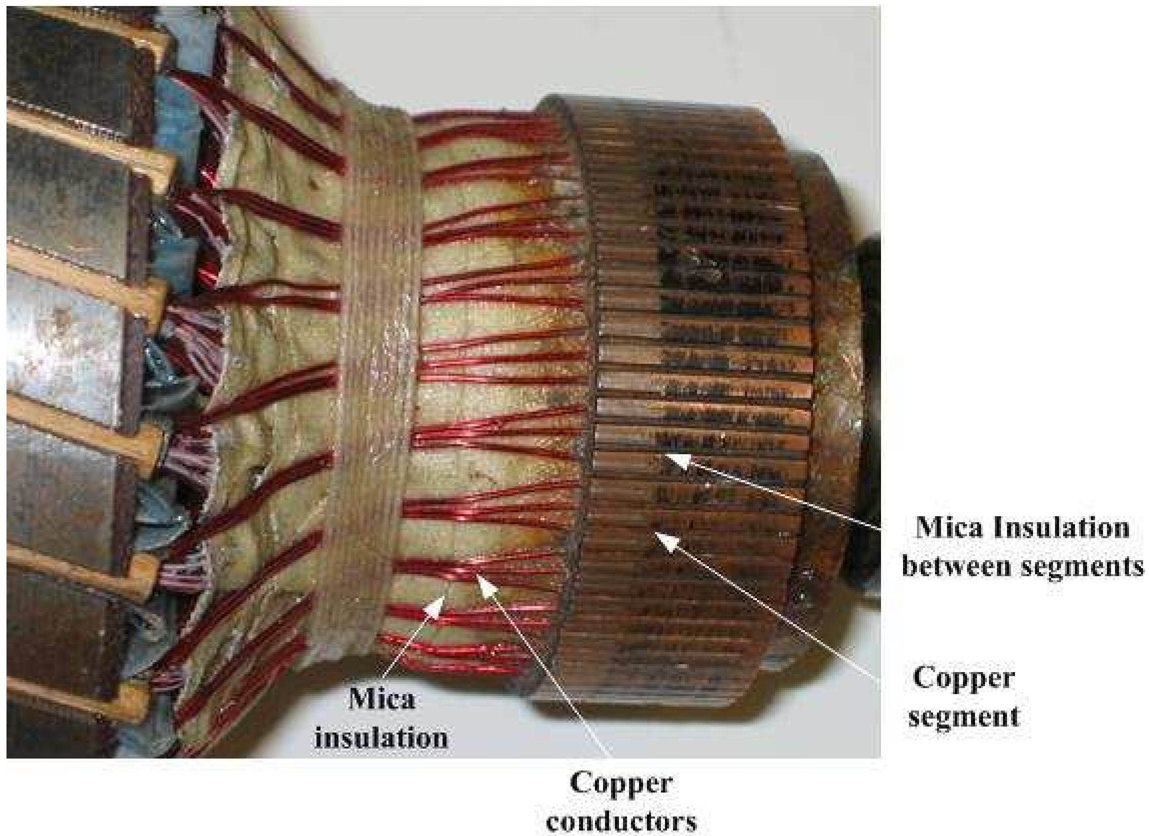


Figure 8.3 Details of the commutator of a dc motor.

DC Machine Construction

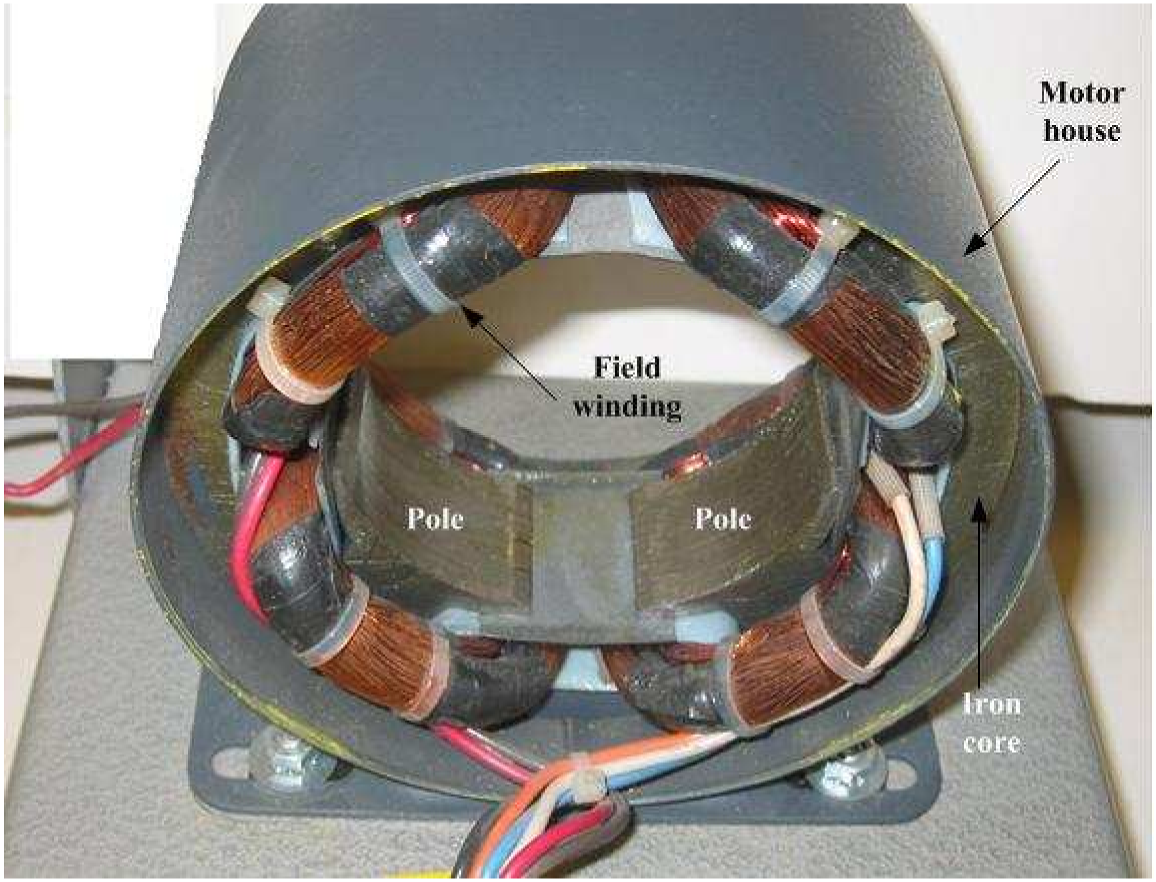


Figure 8.4 DC motor stator with poles visible.

DC Machine Construction

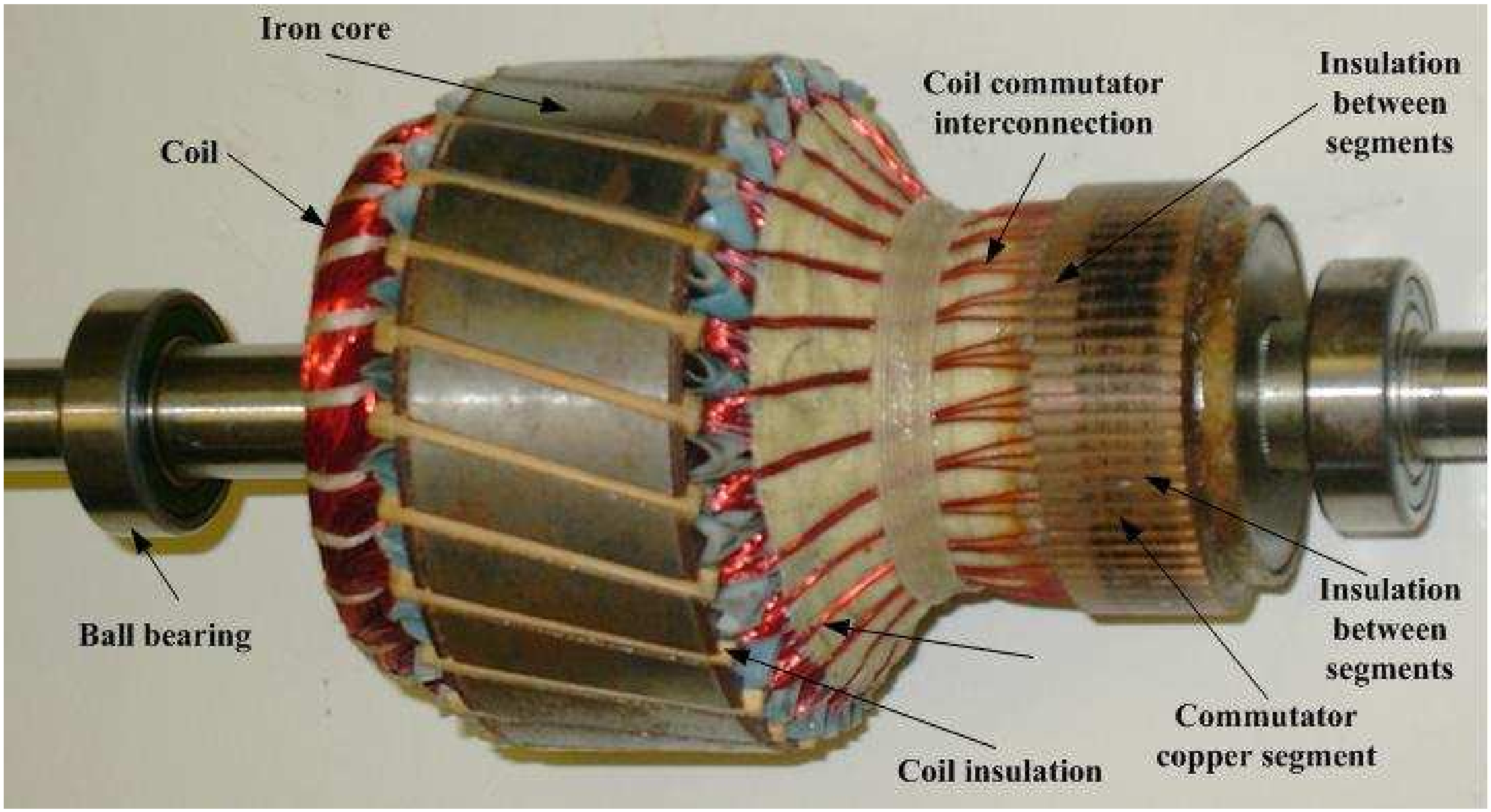


Figure 8.5 Rotor of a dc motor.

DC Machine Construction

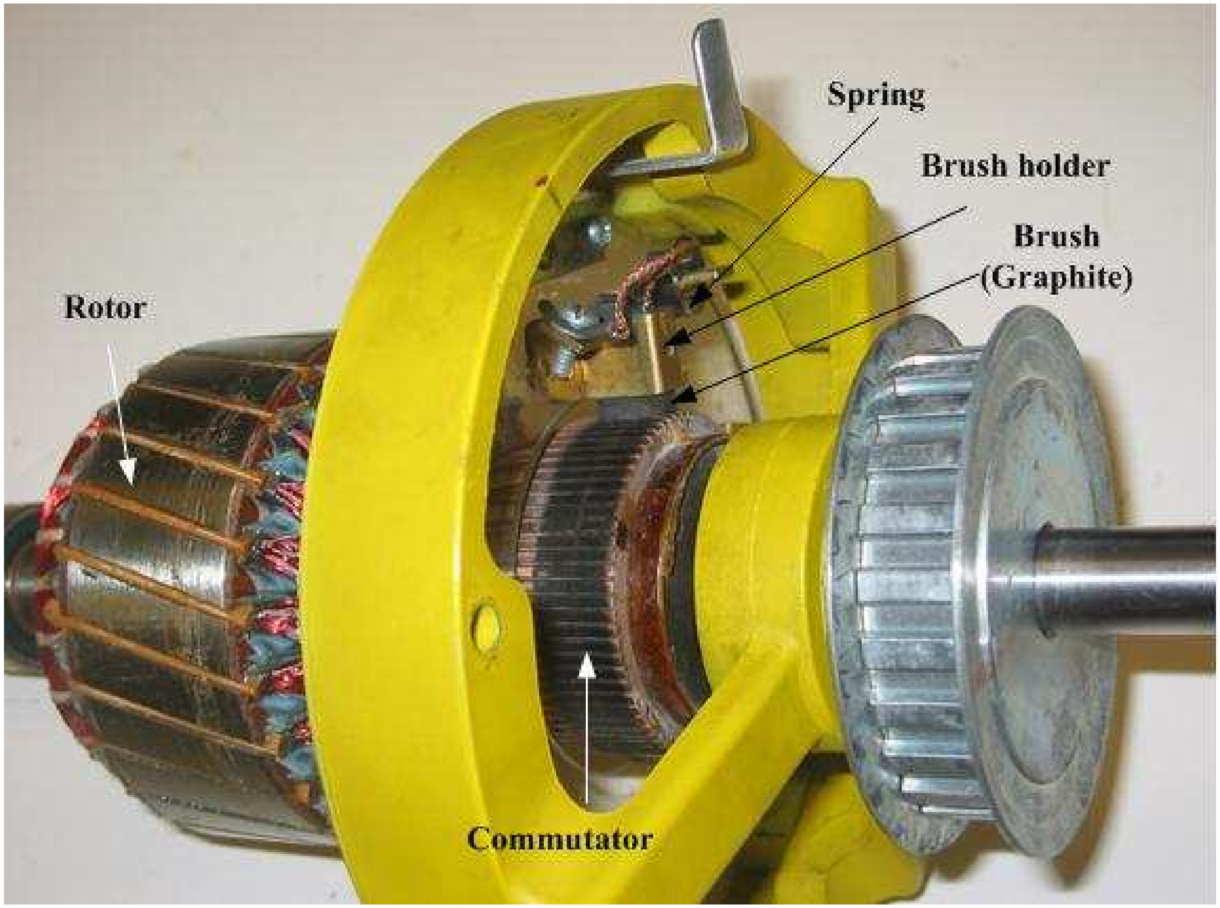


Figure 8.6 Cutaway view of a dc motor.

1) Total Magnetic loading :-

The total amount of flux available at the air gap of the armature periphery is called Total magnetic loading. It is given by

$$p\phi = B_{av} \times \pi D L \quad , \text{wb}$$

W-00
S-96
S-96
W-90

2) Specific Magnetic loading:-

The total amount of flux available at the air gap of the armature periphery per unit area is called Specific Magnetic loading. It is given by

$$B_{av} = \frac{p\phi}{\pi D L}, \quad wb/m^2$$

Avg. flux density

(or) Avg. gap density

3) Total Electric loading :-

The total amount of ampere conductors available at the armature periphery is called Total Electric loading. It is given by

$$\boxed{I_z Z = ac \times \pi D}, \quad A \text{ (or) } AC$$

4) Specific electric loading :-

The total amount of ampere conductors available at the armature periphery per unit length is called Specific electric loading.

It is given by

$$ac = \frac{I_i \cdot Z}{\pi D}$$

, A/m or AC/m

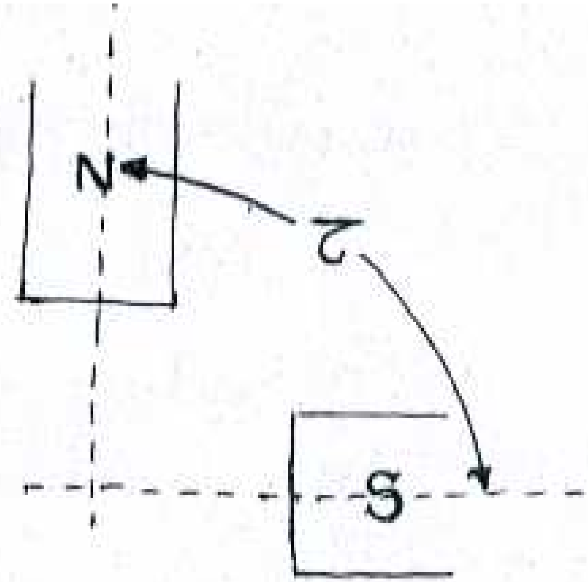
POLE PITCH:

The peripheral distance measured between the centres of two adjacent poles is called pole pitch. It is given by

$$\tau = \frac{\pi D}{p}, \text{ m}$$

where, $D \rightarrow$ Dia. of machine, m

$p \rightarrow$ No. of poles.



SLOT PITCH:

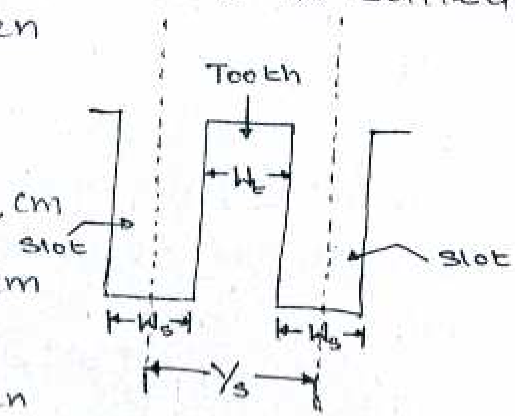
(131)

The distance measured between centres of two consecutive slots is called slot pitch. It is given by

$$Y_s = W_t + W_s \text{ cm}$$

where, $W_t \rightarrow$ Width of tooth, cm

$W_s \rightarrow$ Width of slot, cm

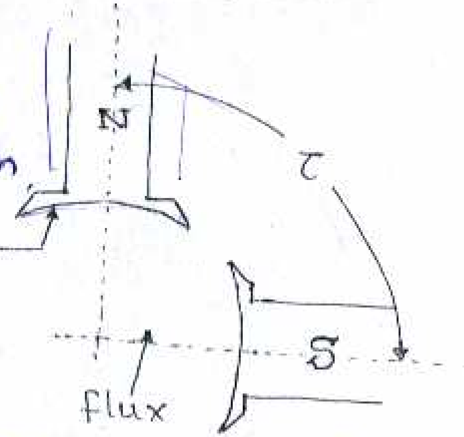


Also the slot pitch can be expressed as given below.

$$Y_s = \frac{\pi D}{S}, \text{ cm}$$

Relation between avg. gap density and max. gap density :-

The flux density that is calculated over one pole pitch is called avg. gap density. It is denoted by B_{av}.



The Flux density that is calculated over one pole arc is called max. gap. density. It is denoted by B_g.

The relation is given by $\boxed{B_{av} = \psi B_g} = k_f B_g$

Where B_{av} = Avg. gap density

0.4 to 0.8 wb/m^2

B_g = Max. gap density

= 0.64 to 0.72

Field form factor (or) Field form Co-efficient:

It is defined as the ratio of avg. gap density to the max. gap density.

It is given by

$$K_f = \frac{B_{av}}{B_g}$$

, No unit

OUTPUT EQUATION :-

Let, P_a = Power developed by armature, kw

E = Emf Induced in armature, V

I_a : Armature current, A

ϕ = Useful flux/pole, wb

Z = No. of armature conductors

n = Speed in r.p.s

N = Speed in r.p.m

p = No. of poles

a = No. of parallel path

I_z = Current per armature conductor, A

D = Dia. of armature, m

L = length of armature, m

B_{av} = avg. Sp. Mag. loading, wb/m^2

ac = Sp. elec. loading, [illegible] A/m

∴ Power developed by armature, $P_a = E I_a \times 10^{-3}$ kW

But $E = \phi Z n \times \frac{p}{a}$ volt

where $n = \frac{N}{60}$ r.p.s

$$\therefore P_a = \left(\phi Z n \times \frac{P}{a}\right) \times I_a \times 10^{-3} \text{ kW}$$

$$= (P\phi) \times \left(\frac{I_a}{a} \times Z\right) \times n \times 10^{-3} \text{ kW}$$

$$= (P\phi) \times (I_2 \times Z) \times n \times 10^{-3} \text{ kW}$$

where, $I_z = \frac{I_a}{a}$ = Current per parallel path

$$= (B_{av} \times \pi D L) \times (ac \times \pi D) \times n \times 10^{-3} \text{ kW}$$

$$= (\pi^2 B_{av}\, ac \times 10^{-3}) \times D^2 L n \text{ kW}$$

$$\therefore \boxed{P_a = C_1 D^2 L n, \text{kw}}$$

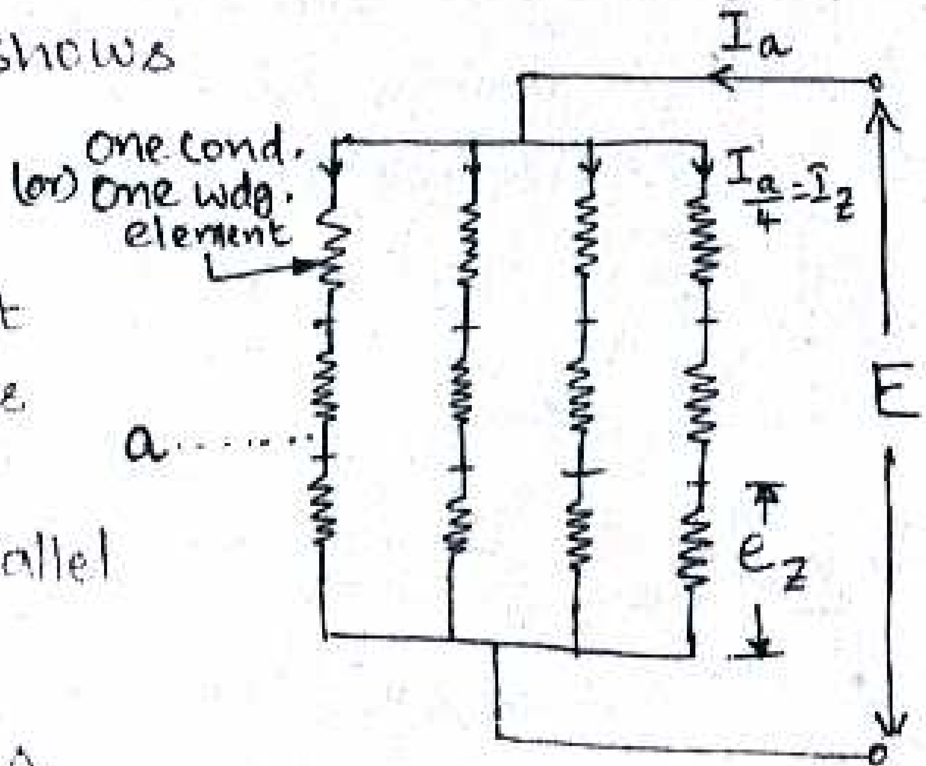
where, C_0 is called output co-efficient of d.c. machine.

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

NOTE :-

The fig. shows developed diagram of an armature wdg. The current per conductor i.e the same as current per parallel path.

$$\boxed{I_z = \frac{I_a}{a}}\ , A$$



5.(a) Volume of the machine related with B_{av} & ac:-

From output Eqn.

Volume of the machine is given by,

$$D^2L = \frac{P_a}{C_o n}, \; m^3$$

For a given power rating, when volume of the machine decreases, both C_o and n are increased.

Voltage rating:

$$\overset{\uparrow}{ac} = \frac{\overset{\uparrow}{I_z} Z}{\pi D}, \quad \overset{\uparrow}{I_z} Z \Rightarrow I_z \frac{Z}{2}, \quad \overset{\uparrow}{AT_a} \Rightarrow \overset{\uparrow}{AT_{fl}}, \quad \overset{\uparrow}{AT_{fl}} \Rightarrow \overset{\uparrow}{\phi},$$

$$\overset{\uparrow}{\phi} \Rightarrow \overset{\uparrow}{E}, \quad \overset{\uparrow}{E} \Rightarrow \overset{\uparrow}{V}$$

When ac increases, the armature ampere turns pole increases. To overcome the effect of armature reaction, the field mmf has to be increased. Since field flux increases the Induced emf becomes more and hence the terminal voltage Increases. But high voltage requires more Insulation and hence cost of Insulation rises. So suitable value of ac should be used.

Speed of machine:

$$\overset{\uparrow}{ac} = \frac{I_2 Z}{\pi D\downarrow}, \quad D\downarrow \Rightarrow \overset{\downarrow}{\text{Volume}}, \quad \overset{\downarrow}{\text{Volume}} \Rightarrow \overset{\uparrow}{\text{Speed}},$$

$$\overset{\uparrow}{\text{Speed}} = \overset{\uparrow}{\text{Cooling}}$$

With higher value of ac, the dia. of armature decreases as the volume becomes less higher speed can be achieved. More air inside the machine results better cooling. Hence higher value of ac is preferable.

Size of machine:

$$ac\uparrow = \frac{I_z Z}{\pi D\downarrow}, \quad D\downarrow \Rightarrow \text{Volume}\downarrow, \quad \text{Volume}\downarrow \Rightarrow \text{size}\downarrow$$

When ac increases, the dia. of armature decreases since volume of machine decreases, the size becomes less and it results less cost. So value ac should be higher.

Show that

Copper loss $\propto \delta^2 \rho V$

where $\delta =$

Proof :

Copper loss $= I^2 R$

$$= (\delta \times a)^2 \times \left(\frac{\rho l}{a}\right)$$

$$= \delta^2 \rho (a l)$$

$$= \delta^2 \rho V$$

$\therefore$ Copper loss $\propto \delta^2 \rho V$ if proportionality constant is unity

The diameter and length of a 500 kW, 500 V, 455 rpm 6 pole, d.c. Generator are 84 cm and 35 cm respectively. If it is lap wound with 660 conductors, Estimate the specific electric and magnetic loading.

Given data:

D = 84 cm, L = 35 cm, P = 500 kW, V = 500 V,

N = 455 r.p.m, p = 6, Gen., a = p, Z = 660

Reqd. data:

$ac = ?$ $B_{av} = ?$

Solution:

Full load current, $I_L = \frac{P}{V} = \frac{500 \times 10^3}{500}$

$= 1000 A$

Armature current, $I_a = I_L \quad (\because I_f = 0)$

$= 1000 A$

Current per conductor, $I_z = \frac{I_a}{a} = \frac{I_a}{p} = \frac{1000}{6}$

$I_z = 166.67 A$

$\therefore$ Sp. electric loading, $ac = \frac{I_z Z}{\pi D}$

$= \frac{166.67 \times 660}{\pi \times 84 \times 10^{-2}}$

$= 29,412 \ AC/m$

Induced emf, $E = V \quad (\because I_a R_a = 0)$

$= 500$ Volt

flux per pole, $\phi = \frac{E \times 60 \times a}{ZNP} = \frac{500 \times 60 \times 6}{660 \times 455 \times 6}$

$\phi = 0.09$ wb

$\therefore$ sp. mag. loading, $B_{av} = \frac{P\phi}{\pi DL} = \frac{6 \times 0.09}{\pi \times 0.84 \times 0.35}$

$B_{av} = 0.58 \text{ wb/m}^2$

Choice of Specific Loadings

(i) Choice of specific magnetic loading

(II) Choice of specific electric loading

Choice of specific magnetic loading

(1) Teeth Flux density

(2) Frequency

(3) Voltage

Teeth Flux density

- If flux density in the air gap is high, it may lead to high flux density in armature teeth beyond the maximum permissible limit.
- The maximum flux density in the teeth at minimum section should not go beyond 2.2 wb/m^2

. The reasons are obvious as higher flux density

(i) Causes increased iron losses

(ii) Requires higher ampere- turns for passing the flux through teeth leading to increased field copper losses and increased cost of copper

(2) Frequency

- The frequency of flux reversal in the armature is given by

$$f = \frac{np}{2}$$

The higher frequency will result in increased iron losses in the armature core and teeth. Therefore, there is a limitation in choosing higher Bav for a machine having higher frequency.

(3) Voltage

- For high voltage machine, space required for insulation is comparatively more.
- Thus for a given diameter less space available for iron on the periphery leading to narrower teeth
- Therefore, lower value of Bav has to be taken. Otherwise teeth flux density increases beyond permissible limit.

- Usually, Bav lies between 0.45 to 0.75 wb/m^2
- The corresponding value of maximum flux density in the gap Bg varies from 0.64 to 1.1 Wb/m2.

- Maximum flux density in the air gap $B_g = \frac{B_{av}}{K_f}$

Lower value of flux density for lower rating machines and higher values of flux density, for higher rating machines is the usual choice.

Choice of specific electric loading

- ***1) Heating or Temperature Rise***
- *(2) Speed*
- (3) ***Voltage***
- ***(4) Size of Machine***
- ***(5) Armature Reaction***
- ***6) Commutation***

(1) Heating or Temperature Rise

- Using a high value of armature conductors (ac) creates problem of heat dissipation
- A high value of ac means either copper used is more i.e., having large number of conductors
- large number of coils obviously having increased insulation thickness
- leading to poor heat dissipation or diameter is less leading again to poor heat dissipation because of reduced surface area. Both of these results in high temperature rise in armature.

(2) Speed

- For a high-speed machine, ventilation is obviously better and greater losses could be dissipated
- Thus, a higher value of 'ac' can be used for higher speed machine.

3) ***Voltage***

- Machines with high voltage require large space for insulation
- Thus for a given diameter, it may not be possible to reduce the space required for iron because of the limitation imposed by flux density in the teeth
- Therefore, space for copper is reduced. So, lesser value of 'ac' is used in such cases.

(4) Size of Machine

- In large size machine, there is more space for accommodating copper therefore higher ac should be used.

(5) Armature Reaction

- With high value of ac, armature ampere turns also increases. Therefore armature reaction will be severe
- To counter this, field mmf is increased and so the cost of machine goes high.

(6) Commutation

- High value of ac worsens the commutation condition in machines. From the point of view of commutation, a small value of ac is desirable.
- The value of ac usually lies between 15,000 to 50,000 amp. conductors /m.

Advantage of having more number of poles

Weight of armature core and yoke is reduced

1. Cost of copper in the field and armature is reduced
2. Overall diameter and length of machine is reduced
3. Length of commutator is reduced
4. Distortion of field form is not excessive

Disadvantages of having more number of poles

1. Frequency of flux reversal is increased and causes more iron losses.
2. Labour charges are increased
3. Possibility of flash over between brush arms

Guiding Factors for selecting number of poles

The following may be taken as guiding factors for the choice of number of poles:

Guide lines for selecting for number of poles

1. Keep frequency of flux reversals in the armature between 25 to 50 Hz. Lower value of frequency is used for large machines is advisable.

2. The current per parallel path is limited to 200A.Thus the current per brush arm should not be more than 400 A.

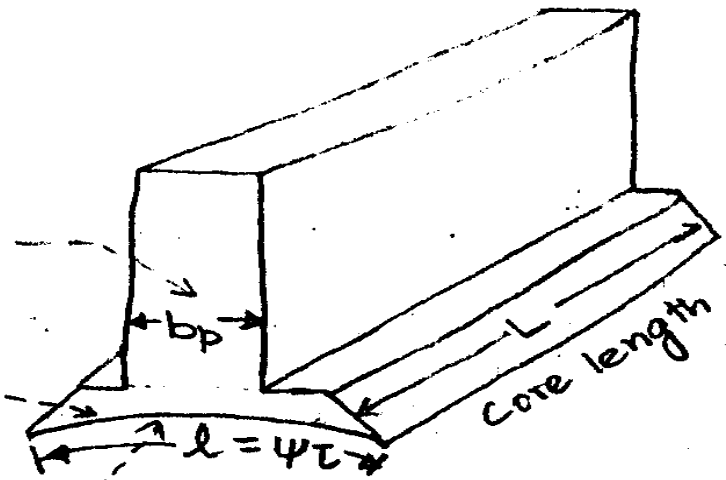
3. The armature mmf should not be too large. The normal values of armature mmf per pole are listed in Table 2.4.

Table 2.4. : Armature mmf per pole

Output in KW	Armature mmf per pole (AT)
Upto 100	5000 or less
100 to 500	5000 to 7500
500 to 1500	7500 to 10000
Over 1500	Upto 12,500

4. If there are more than one choice for number of poles which satisfies the above three conditions, then choose the largest value for poles. This results in reduction in iron and copper.

Pole proportions :-



The cross-section of pole may be rectangular (or) Square.

Length of pole, $L_p = b_p$ to $2 b_p$

Breadth of pole, $b_p = (0.45 \text{ to } 0.55)\tau$

Now $L_p = 0.45\tau$ to 1.1τ

$= (0.45 \text{ to } 1.1)\tau$

$$\therefore \boxed{\frac{L}{\tau} = 0.45 \text{ to } 1.1} \rightarrow \text{In general}$$

Case - I :

For rectangular pole face

$$\boxed{\frac{L}{\tau} = 0.7 \text{ to } 0.9}$$

Case - II :

For square pole face

$$\boxed{\frac{L}{\tau} = \psi} = 0.64 \text{ to } 0.72$$

Where, $\frac{L}{\tau} \rightarrow$ Ratio of core length to pole pitch

$\psi \rightarrow$ Ratio of pole arc to pole pitch.

NOTE:

1) $P_a = P\left[\frac{1+2\eta}{3\eta}\right] \longrightarrow (M) \longrightarrow P \leq 50\,\text{kW}$

$= P\left[\frac{2+\eta}{3\eta}\right] \longrightarrow (G) \longrightarrow P \leq 50\,\text{kW}$

$= P \longrightarrow (M) \longrightarrow P > 50\,\text{kW}$

$= \frac{P}{\eta} \longrightarrow (G) \longrightarrow P > 50\,\text{kW}$

} When η_f is given

2) $P_a = E_g I_a \times 10^{-3}$ kW $\longrightarrow$ (G)

$= E_b I_a \times 10^{-3}$ kW $\longrightarrow$ (M)

} From fundamentals

3) $E_g = V + I_a R_a \longrightarrow$ (G)

$E_b = V - I_a R_a \longrightarrow$ (M)

4) $I_a R_a = (x)\%$ of V

5) $I_a = I_L + I_f \longrightarrow$ (G)

$= I_L - I_f \longrightarrow$ (M)

6) $I_f = (x)\%$ of I_L

7) $I_L = \dfrac{\text{o/p in watts}}{V} \longrightarrow$ (G)

$= \dfrac{\text{I/p in watts}}{V} \longrightarrow$ (M)

8) $I_a \leq 400A$, Assume lap or Wave ~~wound~~ winding
But wave winding is preferable.

$I_a > 400A$, Assume lap winding

9) Effect of series field winding is neglected.

10) $$l_g = \frac{AT_g}{800,000\, K_g B_g}$$

Where, $K_g \rightarrow$ Gap contraction factor

$B_g \rightarrow$ Max. gap density

Problems :-

A 5 kW, 250 V, 4 pole, 1500 r.p.m, shunt generator is designed to have a square pole face. The loadings are:

Average flux density in the gap = 0.42 wb/m^2

Ampere conductors per metre = 15000

Find the main dimension of the machine. Assume full load efficiency = 87% and ratio of pole arc to pole pitch = 0.66

//

Solution: **Given data:**

$P = 5\,kW$, $V = 250\,V$, $p = 4$, $N = 1500$ r.p.m, Shunt gen.,

Square pole face, $B_{av} = 0.42\,Wb/m^2$, $ac = 15000\,AC/m$,

$\eta_{F.L} = 0.87$, $\psi' = 0.66$

Reqd. data:

$D = ?$ $L = ?$

Power developed by armature, $P_a = P\left[\dfrac{2+\eta}{3\eta}\right]$

$$= 5 \left[\frac{2+0.87}{3 \times 0.87}\right]$$

$$P_a = 5.5\,kW$$

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

$= \pi^2 \times 0.42 \times 15{,}000 \times 10^{-3}$

$C_o = 62.18$

Speed, $n = \frac{N}{60} = \frac{1500}{60}$

$n = 25$ r.p.s

∴ Volume of machine, $D^2L = \frac{P_a}{C_o\, n}$

$= \frac{5.5}{62.18 \times 25}$

$D^2L = 3.54 \times 10^{-3}\ m^3 \longrightarrow (1)$

Given sq. pole face, $\therefore \frac{L}{\tau} = \psi \Rightarrow L = \psi\tau$

$$L = \psi \times \frac{\pi D}{p}$$

$$= 0.66 \times \frac{\pi D}{4}$$

$$L = 0.5184\, D \longrightarrow (2)$$

Putting the value of L in eqn. (1).

$$0.5184\, D^3 = 3.54 \times 10^{-3}\ m^3$$

$$\therefore D = \sqrt[3]{\frac{3.54 \times 10^{-3}}{0.5184}}$$

$$D = 0.1897\ m$$

and

$$L = 0.5184 \times 0.1897$$

$$L = 0.0983\ m$$

Determine the main dimensions, no of poles and the length of airgap of a 500 volt, 600 KW, 900 rpm, Assume average gap density as 0.6 wb/m² and ampere conductors per metre as 35000. The ratio of pole arc is 0.75 and the efficiency is 91 percentage. The following are the design constraints: Peripheral speed ≯ 40 m/s, Frequency of flux reversals ≯ 50 Hz, current per brush arm ≯ 400 A and armature mmf per pole ≯ 7500 A. The mmf required for air gap is 50 percent of armature mmf and gap contraction factor is 1.15. (157)

Given data:

V = 500 v, P = 600 kW, N = 900 rpm, Gen., B_{av} = 0.6 wb/m²

ac = 35,000 AC/m, ψ = 0.7, $\eta_{F.L}$ = 0.91, K_g = 1.15,

$AT_g = 0.5 \times AT_a$

Reqd. data:

D = ?, L = ?, p = ?, l_g = ?

Soln:-

Speed, $n = \frac{N}{60} = \frac{900}{60}$

$n = 15$ r.p.s

Frequency, $f = \frac{pn}{2}$ Hz = 25 to 50 Hz

let p = 2 ⇒ $f = \frac{2 \times 15}{2}$ = 15 Hz ✗

= 4 = $\frac{4 \times 15}{2}$ = 30 Hz ✓

= 6 = $\frac{6 \times 15}{2}$ = 45 Hz ✓

= 8 = $\frac{8 \times 15}{2}$ = 60 Hz ✗

p may be 4 or 6 (158)

Full load current, $I_L = \frac{P}{V} = \frac{600 \times 10^3}{500}$

$I_L = 1200A$

Armature current, $I_a = I_L$ ($\because I_f = 0$)

$\therefore I_a = 1200A$

Assuming Lap winding, $a = p$

$\therefore$ Current/brush arm, $I_b = \frac{2 \times I_a}{p} \not> 400A$

When $p = 4$. $\Rightarrow I_b = \frac{2 \times 1200}{4} = 600A$ ✗

$= 6 \Rightarrow = \frac{2 \times 1200}{6} = 400A$ ✓

$\therefore$ p = 6 is selected

power developed by armature, $P_a = \frac{P}{\eta}$ ($\because P > 50\,kW$)

$$= \frac{600}{0.91}$$

$$P_a = 659\ kW$$

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

$$= \pi^2 \times 0.6 \times 35{,}000 \times 10^{-3}$$

$$C_o = 207.26$$

$\therefore$ Volume of machine, $D^2L = \frac{P_a}{C_o n} = \frac{659}{207.26 \times 15}$

$$D^2L = 0.212\ m^3 \longrightarrow (1)$$

Assuming sq. pole face,

$$\frac{L}{\tau} = \psi \Rightarrow L = \psi\tau$$

$$= \psi \times \frac{\pi D}{p}$$

$$L = 0.7 \times \frac{\pi D}{6}$$

$$L = 0.3665\, D \longrightarrow (2)$$

Sub. 'L' in eqn. ①

$$0.3665\, D^3 = 0.212\, m^3$$

$$D = \sqrt[3]{\frac{0.212}{0.3665}}$$

$$D = ~~0.3054m~~\ 0.8832\, m$$

∴ $L = 0.3605 \times 0.8832$

$$L = 0.3054m$$

Peripheral speed of armature, $V_a = \pi D n \not> 40\ m/sec$

$$= \pi \times 0.8832 \times 15$$

$$V_a = 39.26\ m/sec$$

∴ $D = 0.8832\ m$ is selected

and $L = 0.3054\ m$ is selected

Armature mmf/pole, $AT_a = \frac{I_z Z}{2 \times p} = \frac{ac \times \pi D}{2 \times p} \times 10{,}000$

$= \frac{35{,}000 \times \pi \times 0.8832}{2 \times 6}$

$AT_a = 8092\ AT$

Given $AT_g = 0.5 \times AT_a = 0.5 \times 8092$

$\doteq 4096\ AT$

max. gap density, $B_g = \frac{B_{av}}{\psi} = \frac{0.6}{0.7}$

$= 0.857\ wb/m^2$

∴ length of Air gap, $l_g = \frac{AT_g}{8{,}00{,}000\ K_g B_g}$

$= \frac{4096}{8{,}00{,}000 \times 1.15 \times 0.857}$

$= 5.13 \times 10^{-3}\ m$

$l_g = 5.13\ mm$

" The diameter and length of a 500 kW, 500V, 455 rpm 6 pole, d.c. Generator are 84 cm and 35 cm respectively. If it is lap wound with 660 conductors, Estimate the specific electric and magnetic loading."

Given data :

Given data:

$D = 84$ cm, $L = 35$ cm, $P = 500$ kW, $V = 500$ V,
$N = 455$ r.p.m, $p = 6$, Gen., $a = p$, $Z = 660$

Reqd. data:

$ac = ?$ $B_{av} = ?$

Solution:

Full load current, $I_L = \frac{P}{V} = \frac{500 \times 10^3}{500}$

$= 1000A$

Armature Current, $I_a = I_L$ ($\because I_f = 0$)

$= 1000A$

Current per conductor, $I_z = \frac{I_a}{a} = \frac{I_a}{p} = \frac{1000}{6}$

$I_z = 166.67A$

∴ Sp. electric ...

$I_z = 166.67 A$

$\therefore$ Sp. electric loading, $ac = \frac{I_z Z}{\pi D}$

$= \frac{166.67 \times 660}{\pi \times 84 \times 10^{-2}}$

$= 29,412$ Ac/m

Induced emf, $E = V$ ($\because I_a R_a = 0$)

$= 500$ Volt

flux per pole, $\phi = \frac{E \times 60 \times a}{Z N p} = \frac{500 \times 60 \times 6}{660 \times 455 \times 6}$

$\phi = 0.09$ wb

$\therefore$ sp. mag. loading, $B_{av} = \frac{p\phi}{\pi D L} = \frac{6 \times 0.09}{\pi \times 0.84 \times 0.35}$

$B_{av} = 0.58$ wb/m^2

4) Find out...

Determine the no of poles, main dimensions, Pole pitch and armature mmf/pole of a 92 kW 220 volt, 1480 r.p.m d.c motor whose full load efficiency is 89.76%.

Specific magnetic loading is 0.545 T and specific electric loading is 32,750 AC/m

The pole arc to pole pitch ratio as 0.67

Assume square pole face.

Soln. Given data: 10

$P = 92$ kW, $V = 220$ V, $N = 1480$ rpm, Motor, $\eta_{F.L} = 0.8$

$B_{av} = 0.545$ T, $ac = 32,750$ AC/m, $\psi = 0.67$, Sq. pole fa

Reqd. data:

$P = ?$ $L = ?$ $D = ?$ $\tau = ?$ $AT_a = ?$

Speed $n = \frac{N}{60} = \frac{1480}{60}$

$n = 24.67$ r.p.s

Frequency, $f = \frac{pn}{2}$ Hz $= 25$ to 50 Hz

Let $p = 2 \Rightarrow f = \frac{2 \times n}{2} = \frac{2 \times 24.67}{2} = 24.67$ Hz ✗

$= 4 \qquad = \frac{4 \times 24.67}{2} = 49.34$ Hz ✓

$= 6 \qquad = \frac{6 \times 24.67}{2} = 74.01$ Hz ✗

$\therefore$ $p = 4$ is selected

Power developed by armature, $P_a = P$ ($\because P > 50$ kW)

$P_a = 92$ kW

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

$$= \pi^2 \times 0.545 \times 32{,}750 \times 10^{-3}$$

$$C_o = 176.16$$

$\therefore$ Volume of machine, $D^2L = \dfrac{P_a}{C_o n}$

$$= \frac{92}{176.16 \times 24.67}$$

$$D^2L = 0.0212\ m^3 \longrightarrow (1)$$

Given Sample Case

Given sq. pole face

$$\frac{L}{\tau} = \psi$$

$$\therefore L = \psi\tau \Rightarrow \psi \times \frac{\pi D}{p}$$

$$= 0.67 \times \frac{\pi D}{4}$$

$$L = 0.526 D \longrightarrow (2)$$

Putting value of 'L' in (1)

$$0.526 D^3 = 0.0212 \ m^3$$

$$D = \sqrt[3]{\frac{0.0212}{0.526}}$$

$$\underline{D = 0.3428 \ m}$$

$$L = 0.526 \times 0.3428$$

$$\underline{L = 0.1803 m}$$

$= 0.1803 m$

$\therefore$ Pole pitch, $\tau = \frac{\pi D}{p} = \frac{\pi \times 0.3428}{4}$

$$\tau = 0.2692\ m$$

$\therefore$ Armature mmf/pole, $AT_a = \frac{ac \times \tau}{2} = \frac{32,750 \times 0.2692}{2}$

$$AT_a = 4,408\ AT$$

//

A design is required for a 50 kW, 4 pole, 600 r.p.m. d.c shunt Generator with full load terminal voltage being 220V. If the max air gap flux density is 0.83 wb/m² and armature ampere conductors/metre is 30,000 calculate the suitable dimensions of armature core to give square pole face. Assume full load armature voltage drop 3% of the rated terminal voltage and the field current 1% of rated full load current. ratio of pole arc to pole pitch

Given data:

$P = 50\ kW$, $p = 4$, $N = 600$ r.p.m, shunt Gen., $V = 220V$,

$B_g = 0.83\ wb/m^2$, $ac = 30{,}000\ Ac/m$, sq. pole face,

$I_a R_a = 0.03$ of $V_{term.}$ i.e. $0.03 \times V$

$I_f = 0.01 \times I_L$, $\psi = 0.67$

Reqd. data:

$D = ?$ $L = ?$

Solution:

Load current, $I_L = \frac{P}{V} = \frac{50 \times 10^3}{220}$

$I_L = 227.27\ A$

Field current, $I_f = 0.01 \times I_L$

$= 0.01 \times 227.27$

$I_f = 2.27\ A$

Armature current, $I_a = I_L + I_f$

$= 227.27 + 2.27$

$I_a = 229.54\ A$

Armature resis. drop, $I_a R_a = 0.03 \times V$

$= 0.03 \times 220$

$I_a R_a = 6.6$ volt

Generated emf, $E_g = V + I_a R_a$

$= 220 + 6.6$

$E_g = 226.6$ V

$E_g = 226.6\ V$

$\therefore$ Power developed by armature, $P_a = E_g I_a \times 10^{-3}\ k$

$= 226.6 \times 229.54 \times 10^{-3}$

$P_a = 52\ kW$

Average gap density, $B_{av} = \psi B_g$

$= 0.67 \times 0.83$

$B_{av} = 0.5561\ Wb/m^2$

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

$= \pi^2 \times 0.5561 \times 30{,}000 \times 10^{-3}$

$C_o = 164.65$

Speed, $n = \frac{N}{60} = \frac{600}{60}$

$n = 10$ r.p.s

Volume of machine, $D^2L = \frac{P_a}{C_o n} \Rightarrow \frac{52}{164.65 \times 10}$

$D^2L = 0.0316\ m^3 \longrightarrow (1)$

Given sq. pole face,

$\frac{L}{\tau} = \psi \Rightarrow L = \psi\tau$

$L = 0.67 \times \frac{\pi D}{P} \Rightarrow 0.67 \times \frac{\pi D}{4}$

$L = 0.5262D \longrightarrow (2)$

sub. 'L' in (1)

$0.5262\ D^3 = 0.0316\ m^3$

$D = \sqrt[3]{\frac{0.0316}{0.5262}}$

$D = 0.3916\ m$

$L = 0.5262 \times 0.3916$

$L = 0.206\ m$

W-00 8) Determine the max. rated output that can be obtained from a 375 r.p.m d.c generator without exceeding a peripheral speed of 40 m/sec, an average emf of 7 volt in each Conductor and an electric loading of 450 Ac/cm (10) 4

Given data:

$N = 375$ r.p.m, Gen., $V_a = 40$ m/sec., $e_z = 7$ volt

$ac = 450$ Ac/cm

Reqd. data:

$P_a = ?$

Solution:

Max. rated output, $P_a = E I_a \times 10^{-3}$ kW

$$= \left(e_z \times \frac{Z}{a}\right) \times I_a \times 10^{-3} \text{ kW} \quad \left(\because E = e_z \times \frac{Z}{a}\right)$$

$$= e_z \times (I_z Z) \times 10^{-3} \text{ kW} \quad \left(\because I_z = \frac{I_a}{a}\right)$$

$$= e_z \times (ac \times \pi D) \times 10^{-3} \text{ kW} \quad \left(\because ac = \frac{I_z Z}{\pi D}\right)$$

$$= e_z \times ac \times \frac{V_a}{n} \times 10^{-3} \text{ kW} \quad (\because V_a = \pi D n)$$

$$= e_z \times ac \times \frac{V_a}{\left(\frac{N}{60}\right)} \times 10^{-3} \text{ kW} \quad \left(\because n = \frac{N}{60} \text{ r.p.s}\right)$$

$$= 7 \times (450 \times 10^{2}) \times \frac{40}{\left(\frac{375}{60}\right)} \times 10^{-3} \text{ kW}$$

$P_a = 2016$ kW

9)

Determine the main dimensions of a 10 H.P ,400 V, 1500 r.p.m , dc shunt motor, the average gap density is 0.45 tesla and ampere conductors/meter are 20,000 . The max efficiency is 85%. Assume shunt field current to be 0.9 A and the diameter to length ratio is 2.7. The pole arc to pole pitch is 0.7

15

Given data:

$P = 10$ H.P, $V = 400V$, $N = 1000$ r.p.m, motor, $B_{av} = 0.\ell$

$ac = 20{,}000$ Ac/m, $\eta_{max} = 0.85$, $I_f = 0.9A$, $\frac{D}{L} = 2.7$

$\psi = 0.7$

Reqd. data:

$D = ?$ $L = ?$

Solution:

Output power, $P = 10$ H.P

$= 0.746 \times 10$

$P = 7.46$ kW

> 1 H.P = 735.5 watts
> = 746.6 watts
> both is correct

Input power, $P_{in} = \frac{P}{\eta} = \frac{7.46}{0.85}$

$P_{in} = 8.78$ kW

Full load losses $= P_{in} - P \Rightarrow 8.78 - 7.46$

$= 1.32$ kW

Constant loss $= \frac{\text{Full load losses}}{2}$ ($\because \eta_{max}$ is given)

$= \frac{1.32}{2}$

$= 0.66$ kW

Resistance of field wdg., $R_f = \frac{V}{I_f} = \frac{400}{0.9}$

$$R_f = 444.44\ \Omega$$

Shunt field cu. loss $= I_f^2 R_f$

$$= (0.9)^2 \times 444.44$$

$$= 360 \text{ watts}$$

$$= 0.36 \text{ kW}.$$

∴ Friction, windage & iron losses (164)

$$= \text{Const. loss} - I_f^2 R_f$$

$$= 0.66 - 0.36$$

$$= 0.3 \text{ kW}$$

∴ Power developed by armature, $P_a = P +$ Friction, windage & iron losses

$$= 7.46 + 0.3$$

$$= 7.76 \text{ kW}$$

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

$= \pi^2 \times 0.45 \times 20,000 \times 10^{-3}$

$C_o = 88.83$

Speed, $n = \frac{N}{60} = \frac{1000}{60}$

$n = 16.67$ r.p.s

$\therefore$ Volume of the machine, $D^2L = \frac{P_a}{C_o n}$

$= \frac{7.76}{88.83 \times 16.67}$

$D^2L = 5.24 \times 10^{-3}\ m^3 \longrightarrow (1)$

Given $\frac{D}{L} = 2.7$

$\therefore L = \frac{D}{2.7} \Rightarrow 0.37D \longrightarrow (2)$

Sub. 'L' in (1)

$0.37\ D^3 = 5.24 \times 10^{-3}\ m^3$

$D = \sqrt[3]{\frac{5.24 \times 10^{-3}}{0.37}}$

$D = 0.2419\ m$

$L = 0.37 \times 0.2419$

$L = 0.0895\ m$

2.6. *Armature Design*

Mean emf induced per conductor $e_z = B_{av} L V_a$ (volt)

Peripheral speed $V_a = \pi D n$ m/sec.

2.6.1. *Number of armature conductors*

On full load, in case of generator, the emf induced in the armature winding exceeds the terminal voltage by an amount equal to the sum of the voltage drops in the armature winding, the interpole winding, the series winding and the contact drop at the brushes.

Thus, the generated emf in the armature.

$$E = V + I_a R_m \text{ for Generator} \quad \text{... (2.25)}$$

$$E = V - I_a R_m \text{ for Motor} \quad \text{... (2.26)}$$

Where V = Terminal voltage

$I_a R_m$ = Sum of Voltage drop in armature winding, interpole winding, series winding and Brush drop.

* For 500V machines, $I_aR_m \simeq 2$ to 2½% of Terminal voltage
* For 250V machines, $I_aR_m \simeq 5$ to 10% of Terminal voltage

Thus number of conductors in series

$$Z_c = \frac{E}{Mean\,emf\;\;per\,conductor} = \frac{E}{e_z}$$

* For a simplex lap winding (with single turn coil), Z_c represents total number of armature conductors per pole

(Since Number of Parallel Paths = Number of Poles)

* For a simplex wave winding (with single turn coil), Z_c represents half the total number of conductors on the armature irrespective of number of poles (Since Number of parallel paths = 2)

2.6.2. Choice of armature winding

Simplex windings are normally used in comparison with multiplex windings because equalizer rings are used for multiplex windings which may make the machine costlier.

Simplex Lap Winding		Simplex Wave Winding	
1.	Number of parallel paths = Number of poles	1.	Number of parallel Paths=2
2.	Current in each path = 1 / p of full load current	2.	Current in each path = half the full load current
3.	Each parallel path will develop an emf = E	3.	Each of the 2 paths will develop an emf = E
4.	Total number of armature conductors are large. Current per path is less. Therefore conductor cross sectional area is also reduced.	4.	Total number of armature conductors are less. Current per path is high. Therefore large cross Sectional area is required.
5.	Equalizer connections are necessary which makes the machine costlier.	5.	No equalizer connections and less cost for machine.
6.	Normally used for large machines	6.	Normally used for small machines

Factors to be considered for choice of armature winding

(i) Simplex lap winding is used for machines with current rating greater than 400A.

(ii) Simplex wave winding is used for machines with current rating less than 400 A

Normally, single turn coils are used. If multi turn coils are to be used, maximum voltage between adjacent commutator segments should not exceed 28 to 30 volts.

Total number of conductors $Z = P * Z_c$ for simplex Lap Winding

$= 2 * Z_c$ for simplex wave winding

Number of coils $= \frac{Z}{2}$ for single turn coils

$= \frac{Z}{2T_c}$ for multi turn coils

Where T_c = Number of turns in one coil.

2.6.3. Choice of number of commutator segments

Number of commutator segments = Number of armature coils

Number of armature coils should always be checked as the number of commutator segments cannot exceed a certain limit.

Thickness of commutator segment at outer surface = 3 to 4 mm

Mica insulation between each segment $\simeq$ 0.8mm

Pitch of commutator segment $\simeq$ 4 to 5 mm

Commutator diameter $D_c \simeq (0.62 \text{ to } 0.75) D$ depending upon the voltage and rpm.

$$\text{Commutator pitch} = \frac{\pi D_c}{C}$$ should not be less than 4mm.

Where C = Number of commutator segments or armature coils.

2.6.4. *Number of armature slots*

The following factors are to be considered while selecting the number of armature slots.

(1)Flux Pulsations

Flux pulsations mean changes, in the air gap flux because of changes in the air gap reluctance between the pole faces and the irregularly shaped armature core surface under running condition. This flux pulsations give rise to eddy current losses in the pole-shoes and produce magnetic noise. The flux pulsations are reduced with increased number of armature slots.

(a) To avoid flux pulsations, the air gap reluctance per pair of poles should be practically constant which is possible if the number of slots per pair of poles is an odd integer i.e., the slots per pole is an integer plus ½.

(b) To prevent the flux oscillations, the air gap reluctance under pole faces must be kept constant for all reactive positions of pole shoes and armature core. These conditions are approximated by

(i) Properly chamfering the tips of pole faces.

(ii) Making the number of slots per pole shoes an integer plus ½

In actual design, the number of slots per pole arc should be an integer with slots per pole equal to an integer plus 1/2.

(2)Cooling

For large of number slots, lesser number of conductors per slot. Therefore cooling is obviously better.

(3) Tooth Width

For large number of slots, the slot pitch reduces and also the tooth width. Two problem occurs by reduced tooth width.

(i) Flux density at the minimum section of tooth increases causing increased iron losses

(ii) It is difficult to support the teeth at the ventilating duct| without obstructing the ventilation

(4) Commutation |

From commutation point of view, large number of slots smaller number of conductors per slot are better.

(5) Cost

A smaller number of slots are desirable considering the as the charges for punching the slots increase with their num'

Further with smaller number of slots, there are fewer slots to insulate and therefore the cost of insulation also goes down.

Guiding factors for choice of number of armature slots

(1) Slot Pitch

The value of slot pitch lies between 20 to 40mm. The usual limit is between 25 to 35mm except in case of very small machines, where it may be 20min and even less.

(2) Slot Loading

The slot loading i.e. number of ampere conductors per slot should not exceed about 15,000 A.

(3) Flux Pulsations

The number of slots per pole pair should be an odd integer in order to minimize pulsation losses.

(4) Commutation

The number of slots per pole usually lies between 9 to 16 to prevent sparking.

(5) Suitability for Winding

When selecting number of slots, we must confirm that the number selected suits the armature windings. The number of slots per pole should match the value given in Table 2.5

Table 2.5. Number of Armature slots

Rating (KW)	Slots per pole
Upto 5 KW	8
5 Kw to 50 KW	10
Above 50 KW	above 12

Number of Armature Coils

The number of turns per coil and the number of coils are so chosen that the voltage between commutator segments is limited to a value where there is no possibility of flashover. For very small machines, this limit may rise to 60V owing to their high internal resistance. Normally, the maximum voltage between adjacent segments at load should not exceed 30V.

Average voltage between adjacent segments at no load

Dimensions of armature conductor

Armature current $I_a = \frac{P_a}{E} * 1000$

Also I_a = $I_L + I_{sh}$ in case of generator

= $I_L - I_{sh}$ in case of motor

Where I_L = Line Current in amperes.

I_{sh} = Shunt field current in amperes.

$$\text{Now conductor Current } I_z = \frac{I_a}{a}$$

$$\therefore \text{Conductor cross section area } A_z = \frac{I_z}{\delta_z} \text{ mm}^2$$

Where δ_z =Current density in armature conductors, A/mm^2

CHOICE OF CURRENT DENSITY

(a) δ_z = 4.5 A/mm^2, for large strap – wound armature with very good normal ventilation

(b) δ_z = 5 A/mm^2, for small wire– wound armature with very good normal ventilation

(c) δ_z = 6 to 7 A/mm^2, for fairly high speed fan ventilated machine

Design of shunt field winding

Design Procedure

(1) Assume a suitable depth d_f, for the winding from Table 2.7

(2) Calculate the length of mean turn. The length of mean turn is
$L_{mt} = 2\,(L_p + b_p) + 2\,d_f$ ... *(2.45)*

(3) In order to allow for voltage regulation, in generators assume that 15 to 20 percent of rated voltage is absorbed by the field rheostat.

$\therefore$ Voltage across the shunt field winding = (0.8 to 0.85) V and voltage across each shunt field coil is

$$E_f = \frac{(0.8 \text{ to } 0.85)V}{p} \qquad \text{... (2.46)}$$

as there are as many shunt field coils as the number of poles and they are all connected in series.

(4) Resistance of each field coil $R_f = \dfrac{T_f \rho L_{mt}}{a_f} = \dfrac{E_f}{I_f}$

or area of shunt field conductor $a_f = \dfrac{I_f T_f \rho L_{mt}}{E_f} = \dfrac{AT_{fl} \rho L_{mt}}{E_f}$ ...*(2.47)*

(5) Choose a suitable cross – section for the conductor. For small cross-section, standard round wire should be used. For larger cross-section, square or rectangular conductor should be used.

(6) Calculate the winding height

The space for winding along radial height is,

h_f = h_{pl} – height of pole shoe – insulation and clearance

= h_{pl} – (0.1 to 0.2) h_{pl} – (0.1 to 0.15) τ ...(2.48)

(7) Number of turns provided $T_f = \frac{S_f h_f}{a_f} d_f$ ...(2.49)

Where S_f = space factor for the winding

= $0.8\,(d/d_1)^2$ for round insulated conductor