# Review Last Class

# Transformer

- Classification
- Equivalent Circuit of a Transformer
- Why Transformer Rating is kVA?
- Regulation of Transformer
- Some Applications of Transformer
- Losses in a Transformer
- Transformer Test
- Efficiency of Transformer
- Cooling of Transformer

# Basic of Electrical Machines

- Electromechanical Energy Conversion Principles
- Some Basic Mathematical Relation of Electrical Machines
- Classification of Electrical Machines
- Basic Elements and Parts Electrical Machine
- AC Generation and DC Generation

# DC Machines

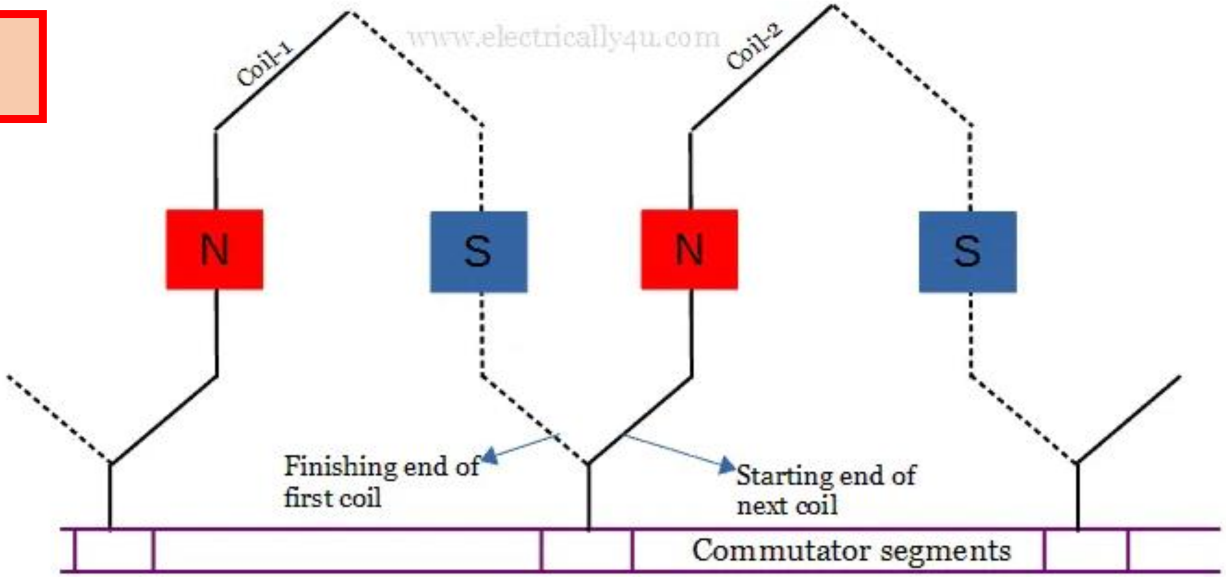
- Construction of DC Machines
- Classification of DC Machines

# Armature Winding of DC Machine

Armature windings can be divided into two groups, depending on how the wires are joined to the commutator. These are called:

(*a*) **Wave windings** and

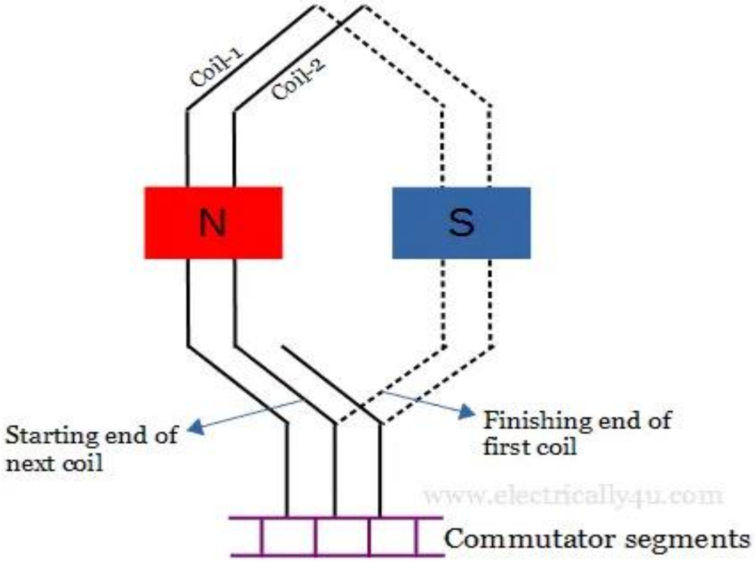
(*b*) **Lap windings**




***Wave winding***

(*a*) In **wave windings** there are **two paths in parallel**, irrespective of the number of poles, each path supplying half the total current output. Wave wound generators produce high-voltage, low-current outputs.

**Parallel path (*A*) = 2**




***Lap winding***

(*b*) In **lap windings** there are as many paths in parallel as the machine has poles. The total current output divides equally between them. Lap-wound generators produce high-current, low-voltage output.

**Parallel path (*A*) = number of magnetic pole (P)**

# DC Generator
# Chapters 29

B. L. Theraja, A. K. Theraja, “A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines,” S. Chand & Company Ltd.

# Working Principle of a DC Generator

- Let, a coil is rotating clock-wise direction having two sides *AB* and *CD* (**Fig. 26.2**). As the coil cuts the magnetic field, according to Faraday's law of electromagnetic induction an emf is induced in it which is proportional to the rate of change of flux ($e=Nd\phi/dt$).
- When the coil side ***AB*** is at position 1, it produces zero **EMF** because ***the flux linked with the coil is maximum*** but ***rate of change of flux is zero***.
- As it moves in the clockwise direction, the rate of change of flux increases so does the **EMF**.
- When the conductor portion is at position 2, it produces maximum **EMF** because ***the flux linked with the coil is minimum*** but ***rate of change of flux is maximum***.
- At position 3, the **EMF** is zero, at position 4 negative maximum and at position 5 zero again.
- The wave shape of the generated **EMF** which is shape is sinusoidal is given in **Fig. 26.3**.
- The sinusoidal voltage is converted to dc voltage by using commutator segment.

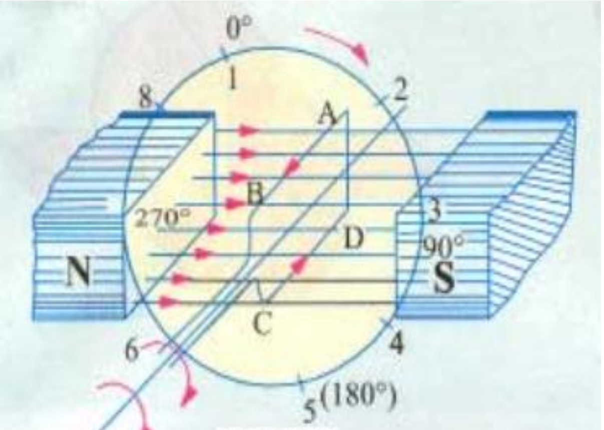


Fig. 26.2

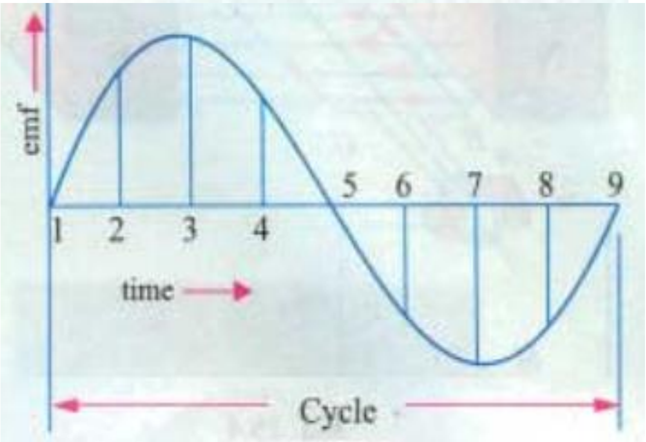
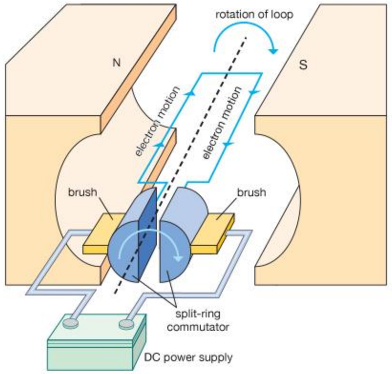
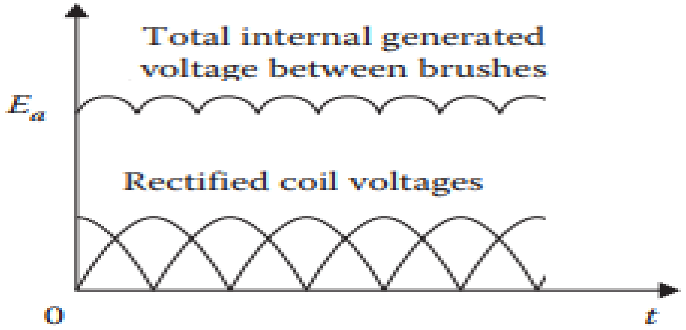


Fig. 26.3



# EMF Equation of DC Generator

The developed emf ($E_g$) per parallel path of a DC generator is given by:

$$E_g = E_a = \frac{\Phi PN}{60}\left(\frac{Z}{A}\right) = \frac{\Phi P\omega_m}{2\pi}\left(\frac{Z}{A}\right) \qquad (26.1)$$

For a given DC machine, $Z$, $P$, $A$ are constant, thus Eq. (26.1) can be written as follows:

$$E_g = K_n \Phi N = K_\omega \Phi \omega_m \qquad (26.2)$$

For an electromagnetic system flux is proportional to field current i.e. $\Phi \propto I_f$. So, Eq. (26.2) can be written as follows:

$$E_g = K_1 I_f N = K_2 I_f \omega_m \qquad (26.2)$$

$K_1$ and $K_2$ are constant

$I_f = I_{sh}$ for shunt wound DC motor

$= I$ for series wound DC motor

$\Phi$ = Flux/pole [Wb]

$Z$ = Total number of armature conductor

= Number of Slots × (Number of conductor/slot)

= 2 × Number of turns

$P$ = Number of generator poles

$N$ = Armature rotation in revolution per minute (rpm)

$\omega_m$ = Armature rotation in rad/s

$A$ = Number of parallel paths in armature

= 2 for wave winding

= $P$ for lap winding

$E_g$ or $E_a$ = EMF induced in any of the parallel paths

$$K_n = \frac{PZ}{60A}$$

$$K_\omega = \frac{PZ}{2\pi A}$$

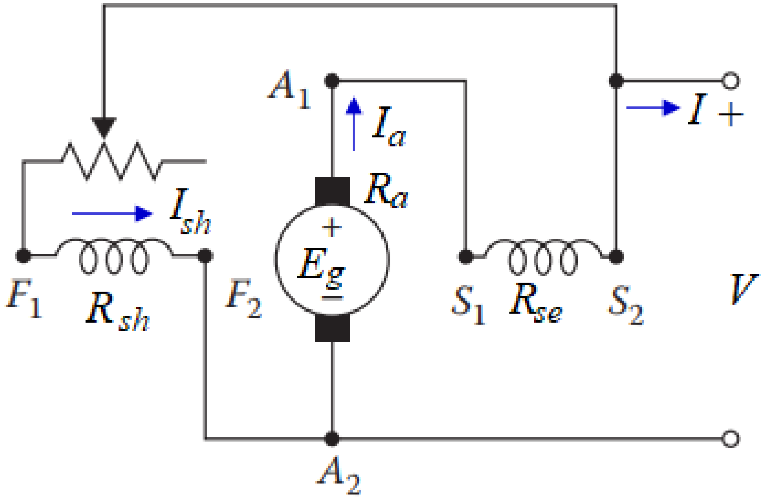
**Example 26.8.** *A four-pole generator, having wave-wound armature winding has 51 slots, each slot containing 20 conductors. What will be the voltage generated in the machine when driven at 1500 rpm assuming the flux per pole to be 7.0 mWb ?*

**Solution.** Here, $\Phi = 7 \times 10^{-3}$ Wb, $Z = 51 \times 20 = 1020$, $A = 2$, $P = 4$, $N = 1500$ r.p.m.

$$E_g = \frac{\Phi Z N}{60}\left(\frac{P}{A}\right) \text{ volts}$$

$$\therefore \quad E_g = \frac{7 \times 10^{-3} \times 1020 \times 1500}{60}\left(\frac{4}{2}\right) = \mathbf{178.5\ V}$$

**EXAMPLE 26.18**: A 4-pole, lap-wound, long-shunt, dc compound generator has useful flux per pole of 0.07 Wb. The armature resistance is 0.055 ohm with 220 turns. Calculate the terminal voltage if the resistance of shunt and series fields are 100 ohm and 0.02 ohms, respectively; when the generator is running at 900 rpm with armature current of 50 A. Also calculate the power output in kW for the generator.




**Solution**: here, $P$ = 4, $A$ = $P$ = 4, $R_a$ = 0.055 ohm, $R_{sh}$ = 100 ohm, $R_{se}$ = 0.02 ohm, $N$ = 900 rpm, and $I_a$ = 50 A, Z = 2×Number of turns = 2 × 220 = 440

The circuit is shown in the following Figure.

$$E_g = \frac{\Phi PN}{60}\left(\frac{Z}{A}\right) = \frac{0.07\times 440\times 900}{60}\left(\frac{4}{4}\right) = 462 \text{ V}$$

$$I_a(R_a + R_{se}) = 50\times(0.055+0.02) = 3.75 \text{ V}$$

$$V = 462 - 3.75 = 458.25 \text{ V}$$

$$I_{sh} = 458.25/100 = 4.58 \text{ A}$$

$$I = 50 - 4.58 = 45.42 \text{ A}$$

$$\text{Output} = VI = 458.25\times 45.42$$

$$= 20{,}814 \text{ W} = 20.814 \text{ kW}$$

# Losses and Efficiency of a DC Generator

Losses of DC Generator:

(***a***) **Copper Losses** ($P_{Cu}$):

(***i***) Armature Cu loss, $P_a = I_a^2 R_a$

(***ii***) Shunt Field Cu loss , $P_{sh} = I_{sh}^2 R_{sh}$

(***iii***) Series Field Cu loss, $P_{se} = I^2 R_{se}$

(***b***) **Stray Losses** ($P_{st}$):

(***I***) **Core or Iron Losses** ($P_i$):

(***i***) Eddy Current loss ($P_e$)

(***ii***) Hyteresis loss ($P_h$)

(***II***) **Mechanical Losses** ($P_{mech}$):

(***i***) Friction loss ($P_f$)

(***ii***) Windage loss ($P_w$)

Total Loss = **Copper Losses** ($P_{Cu}$) + **Stray Losses** ($P_{st}$)

$= (P_a + P_{sh} + P_{se}) + (P_i + P_{mech}) = P_a + \text{Constant Loss } (P_{cons})$

$= \text{Variable Loss } (W_v) + \text{Constant Loss } (W_c)$

where, Variable Loss ($P_v$) $= P_a = I_a^2 R_a = I^2 R_a$ [Neglecting the $I_{sh}$]

Constant Loss ($P_{cons}$) $= P_{sh} + P_{se} + (P_i + P_{mech})$

$= P_{sh} + (P_i + P_{mech})$ [Neglecting the $P_{se}$]

**Output Power,** $P_{out} = VI$

$$\text{Efficiency}(\eta) = \frac{\text{Output}\,(P_{out})}{\text{Input}\,(P_{in})} = \frac{\text{Output}}{\text{Output} + \text{Losses}} = \frac{VI}{VI + (P_v + P_{cons})}$$

**Condition for Maximum Efficiency**:

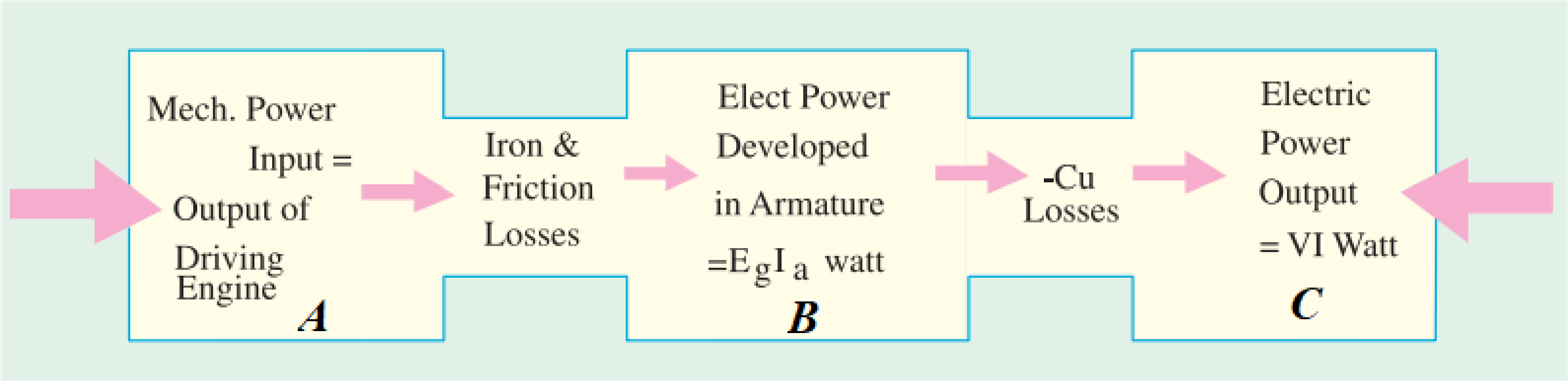
For Shunt and Compound Generator:

Efficiency is maximum when **Variable Loss** = **Constant Loss**

$$I^2 R = P_{cons}$$

# Power Stages of a DC Generator

The various power stages in a DC generator are represented diagrammatically in Figure below.




**Mechanical Efficiency**

$$\eta_m = \frac{B}{A} = \frac{\text{total watts generated in armature}}{\text{mechanical power supplied}} = \frac{E_g I_a}{\text{output of driving engine}}$$

A – B = Iron and Friction Losses

**Electrical Efficiency**

$$\eta_e = \frac{C}{B} = \frac{\text{watts available in load circuit}}{\text{total watts generated}} = \frac{VI}{E_g I_a}$$

B – C = Copper (Cu) Losses

**Overall or Commercial Efficiency**

$$\eta_c = \frac{C}{A} = \frac{\text{watts available in load circuit}}{\text{mechanical power supplied}}$$

# Applications of DC Generator

| | |
|---|---|
| Separately Excited DC Generators | • Primarily used in laboratory and commercial testing<br>• Speed regulation Tests<br>• Supplying power to the DC motors, whose speed being to be controlled |
| Series wound DC Generators | ○ Voltage boosting in the feeders in the various types of distribution systems<br>○ Used to provide high voltage DC power transmission at constant load current<br>○ In supplying field excitation current in DC locomotives for regenerative breaking<br>○ Arc lightening |
| Shunt wound DC Generators | ❑ Battery charging applications<br>❑ Lighting and power supply purposes<br>❑ Excitation to the alternators |
| Compound wound DC Generators | • Over compounded generators are used in supplying loads through long transmission lines.<br>• Cumulative compound generators are used for supplying power to DC motors and for lighting, power supply purposes and for heavy power services, etc.<br>• The differential compound generators are used for arc welding purposes where a large voltage drop and constant current is required. |

**EXAMPLE 26.28**: A long-shunt compound generator gives 240 V at full-load output of 100 A. The resistance of various windings of the machines are: armature (including brush contact) 0.1 Ω, series field 0.02 Ω, interpole field (which is connected in series with armature) 0.025 Ω, shunt field (including regulation resistance) 100 Ω. The iron loss at full-load is 1000 W; windage and friction loss total 500 W. Calculate full-load efficiency of the machine.

**Solution.** Output $= 240 \times 100 = 24{,}000$ W

Total armature circuit resistance $= 0.1 + 0.02 + 0.025 = 0.145\ \Omega$

$I_{sh} = 240/100 = 2.4$ A $\quad \therefore I_a = 100 + 2.4 = 102.4$ A

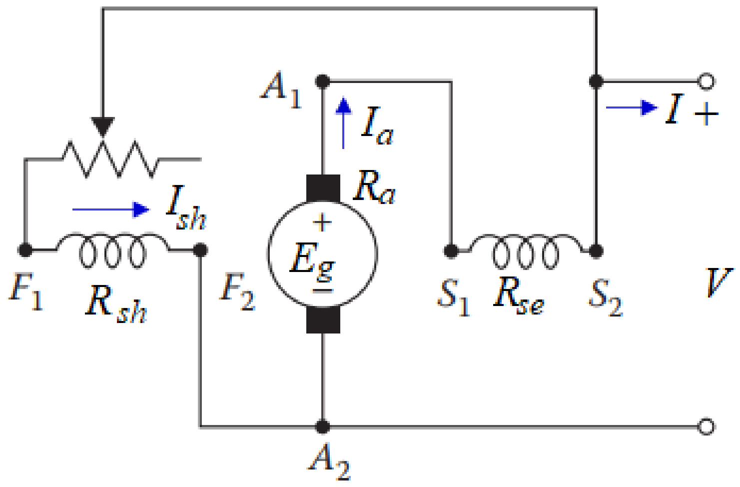
Armature circuit copper loss $= 102.4^2 \times 0.145 = 1{,}521$ W

Shunt field copper loss $= 2.4 \times 240 = 576$ W

Iron loss $= 1000$ W ; $\quad$ Friction loss $= 500$ W

Total loss $= 1{,}521 + 1{,}500 + 576 = 3{,}597$ W

$$\eta = \frac{24,000}{24,000 + 3,597} = 0.87 = 87\%$$



# DC Motor
# Chapters 29

B. L. Theraja, A. K. Theraja, “A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines,” S. Chand & Company Ltd.

# Working Principle of a DC Motor

Consider a part of a DC. motor as shown in **Figure DCM 01**. When the terminals of the motor are connected to DC supply:

(*i*) the field magnets are excited developing alternate *N* and *S* poles.

(*ii*) the armature conductors carry currents. All conductors under *N*-pole carry currents in one direction while all the conductors under *S*-pole carry currents in the opposite direction.

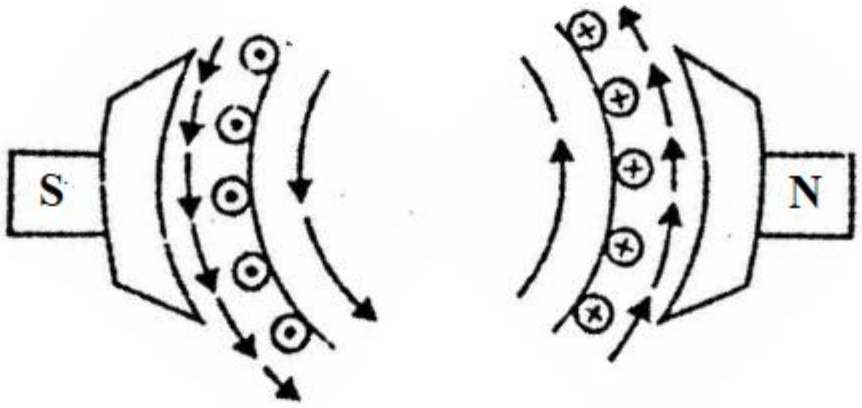



**Figure DCM 01**

Since each armature conductor is carrying current and is placed in the magnetic field, mechanical force (*F*) Developed on it as shown in **Figure DCM 02**.

Referring to Figure DCM 01 and Figure DCM 01 and applying ***Fleming's left hand rule***, it is clear that force on each conductor is tending to rotate the armature in anticlockwise direction.

Force of individual conductor add together to produce a driving torque which sets the armature rotating.

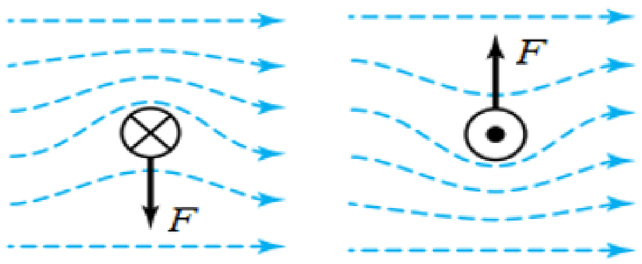



**Figure DCM 02**

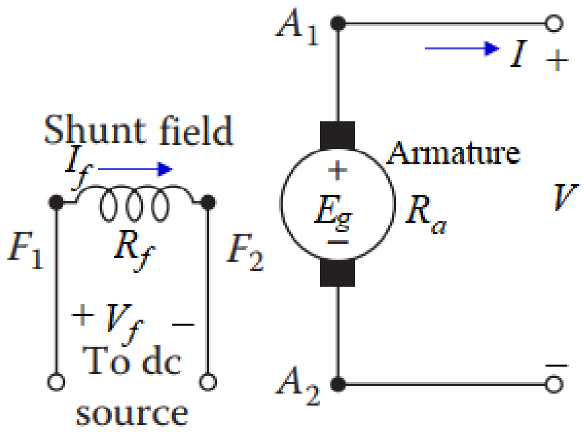
## Back or Counter EMF

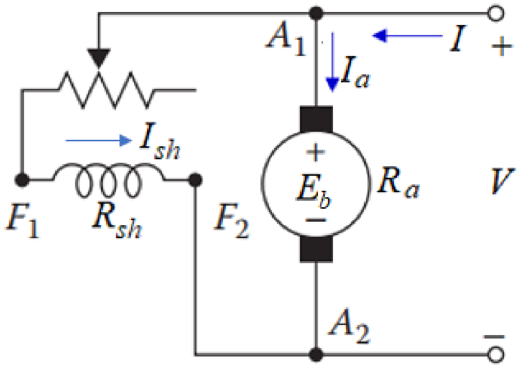
When the armature conductor of a DC. motor rotates through the magnetic field an emf is induced (Faraday's Law). The induced emf acts in opposite direction to the applied voltage (Lenz's law) and in known as back or counter emf which is given by:

$$E_b = K_n \Phi N = K_\omega \Phi \omega_m = V - I_a R_a \qquad (29.1)$$

From Eq. (29.1), we have:

$$I_a = \frac{V - E_b}{R_a} \qquad (29.2)$$




## Electromagnetic Torque Equations

The product $E_b I_a$ known as the electromagnetic power ($P_{em}$) (which is developed in armature) being converted, is related to the electromagnetic torque by the relation:

$$P_{em} = E_g I_a = T_e \omega_m \qquad (29.3)$$

Combining Eq. (29.1) and Eq. (29.3) the electromagnetic torque can be written as follows:

$$T_e = \frac{E_b I_a}{\omega_m} = K_\omega \Phi I_a \qquad (29.4)$$

For an electromagnetic system flux is proportional to field current i.e. $\Phi \propto I_f$. So, Eq. (29.3) can be written as follows:

$$T_e = K_1 I_f I_a \qquad (29.5)$$

$K_1$ = Constant

$I_f$ = $I_{sh}$ for shunt wound DC motor

= $I$ for series wound DC motor

# Significance of Back EMF

Back emf has important role to regulate armature current as is just sufficient to develop the torque required by the load.

(***i***) When the motor is running on no load, the back emf is nearly equal to the applied voltage since very small current $I_a$ required to developed required torque ($T_e$).

(***ii***) As seen in Eq. (29.1) that back emf is directly related to the armature speed. If speed is high, $E_b$ is large, hence armature current $I_a$, seen from the Eq. (29.4), is small.

(***iii***) If the speed is less, then $E_b$ is less, hence more current flows which develops more torque, as seen in Eq. (29.3).

So, it is observed that $E_b$ acts like a ***governor*** *i.e*, it makes a motor ***self-regulating*** so that it draws as much current as is just necessary.

# Applications of DC Motor

| Types of Motor | Characteristics | Applications |
|---|---|---|
| **Shunt wound DC Generators** | Approximately Constant Speed<br>Adjustable Speed<br>Medium starting torque | ○ For driving constant speed line shafting lathes<br>○ Centrifugal and Reciprocating pumps<br>○ Machine tools<br>○ Blowers and fans |
| **Series wound DC Generators** | Variable Speed<br>Adjustable varying Speed<br>High starting torque | ○ For Traction work *i.e*. Electrical locomotives<br>○ Rapid transit systems<br>○ Trolley, cars etc.<br>○ Cranes and hoists<br>○ Conveyors |
| **Compound wound DC Motors** | Variable Speed<br>Adjustable varying Speed<br>High starting torque | ○ For intermittent high torque loads<br>○ For sheares and punches<br>○ Elevators, Conveyors, Heavy planers<br>○ Rolling mils, Ice machines<br>○ Printing process, Air compressor |

**EXAMPLE**: A 200V d.c. shunt-wound motor has an armature resistance of 0.4 and at a certain load has an armature current of 30 A and runs at 1350 rev/min. If the load on the shaft of the motor is increased so that the armature current increases to 45 A, determine the speed of the motor, assuming the flux remains constant.

**Solution**: There are two cases.

In case 1: $I_{a1}$ = 301 A, $N_1$ = 1350 rpm

In case 2: $I_{a2}$ = 45 A, $N_2$ = ?

$$\text{In Case 1: } E_1 = V - I_{a1}R_a = 220 - 30 \times 0.4 = K_2 I_f \omega_m = 188 \text{ V}$$

$$\text{In Case 2: } E_2 = V - I_{a2}R_a = 220 - 40 \times 0.4 = K_2 I_f \omega_m = 182 \text{ V}$$

Since flux is remain constant: $E \propto N$, thus we have $\dfrac{E_2}{E_1} = \dfrac{N_2}{N_1}$

$$\therefore \quad N_2 = \frac{E_2}{E_1} N_1 = \frac{182}{188} \times 1350 = \mathbf{1307\ rpm}$$

**Example 29.2.** *A separately excited D.C. generator has armature circuit resistance of 0.1 ohm and the total brush-drop is 2 V. When running at 1000 r.p.m., it delivers a current of 100 A at 250 V to a load of constant resistance. If the generator speed drop to 700 r.p.m., with field-current unaltered, find the current delivered to load.*

**Solution.** $R_L = 250/100 = 2.5$ ohms.

$$E_{g1} = 250 + (100 \times 0.1) + 2 = 262 \text{ V.}$$

At 700 r.p.m., $E_{g2} = 262 \times 700/1000 = 183.4$ V

If $I_a$ is the new current, $E_{g2} - 2 - (I_a \times 0.1) = 2.5\ I_a$

This gives $I_a = 96.77$ amp.

**Practice Tutorial Problems 29.1: 1, 2, 3**

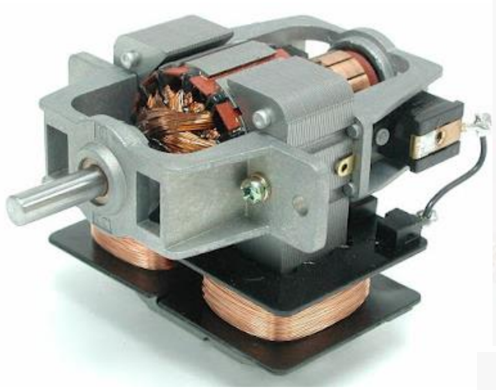
# 36.17 Universal Motor

B. L. Theraja, A. K. Theraja, “A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines,” S. Chand & Company Ltd.

# Universal Motors

**Definition**: A universal motor is defined as a motor which may be operated either on DC or single-phase AC supply at approximately the same speed and output. Universal motor is also called ac series motor.

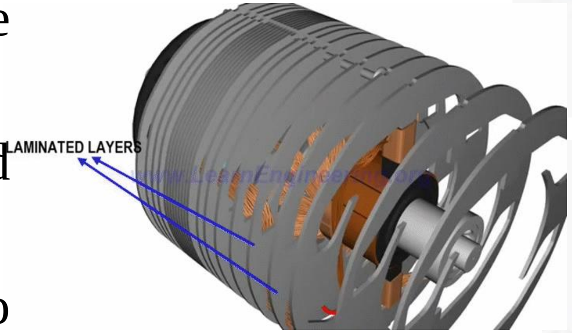
## Construction of Universal Motors



A DC series motor can be operated as a universal motor. But some changes must be made to operate satisfactorily on AC supply. The changes effected are:

(*i*) The entire magnetic circuit is laminated in order to reduce the eddy current loss. Hence, a universal motor requires a more expensive construction than a DC series motor.

(*ii*) The turns of series field winding is reduced as much as possible to reduce the reactance voltage drop of series field winding.




(*iii*) Low-reluctance magnetic circuit is used to obtain high field flux.

(*iv*) High-resistance leads (brushes) are used to connect the coils to the commutator segments to eliminate sparking between the brushes and the commutator.

# Working Principal of Universal Motors

A universal motor works on either DC or single-phase AC supply. When the universal motor is fed with a DC supply, it works as a DC series motor.

When current flows in the field winding, it produces a magnetic field. The same current also flows from the armature conductors. When a current carrying conductor is placed in an electromagnetic field, it experiences a mechanical force.

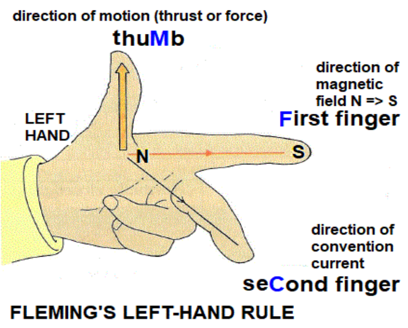
Due to this mechanical force, or torque, the rotor starts to rotate. The direction of this force is given by Fleming's left hand rule.

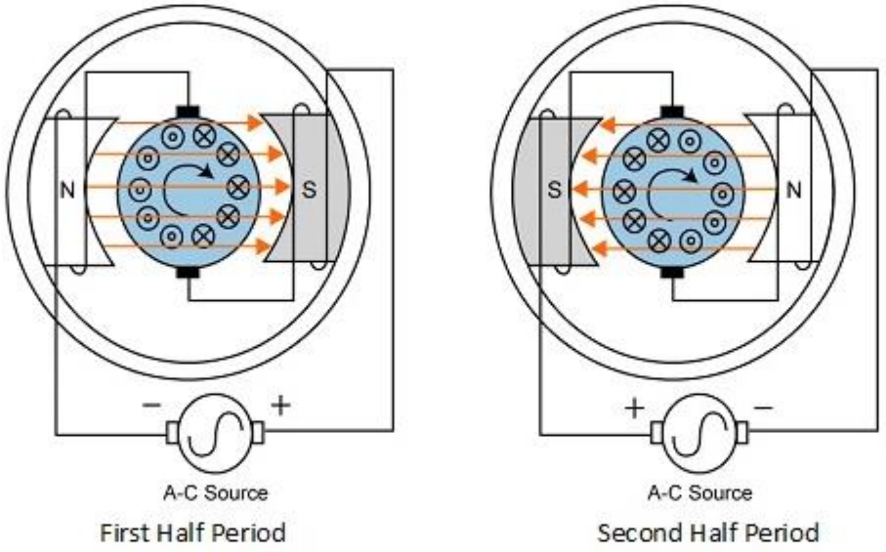
If the supply is DC, the polarity never reverses. So, we get the field and the current in the same direction always and hence a net force in a particular direction on the conductors due to which the rotor rotates.

If the supply is AC, the polarity changes between +ve and –ve. So, the direction of current and the Magnetic Field changes.

Since the field is connected in series with the Armature, both the armature current and field direction changes simultaneously and as a result, the resultant force always remains in the same direction.

Thus, even if the polarity is changed, the motor continues to run in the same direction.




https://www.youtube.com/watch?v=0PDRJKz-mqE

# Characteristics of Universal Motors

- The speed of a universal motor varies just like that of a DC. series motor *i.e.* low at full-load and high on no-load (about 20,000 r.p.m. in some cases).
- In fact, on no-load the speed is limited only by its own friction and windage load.
- Fig. 36.48 shows typical torque characteristics of a universal motor both for DC. and AC supply.

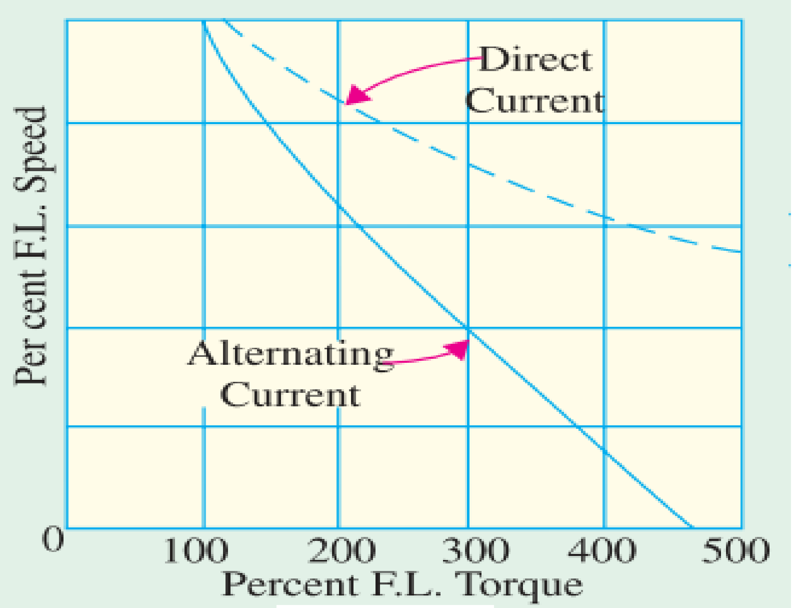
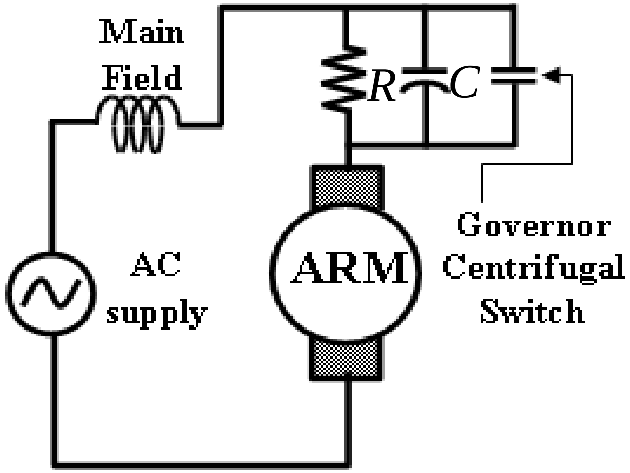


**Fig. 36.48**

# Purpose of Governor Universal Motors

A governor (which is control the speed) may be used to maintain reasonable speeds since it is dangerous to operate at high no load speed. This governor consists of a ***centrifugal switch*** mounted on the shaft of the motor. The tension of the ***springs*** of the switch is adjusted so that the switch contacts open at a ***predetermined speed*** and thus place a ***resistor in series with the armature***, thereby reducing the speed. When the speed falls because of loading, the switch contacts close, thereby shorting out the series resistor, thus again raising the speed. The connections are shown in **Fig. 22.3**. The ***capacitor*** is placed across the governor contacts ***to reduce sparking***.



## Advantages of Universal Motors

- High speed from above 3600 rpm to 25000 rpm
- High power output in small physical sizes fro use in portable tools.
- High torque at low and intermediate speeds top carry a particularly severe load.
- Variable speed by adjustable governor by line voltage or especially by modern pulse technique.

## Disadvantages of Universal Motors

- Increased service requirement due to use of brushes and commutators. The life of these parts is limited in severe service.
- Relatively high noise level at high speeds.
- Moderate to severe radio and television interference due to brush sparking.
- Requirement for careful balancing to avoid vibration.
- Requirement for reduction gearing in most portable tools.

## Applications of Universal Motors

The universal motors have high-speed (and corresponding small size) and large starting torque. They can, therefore, be used to drive:

(***a***) High-speed vacuum cleaners

(***b***) Sewing machines

(***c***) Electric shavers, hair driers

(***d***) Drills

(***e***) Drink and food mixer, blender

(***f***) Machine tools etc.

**Example 36.4.** *A 250-W, single-phase, 50-Hz, 220-V universal motor runs at 2000 rpm and takes 1.0 A when supplied from a 220-V dc. supply. If the motor is connected to 220-V ac supply and takes 1.0 A (r.m.s), calculate the speed, torque and power factor. Assume $R_a = 20\,\Omega$ and $L_a = 0.4$ H.*

**Solution. DC Operation :** $E_{b.dc} = V - I_a R_a$

$$= 220 - 20 \times 1 = 200 \text{ V}$$

**AC Operation** $X_a = 2\pi \times 50 \times 0.4 = 125.7\,\Omega.$

As seen from Fig.36.53.

$$V^2 = (E_{b.ac} + I_a R_a)^2 + (I_a \times X_a)^2$$

$$\therefore \quad E_{b.ac} = -I_a R_a + \sqrt{V^2 - (I_a X_a)^2}$$

$$= -1 \times 20 + \sqrt{220^2 - (125.7 \times 1)^2} = 160.5 \text{ V}$$

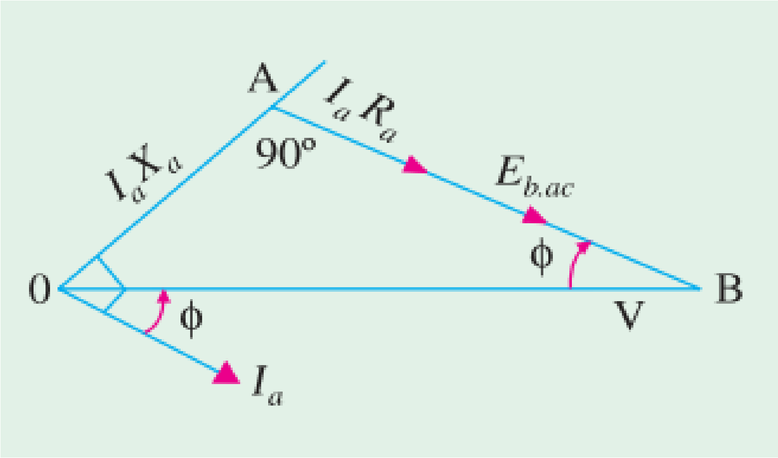



**Fig. 36.53**

Since armature current is the same for both dc and ac excitations, hence

$$\frac{E_{b.dc}}{E_{b.ac}} = \frac{N_{dc}}{N_{ac}}; \qquad \therefore \quad N_{ac} = 2000 \times \frac{160.5}{200} = 1605 \text{ rpm}$$

$$\cos\phi = AB/OB = (E_{b.ac} + I_a R_a)/V = (160.5 + 20)/220 = 0.82 \text{ lag}$$

# Induction Motor
# Chapter 34

B. L. Theraja, A. K. Theraja, "A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines," S. Chand & Company Ltd.

# Construction of Induction Motor

An induction motor consists of two main parts:

(*a*) Stator (*b*) Rotor

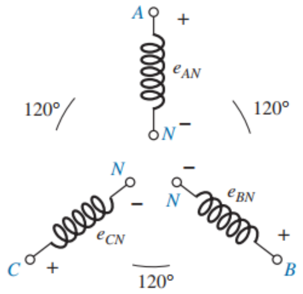
## Stator

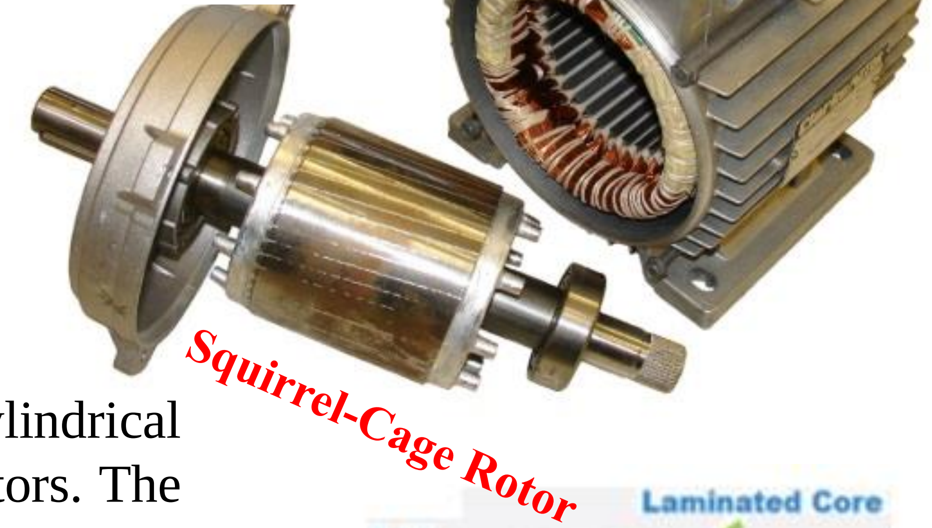
The stator carries a three-phase winding and is fed from a three-phase supply. It is wound for a definite number of poles, the exact number of poles being determined by the requirements of speed. Greater the number of poles, lesser the speed and ***vice versa***.

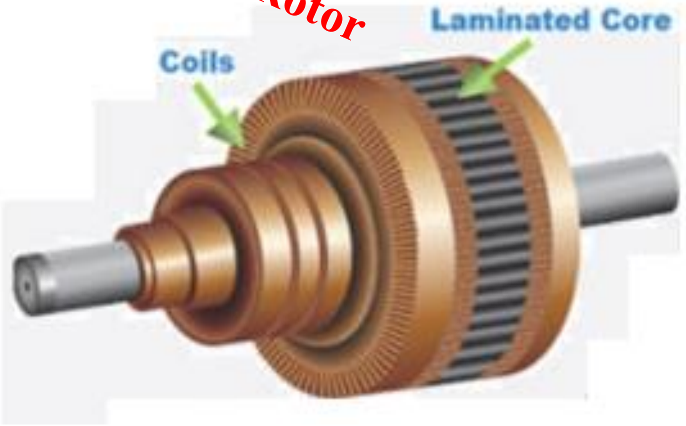
**Rotor:** The rotor of an induction is two type:

**Squirrel-Cage Rotor**: The squirrel-cage rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor conductors. The rotor conductors are heavy bars of copper, aluminium or alloys. The rotor bars are permanently short-circuited by the two end-rings.

**Phase-wound or Wound Rotor**: This type of rotor is provided with three-phase double layer windings consisting of coils. One layer of winding permanently shorted, another layer winding connected with 3-slip rings to control externally from rotor side. The rotor is wound for as many poles as the number of stator poles.



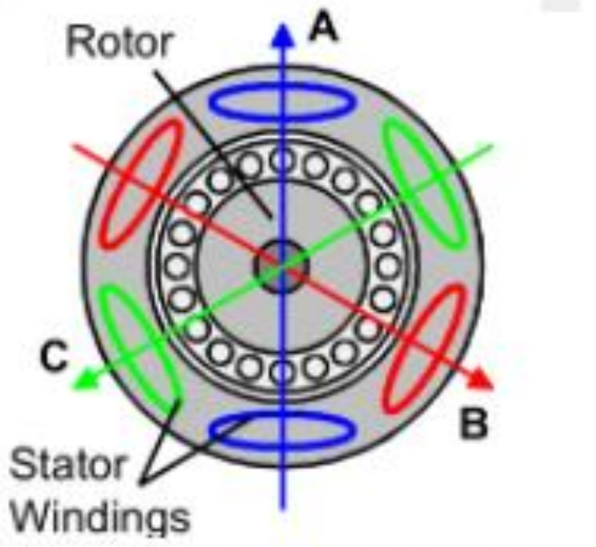

Phase-Wound or Wound Rotor

# Working Principal of an Induction Motor

- When 3-phase stator winding is energized from a 3-phase supply, a rotating magnetic field is set up which rotates round the stator at synchronous speed [$N_s = 120f/P$].
- The rotating field cuts the rotor conductors. Due to the relative speed between the rotating flux and the stationary rotor, emfs are induced in the rotor conductors. Since the rotor circuit is short-circuited, currents start flowing in the rotor conductors.
- Since the current-carrying rotor conductors are placed in the magnetic field produced a mechanical force acts on the rotor conductors. The sum of the mechanical forces on all the rotor conductors produces a torque which tends to rotating the rotor in the same direction as that of stator field and tries to catch it.

Induction motor starts to run immediately supply the power. That's why three phase induction motor is a ***self-starting motor***.

The working principle of an induction motor is almost similar to a transformer except that the secondary side is rotating that's why an induction motor is also called ***rotating transformer***.




Motor Cross Section View