INTRODUCTION TO ELECTRICAL CIRCUITS
SEC: D

FINALTERM
WEEK: 11

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Contents To be Covered :		
Electromagnetism and fundamental laws: Magnet; Magnetic materials, poles, field, flux; Faraday's law, Len's law, Fleming's left hand and right hand rules. **DC Generator:** Definition, Basic working principle and construction of DC generator; classification, emf equation, power stages, losses, efficiency and applications of DC generators; **DC Motor**: Definition, Basic working principle and construction of DC motor; classification, voltage equation , power stages, losses, efficiency; back emf and its significance; condition for maximum power; applications	26.8, 26.28, 29.1, 29.2	No Quiz

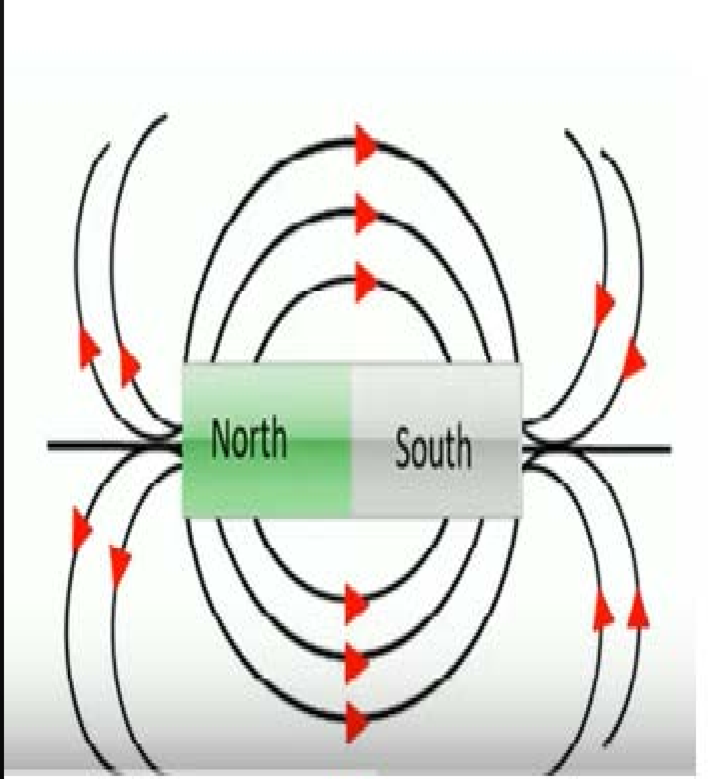
Electromagnetism and Fundamental Laws

Magnet:

A magnet is a material or object that produces a magnetic field. This magnetic field is invisible but is responsible for the most notable property of a magnet: a force that pulls on other ferromagnetic materials, such as iron, and attracts or repels other magnets. A permanent magnet is an object made from a material that is magnetized and creates its own persistent magnetic field. An everyday example is a refrigerator magnet used to hold notes on a refrigerator door.

Classification of Magnetic Materials:

Because all materials have a different atomic structure different materials react differently when placed in a magnetic field. In its simplest form, the magnetic behaviour of a material is determined by its number of unpaired electrons in each atom. In the atoms of most elements electrons exist in pairs with each electron spinning in a different direction causing them to cancel out each other's magnetic field, therefore no net magnetic field exists. However, some materials have unpaired electrons which will generate a net magnetic field and therefore have a greater reaction to an external magnetic field. Most materials are classified either as ferromagnetic, diamagnetic or paramagnetic.



Magnetic Field

Magnetic Field:

The area around the magnetic field where the poles experience the force of attraction and repulsion is known as magnetic field

Most magnets have magnetic fields and electromagnets create such fields from electric current moving through coils .The alternative name of magnetic field is magnetic flux density that is represented by

Magnetic Flux density, $B = \frac{\varphi}{A}$.

The unit of magnetic flux density is Wb/m^2 or T (Tesla).

Magnetic Flux:

Magnetic flux is a measurement of the total magnetic field which passes through a given area. Magnetic flux is commonly denoted by φ . The SI unit of magnetic flux is Wb (Weber).

Magnetic Flux, $\varphi = AB$

Faraday's Laws of Electromagnetic Induction

In 1831, Michael Faraday, an English physicist gave one of the most basic laws of electromagnetism called Faraday's law of electromagnetic induction. This law explains the working principle of most of the electrical motors, generators, electrical transformers and inductors.

Faraday's First Law

Any change in the magnetic field of a coil of wire will cause an emf to be induced in the coil. This emf induced is called induced emf and if the conductor circuit is closed, a current will also circulate through the circuit and this current is called induced current.

Faraday's Second Law

It states that the magnitude of emf induced in the coil is equal to the rate of change of flux that linkages with the coil. The flux linkage of the coil is the product of number of turns in the coil and flux associated with the coil. It can be represented mathematically by the following equation-

$$\varepsilon = N\frac{d\Phi}{dt} \qquad (1)$$

Where,

ε = Induced emf

$d\Phi$ = Change in magnetic flux

N = Number of turns in coil

Lenz's Law

Lenz's law states that when an emf is generated by a change in magnetic flux according to Faraday's Law, the polarity of the induced emf is such, that it produces a current that's magnetic field opposes change which produces it.

The negative sign used in Lenz's law, indicates that the induced emf (ε) and the change in magnetic flux (dΦ) have opposite signs. Its mathematical notation is given below.

$$\varepsilon = -N\frac{d\Phi}{dt} \qquad (2)$$

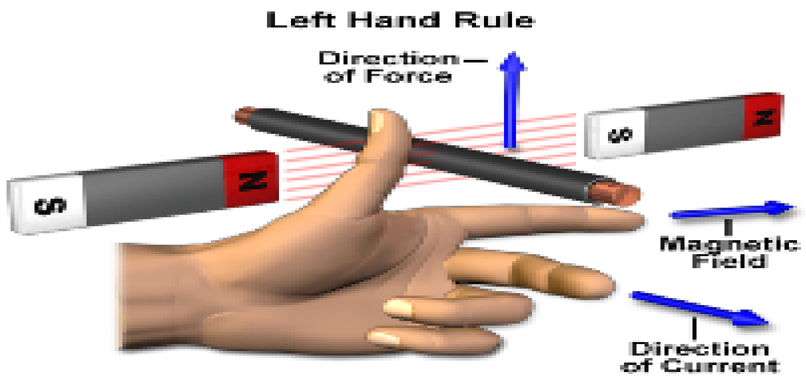
You'll find two of the most useful tools for understanding electromagnetism right at the end of your arms.

Right hand rule.

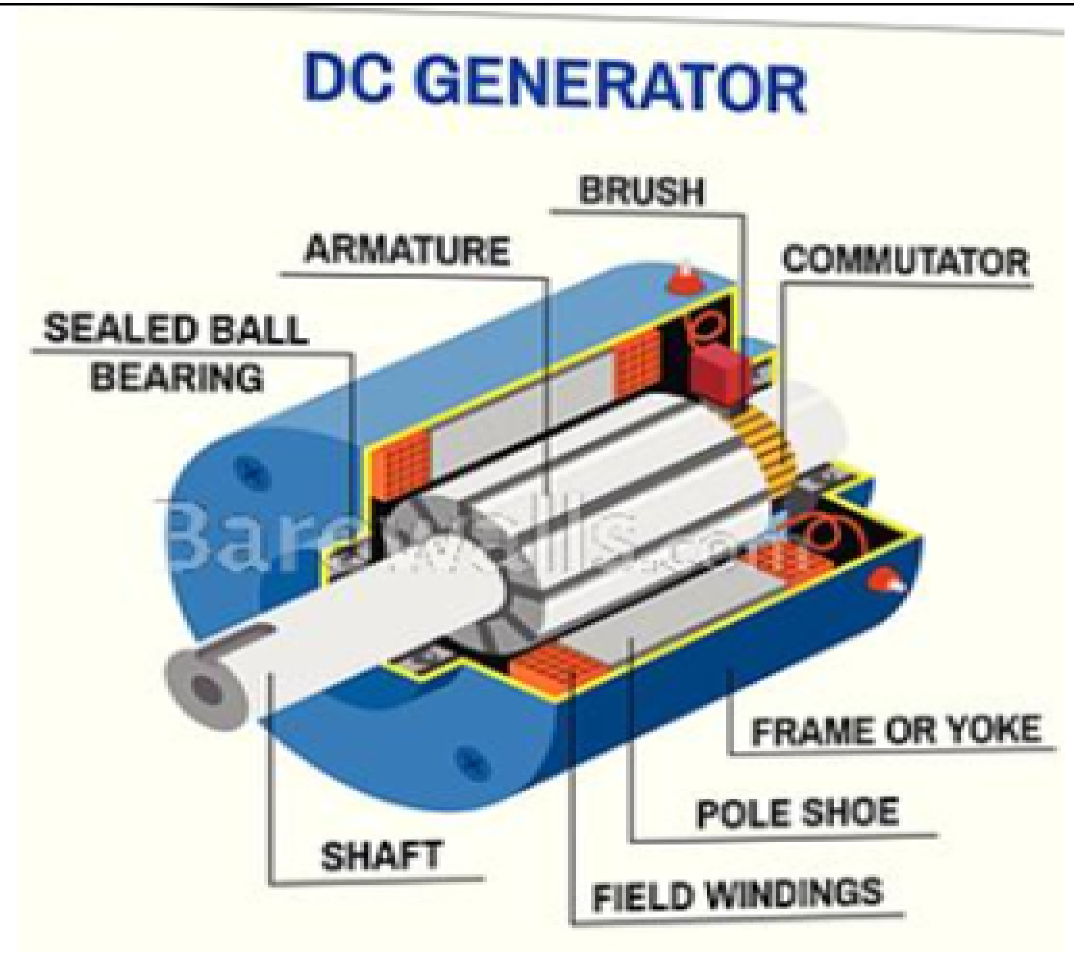
These convenient appendages help us understand the inter-action between electricity and magnetism via the Right Hand Rule and the Left Hand Rule.

The **Right Hand Rule**, illustrated at left, simply shows how a current-carrying wire generates a magnetic field. If you point your thumb in the direction of the current, as shown, and let your fingers assume a curved position, the magnetic field circling around those wires flows in the direction in which your four fingers point.

The **Left Hand Rule** shows what happens when charged particles (such as electrons in a current) enter a magnetic field. You need to contort your hand in an unnatural position for this rule, illustrated below. As you can see, if your index finger points in the direction of a magnetic field, and your middle finger, at a 90 degree angle to your index, points in the direction of the charged particle (as in an electrical current), then your extended thumb (forming an L with your index) points in the direction of the force exerted upon that particle. This rule is also called Fleming's Left Hand Rule, after English electronics pioneer John Ambrose Fleming, who came up with it.



DC Generator

An electrical generator is a machine which converts mechanical energy (or power) into electrical energy(or power). Whenever a conductor cuts magnetic flux dynamically induced e.m.f is produced in it according to Faraday's law of electromagnetic induction. This e.m.f. causes a current to flow if the conductor circuit is closed.	

Basic Working Principle of a Single Loop DC Generator :

When a conductor is rotated in a magnetic field emf is generated in that conductor according to the Faraday's law of electromagnetic induction. The direction of the current flow can be determined by using the Fleming's Right Hand Rule.

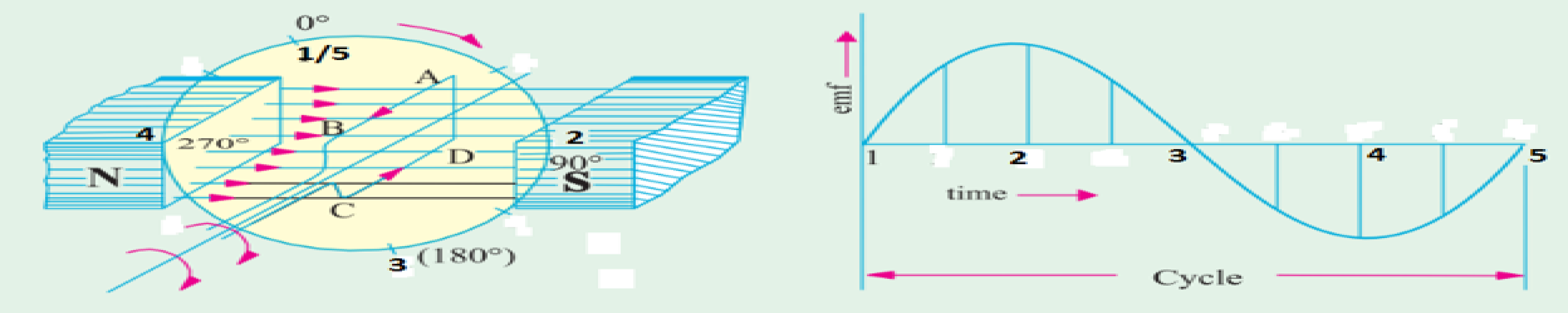


Figure 1: Construction and Basic Working Principle of a DC Generator

The above figure shows the working principle of a generator. When the conductor portion AB is at position1, it produces zero emf because the rate of change in flux is zero though the flux linkage is maximum. As it moves in the clockwise direction, the rate of change in flux increases so does the emf. When the conductor portion is at position2, it produces maximum emf because at that position the flux linkage is minimum but the rate of change in flux is maximum.

At position3, the emf is zero, at position4 negative maximum and at position5 zero again. The wave shape of the generated emf is given alongside the construction of the simple loop generator.

Classification of Generator :

Generators are usually classified according to the way in which their field magnet are excited. They may be divided into 2 broad categories as **Separately-excited** and **Self-excited** generators.

1. Separately-excited generators are those whose field magnets are energised from an independent external source of dc current as shown in the figure.

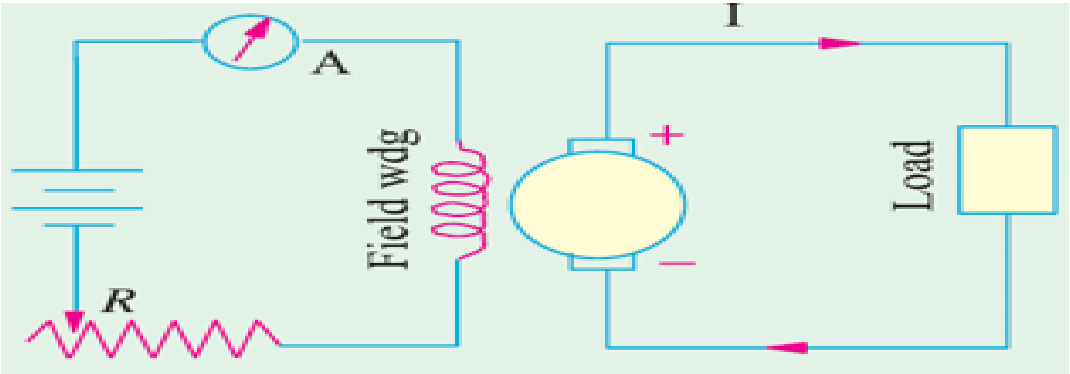


Figure 2: Separately-excited Generator

2. Self-excited generators

Self-excited generators are those whose field magnets are energised by the current produced by the generator themselves. They can be further classified into a) shunt, b) series and c) compound

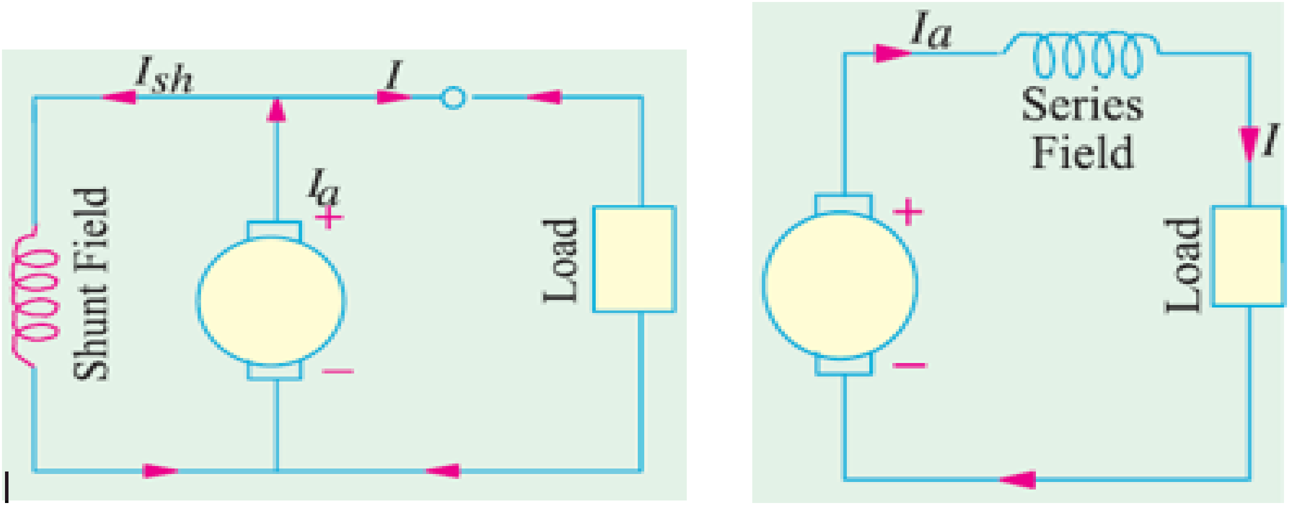


Figure 3: (a) Shunt Self-excited Generator, (b) Series Self-excited Generator

Compound wound generator is a combination of a few series and a few shunt windings and can be either short shunt or long shunt as shown in the **figure 4**.

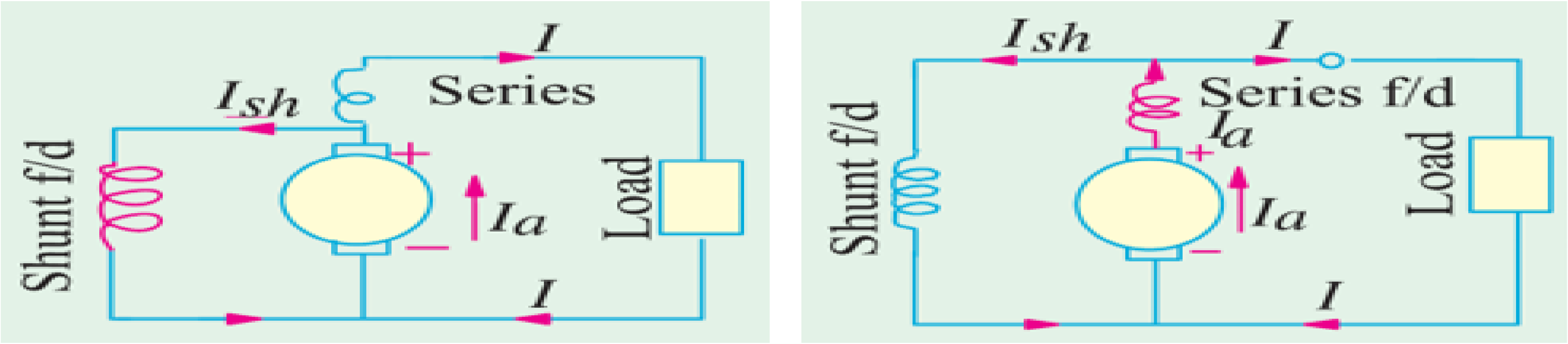


Figure 4: (a) Short shunt Self-excited, (b) Long Shunt Self-excited compound Generator

EMF Equation of DC Generator

Let, Φ= flux/pole in weber (Wb)

Z= total number of armature conductors

= Number of slots × Number of conductors/slot

P= number of Generator poles

A= number of Parallel paths in armature

N= armature rotation in revolution per minute (rpm)

Eg= emf induced in any parallel path in armature

$$E_g = \frac{P\Phi N}{60} \times \frac{Z}{A} = \frac{P\Phi Z N}{60 A}$$

Power Stages :

The various power stages in a d.c. generator are represented diagrammatically in Figure 5.

A - B = Iron and friction losses
B - C = Copper losses

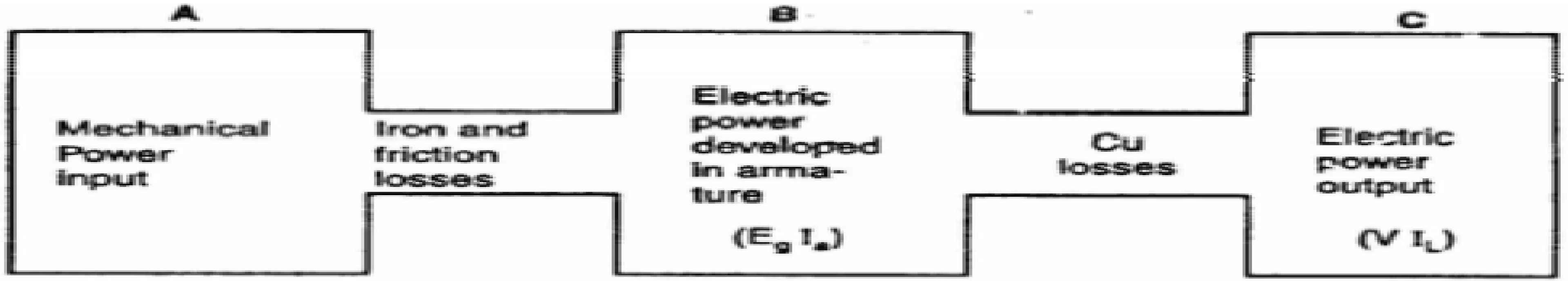


Figure 5: Demonstration of various power stages of a DC generator

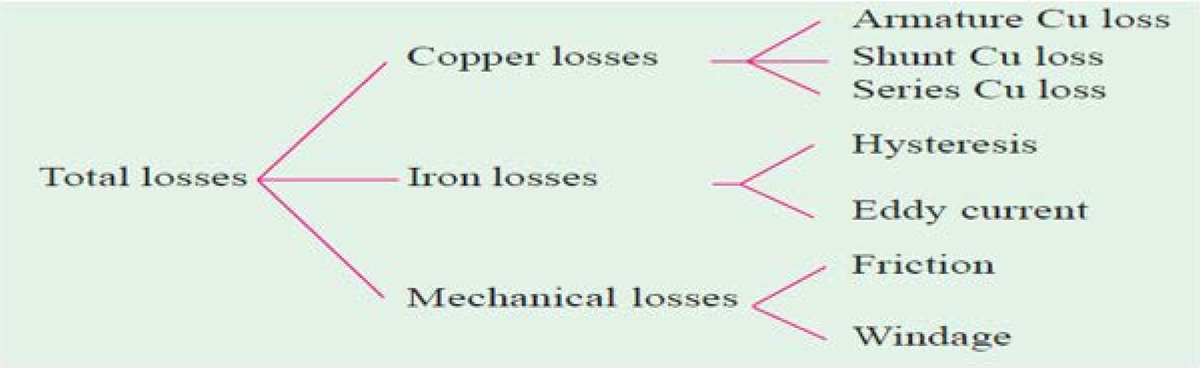
(i) Mechanical efficiency, $\eta_m = \dfrac{B}{A} = \dfrac{E_g I_a}{\text{Mechanical Power Input}}$

(ii) Electrical efficiency, $\eta_e = \dfrac{C}{B} = \dfrac{VI_L}{E_g I_a}$

(iii) Commercial or overall efficiency, $\eta_c = \dfrac{C}{A} = \dfrac{VI_L}{\text{Mechanical Power Input}}$

Clearly, $\eta_C = \eta_m \times \eta$

Total losses in a generator :



Condition for Maximum Efficiency:

The efficiency of a d.c. generator is not constant but varies with load. Consider a shunt generator delivering a load current I_L at a terminal voltage V.

Generator output = VI_L

Generator input = Output + Losses

$= VI_L$ + Variable losses + Constant losses

$= VI_L + I_a^2 R_a + CL$; where CL= Constant Loss

$= VI_L + (I_L + I_{sh})^2 R_a + CL$; $\qquad \because I_a = I_L + I_{sh}$

The shunt field current I_{sh} is generally small as compared to I_L and, therefore, can be neglected.

Generator input $= VI_L + I_L{}^2 R_a + CL$

$$\text{Now, efficiency, } \eta = \frac{output}{input} = \frac{VI_L}{VI_L + I_L{}^2 R_a + CL} = \frac{1}{1 + \left(\frac{I_L R_a}{V} + \frac{CL}{VI_L}\right)} \qquad (1)$$

The efficiency will be maximum when the denominator of Equation (1) is minimum.

$$\frac{d}{dI_L}\left(\frac{I_L R_a}{V} + \frac{CL}{VI_L}\right) = 0$$

$$\text{Thus, } \Rightarrow \frac{R_a}{V} - \frac{CL}{VI_L^2} = 0$$

$$\Rightarrow \frac{R_a}{V} = \frac{CL}{VI_L^2}$$

$$\Rightarrow I_L^2 R_a = CL \qquad (2)$$

Thus, Variable Loss = Constant Loss $\qquad \because I_L \approx I_a$

The load current corresponding to maximum efficiency can be obtained by rearranging equation (2) as

$$I_L = \sqrt{\frac{CL}{R_a}} \qquad (3)$$

Applications of DC Generator:

Separately Excited DC Generators	Shunt wound Generators	Series Wound Generators
Separately excited DC Generators are used in laboratories for testing as they have a wide range of voltage output. Used as a supply source of DC motors.	DC shunt wound generators are used for lighting purposes. Used to charge the battery. Providing excitation to the alternators.	Used as a booster in distribution networks. Over compounded cumulative generators are used in lighting and heavy power supply. Flat compounded generators are used in offices, hotels, homes, schools, etc.

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 ?* **(Elect. Machines-I, Allahabad Univ. 1993)**

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

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

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

Example 26.28. *A long-shunt compound-wound generator gives 240 volts at F.L. output of 100 A. The resistances of various windings of the machine are : armature (including brush contact) 0.1 Ω, series field 0.02 Ω, interpole field 0.025 Ω, shunt field (including regulating resistance) 100 Ω. The iron loss at F.L. is 1000 W ; windage and friction losses total 500 W. Calculate F.L. efficiency of the machine.* **(Electrical Machinery-I, Indore Univ. 1989)**

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

$\therefore$ 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 ; Friction loss $= 500$ W

Total loss $= 1{,}521 + 1{,}500 + 576 = 3{,}597$ W ; $\eta = \dfrac{24{,}000}{24{,}000 + 3{,}597} = 0.87 = \mathbf{87\%}$

DC Motor

Motor:

An electrical motor is a machine which converts electrical energy into mechanical energy.

Working Principle of a DC Motor:

An electrical motor is a machine which converts electrical energy into mechanical energy. Its action is based on the principle that when a current carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's Left-hand Rule.

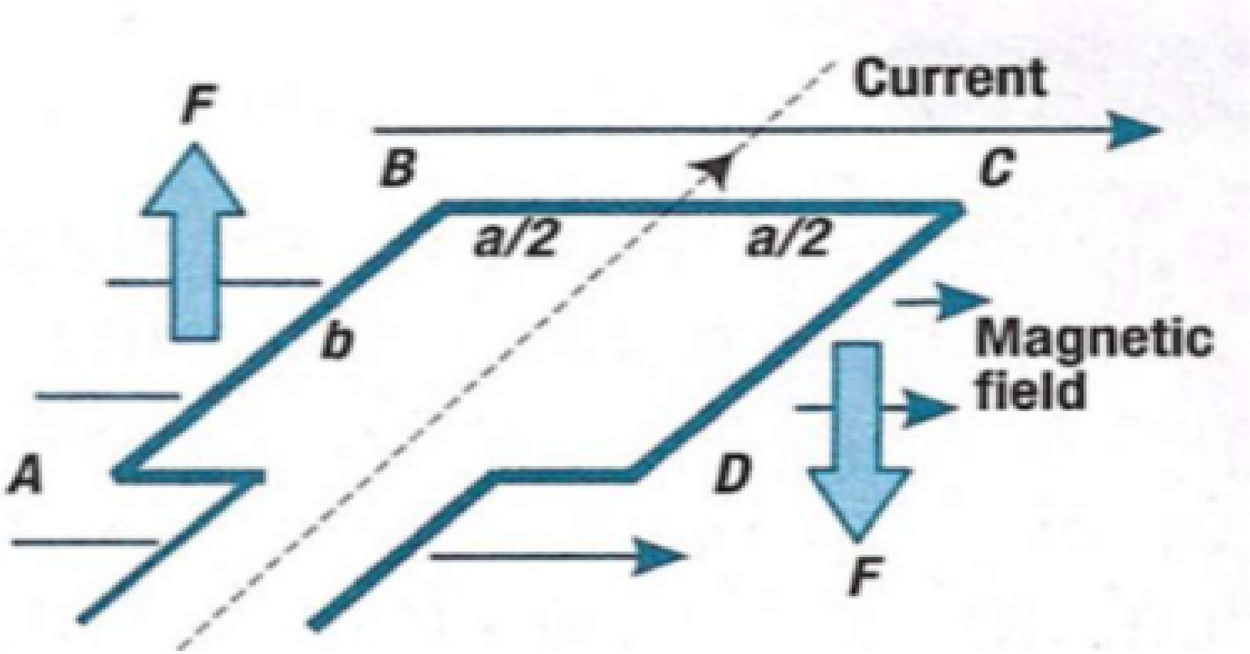
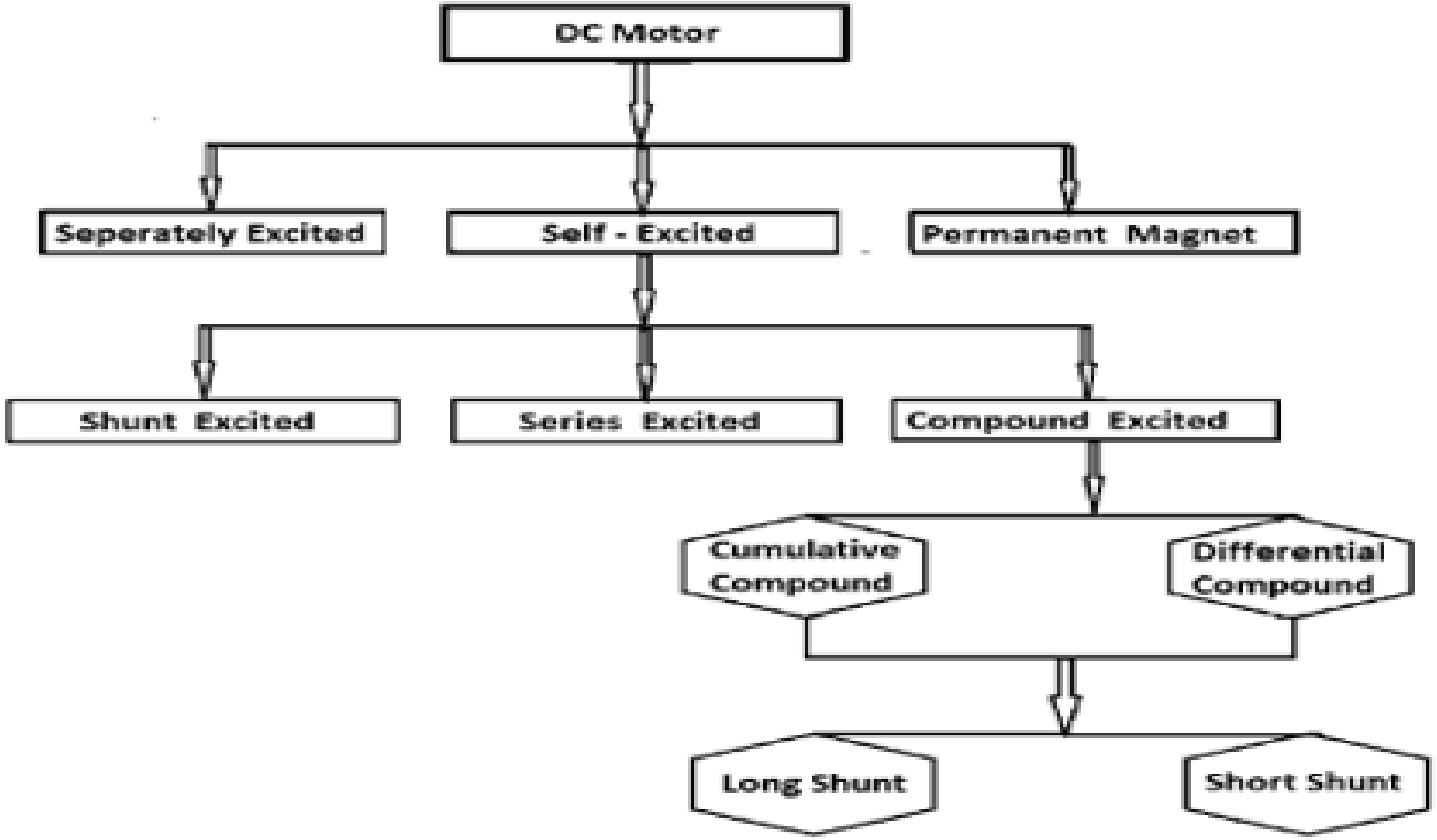


Figure 1: Demonstration of DC Motor Working Principle

When the field magnets are excited and its armature conductors are supplied with the current, they experience a force tending to rotate the armature. Each conductor experiences a force which tends to rotate the armature in one direction only. These forces collectively produces a driving torque which sets the armature rotating.

Classification of DC Motor



Back emf:

When the motor armature rotates, the conductors also rotate and hence cut the flux. In accordance with the laws of electromagnetic induction, emf is induced in them whose direction, as found by Fleming's Right-hand Rule, is in opposition to the applied voltage. Because of its opposing direction, it is referred to as counter emf or back emf (V_b).

Significance of back emf:

The armature current will be established by the resultant voltage (algebraic sum of applied voltage and back emf) and armature resistance as follows

$$I_a = \frac{Net\,Voltage}{Armature\,\text{Resistance}} = \frac{V - V_b}{R_a}$$

Back emf depends on a number of factors. It is directly related to the armature speed. If speed is high, V_b is large, hence armature current I_a, seen from the above equation, is small. If the speed is less, then V_b is less, hence more current flows which develops more torque. So, it is observed that V_b acts like a governor i.e, it makes a motor self-regulating so that it draws as much current as is just necessary.

Voltage Equation of D.C. Motor:

$$V = E_b + I_a R_a$$

Power Equation of D.C. Motor:

The power equation can be derived by multiplying the voltage equation by I_a.

$$VI_a = E_b I_a + I_a^2 R_a$$

$$VI_a = P_m + I_a^2 R_a$$

Where,

VI_a =electric power supplied to armature (armature input)

$E_b I_a$ =power developed by armature (armature output) or mechanical power, P_m

$I_a^2 R_a$ =electric power wasted in armature (armature Cu loss)

Condition for Maximum Power:

The power equation of a DC motor is, $VI_a = P_m + I_a^2 R_a$. Rearranging this equation,

$$P_m = VI_a - I_a^2 R_a$$

Since, input voltage (V) and armature resistance R_a both are constant; the power of the motor depends only upon the armature current I_a.

Thus, $\dfrac{dP_m}{dI_a} = 0$

$$\frac{d}{dI_a}\left(VI_a - I_a^2R_a\right) = 0$$

$$V - 2I_aR_a = 0$$

$$I_aR_a = \frac{V}{2}$$

Now, rearranging the voltage equation,

$$E_b = V - I_aR_a$$

$$E_b = V - \frac{V}{2}$$

$$E_b = \frac{V}{2}$$

Hence mechanical power developed by the motor is maximum when back e.m.f. is equal to half the applied voltage.

Example 29.1. *A 220-V d.c. machine has an armature resistance of 0.5 Ω. If the full-load armature current is 20 A, find the induced e.m.f. when the machine acts as (i) generator (ii) motor.*
(Electrical Technology-I, Bombay Univ. 1987)

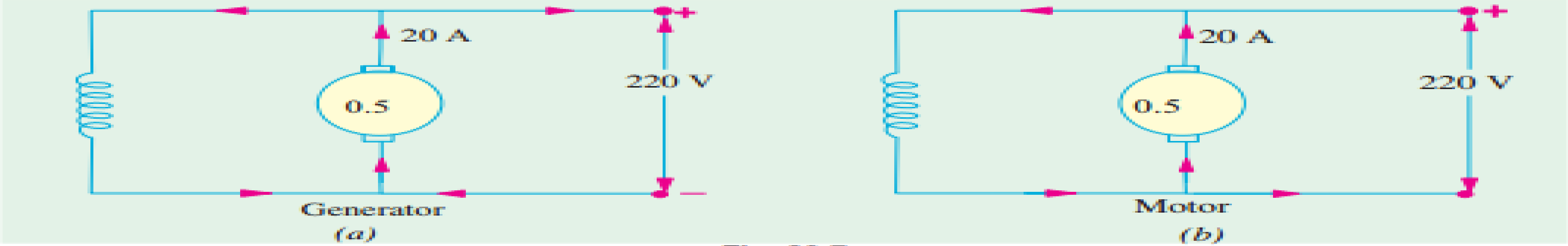


Fig. 29.7

Solution. As shown in Fig. 29.7, the d.c. machine is assumed to be shunt-connected. In each case, shunt current is considered negligible because its value is not given.

(a) As Generator [Fig. 29.7(*a*)] $E_g = V + I_a R_a = 220 + 0.5 \times 20 = \mathbf{230\ V}$

(b) As Motor [Fig 29.7 (*b*)] $E_b = V - I_a R_a = 220 - 0.5 \times 20 = \mathbf{210\ V}$

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.* **(AMIE, Electrical Machines, 2001)**

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

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

Extension to the Question : *With what load resistance will the current be 100 amp, at 700 r.p.m.?*

Solution. $E_{g2} - 2 - (I_a \times 0.1) = R_L \times I_a$

For $I_a = 100$ amp, and $E_{g2} = 183.4$ V, $R_L = 1.714$ ohms.

Applications of DC Motors

Type of motor	*Characteristics*	*Applications*
Shunt	Approximately constant speed Adjustable speed Medium starting torque	For driving constant speed line shafting Lathes Centrifugal pumps Machine tools Blowers and fans Reciprocating pumps
Series	Variable speed Adjustable variying speed High Starting torque	For traction work *i.e.* Electric locomotives Rapid transit systems Trolley, cars etc. Cranes and hoists Conveyors
Comulative Compound	Variable speed Adjustable varying speed High starting torque	For intermittent high torque loads For shears and punches Elevators Conveyors Heavy planers Heavy planers Rolling mills; Ice machines; Printing presses; Air compressors