Chapter 3

DC Machines

LEARNING OBJECTIVES

After reading this chapter, you will be able to understand:

- Armature windings
- Types of generators
- E.M.F. equation of a DC generator
- Performance equations of DC generators
- Losses in a DC generator
- Armature reaction
- Demagnetizing ampere-turns per pole
- Compensating windings
- Commutation
- Equalizing connections
- Characteristics of DC generator
- Parallel operation of DC generators
- DC motors
- Motor characteristics

Fundamentals of DC Machines

Energy can neither be created nor be destroyed. We can change its forms, using appropriate energy -conversion processes. Change of the form of energy requires an energy conversion device.

- DC generator and DC motor are electromechanical energy conversion devices,
- A DC generator converts mechanical energy into electrical energy. It requires a prime mover such as a turbine diesel engine, etc.
- In a DC generator, the energy conversion is based on the principle of the production of dynamically induced e.m.f. This process can be explained by Faraday's laws of electromagnetic induction.
- The two basic essential parts of an electrical generator are
    1. A magnetic field, and
    2. A conductor or conductors which can so move as to cut the flux.
- Whenever there is relative motion between the conductor and the magnetic field, an emf is induced in the conductors which causes a current to flow if the conductor circuit is closed.
- In a DC generator, relative motion is produced by rotation of the armature. The armature winding is on the rotor and field winding is on the stator.
- In normal DC machines stator core is not laminated, armature core is laminated to reduce eddy current losses.

Constructional Details

The major parts of a DC machine are

1. Field system
2. Armature
3. Commutator
4. Brush and brush gear.

Constructionally there is no difference between a DC generator and DC motor.

1. The Field System

The purpose of the field system is to provide a uniform magnetic field within which armature rotates. The magnetic field is generated by electromagnets rather than permanent magnets on account of their greater magnetic strength and field strength regulation (i.e., field flux can be varied according to the requirement). The field system consists of four parts:

1. **Yoke:** This provides mechanical support for the poles and acts as a protecting cover for the whole machine and it carries the magnetic flux produced by the pole.

2. **Pole core:** The pole-core offers low reluctance path for magnetic flux. The pole core is of smaller cross-section than the pole shoe.
3. **Pole shoe:** The pole shoes serve two purposes.
   (a) They spread out the flux in the air-gap and also, being of larger cross-section, reduce the reluctance of the magnetic path.
   (b) They support the exciting coils (or field coils)
4. **Magnetizing coils (or) field winding:** These coils electromagnetize the poles which produce the necessary flux. The field coils which consist of copper wire or strip, are former wound for the correct dimension. Then, the former is removed and wound coil is put into place over the pole core.

2. Armature Core

It houses the armature conductors or coils and causes them to rotate and hence cut the magnetic flux of field magnets.

In addition to this, its most important function is to provide a path of very low reluctance to the flux through the armature from a N-pole to a S-pole. Armature core is made of high permeability material such as silicon steel. The use of high grade steel is made to keep hysteresis loss low. The core is laminated to reduce eddy current losses. These laminations are coated with insulating varnish.

3. Commutator

The function of commutator is to facilitate collection of current from the armature conductors. Inherently the voltage induced in the armature winding is alternating. Commutator acts as a mechanical rectifier to convert induced alternating voltages into DC voltage at brush terminals.

[In a DC Motor commutator acts as a mechanical inverter to convert DC applied voltage to AC Voltage in the armature winding].

- Commutator is of cylindrical structure and is built up of wedge-shaped hard-drawn copper segments. These segments are insulated from each other by thin layers of mica.

4. Brushes and Brush Gear

The function of brushes is to collect current from the commutator and supply it to the external-load circuit. Brushes are usually made of carbon or graphite. These brushes are housed in brush-holders. The brushes are made to bear down on the commutator by a spring to avoid any air-gap which may give rise to sparking.

Armature Windings

Two types of windings are mostly used for DC machine. They are lap winding and wave winding. For a given number of poles and armature conductors, the wave winding gives more emf than lap winding. Conversely for the same emf lap winding would require more no. of conductors which will result in higher winding cost. Wave windings are suitable for low capacity generators with a voltage rating of 500–600 V. Lap windings are used for large capacity generators because lap winding have more parallel paths.

- Another advantage with the wave winding is that it requires no equalizing connections, where in a lap-wound machine they are necessary.
- Lap winding is suitable for comparatively low voltage but high current machines whereas wave winding is used for comparatively high voltage, low-current machines.

Types of Generators

DC generators are broadly classified as

1. Separately excited generators: Field is energized from an independent external source of DC current.
2. Self-excited generators – field current is provided by the generators themselves. Due to residual magnetism, there is always present some flux in the poles. When the armature is rotated some emf and hence some induced current is produced which is partly or fully passed through the field coils there by strengthening the residual pole flux.

- For the process of self-excitation to sustain,

1. There must be residual flux in the field poles.
2. The field winding flux must aid residual flux.

There are 3 types of self-excited generators named according to the manner in which their field coils are connected to the armature.

1. **Shunt wound:** Field winding is connected directly across the armature terminals.
2. **Series wound:** Field winding is connected in series with the armature winding.
3. **Compound wound:** It is a combination of a few series and few shunt windings.

There are two types of connections in a compound machine. They are (1) Short shunt (2) Long shunt.

In a compound generator, the shunt field is stronger, than the series field. When series field aids the shunt field, generator is said to be cumulatively compounded. On the other hand if series field opposes shunt field the generator is said to be differentially compounded.

- By reversing the connections of the series field winding, cumulative connection can be converted to differential connection and vice versa.

EMF Equation of a DC Generator

Let ϕ = Flux / pole in Wb

Z = Total number of armature conductors

P = No. of generator poles

A = No. of armature parallel paths

N = Armature speed in rpm

E = emf induced in any parallel path in armature,

$$\text{The induced E.M.F.E.} = \frac{\phi ZN}{60} \times \frac{P}{A}$$

- The number of parallel paths A, depends upon the type of the armature winding, i.e., whether wave or lap-wound,

For wave-wound armature $A = 2\ m$, where m is multiplicity of the winding.

$m = 1$ for simplex, $m = 2$ for duplex, $m = 3$ for triplex and so on for a lap-wound armature.

$A = Pm$, where m is the multiplicity of the winding

For a given DC machine Z, P and A are constants.

Hence putting $K_a = \dfrac{ZP}{A}$

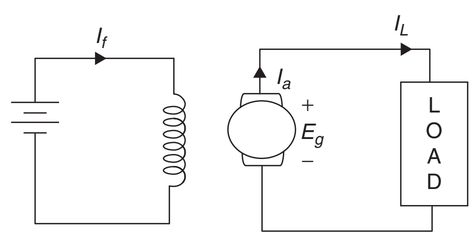
We get $E_g = K_a \phi N$

The induced emf can be increased by

1. Increasing the flux / pole ϕ by increasing the field current (up to saturation point).
2. Increasing the speed of the prime mover.

Performance Equations of DC Generators

Separately Excited

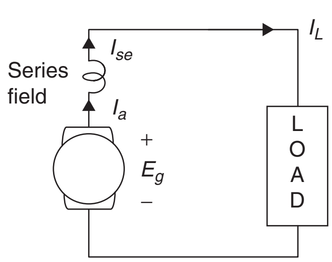


$$I_a = I_L = I$$
$$V = E_g - I_a r_a$$

Power developed = $E_g I_a$

Power delivered to load = $V. I_L$

Series Wound

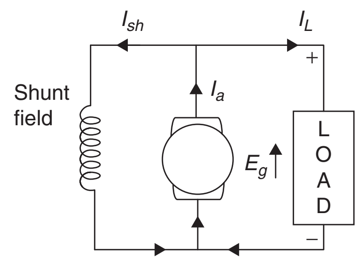


$$I_a = I_{se} = I_L = I$$
$$V = E_g - I(r_a + r_{se})$$

Power developed = $E_g I_a$

Power delivered = VI

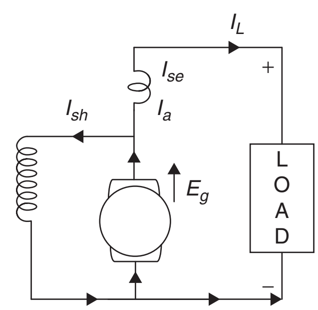
Shunt Wound



$$I_{sh} = \frac{V}{R_{sh}}$$
$$I_a = I_L + I_{sh}$$
$$V = E_g - I_a r_a$$

Power developed = $E_g I_a$

Short Shunt Compound

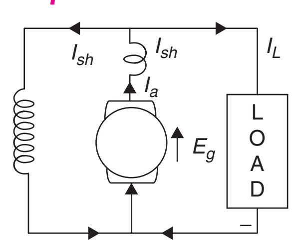


$$I_{se} = I_L$$
$$I_{sh} = \frac{V + I_{se}\ r_{se}}{R_{sh}} \quad \text{suffixes}$$
$$I_a = I_L + I_{sh}$$
$$V = E_g - I_a r_a - I_{se} r_{se}$$

Power developed = $E_g \cdot I_a$

Power delivered = VI_L

Long Shunt Compound



$$I_{sh} = \frac{V}{R_{sh}}$$
$$I_a = I_L + I_{sh}$$
$$V = E_g - I_a r_a - I_{se} r_{se}$$

Power developed = $E_g I_a$

Power delivered = VI_L

Solved Examples

Example 1: A 4-pole lap-connected DC generator with 480 conductors has an armature resistance 0.06 Ω. If the conductors are reconnected to form a wave winding, other things remaining unchanged what is the value of armature resistance?

Solution: $\dfrac{Z_{lap}}{Z_{wave}} = \dfrac{4}{P^2}$ or

$$Z_{wave} = \frac{P^2}{4} \times Z_{Lap}$$

$$= \frac{P^2}{4} \times 0.06 = 0.24\ \Omega$$

Example 2: Calculate commutator pitch for two-circuit simplex-wave winding having 4-poles and 129 commutator segments.

Solution: Commutator pitch for simplex wave winding is given by

$$Y_C = \frac{C \pm 1}{P/2} = \frac{129 \pm 1}{4/2} = \frac{128 \text{ or } 130}{2}$$

The commutator pitch may be 64 or 65.

Example 3: A 4-pole generator with 24 conductors has a two layer lap winding. The pole pitch is ____.

(A) 24 (B) 12 (C) 6 (D) 4

Solution: (C)

Pole pitch $= Y_p = \dfrac{Z}{P}$

$Z = 24$; $P = 4$

$$Y_p = \frac{Z}{p} = \frac{24}{4} = 6$$

Example 4: An 8-pole, lap-wound armature running at 350 rpm is required to generate 260 V. The useful flux/pole is 0.05 Wb. If the armature has 120 slots, the no. of conductors/slot is ________

(A) 6 (B) 8 (C) 10 (D) 4

Solution: (B)

$$E_g = \frac{\phi ZNP}{60A} \Rightarrow 260 = \frac{0.05 \times Z \times 350 \times 8}{60 \times 8}$$

$$\Rightarrow Z = 890$$

$\therefore$ No of conductors/slot $= \dfrac{890}{120} = 7.14$

Conductors/slot should be an integer
Hence, conductors/slot = 8

Example 5: A 4-pole lap-wound generator is run at 900 rpm. The reactance voltage if self inductance is 153×10^{-6} H, armature current is 108 A, no of segments = 55, width of brush = 1.74 segments is __________

(A) 3.195 V (B) 3.915 V
(C) 5.391 V (D) 5.915 V

Solution: (B)

$$I_c = \frac{I_a}{A} = \frac{108}{4} = 27\text{ A}$$

Time taken by one commutator segment to cross brush axis

$$= \frac{60}{900 \times 55}$$

Time taken for 1.74 segments $= \dfrac{60 \times 1.74}{900 \times 55} = 2.11 \times 10^{-3}$ sec

$\therefore$ Reactance voltage $= E = L \cdot \dfrac{2I_c}{t_c}$

$$\therefore E = \frac{153 \times 10^6 \times 2 \times 27}{2.11 \times 10^{-3}} = 3.915\text{ V}$$

Losses in a DC Generator

The various losses occurring in a generator can be subdivided as follows.

Copper Losses

1. Armature copper loss $= I_a^2 R_a$.
   where R_a = resistance of armature and inter poles and series field winding etc.
   This is about 30% to 40% of full-load losses.
2. Field copper loss:
   In case of shunt generators, it is practically constant and $I_{sh}^2 R_{sh}$. In the case of series generator, it is $= I_{se}^2 R_{se}$, where R_{se} is resistance of the series field winding.
3. The loss due to brush contact resistance. It is usually included in the armature copper loss.

Magnetic Losses (Iron or Core Losses)

Hysteresis Loss

This loss is due to the reversal of magnetization of the armature core. Every portion of the rotating core undergoes one complete cycle of magnetic reversal after passing under one pair of poles.

For normal flux densities (i.e., up to 1.5 Wb/m^2), hysteresis loss is given by Steinmetz formula.

$$W_h = \eta B_{max}^{1.6} \times f\, V\, W.$$

where η = Steinmetz hysteresis coefficient
B_{max} = Maximum flux density
f = Frequency of magnetic reversals
V = Volume of the core in m^3

The hysteresis loss is reduced by choosing magnetic materials which have a low hysteresis coefficient such as silicon steel.

Eddy Current Loss

When the armature core rotates, it also Cuts The Magnetic Flux. Hence an emf is induced in the magnetic core which sets up large current in the body of the core due to its small resistance. These currents circulate in the core and find no other path, hence they are known as eddy current. The power loss due to the flow of this current is known as eddy current loss. In order to reduce this loss and consequent heating of the core to a small value, the core is built up of thin laminations which are insulated from each other by a thin coating of varnish. These laminations are stacked and riveted at right angles to the path of the eddy current.

Eddy current loss is given by the following relation

$$W_e = KB^2_{\max} f^2\, t^2\, V\, W.$$

Where

$B_{\max}$ = Maximum flux density

F = Frequency of magnetic reversals

T = Thickness of each lamination

V = Volume of the core.

The iron losses are practically constant for shunt and compound wound generators, because in their case, field current is approximately constant, the iron losses are about 20% to 30% of full-load losses.

Mechanical Losses

These losses consist of

1. Friction loss at bearings and commutators.
2. Air friction or windage loss of rotating armature. These are about 10% to 20% of full load losses.

Stray Losses

Magnetic and mechanical losses are collectively known as stray losses. These are also known as rotational losses as they exist only when the rotor is rotating.

Constant or Standing Losses

Field Cu loss for shunt and compound generators is constant. Hence, stray losses and shunt Cu loss are constant in their case. These losses are together known as standing or constant losses W_C.

Example 6: A 10 kW, 230 V, DC shunt generator operation are 80% efficiency. Input power and total losses are

(A) 5 kW, 2.5 kw (B) 12.5 kW, 1 kW
(C) 12.5 kW, 2.5 kW (D) 5 kW, 1 kW

Solution: (C)

Output = 10 kW

$$\therefore \quad \frac{80}{100} = \frac{10}{\text{input}}$$

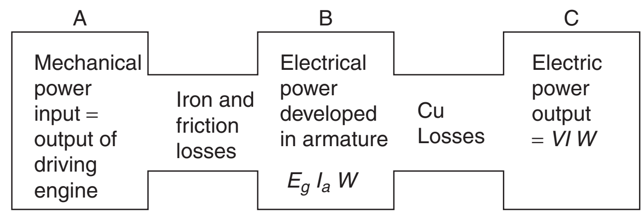
$$\Rightarrow \quad 0.8x = 10$$

$$\Rightarrow \quad x = \frac{10}{0.8} = 12.5 \text{ kW}$$

$\therefore$ Losses = input–output = 2.5 kW.

Power Stages in Generator

Various power stages in generator are as shown below



Following are the three generator efficiencies

1. Mechanical efficiency

$$\eta_M = \frac{B}{A} = \frac{\text{Total power generated}}{\text{Mech power input}}$$

2. Electrical efficiency

$$\eta_E = \frac{C}{B} = \frac{\text{Electric power output}}{\text{Electrical power developed}}$$

3. Overall or commercial efficiency

$$\eta_c = \frac{C}{A} = \frac{\text{Electric power output}}{\text{Mechanical power input}}$$

Condition for Maximum Efficiency

Generator efficiency is maximum, when

Variable loss = Constant loss

Armature Reaction

The effect of the magnetic field set up by armature current on the distribution of flux under main poles of a generator is called armature reaction.

The armature magnetic field has two effects.

1. It demagnetizes or weakens the main flux and
2. It cross magnetizes or distorts it.

- The first effect leads to reduced generated voltage and the second to the sparking at the brushes.
- The flux is strengthened at the trailing pole tips but weakened at the leading pole tips.
- Because of armature reaction there is a shift in the magnetic neutral axis (M. N. A.) in the direction of rotation of the armature.
- Armature reaction gives rise to cross magnetization and de-magnetization.

Demagnetizing Ampere-turns Per Pole

The armature demagnetizing ampere-turns are neutralized by adding extra ampere-turns to the main field winding.

Demagnetizing ampere-turns pole,

$$AT_d / \text{pole} = ZI \times \frac{\theta_m}{360°}$$

where

Z = Total number of armature conductors

I = Current in each armature conductor (or) Current in a parallel path

$I_{a/2}$ for simplex wave winding

$I_{a/p}$ for simple lap winding

θ_m = Forward lead in mechanical or geometrical or angular degrees

Cross-magnetizing Ampere-turns Per Pole

Cross magnetizing ampere-turns per pole,

$$AT_C\,/\text{pole} = ZI\left[\frac{1}{2P} - \frac{\theta_m}{360°}\right]$$

To reduce the effects of armature reaction the following methods are normally used.

1. Provision of inter poles.
2. Provision of compensating windings.
3. Chamfering of the poles.

Compensating Windings

In large direct current machines which are subjected to large fluctuations in load (i.e., rolling mill motors and turbo-generators, etc.) compensating windings are used. Their function is to neutralize the cross-magnetizing effect of armature reaction.

In the absence of compensating winding, with sudden changes in load, the flux will be suddenly shifting backward and forward which will induce an emf in the armature coils. It may be so high as to strike an arc between the consecutive commutator segments which may lead to flash over around the whole commutator there by resulting in a short circuit of armature.

- These windings are embedded in slots in the pole shoes and are connected in series with armature in such a way that the current in them flows in opposite direction to that following in the armature conductors directly below the pole shoes.

Number of Compensating Windings

No. of armature amp-turns/pole for compensating winding

$$= \frac{ZI}{2P} \times \frac{\text{Pole arec}}{\text{Pole pitch}} = 0.7 \times \frac{ZI}{2P} \text{ (approximately)}$$

Commutation

The process by which the current in the short-circuited armature coil is reversed while it crosses the magnetic neutral axis is called commutation.

During the commutation period the brush spans and hence short circuits that particular coil under going reversal of current through it. The self-induced emf in the coil undergoing commutation is known as reactance voltage.

Reactance voltage = (Coefficient of self-inductance) × Rate of change of current

Time of commutation or commutation period,

$$T_c = \frac{W_b - W_m}{v} \text{ second}$$

where

W_b = Brush width in cm

W_m = Width of mica insulation in cm

v = Peripheral velocity of commutator segments in cm/sec

Reactance voltage

$$L \times \frac{2I}{Tc}$$

If commutation is linear = 1.11 $L \times \dfrac{2I}{T_c}$

If commutation is sinusoidal

Methods of Improving Commutation

There are two practical ways of improving commutation, i.e., making current reversal in the short-circuited coil as sparkless as possible.

Resistance Commutation

In this method, low resistance copper brushes are replaced by comparatively high resistance carbon brushes

EMF-commutation

In this method, arrangement is made to neutralize the reactance voltage by producing a reversing emf in the short-circuited coil under commutation. The reversing emf may be produced in two ways.

(a) Either by giving the brushes a forward lead, sufficient enough to bring the short – circuited coil under the influence of next pole of opposite polarity.
Shifting of the brushes is not a solution for reducing the effect of armature reaction. Though the cross-magnetization effect may be reduced somewhat, de-magnetization is also introduced.

(b) By providing inter poles.
Inter poles: These are small poles fixed to the yoke and spaced in between the main poles. They are wound with comparatively few heavy gauge Cu wire turns and are connected in series with the armature so that they carry full armature current.

Their polarity in the case of a generator is the same as that of the main pole a head in the direction of rotation. The function of inter poles is two-fold:

1. As their polarity is the same as that of the main pole ahead, they induce an emf in the coil (under

commutation) which helps the reversal of current. The emf induced by inter-poles is known as commutating or reversing emf The commutating emf neutralizes the reactance emf there by making commutation sparkless. As inter poles carry armature current, their commutating emf is proportional to the armature current. This ensures automatic neutralization of reactance voltage which is also due to armature current.

2. Another function of inter poles is to neutralize the cross-magnetizing effect of armature reaction. Cancellation of cross magnetization is automatic and for all loads because both are produced by the same armature current.

Equalizing Connections

It is characteristic of lap-winding that all conductors in any parallel path lie under one pair of poles. If fluxes from all poles are exactly the same, then the emf induced in each parallel path is same and each path carries same current. But some inequalities in flux inevitably occur due to which there is always a slight imbalance of emf in the various parallel paths.

The function of equalizer rings is to avoid unequal distribution of current at the brushes there by helping to get sparkless commutation.

$$\text{Number of equalizer rings} = \frac{\text{No. of conductors}}{\text{No. of pair of poles}}$$

Equalizer rings are not used in wave-wound armature, because there is no imbalance in the emf's of the two parallel paths, this is due to the characteristic of wave-winding that armature conductors in either parallel path are not confined under one pair of poles as in lap winding but are distributed under all poles.

Characteristics of a DC Generator

There are three important characteristics or curves of a DC generator.

1. **Open-circuit Characteristic:** O.C.C. (or No-load saturation characteristic).
   It shows the relation between the generated emf E_g and field current I_f at a given fixed speed.
   It is also known as magnetic characteristic.
2. **External Characteristic:** It gives relation between the terminal voltage V and the load current I_L.
3. **Internal or total characteristic:** This characteristic gives relation between the emf, E actually induced in the armature (after allowing for the demagnetizing effect of armature reaction) and the armature current I_a.

Characteristic Curves

Separately Excited Generator

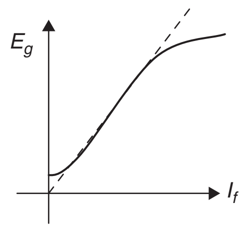
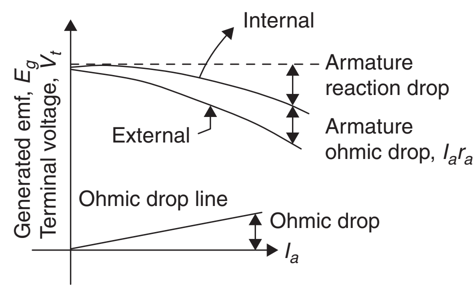


Figure 1 No-load characteristic (For all types of generators)



Series-wound Generators

For a series generator, as the field windings are in series with the armature, the field current (which is same as armature current) is zero, hence we do not have O.C.C. for a series wound generator. But it can be drawn from O.C.C. by considering extra current needed to neutralize the effect of armature reaction.

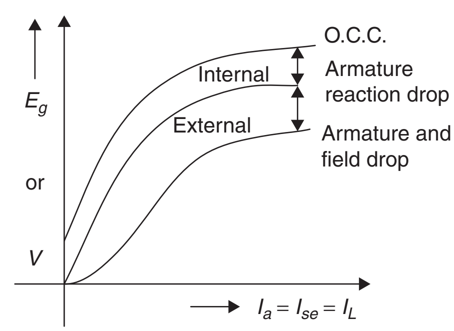
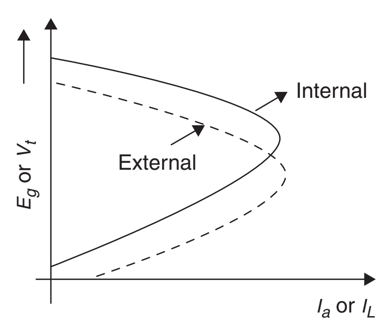
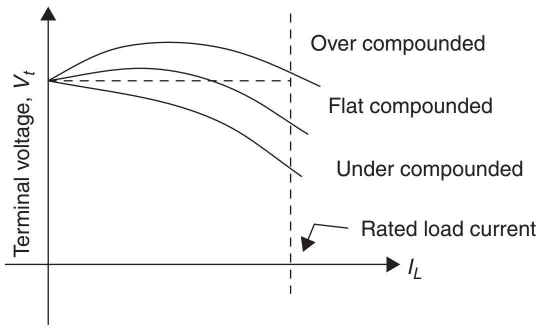


Figure 2 Series generator has rising voltage characteristic

Shunt-wound Generator



Compound Generator



Condition for build-up of a self excited (shunt) generator:

The conditions required to be fulfilled for the build up of a shunt generator are as follows.

1. There must be some residual magnetism in the generator poles.
2. For the given direction of rotation the shunt field coils should be correctly connected to the armature i.e., the shunt field current produces a flux in the direction of residual flux.
3. If excited on open circuit, its shunt field resistance should be less than the critical resistance.
4. If excited on load, then its shunt field resistance should be more than certain minimum value of resistance whose value is given by internal characteristic.

- For a series wound generator the external (or load) circuit resistance should be less than the critical resistance and for a shunt generator load circuit resistance must be greater than critical load resistance.

A DC generator may fail to build up voltage because of failure of any of the above given cases.

Parallel Operation of DC Generators

Parallel operations is extremely desirable for the following reasons

1. Continuity of service
2. Efficiency
3. Maintenance and repair
4. Additions to plant

Condition to be Satisfied

- Polarity of the incoming generator should be same as that of existing generator.
- The no-load induced emf s are to be the same in order to avoid circulating currents on no load.

Shunt generators are best suited for parallel operation because of the drooping nature of their external characteristics

Because of the rising nature of the external characteristics of series generators, their parallel operations will pose some problems, which can be overcome by

1. Cross-connecting the fields.
2. Providing equalizing bar.

Example 7: Two DC generators having rectilinear external characteristics operate in parallel. One machine has the terminal voltage of 270 V on no load and 220 V at the load current of 30 A. The other has a voltage of 280 V at no load and 220 V at the load current of 30 A. Calculate the load shared and bus voltage of each machine when the total load current is 50 A.

Solution: Generator 1: Slope of external characteristic or voltage drop/ampere

$$= \frac{270-220}{30} = \frac{50}{30} = 5/3 \text{ V/A.}$$

Generator 2: Slope of external characteristic or voltage drop/ampere

$$= \frac{280-220}{30} = \frac{60}{30} = 2 \text{ V/A}$$

Let V be the common bus voltage

I_1 = Load current shared by generator 1

I_1 = Load current shared by generator 2.

Then

$$V = 270 - \frac{5}{3} I_1 \text{ for generator 1}$$

$$V = 280 - 2I_2 \text{ for generator 2.}$$

Since the terminal voltage is same

$$\therefore\ 270 - \frac{5}{3} I_1 = 280 - 2I_2$$

$$\Rightarrow \frac{-5}{3} I_1 + 2I_2 = 10 \qquad (1)$$

Also $I_1 + I_2 = 50$ (2)

Solving Equations (1) and (2)

We get,

$I_1 = 24.54$ A and $I_2 = 25.46$ A

and bus bar voltage $V = 229$ V.

DC Motors

An electric motor is a machine which converts electrical energy into mechanical energy. It works 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 and hence the conductor moves in the direction of force.

The magnitude of force is given by

$F = BIL \sin\theta$ Newton

where

B = Flux density in Wb/m^2

I = Current flowing in the conductor

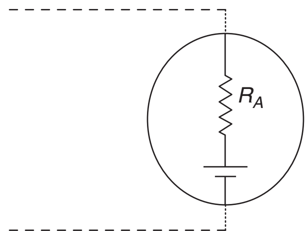
L = Length of the conductor

θ = Angle made by the tangent drawn at conductor with field direction

Significance of the Back emf

As the armature of a DC motor rotates, all the necessary conditions for an emf to be induced in a conductor are satisfied, namely a conductor, a magnetic field and the relative motion between the conductor and magnetic field. Hence an emf is induced in the armature, the direction of which can be determined by Flemings right hand rule. This induced emf is in opposition to the applied voltage hence it is known as back or counter emf.

The applied voltage has to overcome the back emf in addition to the armature drop. The equivalent circuit of armature is shown in below figure.



The voltage equation of a DC motor is

$$V = E_b + I_a R_a$$

Where E_b is the back emf given by

$$E_b = \frac{\phi ZN}{60} \times \frac{P}{A}$$

From the voltage equation, on multiplying both the side by I_a, we get

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

where

VI_a = Electrical input to the armature.

$E_b I_a$ = Electrical equivalent of mechanical power developed in the armature.

$I_a^2 R_a$ = Cu loss in the armature.

Example 8: DC motor gives maximum power when

(A) $V = 2E_b$ (B) $V = E_b/2$

(C) $V = E_b/\sqrt{2}$ (D) $V = E_b$

Solution: (A)

$$V = E_b + I_a R_a$$

$$\therefore \quad P_m = E_b I_a = VI_a - I_a^2 R_a$$

It is maximum when $\dfrac{dP_m}{dI_a} = 0$

$$V - 2I_a R_a = 0 \Rightarrow I_a R_a = \frac{V}{2}$$

$\therefore$ Back emf: $\quad E_b = V - I_a R_a$

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

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

Condition for Maximum Power

The gross mechanical power developed by a motor is $P_m = VI_a - I_a^2 R_a$.

Differentiating both sides w.r.t i_a and equating the result to zero, we get,

$$\frac{dP_m}{dI_a} = V - 2I_a R_a = 0$$

$$\therefore \quad I_a R_a = \frac{V}{2}$$

As $\quad V = E_b + I_a R_a$ and $I_a R_a = V/2$

$$\therefore \quad E_b = V/2$$

Thus gross mechanical power developed by a motor is maximum when back emf is equal to half the applied voltage. This condition is however, not realized in practice, because in that case current would be much beyond the normal current of the motor. Moreover, half the input would be wasted in the form of heat and taking other losses into consideration, the motor efficiency will be below 50 percent.

Condition for Maximum Efficiency

Variable loss = Constant loss

(same as that of generator)

Armature Torque (T_a) or Torque developed (T_d):

Let T_a be the torque developed by the armature of a motor running at N rps. If T_a is in Nm, then

Power developed = $T_a \times 2\pi NW$

$$T_a \times 2\pi N = E_b I_a$$

$$T_a = \frac{E_b I_a}{2\pi N} = \frac{\phi ZN\left(\frac{P}{A}\right) \times I_a}{2\pi N}$$

$$= \frac{1}{2\pi}\phi Z\left[\frac{P}{A}\right] I_a \text{ Nm}$$

$$T_a = 0.159\phi Z I_a \left[\frac{P}{A}\right] \text{Nm}$$

From the above equation for the torque, we find that $T_a \propto \phi I_a$

1. For series motor, ϕ is directly proportional to I_a (before saturation) because field windings carry full armature current

$$\therefore \quad T_a \propto I_a^2$$

2. For shunt motors, ϕ is practically constant hence $T_a \propto I_a$

Alternate expression for torque developed.
If N is in rpm then,

$$T_a \times \frac{2\pi N}{60} = E_b I_a$$

$$T_a = \frac{60 E_b I_a}{2\pi N} = \frac{60}{2\pi} \frac{E_b I_a}{N} = 9.55 \frac{E_b I_a}{N} \text{ Nm}$$

Shaft Torque

The torque which is available for doing useful work is known as shaft torque, T_{sh}.

$$T_{sh} = \frac{\text{Output in watts}}{2\pi N/60} \; N \text{ in rpm}$$

$$= \frac{60}{2\pi} \frac{\text{Output}}{N} = 9.55 \frac{\text{Output}}{N}$$

The difference $(T_a - T_{sh})$ is known as lost torque and is due to iron and friction losses of the motor.

Speed of a DC Motor

From the voltage equation of a DC motor, we get

$$E_b = V - I_a R_a$$

Or $$\frac{\phi Z N}{60} \frac{P}{A} = V - I_a r_a$$

$\therefore$ $$N = \frac{V - I_a r_a}{\phi} \times \frac{60 A}{ZP} \text{ rpm}$$

Or $$N = \frac{E_b}{\phi} \times \left(\frac{60 A}{ZP}\right)$$

For a given DC motor A, Z and P are fixed.

$\therefore$ $$N = K \frac{E_b}{\phi}$$

where K is a constant

$$N \propto \frac{E_b}{\phi} \text{ Or } \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$$

1. For series motor,
   $\phi \propto I_a$ (prior to saturation of magnetic poles)

   $$\therefore \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}}$$

2. For shunt motor,

   $$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$$

   If flux is constant i.e., $\phi_2 = \phi_1$

   Then $$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

Speed Regulation

The speed regulation is defined as the change in speed when the load on the motor is reduced from rated value to zero, expressed as percent of the rated load speed.

$$\%\,\text{Speed regulation} = \frac{\text{No load speed} - \text{Full load speed}}{\text{Full load speed}} \times 100$$

$$\text{P. U. speed regulation} = \frac{\text{No load speed} - \text{Full load speed}}{\text{Full load speed}}$$

Example 9: Determine the full-load speed shunt field, current.

Solution: $I_{sh} = \dfrac{230}{230} = 1$ A

$$I_{a1} = 3 - 1 = 2 \text{ A}$$
$$E_{b1} = 230 - 0.5 \times 2 = 229 \text{ V}$$
$$I_{a2} = 23 - 1 = 22 \text{ A}$$
$$E_{b2} = 230 - 22 \times 0.5 = 219 \text{ V}$$
$$N_2 = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2} \times N_1$$
$$= \frac{219}{229} \times \frac{\phi_1}{0.98\phi_1} \times 1000$$
$$(\because \phi_2 = 0.98\phi_1) = 975.84 \text{ rpm}$$

Example 10: Determine the full load torque

Solution:

$$\text{Power developed} = E_{b2} I_{a2} = 219 \times 22$$
$$= 4.818 \text{ kW}$$
$$\text{Angular speed, } \omega = \frac{2 \times 3.14 \times 975.84}{60}$$
$$= 102.14 \text{ rad/sec}$$
$$\text{Torque} = \frac{4818}{102.14} = 47.17 \text{ Nm.}$$

Common Data for Examples 11 and 12
A 220 V DC shunt motor takes 20 A at rated voltage and runs at 1000 rpm. Its field circuit resistance is 100 Ω and armature circuit resistance is 0.1 Ω. Compute the value of additional resistance required in the armature circuit to reduce the speed to 800 rpm when

Example 11: The load torque is proportional to the speed

Solution: Given the condition torque, $T \propto$ speed, N

$\therefore$ $$\frac{T_1}{T_2} = \frac{N_1}{N_2}$$

Shunt field current, $I_{sh} = \dfrac{220}{100} = 2.2$ A

$$I_{a1} = I_L - I_{sh} = 20 - 2.2 = 17.8 \text{ A}$$

$$E_{b1} = V - I_{a1} R_a = 220 - 17.8 \times 0.1$$

$$= 218.22 \text{ V}$$

$$E_{b2} = E_{b1} \times \frac{N_2}{N_1}$$

$$218.22 \times \frac{800}{1000} = 174.57 \text{ V}$$

Also $T \propto \phi I_a$, where ϕ is constant

$$\therefore \quad I_{a2} = \frac{I_{a1} N_2}{N_1} = \frac{17.8 \times 800}{1000}$$

Total armature circuit resistance

$$R = \frac{V - E_b}{I_a} = \frac{220 - 174.57}{14.24} = 3.19 \ \Omega$$

$$R_{ext} = 3.19 - 0.1 = 3.09 \ \Omega$$

Example 12: The load torque varies as the square of the speed

Solution: Given that $T \propto N^2$

$$\therefore \quad I_{a2} = I_{a1} \times \left(\frac{N_2}{N_1}\right)^2$$

$$= 17.8 \times \left(\frac{800}{1000}\right)^2 = 11.4 \text{ A}$$

$$R = \frac{220 - 174.57}{11.40} = 3.988 \ \Omega$$

$$R_{ext} = 3.988 - 0.1 = 3.89 \ \Omega$$

Example 13: The full-load speed regulation is 8% when the speed at full load is 800 RPM. The no-load speed is ______ RPM.

(A) 832 (B) 864
(C) 736 (D) 768

Solution: (B)

$$\text{Speed regulation} = \frac{N_0 - N}{N}$$

N_0 = No-load speed

N = Speed in load

$$\frac{8}{100} = \frac{N_0 - 800}{800} \Rightarrow 64 = N_0 - 800$$

$$N_0 = 864 \text{ rpm}$$

Example 14: A 230 V shunt motor develops a torque of 48 Nm at an armature current of 12 A. The torque produced when the armature current is 15 A, is

(A) 48 Nm (B) 36 Nm
(C) 60 Nm (D) 72 Nm

Solution: (C)

$$T \propto \phi I_a$$

For a shunt motor, ϕ is constant

$$T \propto I_a$$

$$\frac{T_2}{T_2} = \frac{I_{a2}}{I_{a2}} \Rightarrow T_2 = T_1 \times \frac{I_{a2}}{I_{a1}}$$

$$= 48 \times \frac{15}{12} = 60 \text{ Nm}$$

Example 15: A DC motor develops a torque of 120 Nm at 20 rps. At 30 rps it will develop a torque of ______ Nm.

(A) 160 (B) 120
(C) 80 (D) 40

Solution: (C)

$$T \propto \frac{1}{N}$$

$$N_1 T_1 = N_2 T_2$$

$$T_2 = \frac{N_1 T_1}{N_2} = \frac{20 \times 120}{30} = 80 \text{ Nm}$$

Example 16: A DC motor connected to a 230 V supply has an armature resistance of 0.15 Ω. The value of armature current when the back emf $E_b = 200$ V is ____ A.

(A) 50 (B) 100
(C) 400 (D) 200

Solution: (D)

$$E_b = V - I_a R_a$$

$$I_a = \frac{V - E_b}{R_b}$$

$$= \frac{230 - 200}{0.15} = \frac{30}{0.15} = 200 \text{ A}$$

Motor Characteristics

The characteristic curves of DC motors can be broadly classified as

1. Electrical characteristics: 'T' vs. 'I_a' and 'N' vs. 'I_a'.
2. Mechanical characteristic: 'N' vs. 'T'.

Characteristics of Shunt Motors

1. T_a / I_a characteristic

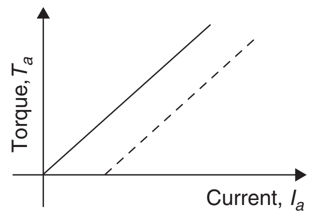
$$T = K \phi I_a$$

where K is a constant

In the case of shunt motors, the flux is assumed to be practically constant (though at heavy loads, ϕ decreases somewhat due to increased armature reaction)

$$\therefore T \propto I_a$$

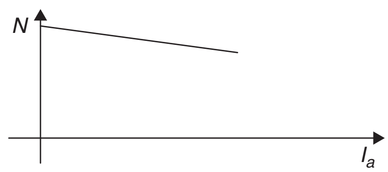
The torque varies linearly with armature current.



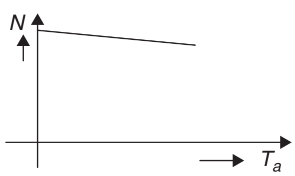
2. N / I_a characteristic
Variations of speed can be obtained from the relation

$$N \propto \frac{E_b}{\phi} \text{ or } \frac{V - I_a\, r_a}{\phi}$$

Since the flux is practically constant for a shunt motor, the speed decreases linearly with armature current. The speed curve is slightly dropping as shown in the figure but for all practical purposes, shunt motor is taken as a constant – speed motor.



3. N / T_a characteristic

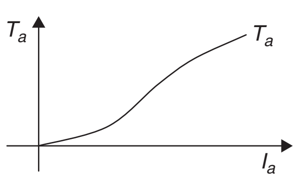


Characteristics of Series Motors

1. T_a / I_a characteristic

$$\text{Torque } T_a \propto \phi\, I_a$$

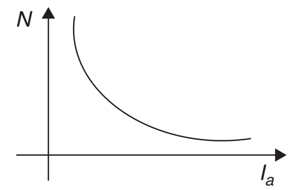
In the case of the series motors field windings also carry the armature current, $\phi \propto I_a$ up to the point of magnetic saturation. At light loads, I_a and hence ϕ are small. But as I_a increases, T_a increases as the square of the current, i.e, $T_a \propto I_a^2$. Hence T_a / I_a curve is a parabola as shown in below figure. After saturation ϕ is almost independent of I_a hence $T_a \propto I_a$ only. So the characteristic becomes a straight line



2. N / I_a characteristic

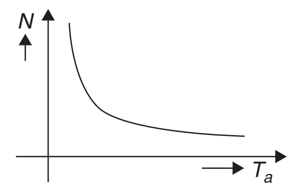
$$N \propto \frac{E_b}{\phi}$$

Change in E_b for various load currents is small and hence may be neglected with increased $I_a \cdot \phi$ also increases hence the speed varies inversely as armature current as shown in the following figure.



- The series motor is a variable speed motor.
- On no-load and at light loads, a DC series motor has a tendency to run at dangerously high value of speed.

3. N / T_a or Mechanical characteristic.



When the speed is high, the torque is low and vice versa.

Characteristic of Compound Motors

These motors have both series and shunt windings. So the characteristics of such motors lie in between those of shunt and series motors. The characteristics approach those of a shunt or a series motor, depending upon the relative field strengths of the shunt and the series field windings.

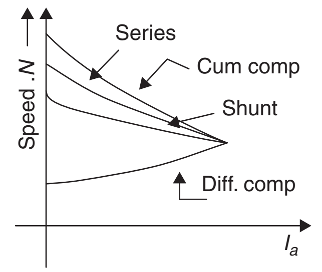
If series excitation helps the shunt excitation, then the motor is said to be cumulatively compounded. If on the other hand, series field opposes the shunt field, then the motor is said to be differentially compounded.

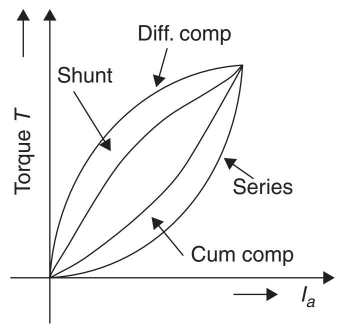
Cumulative Compound Motors

These machines are used where series characteristics are required and where, in addition, the load is likely to be removed totally as in some types of coal cutting machines or for driving heavy machine tools which have to take sudden cuts quite often. Such machines are used to drive electric shovels, metal stamping, machines, reciprocating pumps, hoists and compressors etc.

Differential Compound Motors

Since series field opposes the shunt field, the flux is decreased as load is applied to the motor. This results in the motor speed remaining almost constant or even increasing with the load ($\therefore N \propto E_b/\phi$). Due to this reason there is a decrease in the rate at which the motor torque increases with load. Such motors are not in common use. One of the biggest drawback of such a motor is that due to weakening of flux with increase in load, there is a tendency towards speed instability and motor running away unless designed properly.





Type of motor	Characteristics	Applications
Shunt	Approximately constant speed, adjustable speed	For driving constant speed line shafting. Lathes, centrifugal pumps, machine tools, blowers and fans, reciprocating pumps
Series	Variable speed, Adjustable varying speed, high starting torque	For traction work, i.e., electric locomotives rapid transit systems, trolley, cars, cranes and hoists, conveyors
Cumulative compound	Variable speed, adjustable varying speed, high starting torque	For intermittent high torque loads, for shears and punches, elevators, conveyors, heavy planers, rolling mills, ice machines, printing presses, air compressors.

Speed Control of DC Motors

The speed of a DC motor is given by the relation

$$N = \frac{V - I_a r_a}{Z\phi}\left[\frac{A}{P}\right] = K\frac{V - I_a r_a}{Z\phi}\text{ rps}$$

where K is a constant.

Sometimes, it may become necessary to vary the speed of a DC motor at a given load condition. There are various methods of controlling the speed of a DC motor.

1. By varying the applied voltage
2. By varying the resistance in the armature circuit
3. By varying flux/pole

Example 17: The value of torque produced by armature of 4-pole motor having 774 conductors, two paths in parallel, 24 mWb flux per pole, when the total armature current is 50 A, is ____.

(A) 350 Nm (B) 373 Nm
(C) 295.35 Nm (D) 420 Nm

Solution: (C)

$$T_a = 0.159 \cdot \phi I_a\left(\frac{P}{A}\right)$$

$$= 0.159 \times 774 \times 24 \times 10^{-3} \times 50 \times \frac{4}{2}$$

$$= 295.35 \text{ Nm}$$

Common Data for Example 18

A 230 V DC shunt motor takes a current of 40 A and runs at 1100 RPM. If armature and shunt field resistances are 0.25 Ω and 230 Ω respectively.

Example 18: The torque developed by the motor is _____.

(A) 78.9 Nm (B) 74.66 Nm
(C) 98.7 Nm (D) 87.9 Nm

Solution: (B)

$$E_b = 220.25 \text{ V}$$

$$T_a = \frac{E_b I_a}{N} \times 9.55$$

$$= \frac{220.25 \times 39}{1100} \times 9.55$$

$$\therefore \quad T_a = 74.66 \text{ Nm}$$

Common Data for Examples 19 and 20:

The counter emf of a shunt motor is 227 V, the field resistance is 160 Ω and the field current is 1.5 A.

Example 19: If the line current is 39.5 A, the armature resistance is ________

(A) 0.342 Ω (B) 0.243 Ω
(C) 0.423 A (D) 0.432 Ω

Solution: (A)

Line current = I_L = 39.5 A

$$I_a = I_L - I_{sh} = 39.5 - 1.5 = 38 \text{ A}$$

$$V = E_b + I_a R_a \Rightarrow R_a = \frac{V - E_b}{I_a}$$

$$\therefore \quad R_a = \frac{240 - 227}{38} = 0.342\ \Omega$$

$$[\because\ V = I_{sh}R_{sh} = 1.5 \times 160 = 240 \text{ V}]$$

Example 20: The starting current of the motor is ______.
(A) 250 A (B) 107.57 A
(C) 255.5 A (D) 701.75 A

Solution: (D)
When the motor is starting, $E_b = 0$

$$I_a = \frac{V}{R_a} = \frac{240}{0.342} = 701.75 \text{ A}$$

Common Data for Examples 21 and 22:
A 450 V series motor runs at 500 rpm taking a current of 40 A. Total resistance of the armature and field circuits is 0.8 Ω, assuming flux is proportional to field current and if the load is reduced so that motor draws a current of 30 A.

Example 21: The percentage change in torque is
(A) 38.75% (B) 41.75%
(C) 39.75% (D) 43.75%

Solution: (D)

$$\phi \propto I_a$$

$$\Rightarrow \quad T \propto \phi I_a$$

$$T \propto I_a^2 \quad [\because I_a = I_{sc} \text{ in series motor}]$$

$$\therefore \quad T_1 \propto 40^2$$

$$T^2 \propto 30^2$$

$$\frac{T_2}{T_1} = \frac{9}{16}$$

$$\% \text{ change in torque} = \frac{T_1 - T_2}{T_1} \times 100$$

$$= \frac{7}{16} \times 100 = 43.75\%$$

Example 22: Speed is ________ rpm
(A) 627.94 (B) 697.4
(C) 679.42 (D) 649.72

Solution: (C)

$$E_{b1} = 450 - (40 \times 0.8) = 450 - 32 = 418 \text{ V}$$

$$E_{b2} = 450 - (30 \times 0.8)$$

$$= 450 - 24 = 426 \text{ V}$$

$$E_b \propto \phi N$$

$$\propto I_a N$$

$$\Rightarrow \quad \frac{E_{b2}}{E_{b1}} = \frac{I_{a2} N_2}{I_{a1} N_1}$$

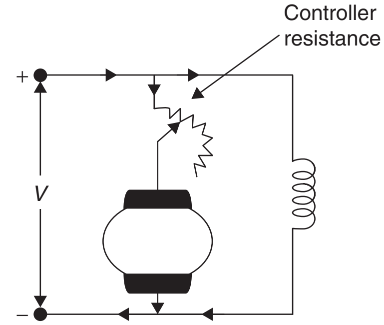
$$\therefore \quad N_2 = N_1 \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}}$$

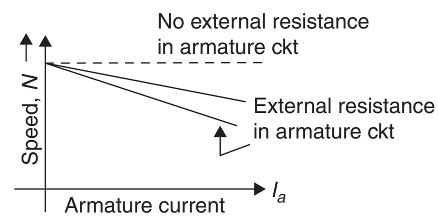
$$= 500 \times \frac{426}{418} \times \frac{40}{30} = 679.42 \text{ rpm}$$

Speed Control of Shunt Motors

Armature or Rheostatic Control Method

This method is used when speeds below the no-load speed are required. As the supply voltage is constant, the voltage across the armature is varied by inserting and additional resistance in series with the armature circuit. Different speeds can be obtained by varying the additional series resistance.





Let I_{a1} = Armature current with no external resistance
I_{a2} = Armature current with external resistance in the armature ckt
N_1, N_2 = Corresponding speeds
V = Supply voltage

Then $N_1 \propto E_{b1}$
Or $\propto V - I_{a1} R_a$

Suppose the external resistance in series with the armature ckt be r, and $r + r_a = R_t$.

$$N_2 \propto E_{b2}$$

$$\propto V - I_a R_t$$

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

If N_0 be the no-load speed (and $I_a \; r_a$ drop at no-load neglected)

$$\text{Then} \quad \frac{N}{N_0} = \frac{V - I_a R_2}{V} = \left(1 - \frac{I_a R_t}{V}\right)$$

It is seen that for a given resistance R_2, speed is a linear function of armature current

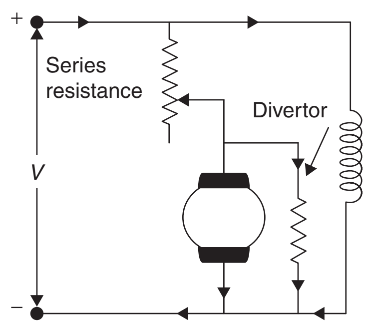
At $N = 0$

$I_a = \dfrac{V}{R_t}$ is the maximum current and is called stalling current

The main disadvantage of this method lies in the fact that a considerable amount of power is lost in the external resistance.

This method is expensive and unsuitable for rapidly changing loads because for a given value of R_t, speed will change with load.

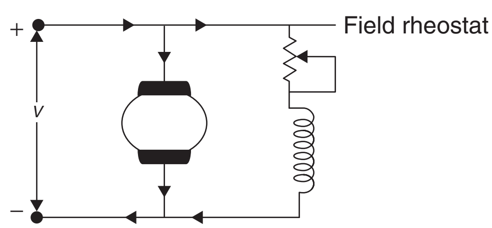
- A more stable operation can be obtained by using a divertor across the armature in addition to armature control resistance as shown in below figure.



Now, the changes in armature current (due to changes in the load torque) will not be so effective in changing the p.d., across the armature. (hence the armature speed).

Flux (or) Field Control

As $N \propto \dfrac{1}{\phi}$, by decreasing the flux, the speed can be increased and vice versa. The flux of a DC shunt motor can be changed by changing I_{sh} with help of a shunt field rheostat as shown in below figure.

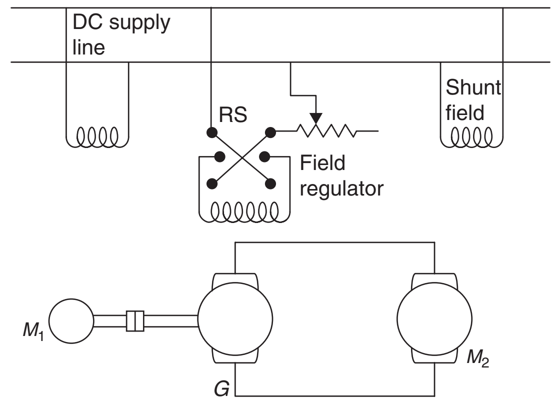


The external resistance connected in series with the shunt field winding is called a regulator.

Voltage Control Method

1. **Multiple voltage control:** In this method, the shunt field of the motor is connected permanently to a fixed exciting voltage, but the armature is supplied with different voltages by connecting it across one of several different voltages by means of suitable switchgear. The armature speed will be proportional to their different voltages. The intermediate speeds can be obtained by adjusting the shunt field regulator. This method is not much used.

2. **Ward Leonard system:**



This system is used where a usually wide (up to 10:1) and very sensitive speed control is required as for coillery winders, electric excavators, elevators and the main drives in steel mills and blooming and paper mills.

With the help of Ward Leonard set speed in both directions can be varied.

M_1 is the main motor whose speed is to be controlled. This motor is separately excited. It is fed from a variable voltage generator G, which is driven by an auxiliary motor M_2 which may be another DC or AC motor. By applying a variable voltage across armature terminals of M_1, any desired speed can be obtained. This variable voltage is supplied by motor-generator set, i.e., $M_2 - G$. By controlling the speed of auxiliary motor M_2, magnitude of voltage can be controlled. The polarity of voltage is changed by changing the direction of field current of generator G with the help of reversing switch RS.

This system has advantages of smooth variation in speed and the change of the sense of rotation.

The disadvantages of this system are

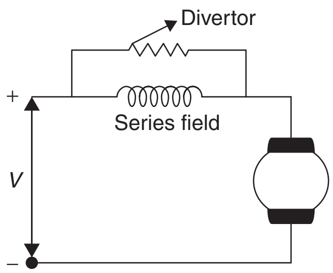
(a) It requires an auxiliary motor to drive the variable voltage generator which involves high capital outlay.
(b) Low efficiency especially at light loads.

Speed Control of Series Motors

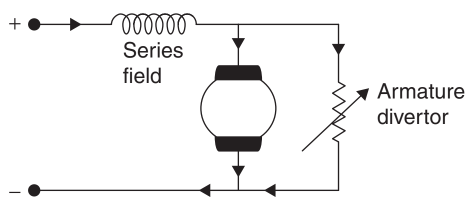
Flux Control Method

A series motor speed can be controlled by changing the flux with the help of any one of the following methods.

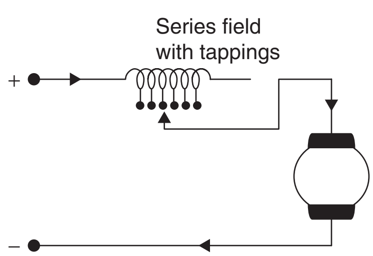
(a) **Field divertors:** The series field winding is shunted by a variable resistance known as field divertor. Any desired amount of current can be passed through the diverter by adjusting its resistance. Hence speed is increased by decreasing flux.



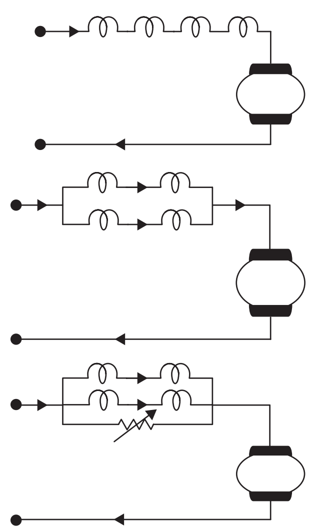
(b) **Armature Divertor:** A divertor across the armature can be used for given speeds lower than the normal speed. For a given constant-load torque, if I_a is reduced due to armature divertor, then ϕ must ($\therefore\ T_a \propto \phi I_a$) an increase in current drawn from the supply $\left(N \propto \dfrac{1}{\phi}\right)$, and hence the speed is reduced.



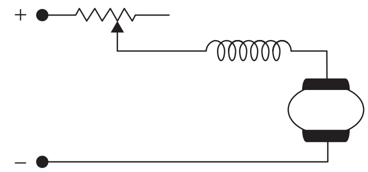
(c) **Tapped field control:** The number of series field turns in the circuit can be changed as per the requirement. With full field, the motor runs at its minimum speed which can be raised in steps by cutting out some of the series turns.



(d) **Paralleling field coils:** In this method, used for fan motors, several speeds can be obtained by regrouping the field coils as shown in below figure.



Variable Resistance in Series with Motor

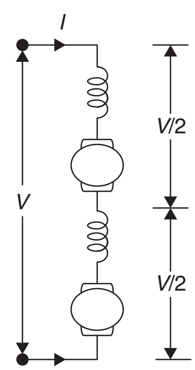


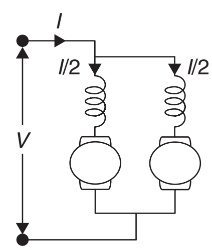
By increasing the resistance in series with the armature as shown in the figure, the voltage applied across the terminals can be decreased. With reduced voltage across the armature, the speed is reduced.

In this method, as full motor current passes through this series resistance there is a considerable loss of power in it.

Series Parallel Control

In this system of speed control, which is widely used in electric traction, two or more similar mechanically coupled series motors are employed. At low speeds, the motors are joined in series and for high speeds, are joined in parallel





When in parallel,

$$\text{Speed} \propto \frac{E_b}{\phi} \propto \frac{V}{I/2} \propto \frac{2V}{I}$$

As torque $\propto \phi I \propto I^2$

$$\therefore \qquad T \propto \left(\frac{I}{2}\right)^2 \propto \frac{I^2}{4}.$$

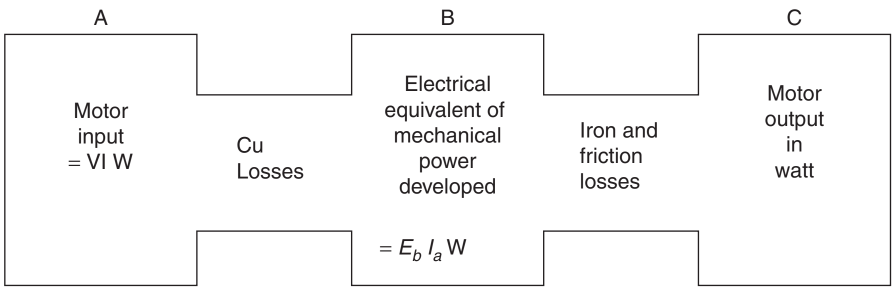
When in series

$$\text{Speed} \propto \frac{E_b}{\phi} \propto \frac{(V/2)}{I} \propto \frac{V}{2I}$$

$$T \propto \phi I \propto I^2$$

This speed is one-fourth of the speed of the motors when in parallel and the torque is four times that produced by two motors when in parallel.

Power Stages in a DC Motor



When the motor is at rest there is, as yet, obviously no back emf developed in the armature. If full supply voltage is applied across the stationary armature, it will draw a very large current because armature resistance is relatively small. This excessive current will blow out the fuses and prior to that it will damage the commutator, and brushes etc

- To limit the starting current to a safe predetermined value, every DC motor is to be provided with a starter or starting resistance. The starting resistance is gradually cut out as the motor gains speed and develops the back emf which then regulates its speed.
- There are two types of starters for DC shunt motors. They are as follows:
  (i) Three-point starter
  (ii) Four-point starter.
- Along with the limiting resistance protective devices are also mounted on the three-point starter of DC shunt motor, they are N.V.R. (no volt release) and the O.L.R. (over load relay)

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

$$\text{Overall or commercial efficiency } \eta_c = \frac{C}{A}$$

$$\text{Electrical efficiency } \eta_e = \frac{B}{A}$$

$$\text{Mechanical efficiency } \eta_m = \frac{C}{B}$$

Example 23: A 440 V shunt motor has an armature resistance of 0.8 Ω. The back emf when giving an output of 7.46 kW at 80% efficiency is __________ V.

(A) 440 (B) 400
(C) 220 (D) 425

Solution: (C)

$$\text{Input power} = \frac{7.46 \times 1000}{0.8}$$

$$= 9325 \text{ W}$$

$$\text{Input current} = \frac{9325}{440} = 21.193 \text{ A}$$

$$I_f = \frac{440}{220} = 2{,}2 \text{ A}$$

$$I_a = 21.193 - 2.2 = 18.99 \text{ A}$$

$$E_b = V - I_a R_a$$
$$= 440 - 18.99 \times 0.8$$
$$= 424.8 \text{ V}$$

Starters for DC Motors

The current drawn by a motor armature is given by the relation

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

- The main drawback of the three-point starter is maloperation of the N.V.R. which makes it unsuitable for use with variable speed motors, if the speed is controlled by the field flux control method.

Electric Braking

A motor comes to rest by applying Brake to the motor. There are generally two breaking phenomenon (i) electro mechanical braking (or) friction braking (ii) electrical braking. In these electro mechanical Breaking drawback is sudden application of braking force.

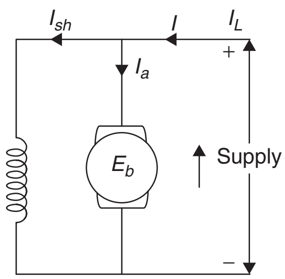
Electrical braking are generally three types.

1. Dynamic (or) rheostatic braking
2. Plugging (or) counter current braking
3. Regenerative braking

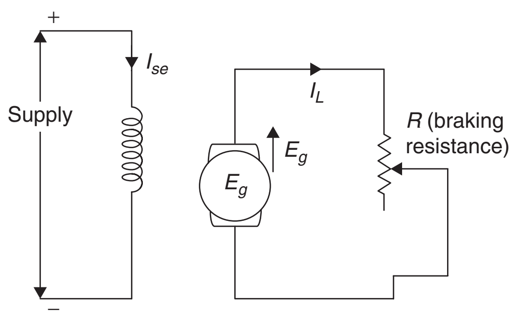
Dynamic (or) Rheostatic Braking

In this method the armature of DC motor is disconnected from the supply and is connected across a Braking (variable) resistance. The different DC motor connection as shown below.

DC Shunt Motor



(i) Under normal condition

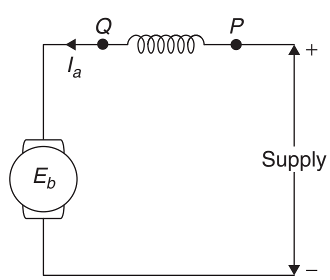


(ii) Under braking condition

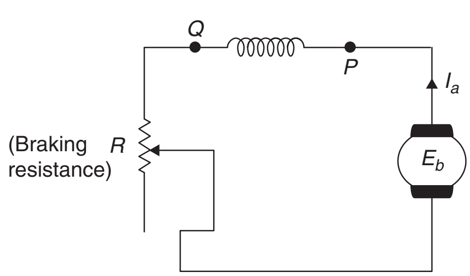
$$\text{Braking torque } T_B = \frac{1}{2\pi}\phi Z I_a \left(\frac{P}{A}\right) \text{Nm}$$

DC Series Motor

In this motor, the field connection also reversed during braking to make the current flowing through the field winding in the same direction. The connection of the motor under normal condition and braking condition is as shown below.



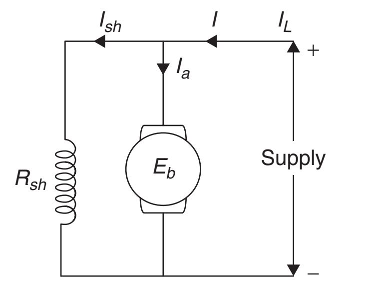
(i) Under normal condition



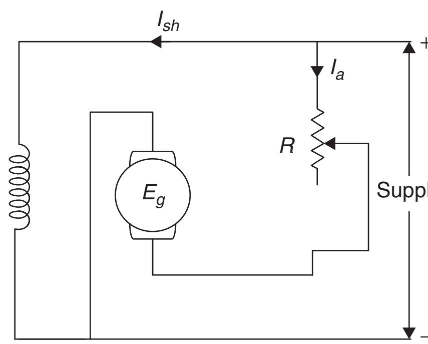
(ii) Under braking condition

Plugging (or) Counter Current Braking

In these method, the armature terminals is reversed without changing the supply terminals and a variable resistance is connected in series with the armature terminals to limit the armature current. The circuit connection of DC motors is as shown below.

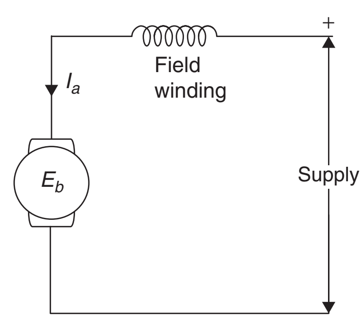


(i) Under normal condition

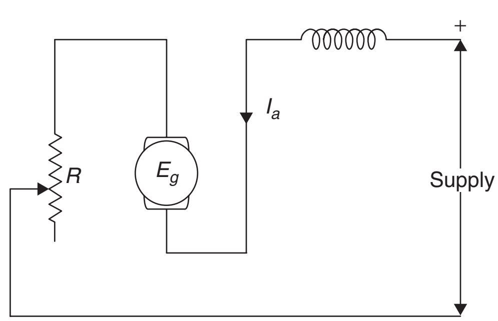


(ii) Under braking condition

Figure 3 DC Shunt motor



(i) Under normal condition



(ii) Under braking condition

Figure 4 DC Series motor

Regenerative Braking

Regenerative braking takes place when E_b becomes greater than supply voltage. Regenerative braking can be easily applied to DC shunt motors without changing any circuit connections. But In DC series motor it is not possible without changing circuit connection because back emf more than the supply voltage and the current flowing through the field winding is in reverse direction. So this method is applied to DC series motor by special arrangements only.

Testing of DC Machines

DC machines are to be tested for determining the efficiency and other performance indices.

There are three types of testing DC machines. They are

1. Direct testing
2. Indirect testing
3. Regenerative or Back-to-Back method.

Brake Test

It is a direct method and consists of applying a brake to a water-cooled pulley mounted on the motor shaft.

Swinburne's Test

It is a simple indirect test in which losses are measured separately and from their knowledge, efficiency at any desired load can be predetermined. However this test is applicable to those machines which have practically flux, i.e., shunt and compound machines.

Advantages

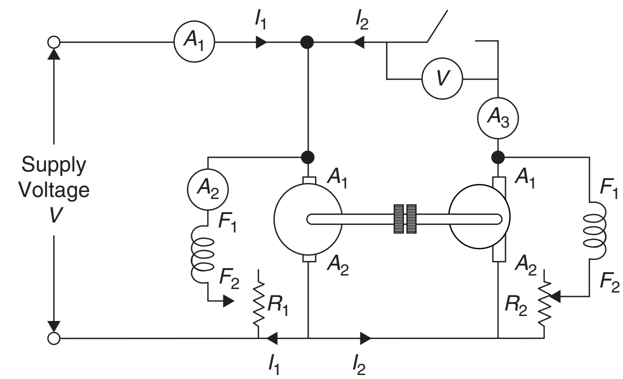
1. It is simple and economical because power required to test a large machine is small, i.e., only no-load input power.
2. The efficiency can be predetermined at any load because constant losses are known.

Disadvantages

1. No account is taken of the change in iron losses from no load to full load. At full-load due to armature, reaction flux is distorted which increases the iron losses in some cases as much as 50%.
2. As the test is on no load, it is impossible to know the effects of the temperature rise and commutation at full load.

Regenerative or Hopkinson's Test (Back-to-Back test)

It is performed on a pair of identical shunt machines, the two machines are mechanically coupled and field excitations are so adjusted that one of them runs as a motor and the other as a generator. By this method full-load test can be carried out, without wasting their outputs and hence the name regenerative test. The mechanical output of motor drives the generator and the electrical output of generator is used in supplying the greater part of input to the motor. The power supplied in this test is to meet the losses in two machines.



If η is efficiency of both motor and generator

Input to motor = $V(I_1 + I_2)$

Output of motor = $\eta \cdot V(I_1 + I_2)$

Output of generator = $\eta \cdot \eta V(I_1 + I_2) = \eta^2\ V(I_1 + I_2)$ but output of generator is $I_2.V$

$$\therefore \quad \eta^2\ V(I_1 + I_2) = I_2 \cdot V$$

$$\eta = \sqrt{\frac{I_2}{I_1 + I_2}}$$

Merits of Hopkinson's Test

1. Power required for the test is small as compared to the full-load powers of the two machines.
2. As machines are being tested under full load conditions, the temperature rise and the commutation qualities of the machines can be observed.
3. Because of full-load conditions, any change in iron loss due to flux distortion at full load, is being taken into account.

*The only disadvantage is with regard to the availability of two identical machines.

Retardation or Running Down Test

This method is applicable to shunt motors and generators and is used for finding stray losses. Then knowing the armature and shunt Cu losses at a given load current, efficiency can be calculated.

The machine under test is speeded up slightly beyond its normal speed and then supply is cut off from the armature while keeping the field excited.

Consequently the armature slows down and its kinetic energy is used to meet the rotational losses if friction, windage and iron losses.

Field Test for Series Motor

This test is applicable to two similar series motors. Series motors mainly used for traction work are easily available in pairs. The two machines are coupled mechanically. One machine runs normally as a motor and drives generator whose output is wasted in a variable load R.

Iron and frictional losses of two machines are made equal

1. By joining the series field winding of the generator in the motor armature circuit so that both machines are equally excited and
2. By running them at equal speed.

Field test is not a regenerative method although the two machines are mechanically coupled, because the generator output is wasted instead of being fed back into the motor as in Hopkinson's test.

Exercises

Practice Problems I

Directions for questions 1 to 29: Select the correct alternative from the given choices.

1. DC motor gives maximum power when
(A) $V = 2E_b$ (B) $V = E_b/2$
(C) $V = E_b/\sqrt{2}$ (D) $V = E_b$

2. The full-load speed regulation is 8% when the speed at full load is 800 rpm. The no-load speed is ______ rpm.
(A) 832 (B) 864
(C) 736 (D) 768

3. A 4-pole generator with 24 conductors has a two-layer lap winding. The pole pitch is _______.
(A) 24 (B) 12
(C) 6 (D) 4

4. A DC motor develops a torque of 120 Nm at 20 rps. At 30 rps, it will develop a torque of _____ Nm.
(A) 160 (B) 120
(C) 80 (D) 40

5. A DC motor connected to a 230 V supply has an armature resistance of 0.15 Ω. The value of armature current when the back emf $E_b = 200$ V is ______ A.
(A) 50 (B) 100
(C) 400 (D) 200

6. A 230 V shunt motor develops a torque of 48 Nm at an armature current of 12 A. The torque produced when the armature current is 15 A, is
(A) 48 Nm (B) 36 Nm
(C) 60 Nm (D) 72 Nm

7. An 8-pole, lap-wound armature running at 350 rpm is required to generate 260 V. The useful flux/pole is 0.05 Wb. If the armature has 120 slots, the no. of conductors/slot is ________
(A) 6 (B) 8
(C) 10 (D) 4

8. The value of torque produced by armature of 4-pole motor having 774 conductors, two paths in parallel, 24 mWb flux per pole, when the total armature current is 50 A, is _______.
(A) 350 Nm (B) 373 Nm
(C) 295.35 Nm (D) 420 Nm

9. A 440 V shunt motor has an armature resistance of 0.8 Ω. The back emf when giving an output of 7.46 kW at 80% efficiency is ______ V.
(A) 440 (B) 400
(C) 220 (D) 425

Common Data for Question 10:
A 230 V DC shunt motor takes a current of 40 A and runs at 1100 rpm. If armature and shunt field resistances are 0.25 Ω and 230 Ω respectively.

10. The torque developed by the motor is _______.
(A) 78.9 Nm (B) 74.66 Nm
(C) 98.7 Nm (D) 87.9 Nm

Common Data for Questions 11 and 12:
The counter emf of a shunt motor is 227 V, the field resistance is 160 Ω and the field current is 1.5 A.

11. If the line current is 39.5 A, the armature resistance is ________
(A) 0.342 Ω (B) 0.243 Ω
(C) 0.423 A (D) 0.432 Ω

12. The starting current of the motor is ______.
(A) 250 A (B) 107.57 A
(C) 255.5 A (D) 701.75 A

Common Data for Question 13:
A 250 V DC shunt motor takes a total current of 20 A. Resistance of shunt field winding is 200 Ω and that of armature is 0.3 Ω.

13. A 4-pole lap-wound generator is run at 900 rpm. The reactance voltage if self inductance is 153×10^{-6} H, armature current is 108 A, no of segments = 55, width of brush = 1.74 segments is _______
(A) 3.195 V (B) 3.915 V
(C) 5.391 V (D) 5.915 V

Common Data for Questions 14 and 15:
A 450 V series motor runs at 500 rpm taking a current of 40 A. Total resistance of the armature and field circuits is 0.8 Ω, assuming flux is proportional to field current and that the load is reduced so that motor draws a current of 30 A.

14. The percentage change in torque is
(A) 38.75% (B) 41.75%
(C) 39.75% (D) 43.75%

15. Speed is ________ rpm
(A) 627.94
(B) 697.4
(C) 679.42
(D) 649.72

16. A cumulative compounded long shunt motor is driving a load at rated torque and rated speed. If the series field is shunted by a resistance of the series field, keeping the torque constant then
(A) the armature current increases
(B) the armature current decreases
(C) the series field current remains the same
(D) the motor fails to run and comes to a standstill

17. A differentially compounded DC motor with interpoles and with brushes on the neutral axis is to be driven as a generator in the direction with the same polarity of the terminal voltage. It will then
(A) be a cumulatively compounded generator but interpole coil connections are to be reversed
(B) be a differentially compounded generator but the interpole coil connections are to be reversed
(C) be a cumulatively compounded generator without reversing the interpole coil connections
(D) be a differentially compounded generator without reversing the interpole coil connections

18. In case of an armature controlled separately excited DC motor drive with closed loop speed control, an inner current loop is useful because it
(A) limits the peak current of the motor to the permissible value.
(B) helps in improving energy efficiency of the drive.
(C) limits the speed of the motor to a safe value.
(D) reduces the steady state speed error.

19. The compensating winding in a DC machine
(A) is located on interpoles for improving commutation
(B) is a separate winding in armature slots for compensation of the armature reaction
(C) is located on pole shoes for avoiding the flashover at the commutator surface
(D) is located on pole shoes to avoid the sparking at the brushes

20. The DC motor which can provide zero speed regulation at full load without any controller is
(A) shunt
(B) series
(C) differential compound
(D) cumulative compound

21. In relation to DC machines, match the following and choose the correct combination:

List-I (performance variables)	List-II (proportional to)
P. Armature emf (E)	1. Flux (ϕ), speed (ω), armature current (I_a)
Q. Developed power (P)	2. I_a only
R. Developed torque (T)	3. ϕ and I_a only
	4. ϕ and ω only
	5. I_a and ω only

(A) P – 4, Q – 3, R – 1
(B) P – 2, Q – 3, R – 4
(C) P – 3, Q – 4, R – 1
(D) P – 2, Q – 5, R – 4

22. A DC series motor driving an electric train faces a constant power load. It is running at rated speed and rated voltage. If the speed has to be brought down to 0.5 p.u., the supply voltage has to be approximately brought down to
(A) 0.25 p.u. (B) 0.5 p.u.
(C) 0.707 p.u. (D) 0.8 p.u.

23. An electric motor whose torque-speed characteristic in the form of a rectangular hyperbola will have
(A) constant speed
(B) constant torque
(C) constant output power
(D) none of the above

24. The armature resistance of permanent magnet DC motor is 0.5 Ω at no load the motor draws 1.2 A from a supply voltage of 25 V and runs at 1500 rpm. The efficiency of the motor while it is operating on load at 1500 rpm drawing a current of 3 A from the same source will be
(A) 48.12%. (B) 54.96%.
(C) 62.28%. (D) 74.56%.

25. A 220 V DC series motor takes 30 A when giving its rated output at 1500 rpm. Its resistance is 0.25 Ω. The value of resistance which must be added to obtain rated torque at 1000 rpm is
(A) 1.26 Ω. (B) 2.36 Ω.
(C) 3.26 Ω. (D) 4.26 Ω.

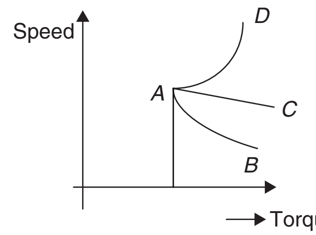
26. A 4-pole lap-wound DC generator has a developed power of P W and voltage of E volt. Two adjacent brushes of the machine are removed as they are worn out. If the machine operates with the remaining brushes, the developed voltage and power that can be obtained from the machine are

(A) $\frac{E}{4}, \frac{P}{4}$ (B) $\frac{E}{2}, \frac{P}{2}$

(C) $E, \frac{P}{4}$ (D) $E\ \frac{P}{2}$

27. An electric motor with 'constant output power' will have a torque speed characteristic in the form of a
(A) straight line parallel to speed axis.
(B) straight line through the origin.
(C) straight line parallel to torque axis.
(D) rectangular hyperbola.

28. A DC series motor fed from rated supply voltage is overloaded and its magnetic circuit is saturated. The torque-speed characteristic of this motor will be approximately represented by which curve of figure.



(A) curve A (B) curve B
(C) curve C (D) curve D

29. A permanent magnet DC commutator motor has a no-load speed of 6000 rpm when connected to 120 V DC supply. The armature resistance is 2.5 Ω and other loses may be neglected. Supply voltage of 60 V developing a torque of 0.5 Nm, is
(A) 2326 rpm (B) 2673 rpm
(C) 2836 rpm (D) 5346 rpm

Practice Problems 2

Directions for questions 1 to 50: Select the correct alternative from the given choices.

1. The core losses of a certain magnetic material, operated at constant flux density are 2200 and 3500 W at frequencies 50 Hz and 75 Hz respectively. Determine the hysteresis and eddy current loss at a frequency of 100 Hz
(A) 1067 W, 3867 W
(B) 3867 W, 1067 W
(C) 2167 W, 1867 W
(D) 1867 W, 2167 W

2. A 4-pole lap-wound DC armature with 600 conductors draws 60 A from the mains. Its armature reaction per pole is
(A) 775 AT peak sinusoidal
(B) 625 AT peak triangular
(C) 500 AT peak triangular
(D) 500 AT peak sinusoidal

3. In a DC motor torque developed in (Nm) is

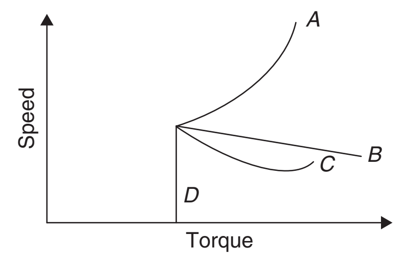
(A) $\frac{\omega_n}{E_b I_a}$ in the direction of ω_n (speed in rad/s)

(B) $\frac{\omega_n}{E_b I_a}$ opposite to the direction of ω_n

(C) $\frac{E_b I_a}{\omega_n}$ in the direction of ω_n

(D) $\frac{E_b I_a}{\omega_n}$ opposite to the direction of ω_n

4. A DC series motor is overloaded and its magnetic circuit is saturated. The torque speed characteristic of this motor will be



(A) A (B) B
(C) C (D) D

5. A 6-pole DC generator with 36 coils has a two layer lap winding. What can be the pole pitch?
(A) 6 (B) 12
(C) 24 (D) 48

6. A separately excited DC generator has ratings of 240 V, 2500 rpm and 10 A. R_a = 10 Ω. Armature and field winding is excited with rated DC voltage. If armature draws 5 A, torque developed is
(A) 1.63 Nm (B) 3.63 Nm
(C) 2.225 Nm (D) 0.25 Nm

7. A 240 V DC series motor, running at 1500 rpm takes 20 A when giving its rated output. Total series resistance = 0.5 Ω. To obtain rated torque at 1000 rpm, value of resistance that must be added is
(A) 3.7 Ω (B) 5.7 Ω
(C) 2.2 Ω (D) 3.2 Ω

8. A permanent magnet DC motor when connected to a 100 V DC supply runs at a no load speed of 4000 rpm. R_a = 2 Ω and other losses may be neglected. When supplied with a voltage of 50 V and developing a torque of 0.5 Nm speed of motor is
(A) 2000 rpm (B) 1832 rpm
(C) 2836 rpm (D) 4346 rpm

9. A cumulatively compounded DC motor runs at 1500 rpm at no load. At full load the combined drop in the armature and field is 8% and the flux increases by 12%. Neglecting magnetic saturation, full-load speed is equal to

(A) 1632 rpm (B) 1432 rpm
(C) 1232 rpm (D) 1032 rpm

10. The prime mover of an over compounded DC generator, supplying power to infinite bus is cut off. Which among the following is true?

(A) Machine stops running
(B) Machine runs as cumulatively compounded motor in reverse direction
(C) Machine runs in reverse direction as a differentially compounded motor
(D) Machine runs in same direction as a differentially compounded motor

11. The armature resistance of a 4-pole lap connected DC generator with 480 conductors is 0.08 Ω. The conductors are reconnected to form a wave winding, other things remaining the same. The new value of armature resistance will be

(A) 0.02 Ω (B) 0.08 Ω
(C) 0.64 Ω (D) 0.32 Ω

12. A DC series motor with 2-poles runs at 500 rpm with its two field coils connected in series. Now if the field coils are connected in parallel. The new speed will be (Assume magnetic circuit is unsaturated and torque is constant)

(A) 250 rpm (B) 500 rpm
(C) $250\sqrt{2}$ rpm (D) 1000 rpm

13. A DC generator on load has its brushes on geometric neutral axis. The magnetic neutral axis gets shifted in the direction of rotation. If a 90° lead is given to the brushes,

(A) The magnetic neutral axis coincides with geometric neutral axis
(B) Magnetic neutral axis is shifted forward by 90°
(C) Magnetic neutral axis is shifted forward by more than 90°
(D) Magnetic neutral axis is shifted forward by less than 90°

14. A 230 V DC series motor has $R_a = 0.4$ Ω and $R_f = 0.2$ Ω. It draws a line current of 20 A and runs at a speed of 1500 rpm. Assuming that flux at 10 A line current is 65% of flux at 20 A, what is the speed of the motor at a line current of 10 A and 230 V?

(A) 1913 rpm (B) 2371 rpm
(C) 2331 rpm (D) 2531 rpm

15. The output of a 220 V DC shunt motor with an input of 15 kW is 13 kW. $R_f = 100$ Ω and $R_a = 0.08$ Ω. The efficiency is maximum when armature copper losses are

(A) 1670 W (B) 2000 W
(C) 3000 W (D) 2670 W

16. A full pitch coil in a 4-pole machine has a mechanical angle span of

(A) 30° (B) 45° (C) 90° (D) 180°

17. The armature circuit resistance and field circuit resistance of a 200 V DC shunt motor are 0.2 Ω, and 200 Ω respectively. It takes 4 A at no load. The efficiency when motor takes an input current of 20 A is

(A) 51.73% (B) 81.17%
(C) 78.2% (D) 73.62%

Common Data Questions 18 and 19:

A 18 kW, 200 V DC shunt motor has an armature resistance of 0.3 Ω and field resistance of 100 Ω. Speed at rated load is 1500 rpm and full-load efficiency is 75%

18. To limit starting current to 300% of rated current, starting resistance is

(A) 0.12 Ω (B) 0.26 Ω
(C) 0.46 Ω (D) 1 Ω

19. If the starting resistance in Q18 remains as it is on full load, the speed at full load will then be

(A) 1134 rpm (B) 1434 rpm
(C) 1500 rpm (D) 1534 rpm

20. A 4-pole, 230 V, 100 kW DC shunt generator has 600 lap-wound conductors. Two-degree brush lead is given from geometric neutral. The cross and demagnetizing turns per pole will respectively be

(A) 7790 A and 362 A
(B) 362 A and 7790 A
(C) 6680 A and 532 A
(D) 532 A and 6650 A

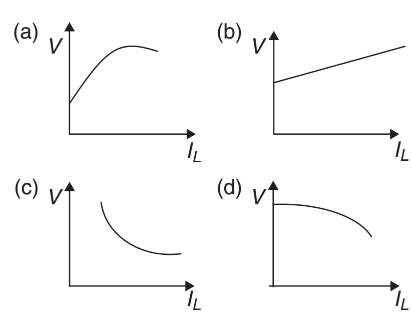
21. The armature of a 6-pole lap-wound DC machine has 600 conductors. Ratio of pole arc to pole pitch is 0.7. The compensating winding carries full armature current. The no. of conductors on each pole of this compensating winding will be

(A) 6 (B) 12 (C) 24 (D) 30

22. At maximum power output, the efficiency of machine is

(A) 0% (B) 75% (C) 50% (D) 100%

23. The terminal voltage vs. load current characteristics of a DC shunt generator is depicted by which among the following curves



24. In a DC generator, polarity of interpole is
(A) always south pole
(B) always north pole
(C) same as the polarity of main pole that follows in the direction of rotation
(D) same as the polarity of main pole that precedes in the direction of rotation

25. The external characteristics of a DC generator is
(A) Magnetisation characteristics + Armature reaction
(B) Magnetisation characteristics – Armature reaction
(C) Magnetisation characteristics – Armature reaction – ohmic drop
(D) Magnetisation characteristics + Armature reaction – ohmic drop

26. Lap-wound DC generators use equalizer rings to
(A) avoid unequal distribution of current at brushes giving sparkless commutation
(B) to provide mechanical balance
(C) to counter armature reaction by producing equalizing voltages in widening
(D) to reduce the load as the bearings

27. The torque developed by a DC series motor at 8 A is 25 Nm. If the current is increased to 16 A, the torque developed is
(A) 50 Nm (B) 25 Nm
(C) 100 Nm (D) 200 Nm

28. Armature reaction in a DC machine is
(A) in same direction as main poles
(B) to make an angle with main pole axis depending on load current
(C) in direct opposition to main poles
(D) to make an angle of 90° with main pole axis

29. Open slots are used in DC machine armature as
(A) it reduces coil reactance and aids in commutation
(B) it increases induced emf per coil
(C) it is easy to place the winding in the slots
(D) it reduces armature voltage drop

Common Data Questions 30 and 31:
A separately excited DC motor runs at 1200 rpm at no load and 250 V applied to armature. The field is given rated excitation. When it delivers a load of 8 Nm, speed is 1100 rpm. Rotational loses and armature reaction can be neglected.

30. Armature resistance of motor is
(A) 3 Ω (B) 5.2 Ω
(C) 4.4 Ω (D) 7.7 Ω

31. For motor to deliver a torque of 4 Nm at 1100 rpm armature voltage to be applied is
(A) 200 V (B) 239.6 V
(C) 250 V (D) 225.2 V

32. A motor has zero speed regulation at full load without the use of any controller. The motor is
(A) DC series motor
(B) DC shunt motor
(C) DC cumulatively compounded motor
(D) DC differentially compounded motor

33. A DC machine supplies 25 A at 250 V as a generator R_a = 0.2 Ω. The machine operated as a motor with 10% increased flux but terminal voltage and current remaining same, then ratio of motor speed to generator speed is
(A) 0.87 (B) 0.95
(C) 0.96 (D) 1.06

34. With regard to a DC machine, the function of compensating winding and interpole is
(A) neutralize armature reaction and produce residual flux, respectively
(B) neutralize armature reaction and improve commutation, respectively
(C) improve commutation and produce residual flux, respectively
(D) improve commutation and neutralize armature reaction, respectively

35. In relation to DC machines, match the following and choose correct combination

P. Developed Power (P)	1. Flux (ϕ), speed (ω) and armature current (I_a)
Q. Developed Torque (T)	2. I_a and ω only
R. Armature EMF (E)	3. ϕ and ω only
	4. ϕ and I_a only
	5. I_a only

(A) P – 1, Q – 4, R – 2
(B) P – 2, Q – 5, R – 3
(C) P – 1, Q – 4, R – 3
(D) P – 2, Q – 5, R – 1

36. A 30 kW DC shunt motor is drawing rated current at a given speed. When driven
(1) at half-rated speed by armature voltage control
(2) 2 times rated speed by field control Output power delivered by the motor are approximately
(A) 15 kW in (1) 45 kW in (2)
(B) 15 kW in (1) 30 kW in (2)
(C) 30 kW in (1) 45 kW in (2)
(D) 30 kW in (1) 30 kW in (2)

37. A DC series motor driving an electric train faces a constant power load at rated speed and rated voltage. For the speed to be 0.5 p.u., the supply voltage should be
(A) 0.8 p.u. (B) 0.5 p.u.
(C) 0.7 p.u. (D) 0.6 p.u.

38. Match the following in Group I and Group II with regard to a DC motor

Group I	Group II
P. Field Control	1. Below base speed
Q. Armature Control	2. Above base speed
	3. Above base torque
	4. Below base torque

(A) P – 1, Q – 4 (B) P – 2, Q – 3
(C) P – 1, Q – 3 (D) P – 2, Q – 1

Common Data Questions 39 and 40:

A 7.5 kW, 200 V, 50 A, 1500 rpm DC series motor has following full-load losses expressed in percentage of motor input

Losses in armature resistance and brush = 2.6%
Losses in field circuit = 2.4 %
Friction and windage losses (Rotational loss) = 2.2%
Assume rotational loss to be constant.

39. When motor draws one half rated current at rated voltage Speed in rpm is
(A) 2057 rpm
(B) 2889 rpm
(C) 3079 rpm
(D) 1500 rpm

40. Shaft power output will be
(A) 2925 W
(B) 3925 W
(C) 4925 W
(D) 5925 W

41. In an electromechanical energy conversion system, the developed electromagnetic force/torque at in a direction that tends to
(A) decrease stored energy at constant flux
(B) increase stored energy at constant mmf
(C) decrease stored energy at constant mmf
(D) decrease co-energy at constant mmf

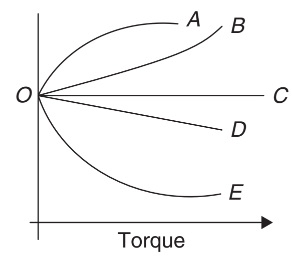
42. The hysteresis loop of a magnetic material has an area of 10 cm^2. The scales are marked as 1 cm = 4AT and 1 cm = 100 mWb Total hysteresis loss at 50 Hz is
(A) 50 W (B) 100 W
(C) 200 W (D) 400 W

43. A DC shunt motor is started with an open circuited field. Then
(A) The motor picks up fast and acquires full speed while drawing large current
(B) Motor does not pick up speed but draws a large current
(C) The motor does not pick up speed but draws only a small current
(D) The motor picks up speed fast and acquires full speed while drawing only a small current

44. In a DC series motor with linear magnetization and negligible armature resistance, the motor speed is
(A) inversely proportional to T
(B) directly proportional to T
(C) directly proportional to $\sqrt{T}$
(D) inversely proportional to $\sqrt{T}$

45. A DC shunt generator coupled to a prime move of constant speed and fixed field resistance is shouted across the terminals. Then short-circuit current is
(A) several times the rated current
(B) equal to full-load rated current
(C) less than maximum rated current
(D) None of the above

46. The speed torque characteristics of a cumulatively compounded DC motor is



(A) Curve OA (B) Curve OB
(C) Curve OD (D) Curve OE

47. The supply terminals of a DC shunt motor are reversed, then
(A) it will run as a DC generator
(B) it will continue to run in same direction
(C) it will reverse its direction
(D) it will stop

48. In Ward Leonard system of speed control of DC motor, the lower speed limit is restricted by
(A) core losses in the motor
(B) residual magnetism of generator
(C) mechanical losses of motor and generator together
(D) All the above

49. A DC machine used as a generator has an efficiency of 80% when output voltage and currents are 200 V and 8 A. If machine is used as a motor and takes 8 A from 200 V supply then efficiency will be
(A) 80% (B) Less than 80%
(C) More than 80% (D) None of these

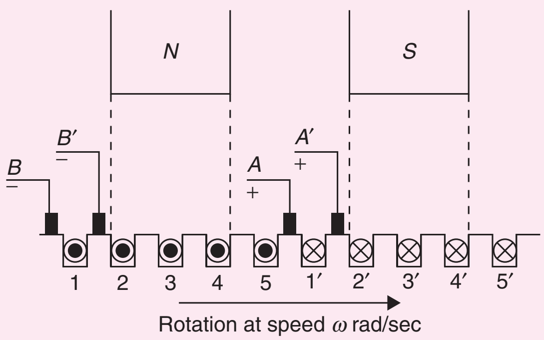
50. A DC shunt motor is running at 1500 rpm with rated voltage applied to its terminals. Neglecting the saturation of magnetic circuit, if applied voltage is reduced to $\frac{2}{3}$ of original value, motor will run at
(A) 1005 rpm (B) 750 rpm
(C) 1500 rpm (D) 2250 rpm

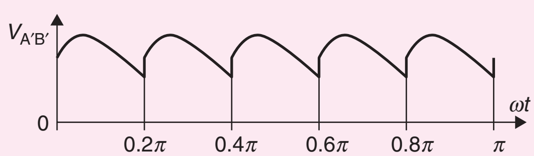
Previous Years' Questions

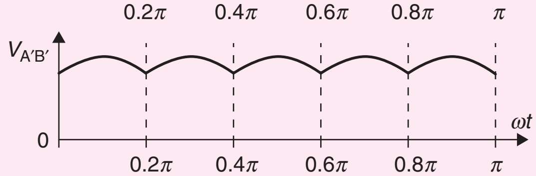
Data for Question 1:
A 240 V, DC shunt motor draws 15 A while supplying the rated load at a speed of 80 rad/s. The armature resistance is 0.5 Ω and the field winding resistance is 80 Ω

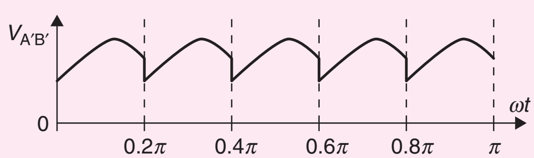
1. The external resistance to be added in the armature circuit to limit the armature current to 125% of its rated value is **[2008]**
(A) 31.1 Ω (B) 31.9 Ω
(C) 15.1 Ω (D) 15.9 Ω

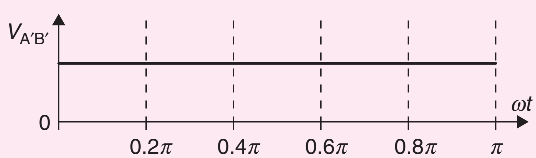
2. Figure shows the extended view of a 2-pole DC machine with 10 armature conductors. Normal brush positions are shown by A and B, placed at the interpolar axis. If the brushes are now shifted, in the direction of rotation, to A' and B' as shown, the voltage waveform $V_{A'B'}$ will resemble **[2009]**



(A)


(B)


(C)


(D)


3. The armature resistance of the motor is, **[2010]**
(A) 2 Ω (B) 3.4 Ω
(C) 4.4 Ω (D) 7.7 Ω

4. For the motor to deliver a torque of 2.5 Nm at 1400 rpm, the armature voltage to applied is **[2010]**
(A) 125.5 V (B) 193.3 V
(C) 200 V (D) 241.7 V

5. A 4-point starter is used to start and control the speed of a **[2011]**
(A) DC shunt motor with armature resistance control
(B) DC shunt motor with field weakening control
(C) DC series motor
(D) DC compound motor

6. A 220 V, DC shunt motor is operating at a speed of 1440 rpm. The armature resistance is 1.0 Ω and armature current is 10 A. If the excitation of the machine is reduced by 10%, the extra resistance to be put in the armature circuit to maintain the same speed and torque will be **[2011]**
(A) 1.79 Ω (B) 2.1 Ω
(C) 3.1 Ω (D) 18.9 Ω

7. A 220 V, 15 kW, 1000 rpm shunt motor with armature resistance of 0.25 Ω, has a rated line current of 68 A and a rated field current of 2.2 A. The change in field flux required to obtain a speed of 1600 rpm while drawing a line current of 52.8 A and a field of 1.8 A is **[2012]**
(A) 18.18 % increase (B) 18.18 % decrease
(C) 36.36 % increase (D) 36.36 % decrease

8. A 15 kW, 230 V DC shunt motor has armature circuit resistance of 0.4 Ω and field circuit resistance of 230 Ω. At no load and rated voltage, the motor runs at 1400 rpm and the line current drawn by the motor is 5 A. At full load, the motor draws a line current of 70 A. Neglect armature reaction. The full load speed of the motor in rpm is ______. **[2014]**

9. A 250 V DC shunt machine has armature circuit resistance of 0.6 Ω and field circuit resistance of 125 Ω. The machine is connected to 250 V supply mains. The motor is operated as a generator and then as a motor separately. The line current of the machine in both the cases is 50 A. The ratio of the speed as a generator to the speed as a motor is ____________. **[2014]**

10. The no-load speed of a 230 V separately excited DC motor is 1400 rpm. The armature resistance drop and the brush drop are neglected. The field current is kept constant at rated value. The torque of the motor in Nm for an armature current of 8 A is _____. **[2014]**

11. A separately excited 300 V DC shunt motor under no load runs at 900 rpm drawing an armature current of 2 A. The armature resistance is 0.5 Ω and leakage inductance is 0.01 H. When loaded, the armature current is 15 A. then the speed in rpm is _______. **[2014]**

12. A separately excited DC generator has an armature resistance of 0.1 | and negligible armature inductance. At rated field current and rated rotor speed, its open-circuited voltage is 200 V. When this generator is operated at half the rated speed, with half the rated field current, an uncharged 1000 μF capacitor is suddenly connected across the armature terminals. Assume that the speed remains unchanged during the transient. At the time (in microsecond) after the capacitor is connected will the voltage across it reach 25 V? **[2015]**

(A) 62.25 (B) 69.3
(C) 73.25 (D) 77.3

13. A separately excited DC motor runs at 1000 rpm on no load when its armature terminals are connected to a 200 V DC source and the rated voltage is applied to the field winding. The armature resistance of this motor is 1 Ω. The no-load armature current is negligible. With the motor developing its full load torque, the armature voltage is set so that the rotor speed is 500 rpm. When the load torque is reduce to 50% of the full load value under the same armature voltage conditions, the speed rises to 520 rpm. Neglecting the rotational losses, the full load armature current (in Ampere) is ______. **[2015]**

14. A DC motor has the following specifications: 10 hp, 37.5 A, 230 V; flux/pole = 0.01 Wb, number of poles = 4, number of conductors = 666, number of parallel paths = 2. Armature resistance = 0.267 Ω. The armature reaction is negligible and rotational losses are 600 W. The motor operates from a 230 V DC supply. If the motor runs at 1000 rpm, the output torque produced (in Nm) is ________. **[2015]**

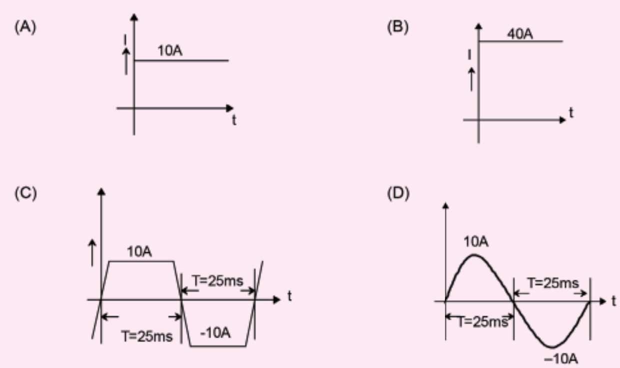
15. A shunt-connected DC motor operates at its rated terminal voltage. Its no-load speed is 200 radian/second. At its torque of 500 Nm, its speed is 180 radian/second. The motor is used to directly drive a load whose load torque T_L depends on its rotational speed ω_r (in radian/second), such that $T_L = 2.78 \times \omega_r$. Neglecting rotational losses, the steady-state speed (in radian/second) of the motor, when it drives this load, is _______. **[2015]**

16. A 4-pole, separately excited, wave wound DC machine with negligible armature resistance is rated for 230 V and 5 kW at a speed of 1200 rpm. If the same armature coils are reconnected to form a lap winding, what is the rated voltage (in volts) and power (in kW) respectively at 1200 rpm of the reconnected machine if the field circuit is left unchanged?

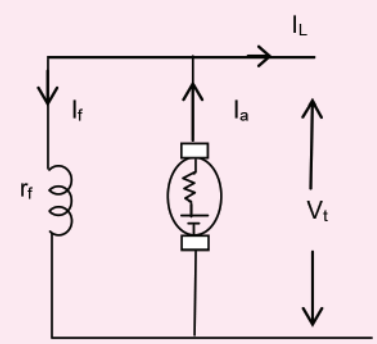
(A) 230 and 5 (B) 115 and 5
(C) 115 and 2.5 (D) 230 and 2.5

17. With an armature voltage of 100 V and rated field winding voltage, the speed of a separately excited DC motor driving a fan is 1000 rpm, and its armature current s 10 A. The armature resistance is 1 Ω. The load torque of the fan load is proportional to the square of the rotor speed. Neglecting rotational losses, the value of the armature voltage (in Volt) which will reduce the rotor speed to 500 rpm is ______. **[2015]**

18. A 4-pole, lap-connected, separately excited dc motor is drawing a steady current of 40 A while running at 600 rpm. A good approximation for the wave shape of the current in an armature conductor of the motor is given by **[2016]**



19. A DC shunt generator delivers 45 A at a terminal voltage of 220 V. The armature and the shunt field resistances are 0.01 Ω and 44 Ω respectively. The stray losses are 375 W. The percentage efficiency of the DC generator is __________. **[2016]**



Answer Keys

Exercises

Practice Problems 1

1. A	**2.** B	**3.** C	**4.** C	**5.** D	**6.** C	**7.** B	**8.** C	**9.** C	**10.** B
11. A	**12.** D	**13.** B	**14.** D	**15.** C	**16.** A	**17.** C	**18.** A	**19.** C	**20.** C
21. A	**22.** C	**23.** C	**24.** C	**25.** B	**26.** C	**27.** D	**28.** C	**29.** B	

Practice Problems 2

1. B	**2.** A	**3.** C	**4.** B	**5.** A	**6.** B	**7.** D	**8.** B	**9.** C	**10.** D
11. D	**12.** D	**13.** C	**14.** B	**15.** A	**16.** C	**17.** C	**18.** B	**19.** A	**20.** A
21. B	**22.** C	**23.** D	**24.** C	**25.** D	**26.** A	**27.** C	**28.** D	**29.** A	**30.** B
31. B	**32.** D	**33.** A	**34.** B	**35.** C	**36.** B	**37.** C	**38.** D	**39.** C	**40.** A
41. A	**42.** C	**43.** B	**44.** D	**45.** C	**46.** D	**47.** B	**48.** B	**49.** A	**50.** C

Previous Years' Questions

1. A	**2.** A	**3.** B	**4.** B	**5.** B	**6.** A	**7.** D	**8.** 1240.63	**9.** 1.27	**10.** 12.5
11. 880	**12.** B	**13.** 8	**14.** 57.78	**15.** 177 to 183		**16.** B	**17.** 47.5 V	**18.** C	**19.** 86.84