Supplementary Learning Material

for

MODULE-II

DC MACHINES

Subject: BASIC ELECTRICAL AND ELECTRONICS ENGINEERING

Subject Code: EEE 103

Class: I/IV-B.Tech- 1st Semester, 2017-18 – MECHANICAL ENGINEERING.

Module Objective: The purpose of the course is to impart the operational principles of DC motors, generators, transformers and three phase induction motors and how they work. Practical analytical models for most types of motors, generators, and transformers commonly used in industry are developed. The models are used to analyze power requirements, power capability, efficiency, operating characteristics, control requirements, and electrical demands of these machines.

Module Outcome: Acquire knowledge about the construction, basic principle of operation, applications, performance parameters and testing methods of DC Machine.

Department of Electrical and Electronics Engineering

GITAM INSTITUTE OF TECHNOLOGY (GIT)

GITAM University

VISAKHAPATNAM

Module-II
DC MACHINES
Frequently Asked Questions

1. Explain the working principle of a D.C. generator (simple loop generator) with a neat sketch.
2. Describe the constructional details of dc machines.
3. Derive the expression for induced emf in a DC generator.
4. List out the types of dc machines and explain
5. Explain the characteristics of a d.c. shunt and series generator.
6. Explain the characteristics of a d.c. separately excited generator.
7. Explain the operation of a dc motor
8. Derive the expression for torque of a dc motor
9. Explain the characteristics of a shunt motor and series motors
10. What is the necessity of a starter. With a neat diagram explain three point starter with neat diagram.
11. Explain about speed control techniques of dc motors
12. Explain about Swinburne's test.

PRINCIPLE OF OPERATION OF DC GENERATOR

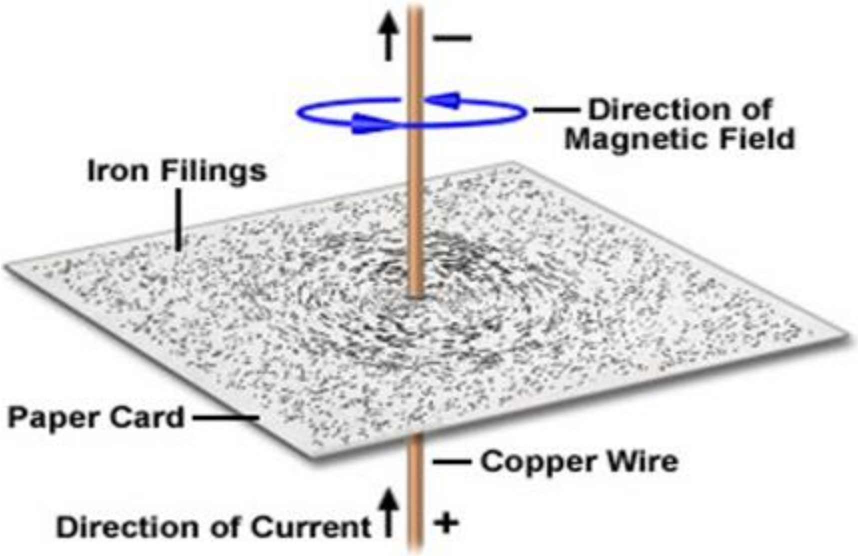
Faraday's law of electromagnetic induction:

Faraday found that the electromotive force (EMF) produced around a closed path is proportional to the rate of change of the magnetic flux through any surface bounded by that path.

- In practice, this means that an electrical current will be induced in any closed circuit when the magnetic flux through a surface bounded by the conductor changes.
- This applies whether the field itself changes in strength or the conductor is moved through it.
- Electromagnetic induction underlies the operation of generators, all electric motors, transformers, induction motors, synchronous motors, solenoids, and most other electrical machines.
- Faraday's law of electromagnetic induction states that:
    - E is the electromotive force (emf) in volts
    - Φ_B is the magnetic flux in webers
    - *N* is the number of turns of wire

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

Right Hand Thumb Rule:



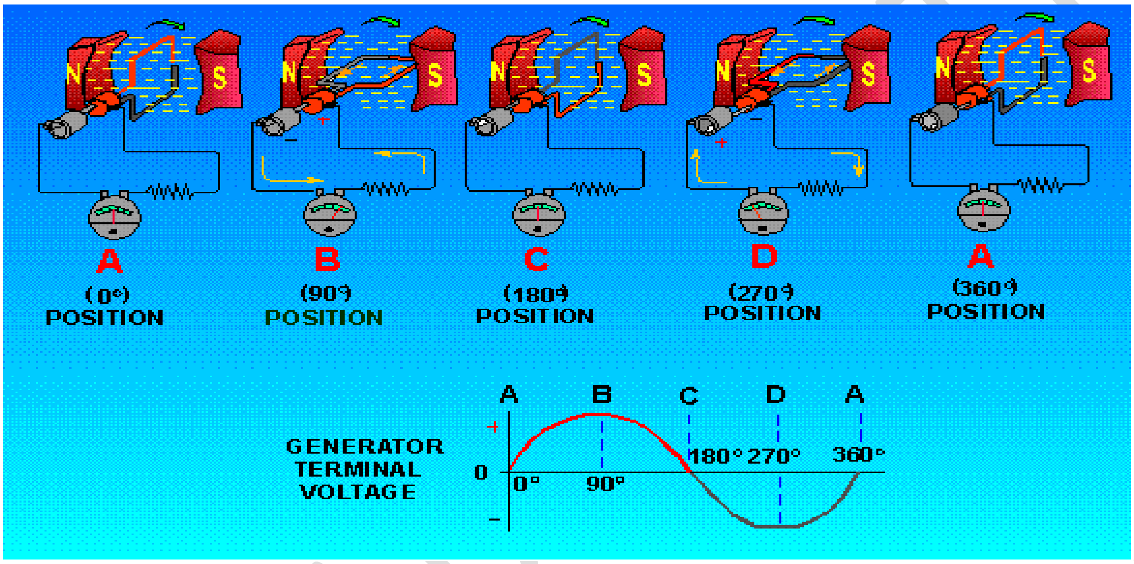
DC Generator Principle:

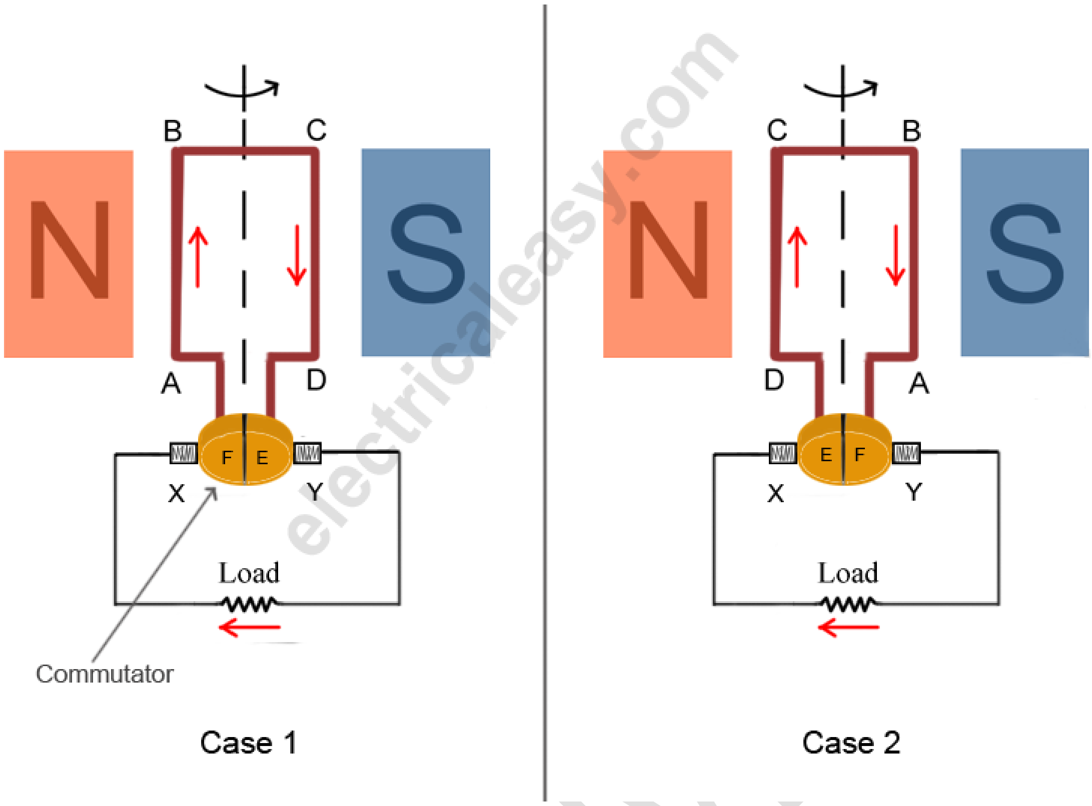
- A generator is a machine that converts mechanical energy into electrical energy by using the principle of magnetic induction.

> ***"Whenever a conductor is moved within a magnetic field in such a way that the conductor cuts across magnetic lines of flux, voltage is generated in the conductor"***

- The AMOUNT of voltage generated depends on the
  - The Strength of the magnetic field,
  - Angle at which the conductor cuts the magnetic field
  - Speed at which the conductor is moved
  - Length of the conductor within the magnetic field.
- The POLARITY of the voltage depends on the
  - Direction of the magnetic lines of flux and
  - Direction of movement of the conductor.
- To determine the direction of current or EMF in a given situation, the Flemings Right-Hand Rule for Generators is used

- According to Faraday's laws of electromagnetic induction, whenever a conductor is placed in a varying magnetic field (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor.
- The magnitude of induced emf can be calculated from the emf equation of dc generator. If the conductor is provided with the closed path, the induced current will circulate within the path.
- In a DC generator, field coils produce an electromagnetic field and the armature conductors are rotated into the field.
- Thus, an electromagnetically induced emf is generated in the armature conductors.

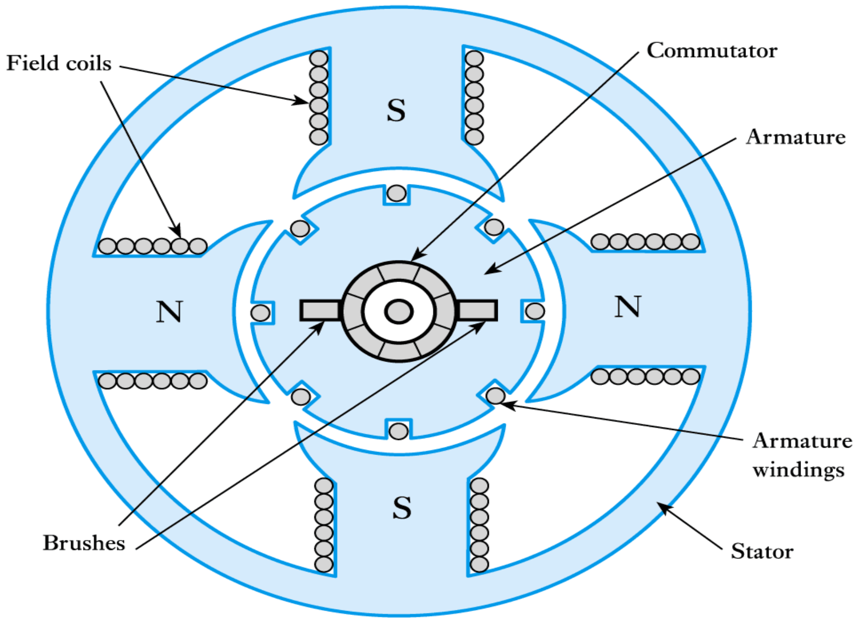




- According to Fleming’s right hand rule, the direction of induced current changes whenever the direction of motion of the conductor changes.
- Let’s consider an armature rotating clockwise and a conductor at the left is moving upward. When the armature completes a half rotation, the direction of motion of that particular conductor will be reversed to downward.
- Hence, the direction of current in every armature conductor will be alternating.
- From the above figure, the direction of the induced current is alternating in an armature conductor.
- But with a split ring commutator, connections of the armature conductors also gets reversed when the current reversal occurs. And therefore, we get unidirectional current at the terminals.

The direction of induced current is given by Fleming’s right hand rule.

CONSTRUCTION OF DC MACHINE:



Main parts of a Dc machine are

1.Magnetic frame or yoke.

2.Pole core and pole shoe.

3.Field winding or exciting winding

4.Armature core

5.Armature winding.

6.Commutator.

7.Brushes and bearings.

- **Yoke:** The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.
- **Poles and pole shoes:** Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in air gap uniformly.
- **Field winding:** They are usually made of copper. Field coils are former wound and placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.
- **Armature core:** Armature core is the rotor of the machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. Armature is keyed to the shaft.
- **Armature winding:** It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding. Double layer lap or wave windings are generally used. A double layer winding means that each armature slot will carry two different coils.
- **Commutator:** Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator, in a dc generator, is to collect the current generated in armature conductors. Whereas, in case of a dc motor, commutator helps in providing current to the armature conductors. A commutator consists of a set of copper segments which are insulated from each other. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the shaft.
- **Brush:** Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

TYPES OF DC MACHINES (Generator /Motor)

The classification of DC machines is according to the ways of excitation of their fields. There are three methods of excitation.

- **Seperately Excited**
- **Self Excited**
- **Shunt wound DC machines**
- **Series wound DC machines**
- **Compound DC machines**

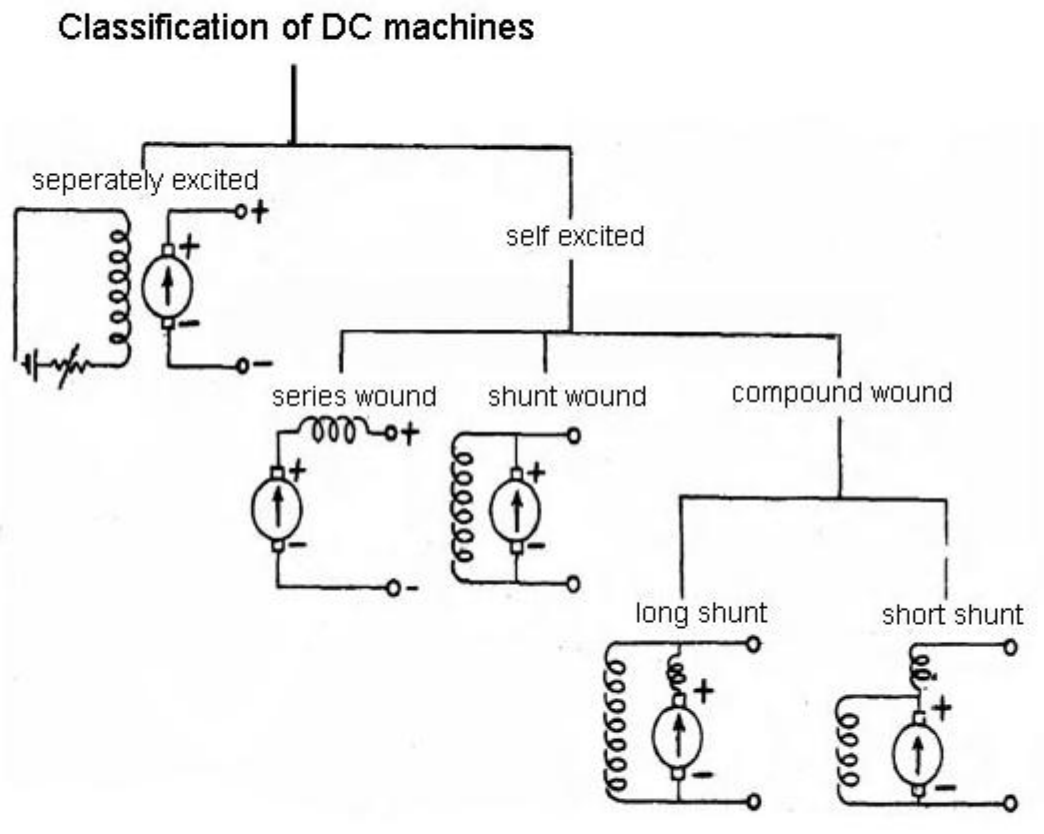
Separately excited: In separately excited dc machines, the field winding is supplied from a separate power source. The field winding is electrically separated from the armature circuit.

Self-excited: In this type, field winding and armature winding are interconnected in various ways to achieve a wide range of performance characteristics In self-excited type of DC generator, the field winding is energized by the current produced by themselves. A small amount of flux is always present in the poles due to the residual magnetism. So, initially, current induces in the armature conductors of a dc generator only due to the residual magnetism. The field flux gradually increases as the induced current starts flowing through the field winding.

- **Shunt wound**
  - ✓ Field winding is connected in parallel with the armature winding.
  - ✓ Shunt winding is made with a large number of turns and the resistance is kept very high
  - ✓ The full voltage is applied across the field winding.
  - ✓ Field winding takes current which is less than 5% of the rated armature current.
- **Series wound**
  - ✓ Field winding is connected in series with the armature winding.
  - ✓ Series winding is designed with few turns of thick wire and the resistance is kept very low.
  - ✓ Field winding carries whole load current (armature current).
- **Compound wound**
  - ✓ In this type, there are two sets of field winding. One is connected in series and the other is connected in parallel with the armature winding.
  - ✓ Compound wound machines are further divided as -

    Short shunt – field winding is connected in parallel with only the armature winding

    Long shunt – field winding is connected in parallel with the combination of series field winding and armature winding



Derivation of EMF Equation of a DC Machine – Generator and Motor

Let,

- **P** – Number of poles of the machine
- **ϕ** – Flux per pole in Weber.
- **Z** – Total number of armature conductors.
- **N** – Speed of armature in revolution per minute (r.p.m).
- **A** – Number of parallel paths in the armature winding.

In one revolution of the armature, the flux cut by one conductor is given as

$$\text{Flux cut by one conductor } = \mathrm{P}\varphi \quad \text{wb} \ldots \ldots (1)$$

Time taken to complete one revolution is given as

$$\mathrm{t} = \frac{60}{\mathrm{N}} \quad \text{seconds} \quad \ldots \ldots (2)$$

Therefore, the average induced e.m.f in one conductor will be

$$\mathrm{e} = \frac{\mathrm{P}\varphi}{\mathrm{t}} \quad \ldots \ldots (3)$$

Putting the value of (t) from Equation (2) in the equation (3) we will get

$$\mathrm{e} = \frac{\mathrm{P}\varphi}{60/\mathrm{N}} = \frac{\mathrm{P}\varphi\mathrm{N}}{60} \quad \text{volts} \quad \ldots \ldots (4)$$

The number of conductors connected in series in each parallel path = Z/A.

Therefore, the average induced e.m.f across each parallel path or across the armature terminals is given by the equation shown below.

$$E = \frac{P\varphi N}{60} \times \frac{Z}{A} = \frac{PZ\varphi N}{60\ A} \text{ volts } \ldots\ldots (5)$$

Where, n is the speed in revolution per second (r.p.s) and given as

For lap winding A=P; wave winding A=2

CHARACTERISTICS OF DC GENERATORS

Magnetic or Open Circuit Characteristics

The curve which gives the relation between field current (I_f) and the generated voltage (E_0) in the armature on no load is called magnetic or open circuit characteristic of a DC generator**.**

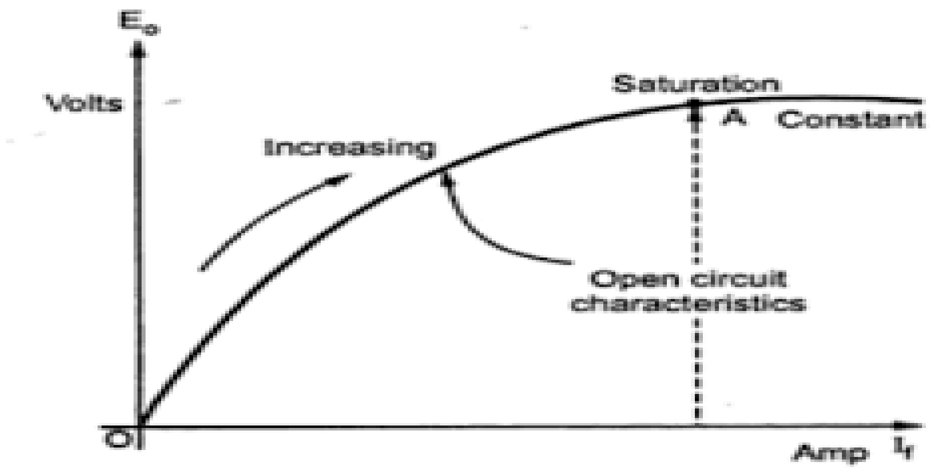
This curve is also known as no load saturation characteristic curve of DC generator**.**

Internal or Total Characteristics

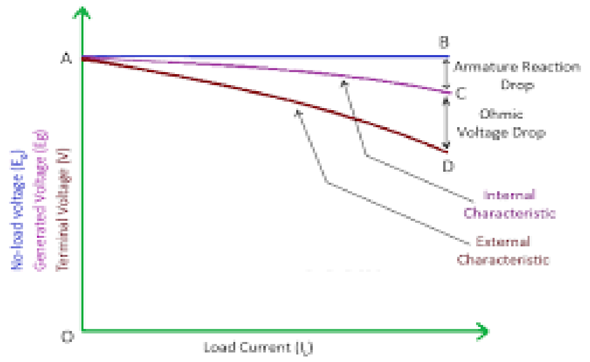
It is the curve between actually generated voltage (E_g) and armature current (I_a)

External Characteristics

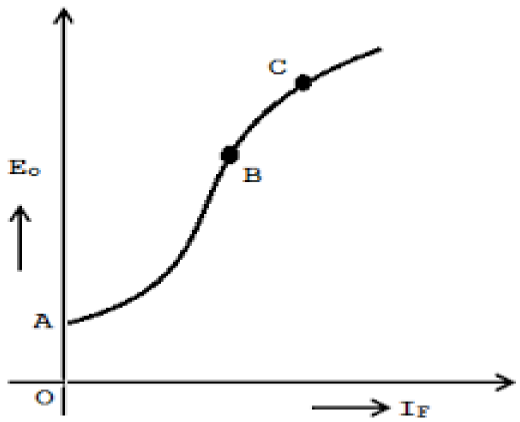
It gives the relation between terminal voltage (V) and load current (I_L)



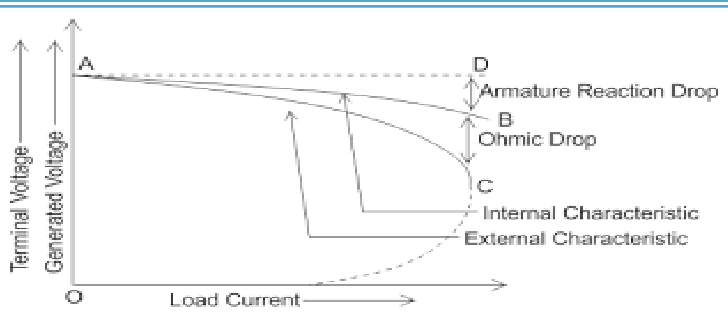
OCC of Separately Excited Characteristics



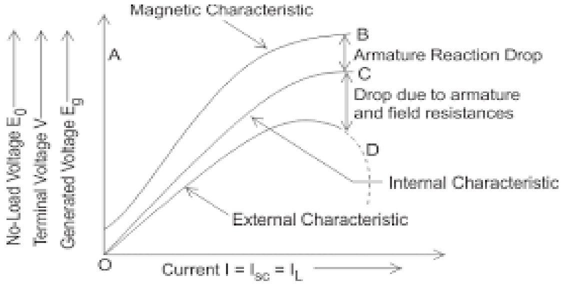
Internal & External Characteristics of Separately Excited Generator



OCC of DC Shunt Generator



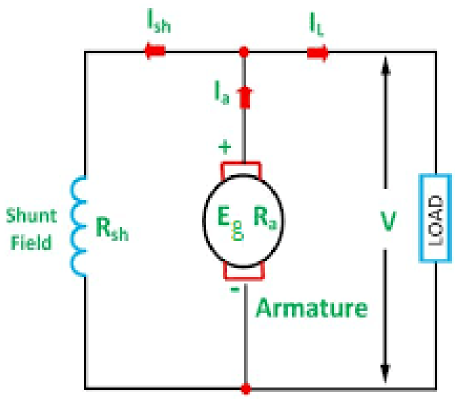
Internal & External characteristics of DC shunt generator



Characteristics of DC series generator

Important Equations of DC Generators

DC Shunt Generator

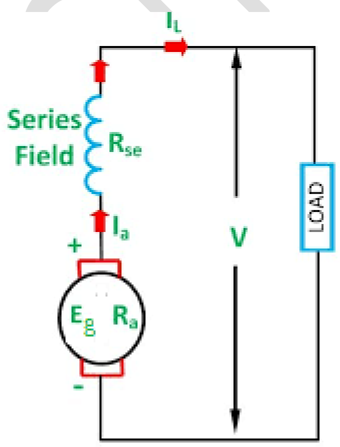


$$V=E_g-I_aR_a$$

$$I_a=I_L+I_{sh}$$

$$I_{sh}=V/R_{sh}$$

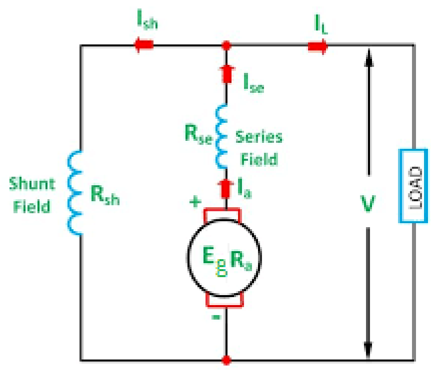
DC Series Generator



$$V=E_g-I_a(R_a+R_{se})$$

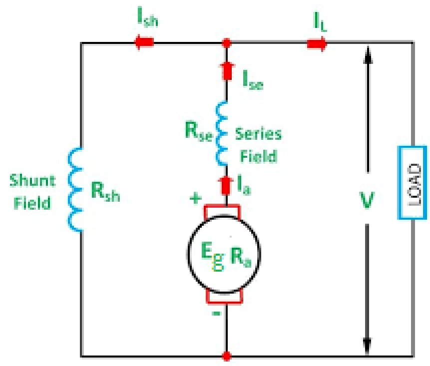
$$I_a=I_L=I_{se}$$

DC Long Shunt Generator



Series field current, $I_{se} = I_a = I_L + I_{sh}$
Shunt field current, $I_{sh} = V/R_{sh}$
Terminal voltage, $V = E_g - I_a(R_a + R_{se})$

DC Short Shunt Generator



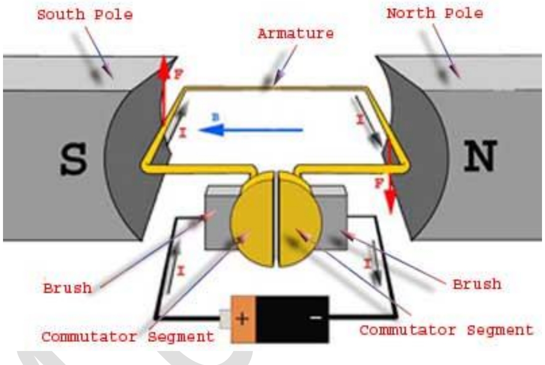
Series field current, $I_{se} = I_L$

Shunt field current, $I_{sh} = \dfrac{V + I_{se}R_{se}}{R_{sh}}$

Terminal voltage, $V = E_g - I_aR_a - I_{se}R_{se}$

PRINCIPLE OF OPERATION OF DC MOTOR

- A motor is an electrical machine which converts electrical energy into mechanical energy. The principle of working of a DC motor is that "whenever a current carrying conductor is placed in a magnetic field, it experiences a mechanical force.
- The direction of this force is given by Fleming's left hand rule
- Fleming's left hand rule: If we stretch the first finger, second finger and thumb of our left hand to be perpendicular to each other AND direction of magnetic field is represented by the first finger, direction of the current is represented by second finger then the thumb represents the direction of the force experienced by the current carrying conductor.
- When armature windings are connected to a DC supply, current sets up in the winding. Magnetic field may be provided by field winding (electromagnetism) or by using permanent magnets. In this case, current carrying armature conductors experience force due to the magnetic field, according to the principle stated above.



Back EMF

When the armature of the motor is rotating, the conductors are also cutting the magnetic flux lines and hence according to the Faraday's law of electromagnetic induction, an emf induces in the armature conductors. The direction of this induced emf is such that it opposes the armature current (Ia). The circuit diagram below illustrates the direction of the back emf and armature current. Magnitude of Back emf can be given by the emf equation of DC generator.

TORQUE EQUATION OF A DC MOTOR

Torque is the quantitative measure of the tendency of a force to cause a rotational motion, or to bring about a change in rotational motion. It is in fact the moment of a force that produces or changes a rotational motion. The equation of torque is given by,

$T=F * r$ -------------(1)

The mechanical power P_m is related to the electromagnetic torque T_a as

$P_m= T_a(2\pi N/60)$------------(2)

The effective mechanical power that is required to produce the desired torque at the armature of a DC motor is given by

$P_m= E_b I_a$--------------(3)

Now equating equation (2) & (3) we get

$E_b I_a= T_a(2\pi N/60)$ ------------(4)

Where ,

$E_b= (\Phi ZN/60)(P/A)$--------(5)

Substituting eq.5 in eq.4

$T_a= (1/2\pi)(\Phi I_a Z)(P/A)$ N-m

Where ,

T_a= Torque developed at the armature, N-m.

Φ= flux per pole, Wb

Z= Number of conductors in the armature

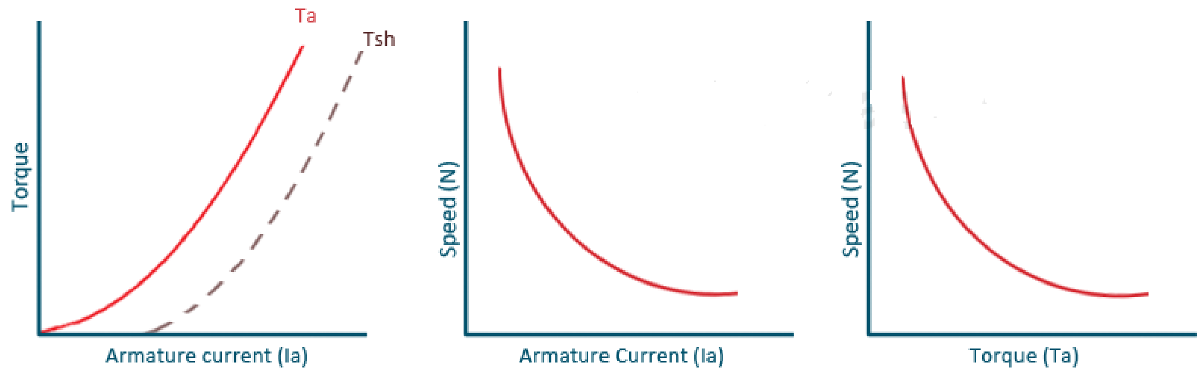
P= Number of poles

A= Number of parallel paths

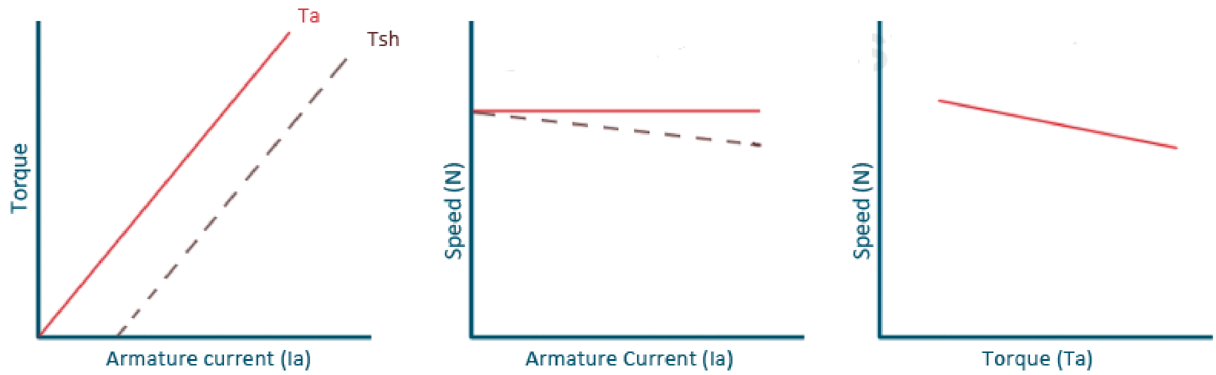
CHARACTERISTICS OF DC MOTORS

1. Torque Vs. Armature Current (Ta-Ia)
2. Speed Vs. Armature Current (N-Ia)
3. Speed Vs. Torque (N-Ta)

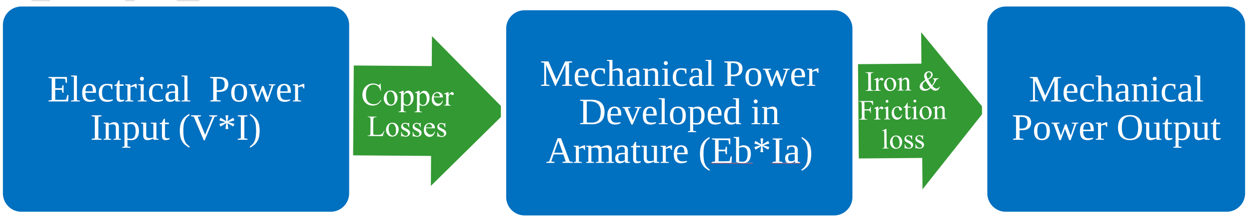
Characteristics of DC Series Motors

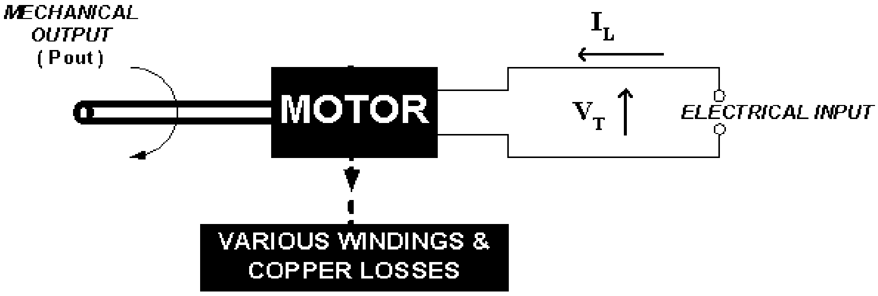


Characteristics of DC Shunt Motors



POWER STAGES IN A DC MOTOR





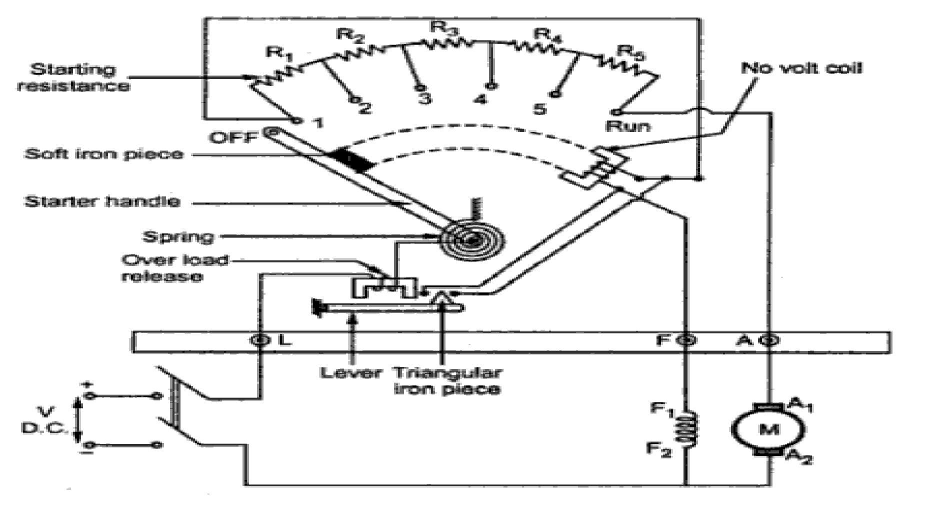
$$Output = VI - I_a^2 R_a - W_c$$

$$\eta = \frac{Output}{Input} = \frac{Input - Losses}{Input}$$

STARTING METHOD

Necessary of starter

- A 3 point starter in simple words is a device that helps in the starting and running of a DC Motor.
- At starting, when the motor is stationary, there is no back e.m.f. in the armature. Consequently, if the motor is directly switched on to the mains, the armature will draw a heavy current (Ia= V/Ra) because of small armature resistance.
- This high starting current may result in:
  (i) Burning of armature due to excessive heating effect,
  (ii) Damaging the commutator and brushes due to heavy Sparking,
  (iii) Excessive voltage drop in the line to which the motor is Connected.



3 point Starter

- Construction wise a starter is a variable resistance, integrated into number of sections as shown in the figure .
- The contact points of these sections are called studs and are shown separately as **OFF, 1, 2,3,4,5, RUN**.
- Other than that there are 3 main points, referred to as
  'L' Line terminal. (Connected to positive of supply.)
  2. 'A' Armature terminal. (Connected to the armature winding.)
  3. 'F' Field terminal. (Connected to the field winding.)
  And from there it gets the name 3 point starter.

- The point 'L' is connected to an electromagnet called overload release (OLR) as shown in the figure.
- The other end of 'OLR' is connected to the lower end of conducting lever of starter handle where a spring is also attached with it and the starter handle contains a soft iron piece housed on it.
- This handle is free to move to the other side RUN against the force of the spring
- This spring brings back the handle to its original OFF position under the influence of its own force. Another parallel path is derived from the stud '1', given to the another electromagnet called No Volt Coil (NVC) which is further connected to terminal 'F'.
- The starting resistance at starting is entirely in series with the armature. The OLR and NVC acts as the two protecting devices of the starter.

Working of Three Point Starter

- To start with the handle is in the OFF position when the supply to the DC motor is switched on.
- Then handle is slowly moved against the spring force to make a contact with stud No. 1.

- As the handle is moved further, it goes on making contact with studs 2, 3, 4 etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed.
- Finally when the starter handle is in 'RUN' position, the entire starting resistance is eliminated and the motor runs with normal speed.
- This is because back emf is developed consequently with speed to counter the supply voltage and reduce the armature current.
- So the external electrical resistance is not required anymore, and is removed for optimum operation.
- The handle is moved manually from OFF to the RUN position with development of speed.
- At this point, field winding of the shunt or the compound motor gets supply through the parallel path provided to starting resistance, through No Voltage Coil.
- While entire starting resistance comes in series with the armature. The high starting armature current thus gets limited as the current equation at this stage becomes $I_a = E/(R_a+R_{st})$.

<u>Working of No Voltage Coil</u>

- The supply to the field winding is derived through no voltage coil. So when field current flows, the NVC is magnetized.
- Now when the handle is in the 'RUN' position, soft iron piece connected to the handle and gets attracted by the magnetic force produced by NVC, because of flow of current through it.
- The NVC is designed in such a way that it holds the handle in 'RUN' position against the force of the spring as long as supply is given to the motor. Thus NVC holds the handle in the 'RUN' position and hence also called **hold on coil**.
- If there is any kind of supply failure, the current flow through NVC is affected and it immediately looses its magnetic property and is unable to keep the soft iron piece on the handle, attracted.
- At this point under the action of the spring force, the handle comes back to OFF position, opening the circuit and thus switching off the motor.
- Hence due to the combination of NVC and the spring, the starter handle always comes back to OFF position whenever there is any supply problems.
- Thus it also acts as a **protective device** safeguarding the motor from any kind of abnormality.

SPEED CONTROL METHODS OF DC MOTORS

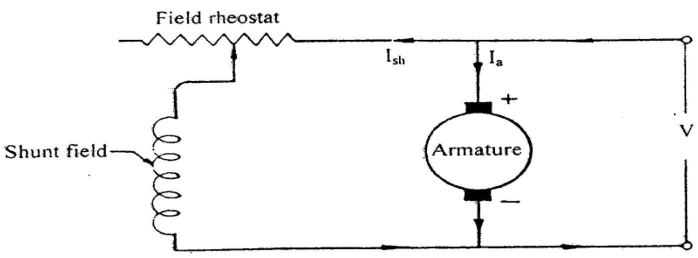
Factors Controlling the Speed are

$$N = \frac{V - I_a R_a}{Z\phi}\left(\frac{60A}{p}\right) = K\frac{V - I_a R_a}{\phi}$$

$$N \alpha \frac{V - I_a R_a}{\phi}$$

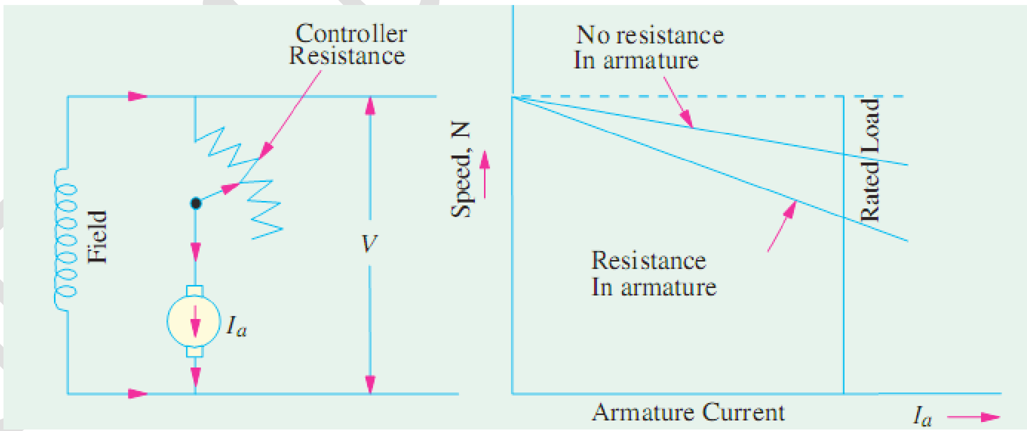
Speed control methods of DC shunt motor:

1. Flux Control Method or Field control method



- In this method, speed variation is accomplished by means of a variable resistance inserted in series with the shunt field .
- An increase in controlling resistances reduces the field current with a reduction in flux and an increase in speed.
- This method of speed control is independent of load on the motor.

2. <u>Armature resistance control</u>

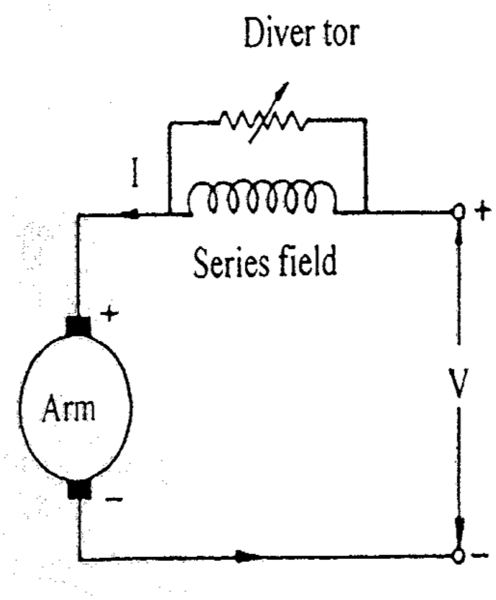


- In this method armature circuit is provided with a variable resistance.
- Field is directly connected across the supply so flux is not changed due to variation of series resistance. This is applied for dc shunt motor.
- This method is used in printing press, cranes, hoists where speeds lower than rated is used for a short period only.

Speed control methods of DC series motor:

1. Diverter field control

- ❖Inductively wound diverter resistor used to avoid oscillations in speed
- ❖A diverter resistor will control the field current ,hence reduces the field Ampere Turns.
- ❖Lesser the diverter resistance less is the field current, less flux therefore more speed.
- ❖This method gives speed above normal and the method is used in electric drives in which speed should rise sharply as soon as load is decreased.



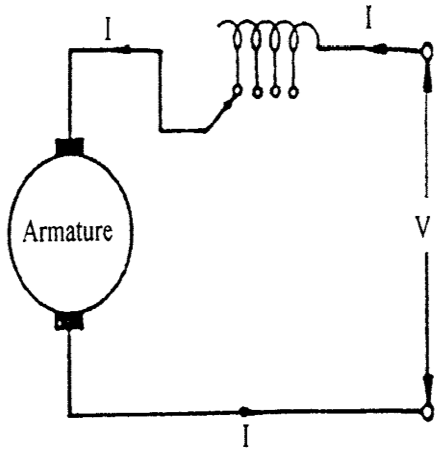
2. Tapped field control

▪In this method a number of tapping from field winding are brought outside

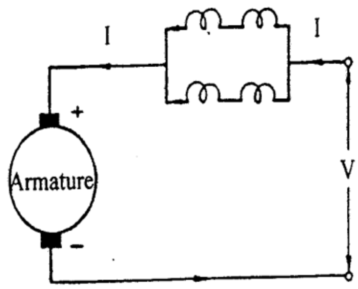
▪Flux or current is increased by including number of turns in field winding

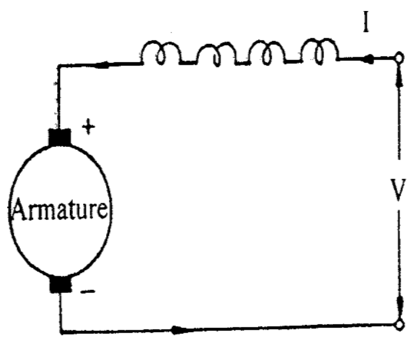
▪When all turns are included ,motor runs at lower speeds

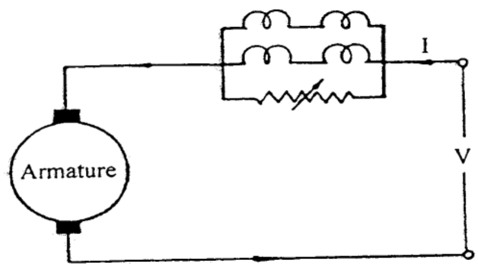
▪App- Electric Traction



3.Series-parallel control

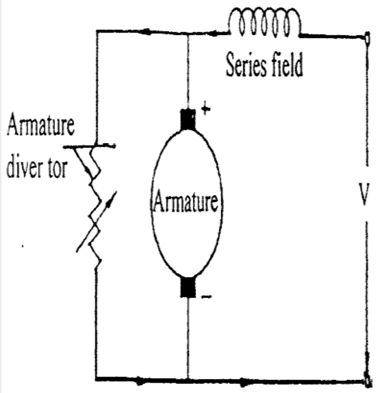






4.Armature diverter

- ❑ To get speed lower than the normal speeds
- ❑The combination of a rheostat shunting the armature and a rheostat in series with the armature is involved in this method of speed control.
- ❑This method of speed control is not economical due to considerable power losses in speed controlling resistances.



NUMERICALS ON DC MACHINES

1. A 4-pole d.c. shunt generator has an armature resistance of 0.018 . The armature is lap-wound with 520 conductors. When driven at 750 rev/min the machine produces a total armature current of 400 A at a terminal voltage of 200 V. Calculate the useful flux/pole .

Sol:

P=4; A=4(lap wound)

Ra=0.018ohms

Z=520

Ia=400A;

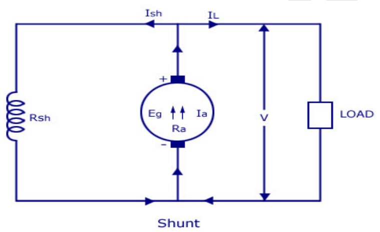
V=200V

Eg=V+I_aR_a= 207.2 V

Eg=(ΦZN/60)*(P/A)⇒ Φ= **31.9milli webers.**

2. A DC shunt generator has shunt field winding resistance of 100 ohms. It is supplying a load of 5KW at a voltage of 250 V. If its armature resistance of 0.22 ohms, calculate the induced e.m.f. of generator?

Sol:



R_{sh}=100 ohms; P=5KW; V=250V; R_a=0.22 ohms,

$Eg = V + I_aR_a$

$I_a = I_{sh} + I_L$

- $I_L = \frac{P}{V} = \frac{5e3}{250} = 20A$
- I_{sh}=250/100=2.5A
- I_a= 22.5A

- E_g=**254.884V**

3. An 8-pole wave connected DC generator has 1000 armature conductors and flux/pole 0.035 webers. At what speed must it be driven to generate an emf of 500V.

Sol:

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

$\emptyset = 0.035$, Z=1000, P=8, Eg =500V

As wave wound A=2
Speed to generate 500V is **214.28 RPM**

4. A long shunt dc compound generator drives 20 lamps, all are connected in parallel. Terminal voltage is 550V with each lamp resistance as 500ohms. If Rsh=25ohms, Ra=0.06ohms and Rse=0.04ohms. Calculate the armature current and the generated emf.

Sol:

No. of lamps=20

V=550V

Resistance of each lamp=500ohms

Rsh=25ohms

Ra=0.06ohms

Rse=0.04

Ia=? & Eg=?

As all lamps are connected in parallel, the voltage across all of them is same i.e., V=550V.

Hence current drawn by each lamp is $I=V/R_{lamp}$=550/500=1.1A

Such 20 lamps are used as a load,

I_L=20*I=20*1.1=22A

$I_{sh}=V/R_{sh}$=550/25=22A

$Ia=I_L+I_{sh}$

= 44A

$Eg = V+I_aR_a+I_aR_{se}$

= 550+(44*0.06)+(44*0.04)

= **554.4 V**

5. A 230V, 4-pole lap wound Dc shunt motor with 882 conductors is rotating with 1150RPM. The armature resistance is 0.2 ohms. If the armature current is 73A , find (i) useful flux (ii) armature torque

Sol:

V=230 volts
P=4
Lap wound , A=P=4
Z=882
N=1150 RPM
Ra=0.2 ohms
Ia = 73 amps

$E_b = V - I_a R_a$
$E_b = 215.4\ volts$

$E_b = \frac{\emptyset ZN}{60}\ \frac{P}{A} \Rightarrow \ \Phi$ = **0.01274 wb**

$T_a = \frac{\emptyset Z I_a}{2\pi}\ \frac{P}{A} = \mathbf{130.617\ \ N - m}$

6. A 220V dc machine has an armature resistance of 0.5ohms. If the full load armature current is 20A, find the induced emf when machine acts as (i) generator (ii) motor.

Sol:

V= 220V
Ra=0.5ohms
Ia=20A

E_g=V+IaRa=230 volts
E_b=V-IaRa= 210 volts

7. Determine developed torque and shaft torque of 220V, 4-pole series motor with 800 conductors wave connected supplying a load of 8.2KW by taking 45A from the mains. The flux per pole is 25m wb and its armature resistance is 0.6ohms.

Sol:

$T_a = \frac{\emptyset Z I_a}{2\pi}\ \frac{P}{A}$ =286.2N-mt

E_b=V-IaRa= 193 volts

$E_b = \frac{\emptyset ZN}{60}\ \frac{P}{A}$ $\Rightarrow$ N= 289.5
Tsh=Pout/(2πN/60)=270.5 N-mt