G.H. RAISONI INSTITUTE OF ENGINEERING & TECHNOLOGY, NAGPUR

(An Autonomous Institute)

Department of Electrical Engineering

Subject:- BASIC ELECTRICAL MACHINE
Subject Code:- UEEL204
3rd Sem EE

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Unit 3: DC MACHINE

- Construction
- Basis principle & operation
- Armature reaction & commutation
- Compensating winding, interpoles.
- Type of excitation
- Characteristics of shunt series & compound motor and generator
- Speed control of d.c. shunt & series motor
- Constant horse power & constant torque drive of d.c. motor
- Numericals

Introduction to DC Machine

- D.C. machines are the electro mechanical energy converters which work from a D.C. source and generate mechanical power or convert mechanical power into a D.C. power.
- In the present day world, electrical energy is generated in bulk in the form of an alternating current. Hence, the use of DC machines, i.e., DC generators and motors are very limited.
- They are mainly used in supplying excitation of small and medium-range alternators. The Industrial Applications of DC Machines are in Electrolytic Processes, Welding processes and Variable speed motor drive

Construction of DC Machine

- A D.C. machine consists mainly of two part the stationary part called stator and the rotating part called rotor.

- The stator consists of main poles used to produce magnetic flux ,commutating poles or interpoles in between the main poles to avoid sparking at the commutator but in the case of small machines sometimes the interpoles are avoided and finally the frame or yoke which forms the supporting structure of the machine.

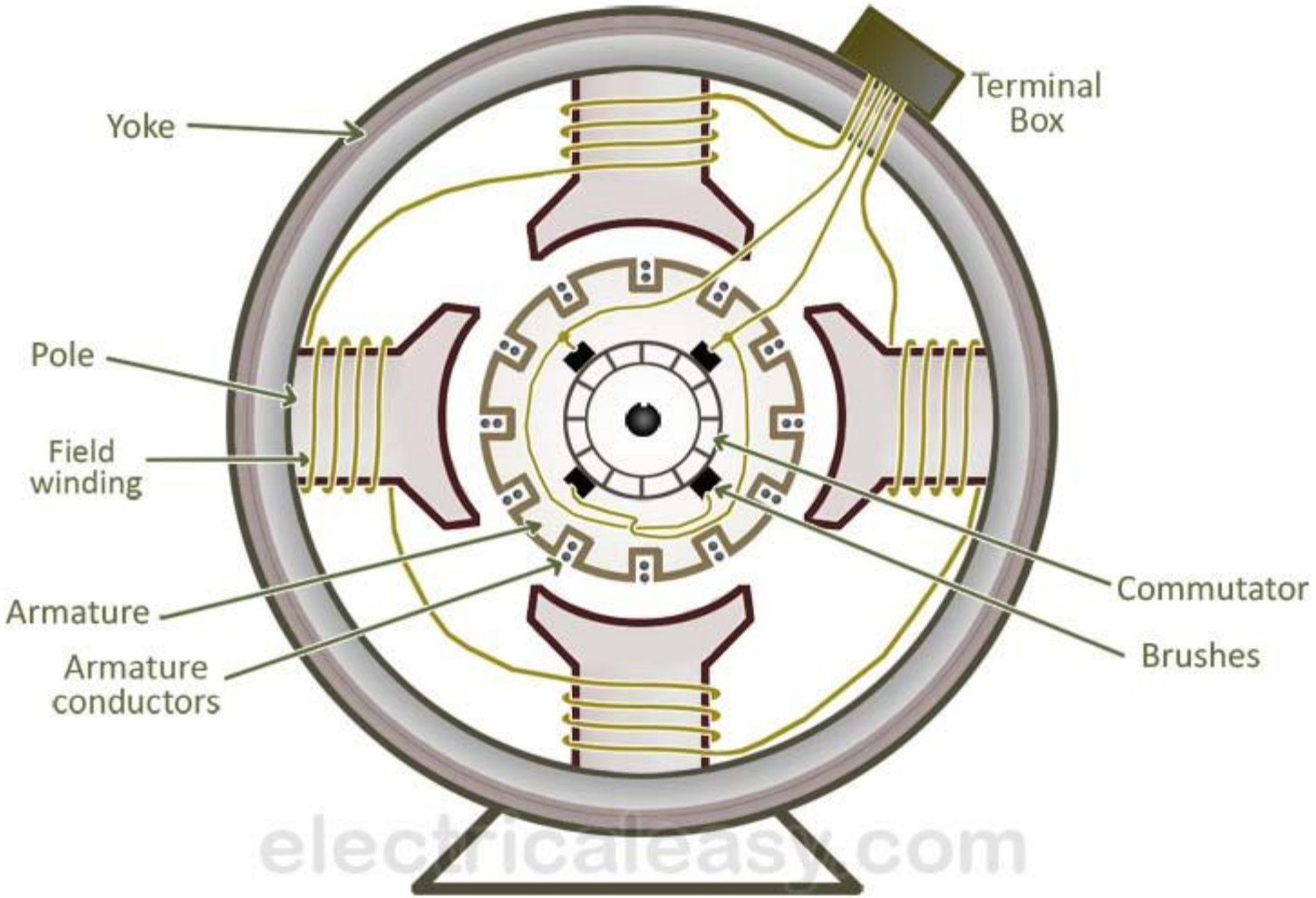
- The rotor consist of an armature a cylindrical metallic body or core with slots in it to place armature windings or bars, a commutator and brush gears

The major parts can be identified as,

1. Frame
2. Poles
3. Armature
4. Commutator and brush gear
5. Commutating poles
6. Compensating winding
7. Other mechanical parts



Parts of a Motor



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1] Frame:

- Frame is the stationary part of a machine on which the main poles and commutator poles are bolted and it forms the supporting structure by connecting the frame to the bed plate.
- The ring shaped body portion of the frame which makes the magnetic path for the magnetic fluxes from the main poles and interpoles is called Yoke.

2] End Shields or Bearings:

- If the armature diameter does not exceed 35 to 45 cm then in addition to poles end shields or frame head with bearing are attached to the frame.
- If the armature diameter is greater than 1m pedestral type bearings are mounted on the machine bed plate outside the frame. These bearings could be ball or roller type but generally plain pedestral bearings are employed.

3] Main poles:

- Solid poles of fabricated steel with separate pole shoes are fastened to the frame by means of bolts.
- Pole shoes are generally laminated. Sometimes pole body and pole shoe are formed from the same laminations.
- The pole shoes are shaped so as to have a slightly increased air gap at the tips.
- Inter-poles are small additional poles located in between the main poles. These can be solid, or laminated just as the main poles. These are also fastened to the yoke by bolts. Sometimes the yoke may be slotted to receive these poles. The inter poles are also called as commutating poles

4] Armature:

- The armature is where the moving conductors are located.
- The armature is constructed by stacking laminated sheets of silicon steel. Thickness of this lamination is kept low to reduce eddy current losses.
- The core is divided into packets to facilitate ventilation.
- Open parallel sided equally spaced slots are normally punched in the rotor laminations. These slots house the armature winding.
- End plates are suitably shaped so as to serve as 'Winding supporters'.
- Armature construction process must ensure provision of sufficient axial and radial ducts to facilitate easy removal of heat from the armature winding.

5] Commutator:

- Commutator is the key element which made the D.C. machine of the present day possible.
- It consists of copper segments tightly fastened together with mica/micanite insulating separators on an insulated base.
- The whole commutator forms a rigid and solid assembly of insulated copper strips and can rotate at high speeds.
- Each commutator segment is provided with a ’riser’ where the ends of the armature coils get connected. The surface of the commutator is machined and surface is made concentric with the shaft and the current collecting brushes rest on the same.

6] Field Winding:

- The coil wound around the pole are called field coils.
- The field coil are connected in series with each other to form a field winding.
- Current is passed through a winding in a specific direction to magnetize the pole and pole shoes. The magnetic flux is produced in the air gap between the pole shoes and armature.
- The material used for the field winding conductor is copper.

7] Brush and brush holders:

- Brushes rest on the surface of the commutator. Normally electro-graphite is used as brush material. The brush holders provide slots for the brushes to be placed.

Other mechanical parts End covers, fan and shaft bearings form other important mechanical parts. End covers are completely solid or have opening for ventilation. They support the bearings which are on the shaft. Proper machining is to be ensured for easy assembly. Fans can be external or internal.

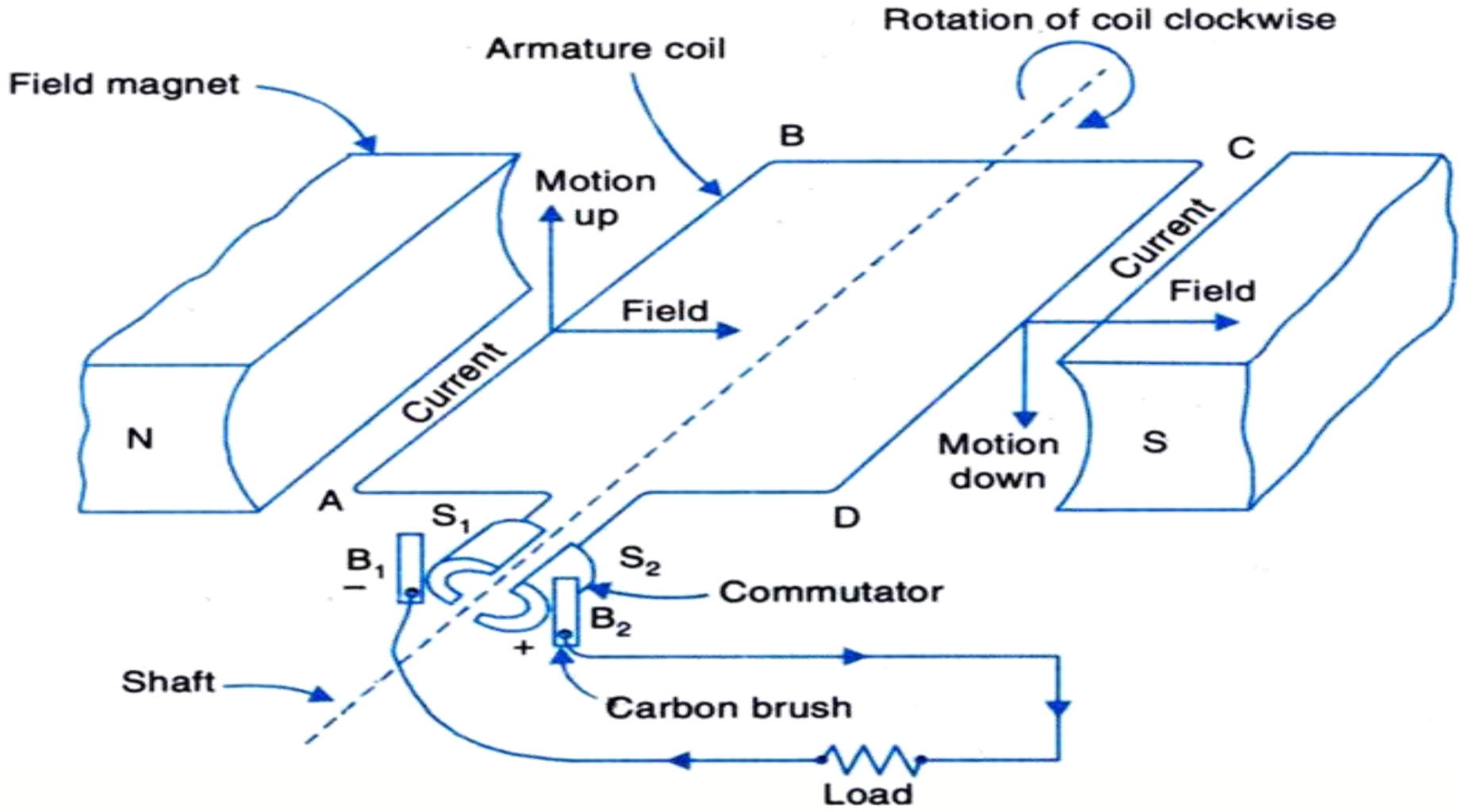
Operating Principle

- When rotor is driven by the prime mover, rotor conductors cut across line of forces, emf is produced and current circulate.
- However these current carrying rotor conductors experienced a mechanical force since placed within magnetic fields.
- According to Lenz's law the direction of this developed force is opposite to that of driven force. Therefore at each stage the developed force will oppose the driven force.
- Due to opposing property the developed force is called "Magnetic Drag". The amount of mechanical energy expended to overcome this magnetic drag is converted to useful electric power output.
- The rest of energy supplied is used to meet various losses.

Working of DC Machine as GENERATOR

- According to Faraday's law of Electroamgnetic Induction, we know that when a current-carrying conductor is placed in a varying magnetic field, an emf is induced in the conductor.
- According to Fleming's right-hand rule, the direction of the induced current changes whenever the direction of motion of the conductor changes.
- Let us consider an armature rotating clockwise and a conductor at the left moving upwards. When the armature completes a half rotation, the direction of the motion of the conductor will be reversed downward. Hence, the direction of the current in every armature will be alternating.
- But with a split ring commutator, connections of the armature conductors get reversed when a current reversal occurs. Therefore, we get unidirectional current at the terminals.

Working of DC Machine as GENERATOR



EMF Equation of DC Generator

Let,

φ = Flux per pole in Weber.

Z = Total number of armature conductors.

N = Armature rotation in revolution per minute (r.p.m).

P = Number of poles.

A = Number of parallel paths in armature.

E = e.m.f induced in any parallel path or generated e.m.f.

According to Faraday's law's of Electromagnetic induction.

$$\text{Average e.m.f generated / conductors} = \frac{d\phi}{dt} = \frac{flux\ cut}{time\ taken}\ volt$$

Flux cut / Conductors in one revolution, $d\varphi = \varphi P$ wb

Number of revolutions / minute = N / 60

Time taken for one revolution, dt = 60 / N sec

e.m.f generated / conductor $= \frac{d\phi}{dt} = \frac{\phi P}{60 / N} \times \frac{\phi PN}{60} volt$

Total e.m.f generated between the terminals

E = average e.m.f generated per conductor * number of conductor in each parallel path

$$= \frac{\phi PN}{60} \times \frac{Z}{A} volt$$

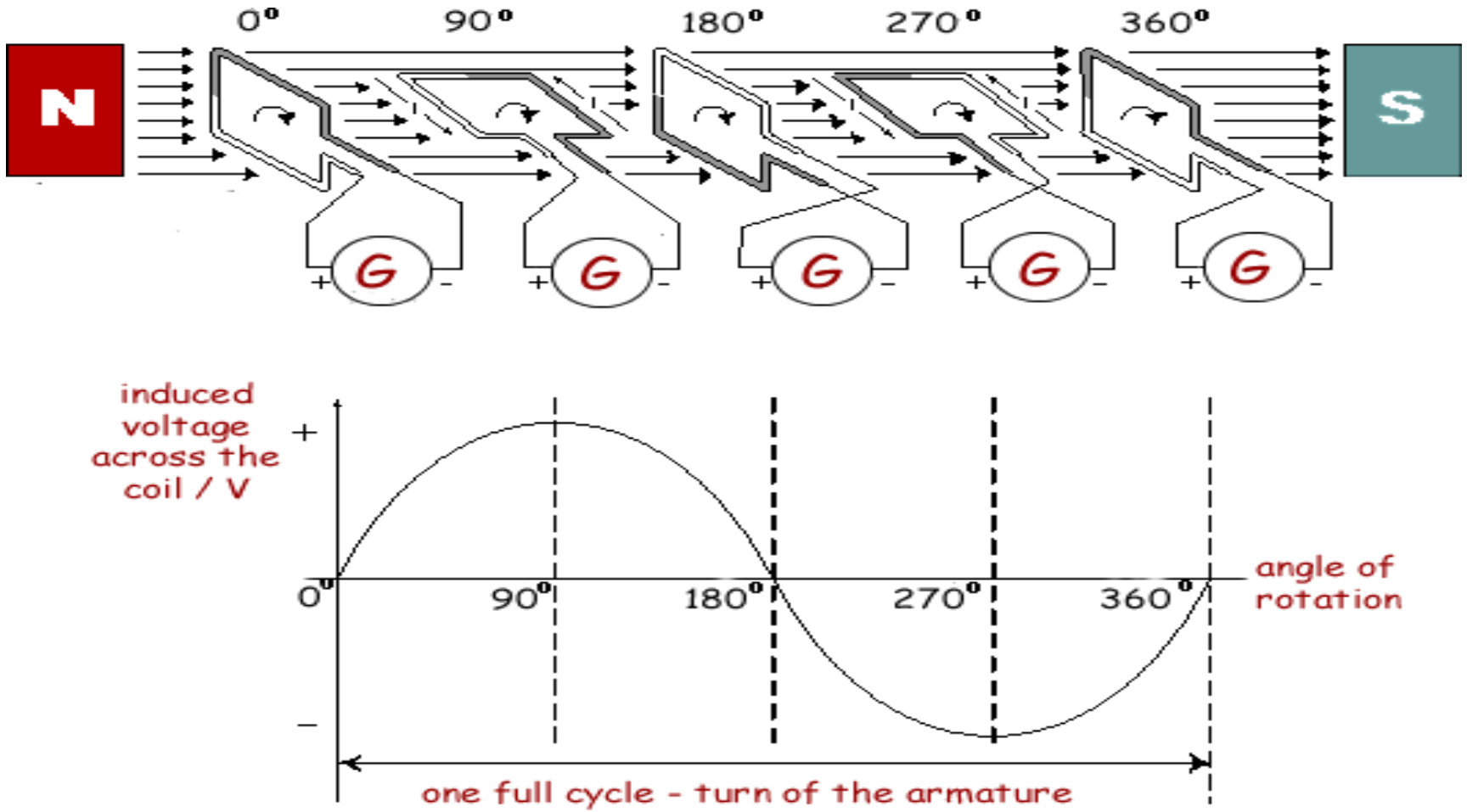
$$E = \frac{\phi PN}{60} \times \frac{Z}{A} volt$$

Where

A = P for Lap Winding

A = 2 for Wave Winding

Generation of AC Voltage



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Working of DC Machine as MOTOR

- The DC motor is the device which converts the direct current into the mechanical work.
- It works on the principle of Lorentz Law, which states that "*the current-carrying conductor placed in a magnetic and electric field experience a force*". The experienced force is called the Lorentz force.
- The Flemming left-hand rule gives the direction of the force. The formula calculates the magnitude of the force,

$$F = BIl \quad \text{newton}$$

- For simplicity, consider that the armature has only one coil which is placed between the magnetic field shown below in the figure A. When the DC supply is given to the armature coil the current starts flowing through it. This current develops its own field around the coil.Figure B shows the field induces around the coil.

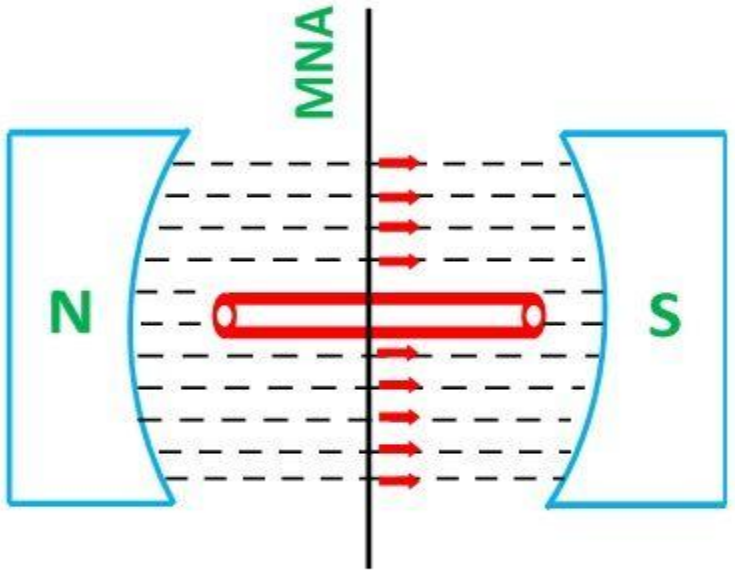


Figure A

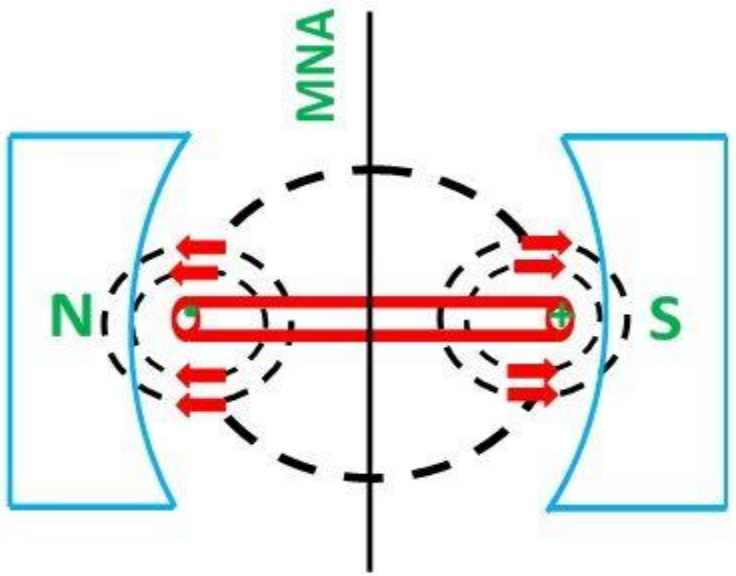


Figure B

Circuit Globe

- By the interaction of the fields (produced by the coil and the magnet), the resultant field develops across the conductor. The resultant field tends to regain its original position, i.e. in the axis of the main field. The field exerts the force at the ends of the conductor, and thus the coil starts rotating.

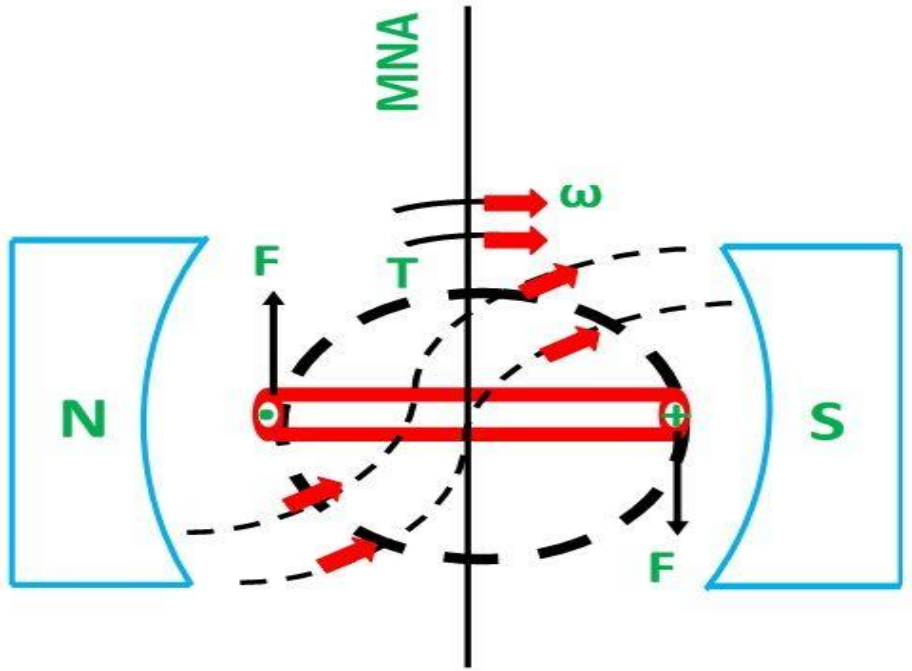
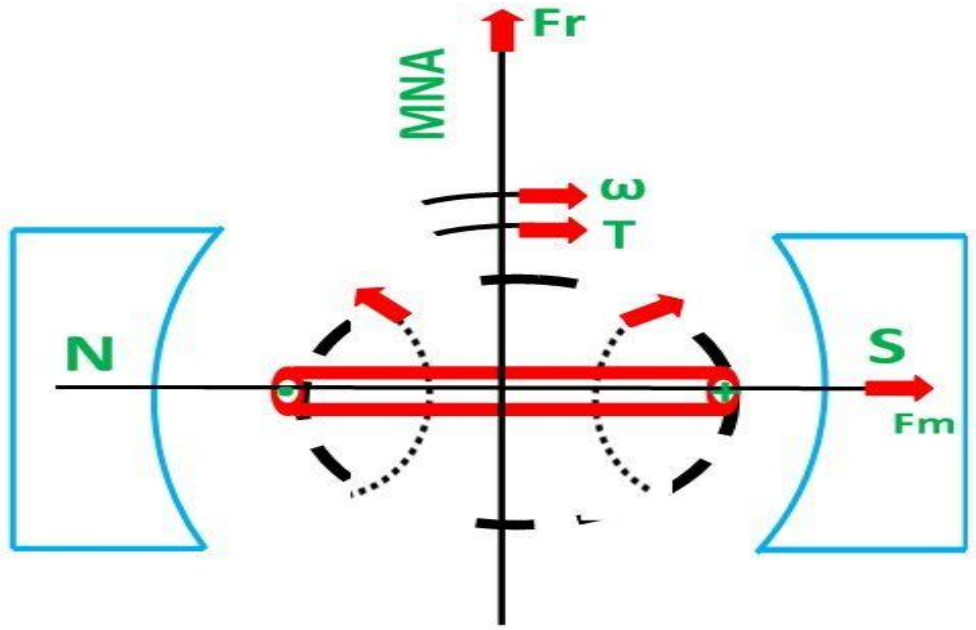


Figure C

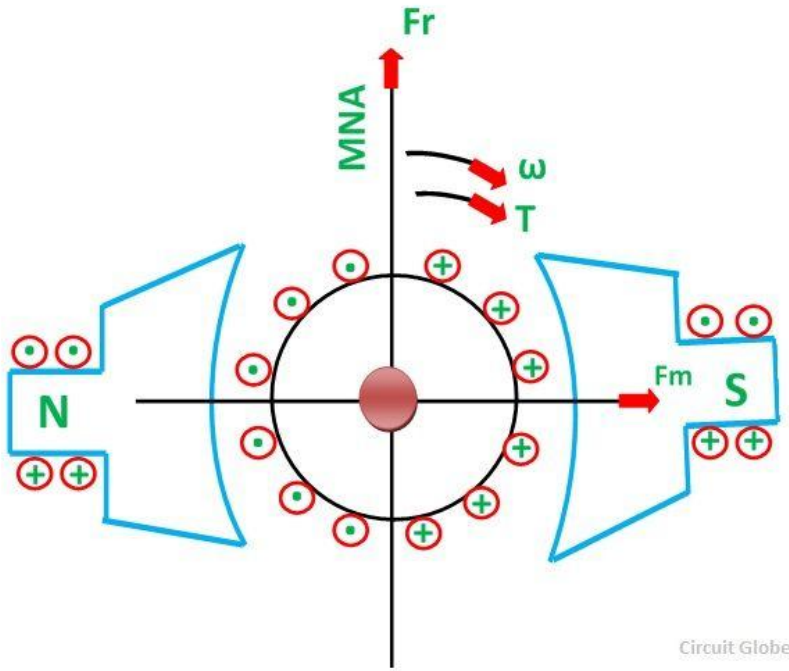
Circuit Globe

- Let the field produced by the main field be F_m, and this field rotates in the clockwise direction. When the current flows in the coil, they produce their own magnetic field say, F_r. The field F_r tries to come in the direction of the main field. Thereby, the torque act on the armature coil.



- The actual DC motor consists of a large number of armature coils. The speed of the motor is directly proportional to the number of coils used in the motor.
- The one end of the conductors is kept under the influence of the north pole, and the other end is kept under the influence of the south pole.
- The current enters into the armature coil through the north pole and move outwards through the south pole. The torque induces in the coil become zero when the armature coil is perpendicular to the main field. The zero torque means the motor stops rotating.
- For solving this problem, the number of armature coil is used in the rotor. So, if one of their coils is perpendicular to the field, then the other coils induce the torque. And the rotor moves continuously.

- Also, for obtaining the continuous torque, the arrangement is kept in such a way that whenever the coils cut the magnetic neutral axis of the magnet the direction of current in the coils become reversed.
- This can be done with the help of the commutator.



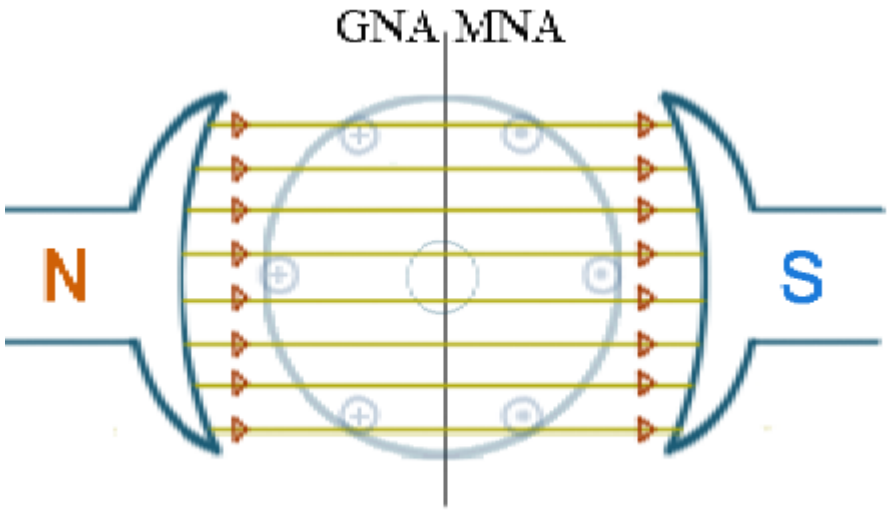
Armature Reaction

- In a DC Machine, two kinds of magnetic fluxes are present; 'armature flux' and 'main field flux'. The effect of armature flux on the main field flux is called as **armature reaction**.

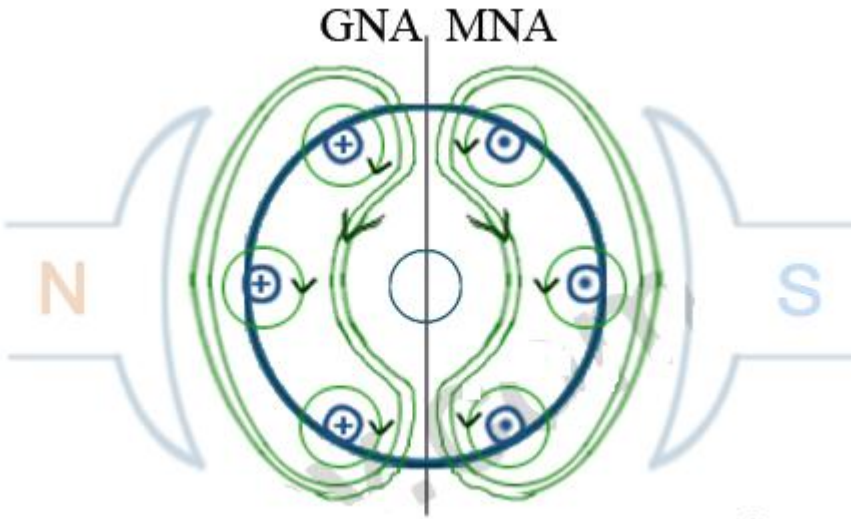
- **MNA And GNA**

- EMF is induced in the armature conductor when they cut the magnetic field lines. There is an axis along which armature conductors move parallel to the flux lines and, hence, they do not cut the flux lines while on that plane.
- MNA (Magnetic Neutral Axis) may be defined as the axis along which no emf is generated in the armature conductors as they move parallel to the flux lines. Brushes are always placed along the MNA because reversal of current in the armature conductors takes place along this axis.
- GNA (Geometrical Neutral Axis) may be defined as the axis which is perpendicular to the stator field axis.

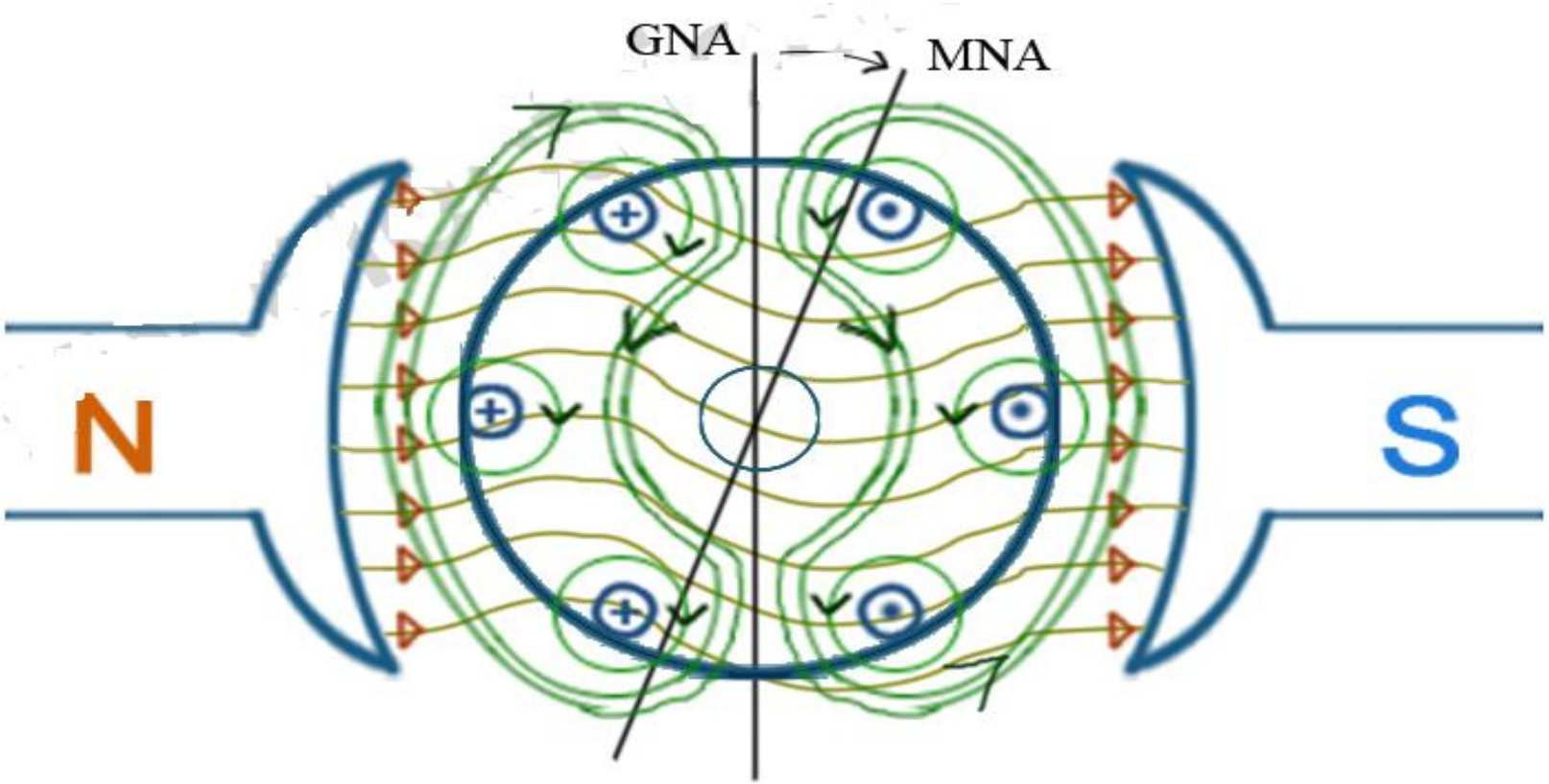
The **effect of armature reaction** is well illustrated in the figure below.



Main field flux



Armature Flux



Distortion of main field flux due to armature flux - Armature reaction

- Consider, no current is flowing in the armature conductors and only the field winding is energized (as shown in the first figure of the above image). In this case, magnetic flux lines of the field poles are uniform and symmetrical to the polar axis. The 'Magnetic Neutral Axis' (M.N.A.) coincides with the 'Geometric Neutral Axis' (G.N.A.).
- The second figure in the above image shows armature flux lines due to the armature current. Field poles are de-energised.
- Now, when a DC machine is running, both the fluxes (flux due to the armature conductors and flux due to the field winding) will be present at a time. The armature flux superimposes with the main field flux and, hence, disturbs the main field flux (as shown in third figure the of above image). This effect is called as **armature reaction in DC machines**.

The Adverse Effects Of Armature Reaction:

1.Armature reaction weakens the main flux. In case of a dc generator, weakening of the main flux reduces the generated voltage

2.Armature reaction distorts the main flux, hence the position of M.N.A. gets shifted (M.N.A. is perpendicular to the flux lines of main field flux). Brushes should be placed on the M.N.A., otherwise, it will lead to sparking at the surface of brushes. So, due to armature reaction, it is hard to determine the exact position of the MNA

For a loaded dc generator, MNA will be shifted in the direction of the rotation. On the other hand, for a loaded dc motor, MNA will be shifted in the direction opposite to that of the rotation.

How To Reduce Armature Reaction?

Usually, no special efforts are taken for small machines (up to few kilowatts) to reduce the armature reaction. But for large DC machines, compensating winding and interpoles are used to get rid of the **ill effects of armature reaction**.

Compensating winding: Now we know that the armature reaction is due to the presence of armature flux. Armature flux is produced due to the current flowing in armature conductors. Now, if we place another winding in close proximity of the armature winding and if it carries the same current but in the opposite direction as that of the armature current, then this will nullify the armature field. Such an additional winding is called as compensating winding and it is placed on the pole faces. Compensating winding is connected in series with the armature winding in such a way that it carries the current in opposite direction.

Interpoles: Interpoles are the small auxiliary poles placed between the main field poles. Winding on the interpoles is connected in series with the armature. Each interpole is wound in such a way that its magnetic polarity is same as that of the main pole ahead of it. Interpoles nullify the quadrature axis armature flux.

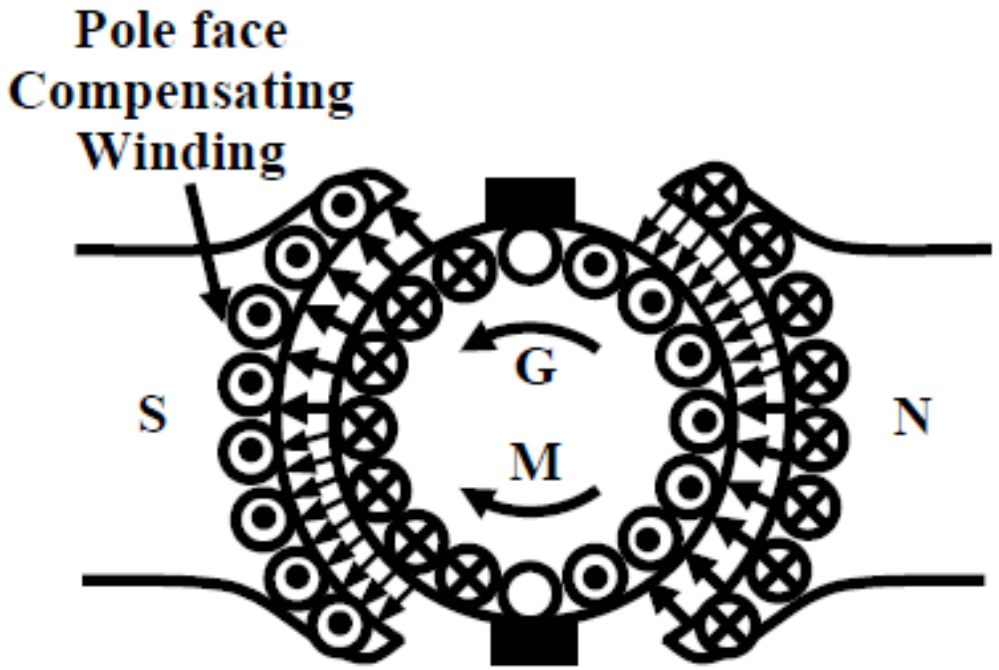


Fig: Compensating Winding

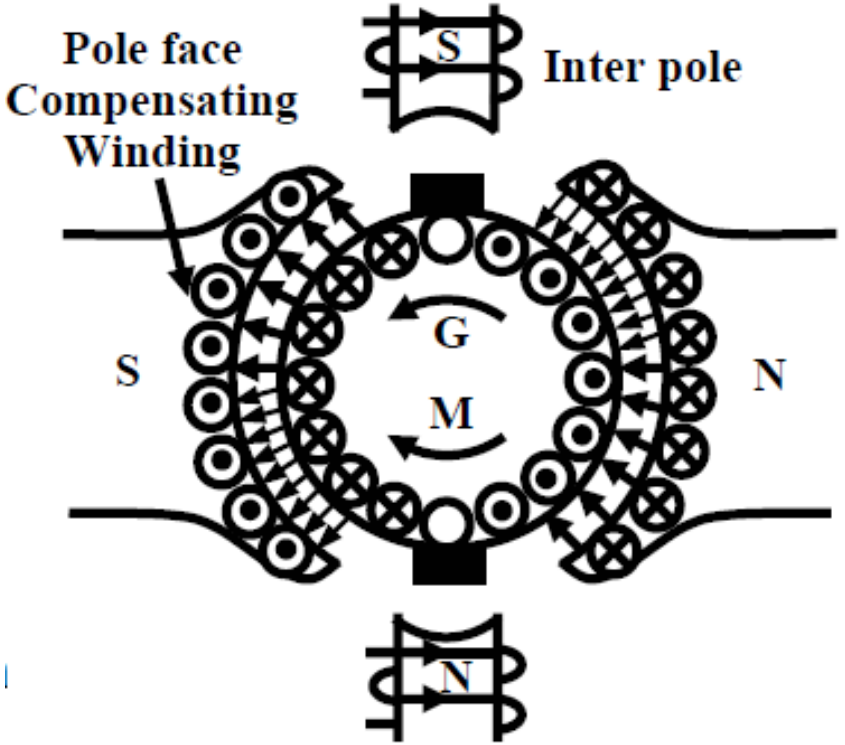
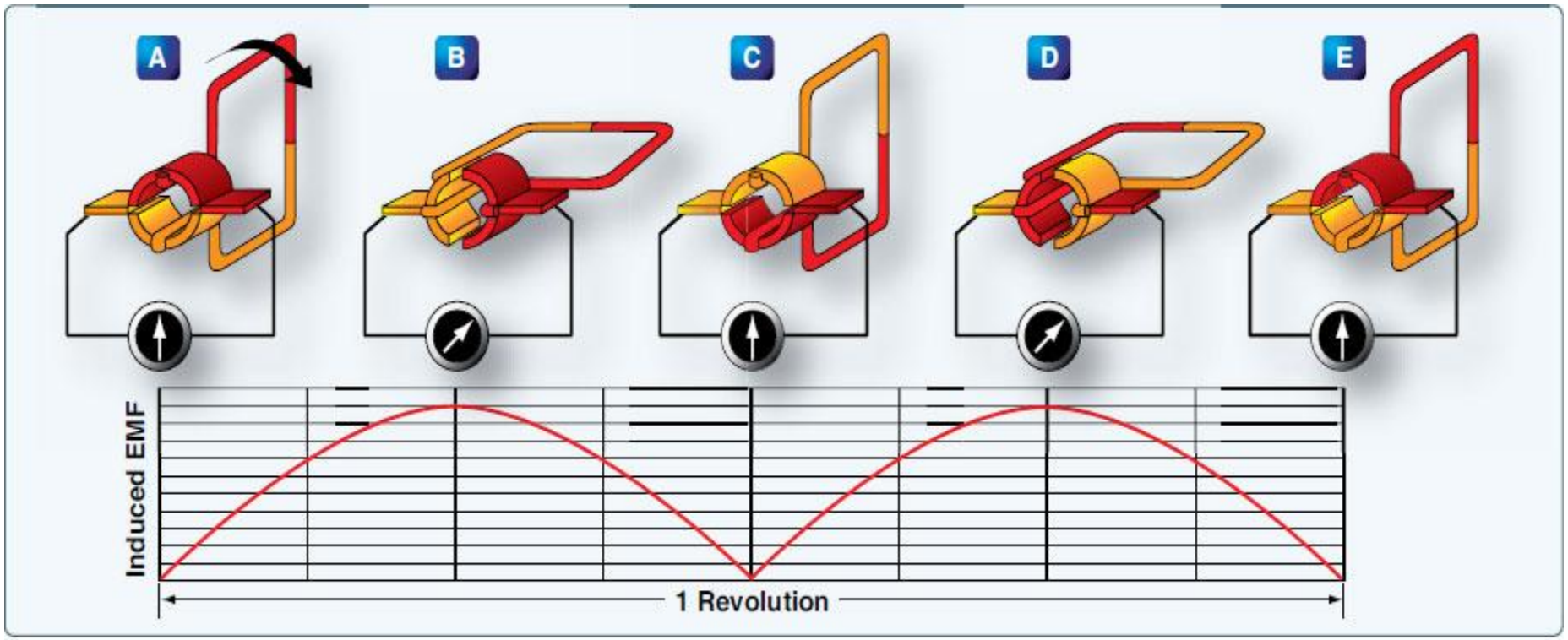


Fig: Inter pole

Commutation



- The voltage generated in the armature, placed in a rotating magnetic field, of a DC generator is alternating in nature.
- The **commutation in DC machine** is the process in which generated alternating current in the armature winding of a dc machine is converted into direct current after going through the commutator and the stationary brushes.
- Again in DC motor, the input DC is to be converted in alternating form in armature and that is also done through commutation.
- This transformation of current from the rotating armature of a DC machine to the stationary brushes needs to maintain continuously moving contact between the commutator segments and the brushes.
- When the armature starts to rotate, then the coils situated under one pole rotates between a positive brush and its consecutive negative brush and the current flows through this coil is in a direction inward to the commutator segments.

- Then the coil is short circuited with the help of a brush for a very short fraction of time (1⁄500 sec). It is called commutation period.
- After this short-circuit time the armature coils rotates under S pole and rotates between a negative brush and its succeeding positive brush.
- Then the direction is reversed which is in the away from the commutator segments. This phenomena of the reversal of current is termed as commutation process.
- We get direct current from the brush terminal.
  The commutation is called ideal if the commutation process or the reversal of current is completed by the end of the short circuit time or the commutation period.
- If the reversal of current is completed during the short circuit time then there is sparking occurs at the brush contacts and the commutator surface is damaged due to overheating and the machine is called poorly commutated.

Methods for Improving Commutation

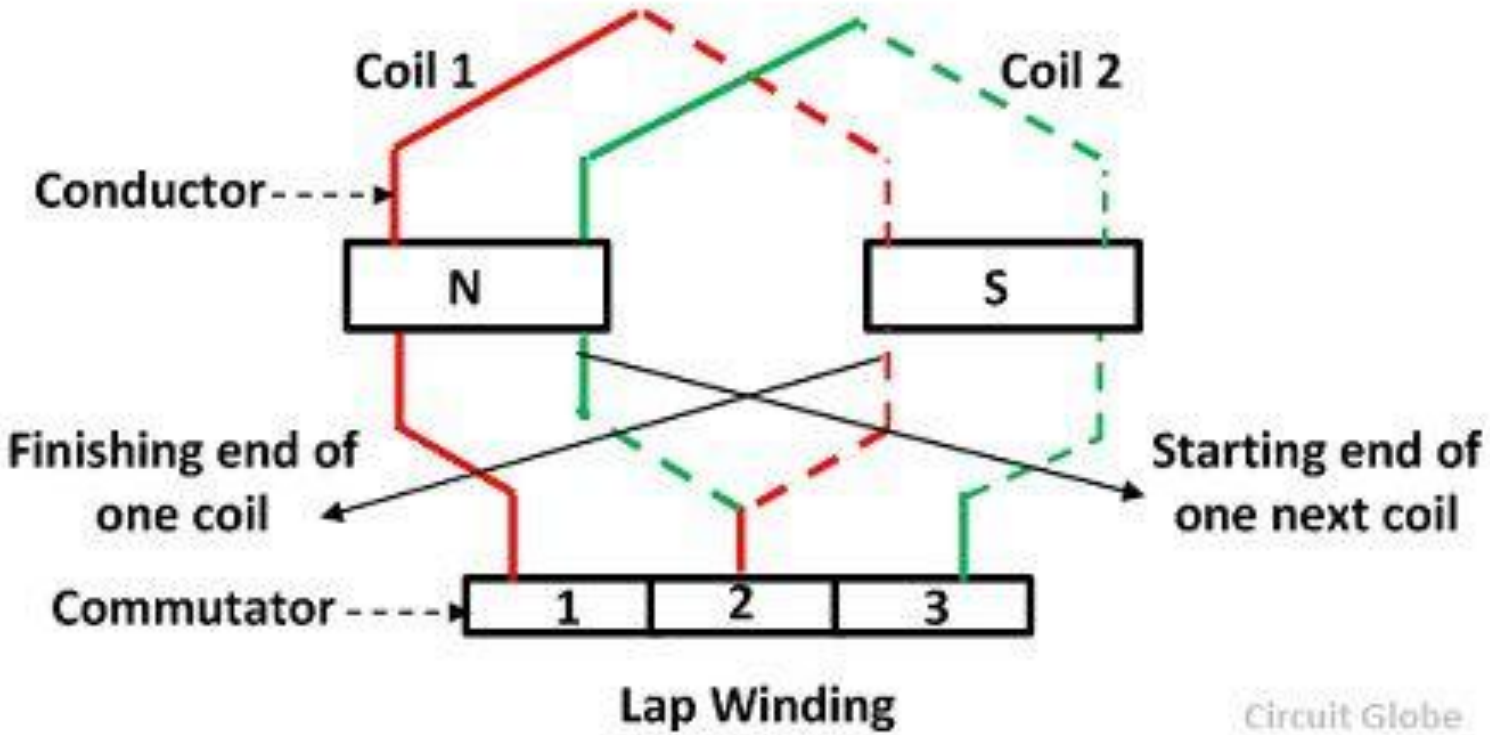
- Resistance Commutation
- Voltage Commutation
- Compensating windings

Lap Winding and Wave Winding

- The armature winding is mainly classified into two types, i.e., the lap winding and the wave winding.

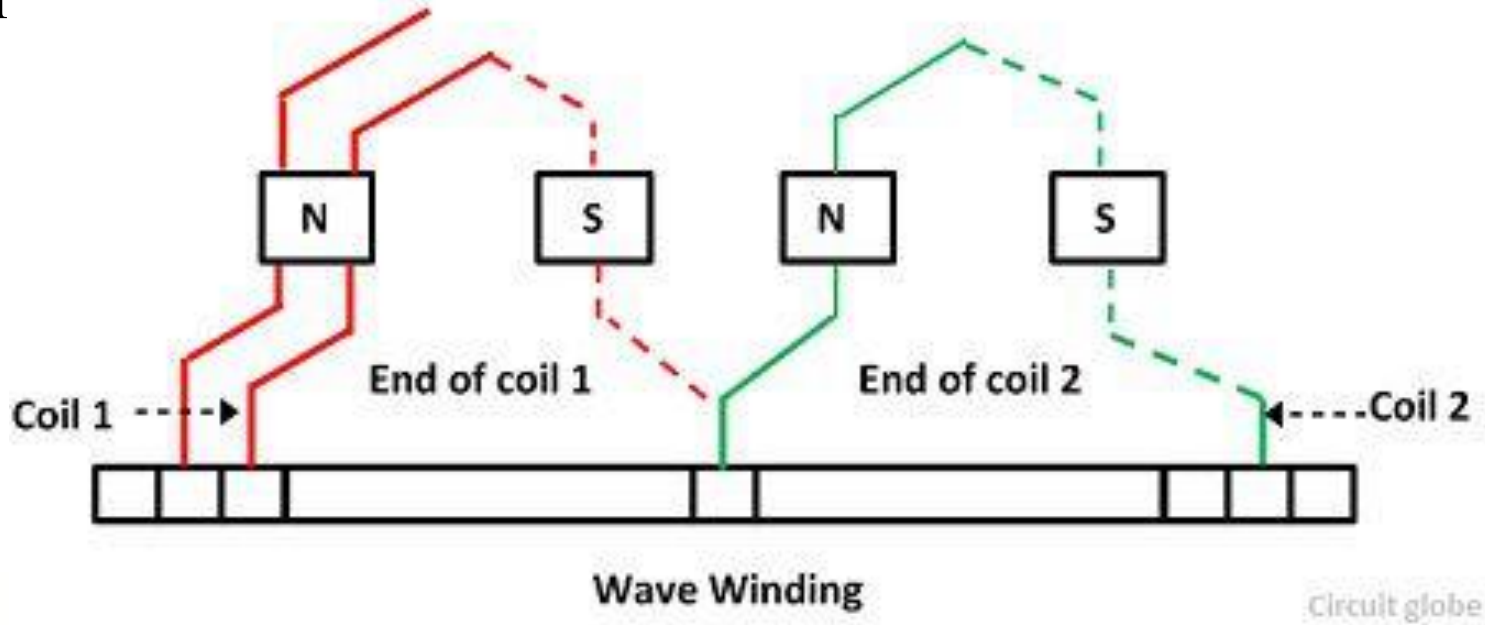
Definition of Lap Winding

- In lap winding, the consecutive coils overlap each other. The first end of the winding is connected to the one segment of the commutator, and the starting end of the other coil is placed under the same magnet (different pole) and join with the same segment of the commutator.
- The conductors are connected in such a way that the number of parallel paths equals to the number of poles. Consider the machine has P poles and Z armature conductors, then there will be P parallel paths, and each path will have Z/P conductors in series. The number of brushes is equivalent to the number of parallel paths. The half of the brush is positive, and the remaining is negative.


Coil 1
Coil 2
Conductor
N
S
Finishing end of one coil
Starting end of one next coil
Commutator
1
2
3
Lap Winding
Circuit Globe

Definition of Wave Winding

- The one end of the coil is connected to the starting end of the other coil which has the same polarity as that of the first coil. The coils are connected in the wave shape and hence it is called the wave winding. The conductor of the wave winding are split into two parallel paths, and each path had Z/2 conductors in series. The number of brushes is equal to 2, i.e., the nur



Difference between Lap and Wave Winding

	Lap Winding	Wave Winding
Definition	The coil is lap back to the succeeding coil.	The coil of the winding form the wave shape.
Connection	The end of the armature coil is connected to an adjacent segment on the commutators.	The end of the armature coil is connected to commutator segments some distance apart.
Parallel Path	The numbers of parallel path are equal to the total of number poles.	The number of parallel paths is equal to two.
Other Name	Parallel Winding or Mulitiple Winding	Two-circuit or Series Winding.
EMF	Less	More
Number of Brushes	Equal to the number of parallel paths.	Two
Efficiency	Less	High

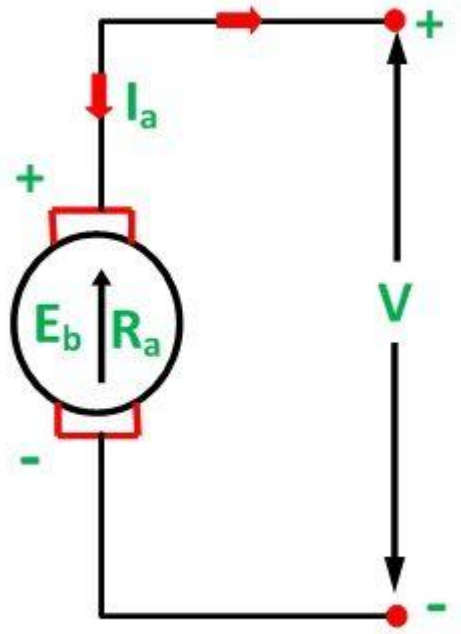
Back EMF in DC Motor

- When the current-carrying conductor placed in a magnetic field, the torque induces on the conductor, the torque rotates the conductor which cuts the flux of the magnetic field. According to the Electromagnetic Induction Phenomenon **"when the conductor cuts the magnetic field, EMF induces in the conductor"**.
- The Fleming right-hand rule determines the direction of the induced EMF.According to which, if we hold our thumb, middle finger and index finger of the right hand by an angle of 90°, then the index finger represents the direction of the magnetic field. The thumb shows the direction of motion of the conductor and the middle finger represents the emf induces on the conductor.
- On applying the right-hand rule, it is seen that **the direction of the induced emf is opposite to the applied voltage.** Thereby the emf is known as the *counter emf or back emf.*
- The back emf is developed in series with the applied voltage, but opposite in direction, i.e., the back emf opposes the current which causes it.

The magnitude of the back emf is given by the same expression shown below:

$$E_b = \frac{NP\varphi Z}{60\ A}$$

Where
E_b= induced emf of the motor known as Back EMF,
A = number of parallel paths
P = number of poles
N = speed
Z = total number of conductors in the armature
ϕ = useful flux per pole.



Circuit Globe

$$E_b = V - I_a R_a$$

Advantages of Back Emf in DC Motor

1. The back emf opposes the supply voltage. The supply voltage induces the current in the coil which rotates the armature. The electrical work required by the motor for causing the current against the back emf is converted into mechanical energy. And that energy is induced in the armature of the motor. Thus, we can say that energy conversion in the DC motor is possible only because of the back emf.The mechanical energy induced in the motor is the product of the back emf and the armature current, i.e., E_bI_a.

2. The back emf makes the DC motor self-regulating machine, i.e., the back emf develops the armature current according to the need of the motor. The armature current of the motor is calculated as:

$$I = \frac{V - E_b}{R_a}$$

Speed Control of DC Motor

We know,

$$N = Eb\ 60A / P\phi Z$$

but, for a DC motor A, P and Z are constants

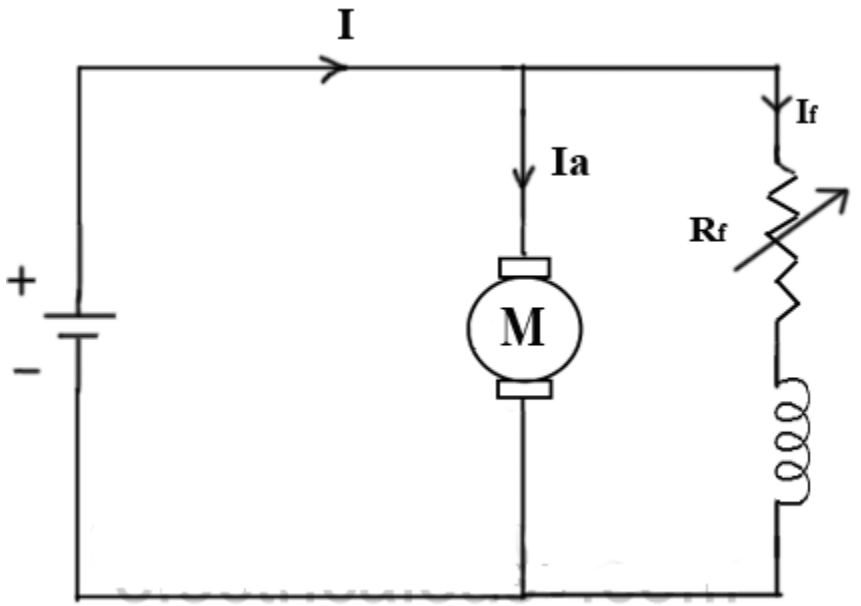
Therefore, $N \propto Eb/\phi$

This shows the **speed of a dc motor** is directly proportional to the back emf and inversely proportional to the flux per pole.

Speed Control Of Shunt Motor

1. Flux Control Method

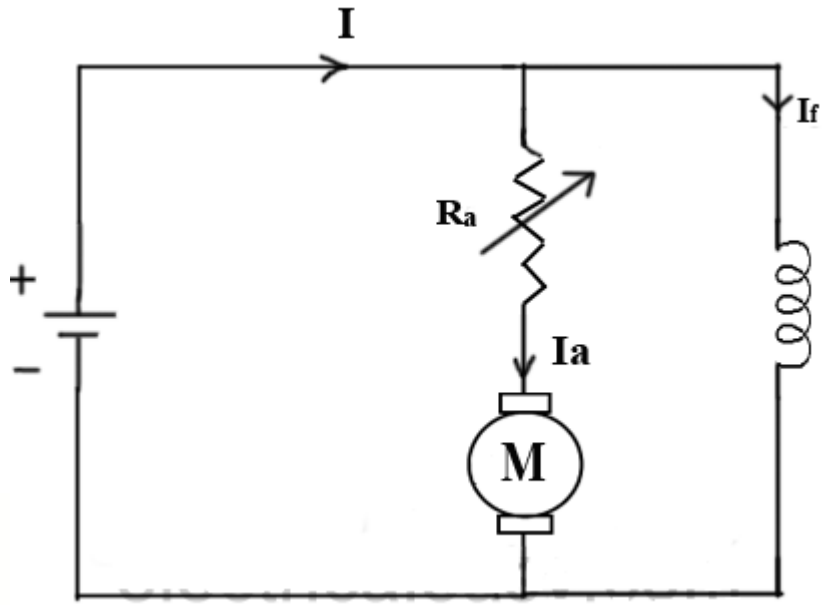
- It is already explained above that the **speed of a dc motor** is inversely proportional to the flux per pole. Thus by decreasing the flux, speed can be increased and vice versa.
- To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram. Adding more resistance in series with the field winding will increase the speed as it decreases the flux.
- In shunt motors, as field current is relatively very small, I_{sh}^2R loss is small. Therefore, this method is quite efficient.
- Though speed can be increased above the rated value by reducing flux with this method, it puts a limit to maximum speed as weakening of field flux beyond a limit will adversely affect the commutation.



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2. Armature Control Method

- Speed of a dc motor is directly proportional to the back emf E_b and $E_b = V - I_aR_a$.
- That means, when supply voltage V and the armature resistance R_a are kept constant, then the speed is directly proportional to armature current I_a.
- Thus, if we add resistance in series with the armature, I_a decreases and, hence, the speed also decreases. Greater the resistance in series with the armature, greater the decrease in speed.



3. Voltage Control Method

a) **Multiple voltage control**:

In this method, the shunt field is connected to a fixed exciting voltage and armature is supplied with different voltages. Voltage across armature is changed with the help of suitable switchgear. The speed is approximately proportional to the voltage across the armature.

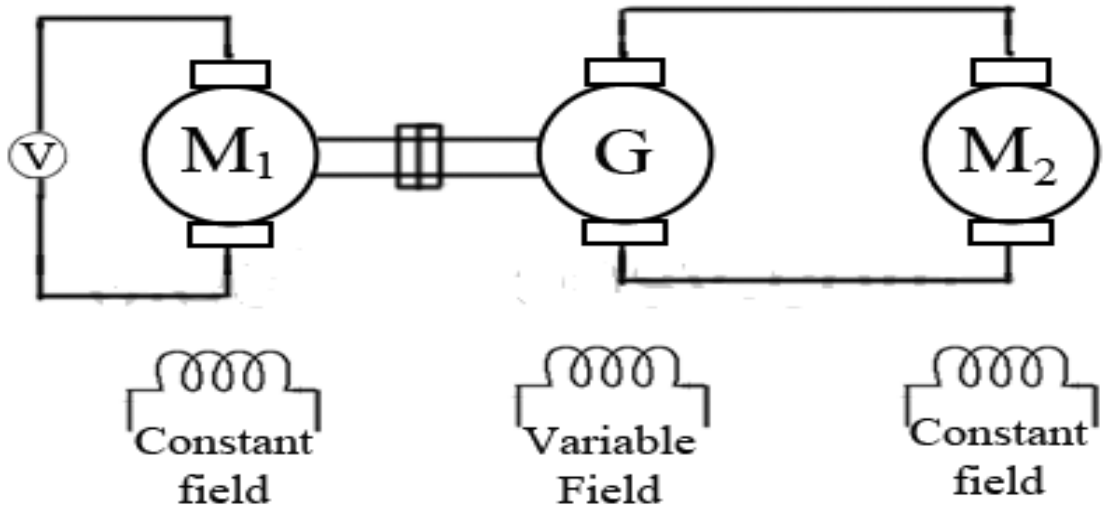
b) **Ward-Leonard System**:

This system is used where very sensitive **speed control of motor** is required (e.g electric excavators, elevators etc.). The arrangement of this system is as shown in the figure.

M_2 is the motor to which speed control is required.

M_1 may be any AC or DC Motor with constant speed.

G is a generator directly coupled to M_1.



In this method, the output from generator G is fed to the armature of the motor M_2 whose speed is to be controlled. The output voltage of generator G can be varied from zero to its maximum value by means of its field regulator and, hence, the armature voltage of the motor M_2 is varied very smoothly. Hence, very smooth **speed control of the dc motor** can be obtained by this method.

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Speed Control Of Series Motor

1. Flux Control Method

•Field diverter: A variable resistance is connected parallel to the series field as shown in fig (a). This variable resistor is called as a diverter, as the desired amount of current can be diverted through this resistor and, hence, current through field coil can be decreased. Thus, flux can be decreased to the desired amount and speed can be increased.

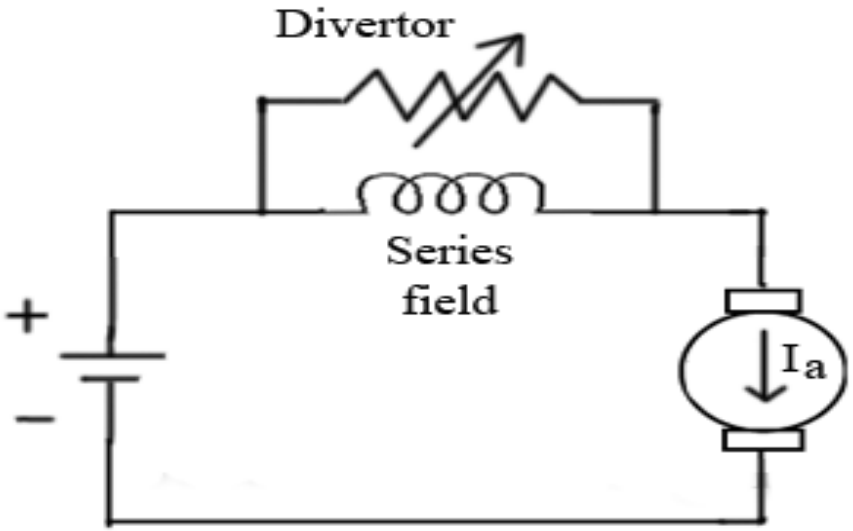


fig (a) Field Divertor

Armature diverter: Diverter is connected across the armature as shown in fig (b). For a given constant load torque, if armature current is reduced then the flux must increase, as Ta ∝ ØIa
This will result in an increase in current taken from the supply and hence flux Ø will increase and subsequently speed of the motor will decrease.

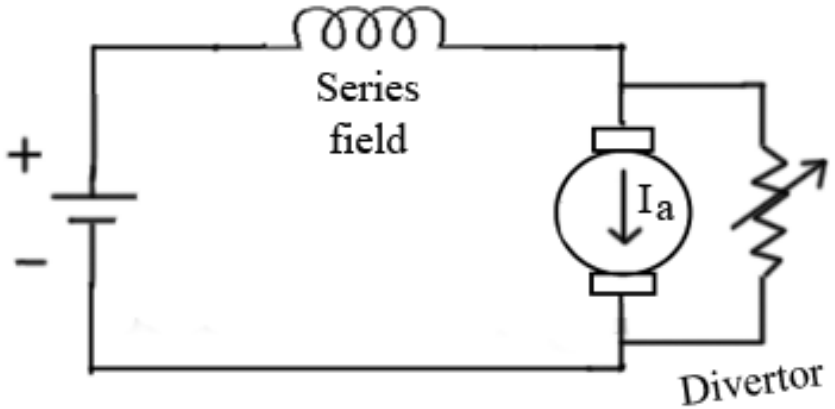


fig (b) Armature Divertor

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•Tapped field control: As shown in fig (c) field coil is tapped dividing number of turns. Thus we can select different value of Ø by selecting different number of turns.

•Paralleling field coils: In this method, several speeds can be obtained by regrouping coils as shown in fig (d).

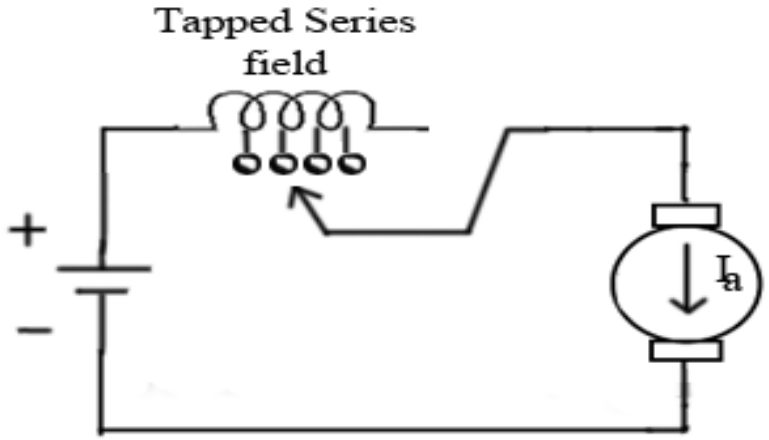


fig (c) Tapped field

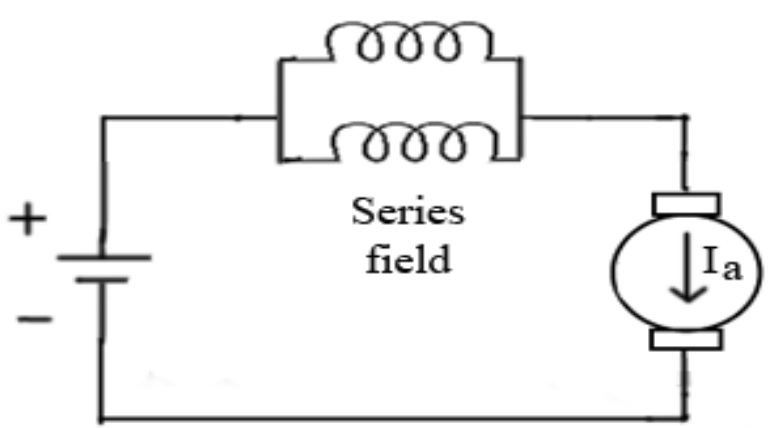


fig (d) Paralleling Field coils

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2. Variable Resistance In Series With Armature

By introducing resistance in series with the armature, voltage across the armature can be reduced. And, hence, speed reduces in proportion with it.

3. Series-Parallel Control

This system is widely used in electric traction, where two or more mechanically coupled series motors are employed. For low speeds, the motors are connected in series, and for higher speeds, the motors are connected in parallel.

When in series, the motors have the same current passing through them, although voltage across each motor is divided. When in parallel, the voltage across each motor is same although the current gets divided.

Need of Starters for DC Motors

- At the starting of the motor, the armature current is controlled by the resistance of the circuit. The resistance of the armature is low, and when the full voltage is applied at the standstill condition of the motor, the armature current becomes very high which damage the parts of the motor.
- Because of the high armature current, the additional resistance is placed in the armature circuit at starting. The starting resistance of the machine is cut out of the circuit when the machine gains its speeds. The armature current of a motor is given by:

$$I_a = \frac{V - E}{R_a} \ldots\ldots\ldots (1)$$

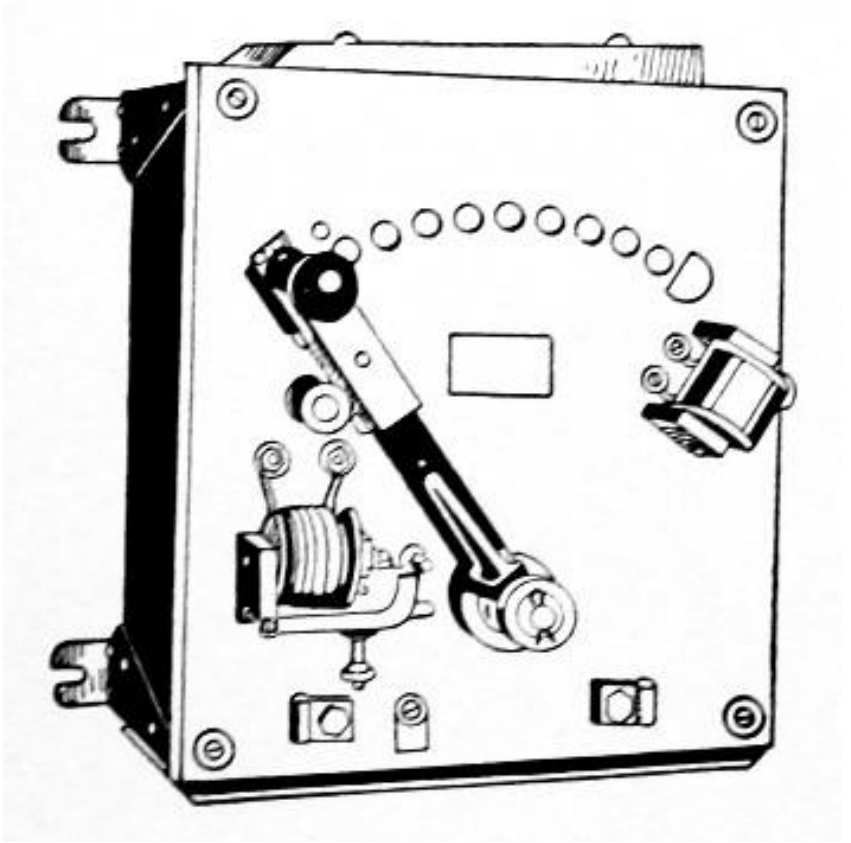
Thus, I_a depends upon E and R_a, if V is kept constant. When the motor is first switched ON, the armature is stationary. Hence, the back EMF E_b is also zero. The initial starting armature current I_{as} is given by the equation shown below:

$$I_{as} = \frac{V - 0}{R_a} = \frac{V}{R_a} \quad \ldots\ldots\ldots\ldots (2)$$

Since, the armature resistance of a motor is very small, generally less than one ohm.
Therefore, the starting armature current I_{as} would be very large
Such a heavy inrush of starting current taken by the motor may result in:-
1)Sparking at the commutators.
2)Damage to the armature winding.
3)Deterioration of the insulation due to overheating.
4)Large dips in the supply voltage

3 Point Starter





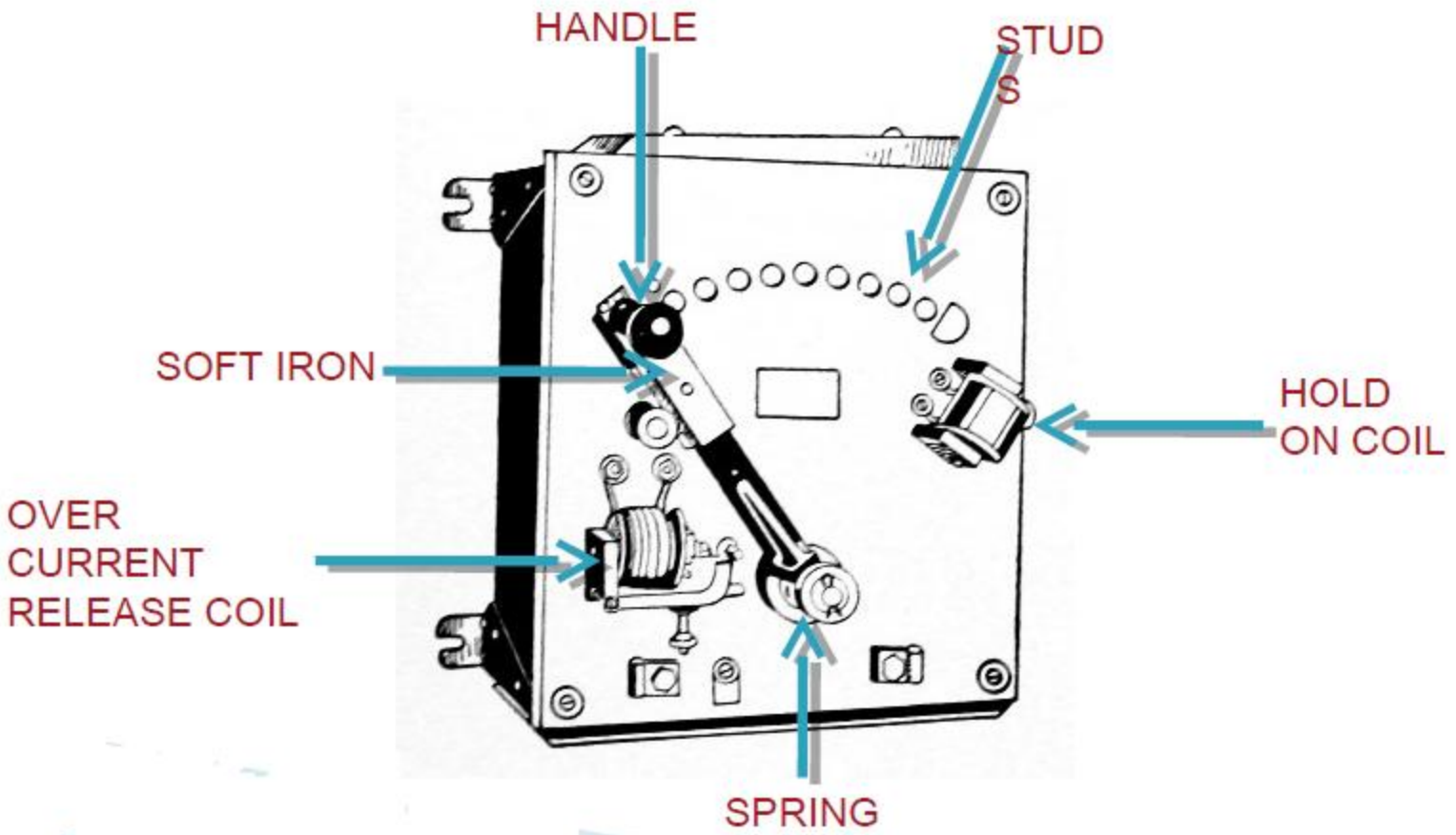

HANDLE
STUD
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SOFT IRON
HOLD
ON COIL
OVER
CURRENT
RELEASE COIL
SPRING

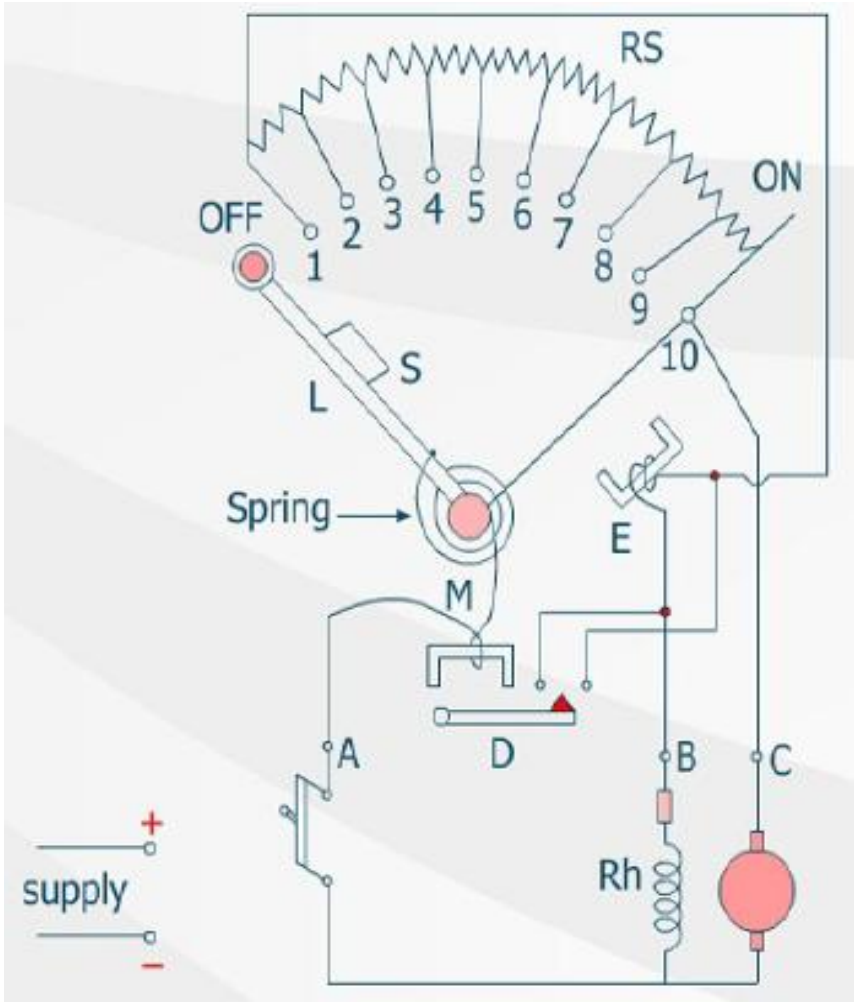
Fig shown is of 3point starter. The three terminals marked A,B,C.

- One line is directly connected to one armature terminal & one field terminal which are tied together.
- The other line is connected to point A which is further connected to the starting arm ‘L’ through the over current release ‘M’

To start the motor the main switch is first closed and starting arm is slowly moved to the right.

- As soon as the arm make contact with stud 1, the field circuit is directly connected across the line and at the same time full

starting resistance R is placed in series with the armature.



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The starting current drawn by the armature is I=V/(Ra + Rs)
Where Rs is the starting resistance.

- As the arm is further moved, the starting resistance is gradually cut out till, when the arm reaches the running position, the resistance is all cut out.
- There is a soft iron piece ‘S’ attached to the arm which in the full ‘ON’ or running position is attracted and held by an electromagnet ‘E’ energised by the shunt current. It is variously known as ‘HOLD ON’ coil, ‘LOW VOLTAGE’ release.

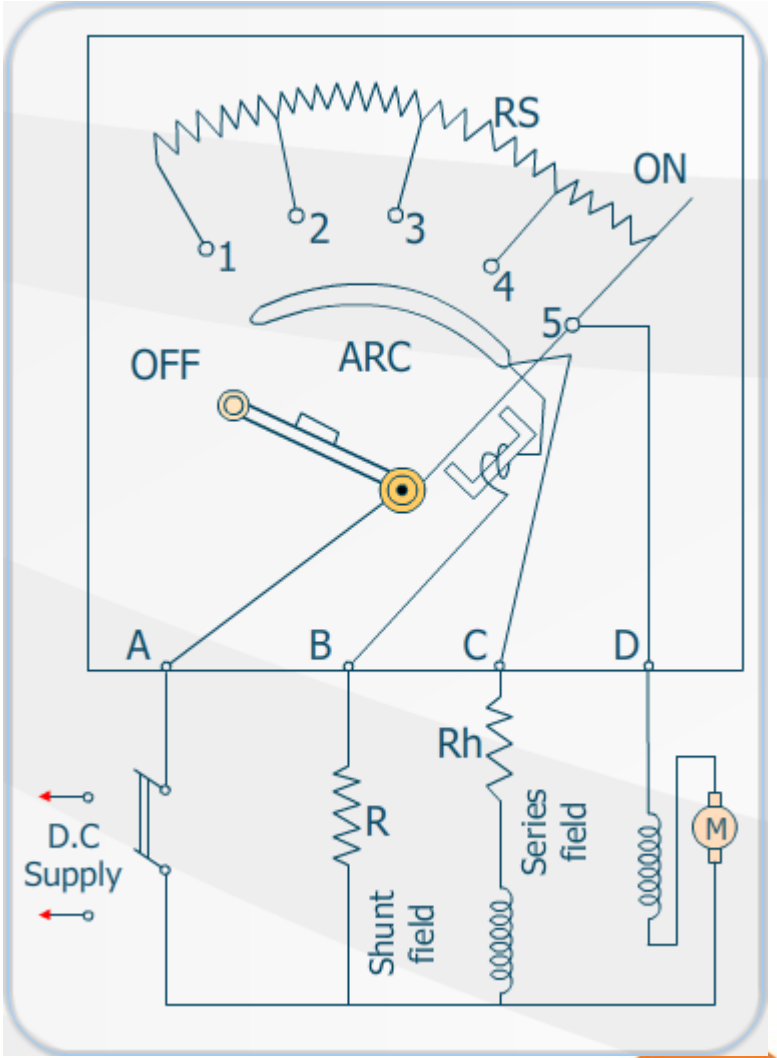
Hold ON :- The normal action of this coil is tohold on the arm in the full running position. But in the case of failure of the supply, it is de-energised, thereby releasing the arm which pulled back by the spring to the ‘OFF’ position.

Over current release:-This consist of an electromagnet connected in the supply line. If the motor becomes overloaded beyond a predetermined value, then arm D is lifted & short circuits the electromagnet. Hence the arm is released back to OFF position.

4 Point Starter

As the name suggests, it has four terminals (L,L,F,A).

- Working is same as that of the 3 point starter.
- When compared to the 3 point starter, it will be noticed that one important change has been made ie. The hold On coil has been taken out of shunt field and has been connected directly across the line through a protecting resistance as shown.



Example 4.2. *The armature of a 4-pole lap-wound D.C. machine has core length = 30 cm, diameter = 40 cm, total conductors = 500, speed = 1200 r.p.m. and current = 20 A. For an average flux density of 0.5 T, find the electromagnetic (or gross mechanical) power developed and the internal torque.*

Solution. Here $l = 0.3$ m, $r = 0.20$ m, speed, $n = \frac{1200}{60} = 20$ r.p.s.

It is known that $B_{av} = \frac{P\phi}{2\pi rl}$

$\therefore$ Flux per pole, $\phi = \frac{0.5 \times 2\pi \times 0.2 \times 0.3}{4} = 0.04712$ Wb

Generated e.m.f., $E_a = \frac{\phi ZnP}{a} = \frac{0.04712 \times 500 \times 20 \times 4}{4} = 471.2$ V.

Gross mechanical power developed $= E_a I_a = 471.2 \times 20 = 9424$ W.

Internal torque, $T_e = \frac{E_a I_a}{\omega_m} = \frac{9424}{2\pi \times 20} = 74.994$ Nm $\simeq 75$ Nm.

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Example 4.49. *A 250 V D.C. shunt motor has an armature resistance of 0.5 Ω and a field resistance of 250 Ω. When driving a constant torque load at 600 rpm, the motor draws 21 A. What will be the new speed of the motor if an additional 250 Ω resistance is inserted in the field circuit.* (GATE, 1988)

Solution. Field current, $I_{f1} = \frac{250}{250} = 1 \text{ A}$

Armature current, $I_{a1} = 21 - 1 = 20 \text{ A}$

Counter e.m.f., $E_{a1} = 250 - 20 \times 0.5 = 240 \text{ V}$

$$I_{f2} = \frac{250}{250 + 250} = 0.5 \text{ A}$$

Neglecting magnetic saturation, $\phi_1 \propto I_{f1}$ or $\frac{\phi_1}{\phi_2} = \frac{I_{f1}}{I_{f2}} = \frac{1}{0.5}$

For constant load torque, $T_{L1} = T_{L2}$ or $T_{e1} = T_{e2}$ $K_a \phi_1 I_{a1} = K_a \phi_2 I_{a2}$

$$\therefore \quad I_{a2} = I_{a1} \times \frac{\phi_1}{\phi_2} = I_{a1} \times \frac{I_{f1}}{I_{f2}} = 20 \times \frac{1}{0.5} = 40 \text{ A}$$

New counter e.m.f., $E_{a2} = 250 - 40 \times 0.5 = 230 \text{ V}$

Now $\frac{E_{a1}}{E_{a2}} = \frac{N_1 \phi_1}{N_2 \phi_2}$ or $\frac{240}{230} = \frac{600}{N_2} \cdot \frac{\phi_1}{\phi_2} = \frac{600}{N_2} \times \frac{I_{f1}}{I_{f2}} = \frac{600}{0.5\, N_2}$

$\therefore$ Motor speed, $N_2 = \frac{600 \times 230}{240 \times 0.5} = 1150 \text{ r.p.m.}$

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Example 4.28. *A 220-V D.C. shunt motor has an armature circuit resistance of 0.2 Ω and field resistance of 110 Ω. At no-load the motor takes 5 A and runs at 1500 r.p.m. If the motor draws 52 A at rated voltage and rated load, calculate the motor speed and its rated shaft torque in Nm. The rotational losses at no-load and full load are the same. Neglect armature reaction.*

Solution. The shunt field current $I_f = \frac{220}{110} = 2$ A.

At no-load, armature current $I_{a1} = 5 - 2 = 3$ A.

Counter e.m.f. $E_{a1} = 220 - 3 \times 0.2 = 219.4$ V.

$\therefore$ Rotational losses $= E_{a1} I_{a1} = 219.4 \times 3 = 658.2$ watts.

At full load, armature current $I_{a2} = I_L - I_f = 52 - 2 = 50$ A.

$\therefore$ Counter e.m.f. $E_{a2} = 220 - 50 \times 0.2 = 210$ V.

Here ϕ_1 (no load flux) $= \phi_2$ (full load flux), because the field current is constant at 2 A and effect of AR is neglected.

$$\therefore \quad \frac{E_{a1}}{E_{a2}} = \frac{n_1 \phi_1}{n_2 \phi_2}$$

or
$$n_2 = \frac{n_1 \phi_1}{\phi_1} \times \frac{E_{a2}}{E_{a1}} = \frac{(1500)(210)}{219.4} = 1435 \text{ r.p.m.}$$

Shaft power, P_{sh} = Electromagnetic power − Rotational losses

$= 210 \times 50 - 658.2 = 9841.8$ watts.

$$\therefore \quad \text{Shaft torque} = \frac{P_{sh}}{\omega_m} = \frac{9841.8 \times 60}{2\pi \times 1435} = 65.4 \text{ Nm.}$$

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Thank you !