

FOR ELECTRICAL ENGINEERING

DC MACHINE

Volume 1



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DC MACHINE

Volume 1

(Chapter 1 – 3)

Chapter 1 : Rahayu binti Jonit

Chapter 2 : Noraziah binti Abu Bakar

Chapter 3 : Jumaliah binti Jahuri

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We hereby declare that this module is our original work. To the best of our knowledge it contains no materials previously written or published by another person. However, if there is any, due acknowledgement and credit are mentioned accordingly in the e-book.

PREFACE

The eBook DC Machine suitable with real situation in study of electrical, mechanical engineering. The content of this eBook volume 1.0 consist three chapters are DC Machine, DC Generator and DC Motor. Very topic covers a whole range of topics learned by the students and is published based on the on the curriculum for Course of Industrial Management issued by the Curriculum Division, Department of Polytechnic Education (DPE), Ministry of Higher Education of Malaysia.

Student will learn about introduces and approach with minimum theory of the basic fundamentals, construction DC machine, basic principle machine as a generator and motor system works. Construct and solve the problem by using fundamental theory and mathematical method calculations. The content , also covering Introduces practical drive techniques of electric motors to enable stable, types of dc machine and efficient control of many application systems.

Rahayu binti Jonit
Noraziah binti Abu Bakar
Jumaliah binti Jahuri

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CHAPTER 1

DC MACHINE



INTRODUCTION

Direct current electrical machines use direct current where the value of current and voltage is low. Direct current has positive and negative polarity. Used on low-powered devices such as dry batteries, phones, cameras and wet cells (1.5V-2V).

A generator is a machine that converts mechanical energy into electrical energy. The energy conversion is based on the production of electric motion or electromagnetic induction.

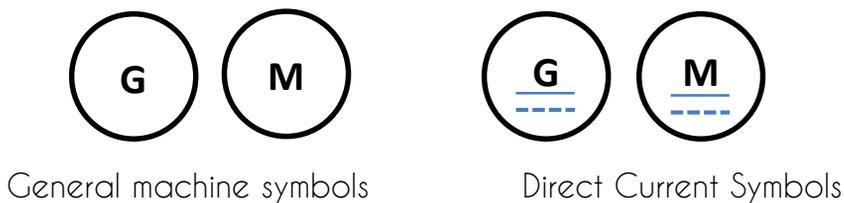


Figure 1.1: Symbols for DC machines

MOTOR DEFINITION – The supply is provided by an electric current and this will produce torque to rotate a rotary type mechanical movement.

DEFINITION OF GENERATOR – Driven by a mechanical type machine and will generate a voltage that produces current flow in an electrical circuit.

ELECTROMAGNETIC INDUCTION

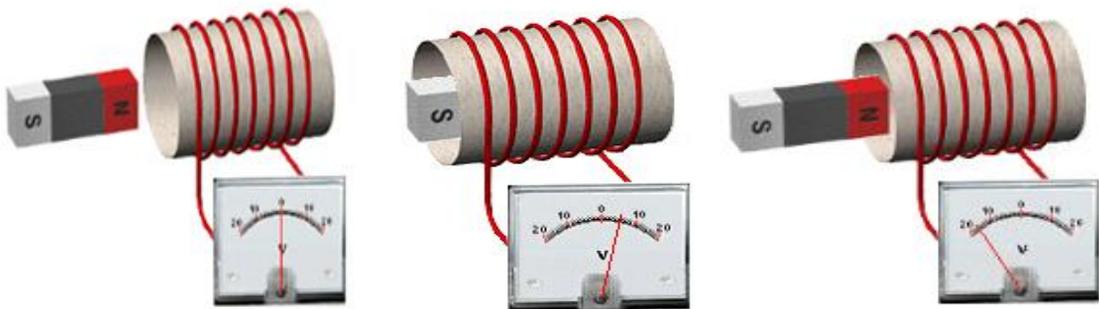
The basis of generator operation is based on two laws of electromagnetic induction, namely Faraday's Law and Lenz's Law.

Faraday's Law:

When there is a magnetic flux cut by the conductor then e.m.f will be induced
the magnitude of the induced e.m.f is directly proportional to the flux cutting rate.

Lenz's law:

States that the direction of the magnetic field produced by the induced current is opposite to the direction of the magnetic field that produced it. Figure 1.2 shows a bar magnet being moved out and into the coil repeatedly. Flux magnetic flux changes only occur when the magnet is moved in the coil. The direction of induced e.m.f depends on the direction of movement and the magnetic pole.



<https://www.daenotes.com/electronics/basic-electronics/faraday-laws-of-electromagnetic-induction>

Figure 1.2: Demonstration of Faraday's law

The parts that need to be in an AT generator to allow e.m.f to be generated are: -

- i. magnetic field to produce flux
- ii. a conductor that can rotate to cut the flux

FACTORS AFFECTING THE STRENGTH OF THE MAGNETIC FIELD

Factors that affect the strength of the magnetic field on the coil of wire: -

- i. the current flowing through the loop increases, the strength of the loop's magnetic field increases
- ii. the number of turns of the loop increases, the strength of the magnetic field of the loop also increases



factors that affect the strength of the magnetic field on a straight wire:

-

- i. if the current flow increases, the strength of the magnetic field also increases
- ii. if the number of current-carrying wires is increased then the strength of the magnetic field also increases
- iii. the greater the distance between the magnetic field line and the wire, the stronger it is the felt magnetic field will decrease.

Factors that affect electromagnetic strength: -

- i. increasing the current flowing through the coil
- ii. increase in the number of turns
- iii. the use of soft-iron core

Factors that affect the magnitude of current carrying conductors: -

- i. the strength of the magnetic field is directly proportional to the resultant force
- ii. the size of the current conductor, the more current flows the more power resulted.
- iii. circumference of the conductor, directly proportional to the resulting force.

BUILDING OF DC MACHINE

The two main parts of an AT machine are the stationary part and the rotating part. The stationary part consists of poles (frames), magnetic fields, carbon brushes. While the rotating part is the armature and regulator.

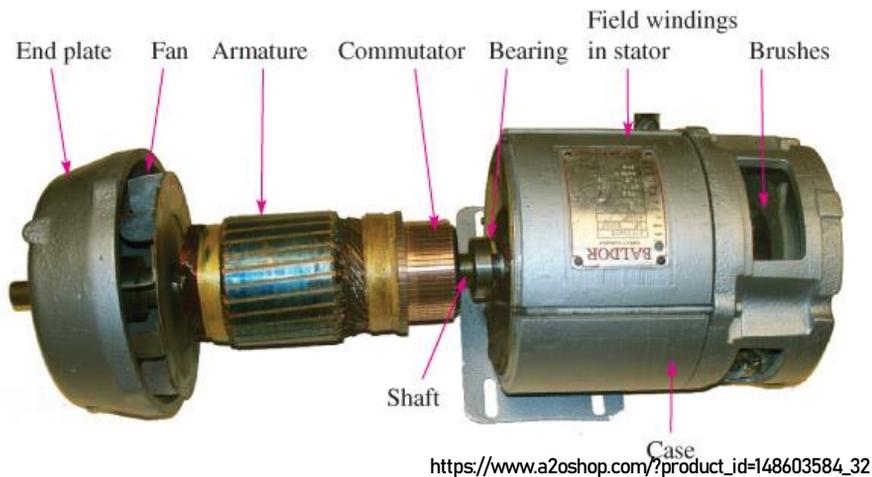


Figure 1.1: Parts for DC machines

Construction of the DC machine

The part of DC machine is not different with DC motor and DC generator but make sure to know the difference between both.

Stator

Comes from the “stationary” meaning stationary parts of a DC machine. Does not move and only produces a magnetic field around the rotor to make the rotor rotating when the voltage is applied to it. Rotor contains of

- Frame/yoke
- Magnetic Field
- Brushes (carbon brushes)

Rotor

Comes from the “rotate” meaning rotating parts of a DC machine. Rotor is the moving parts of a DC machine. It dynamically moves when the voltage is applied to the armature winding. This will produce mechanical movement for a DC machine. Stator contains of

- Armature
- Commutator

Frame @ Yoke

Yoke is an iron frame as a protective cover and protects for inside parts machine.

Dual function first as a cover and mechanical support for the poles and acts as a protecting cover for the whole machine. Second carries the magnetic flux produced by the poles. For small machines made of cast iron. While for large machines made of cast steel or rolled steel that are then assembled into a large frame.



<https://www.gexpro.com/p/1421091/ge/motor-dc-10hp-tefc-xp-frame-1750rpm-230vdc-drip-proof/5by555xd804a801>

Figure 1.4: Frame @ Yoke of DC Machine

Magnetic Field

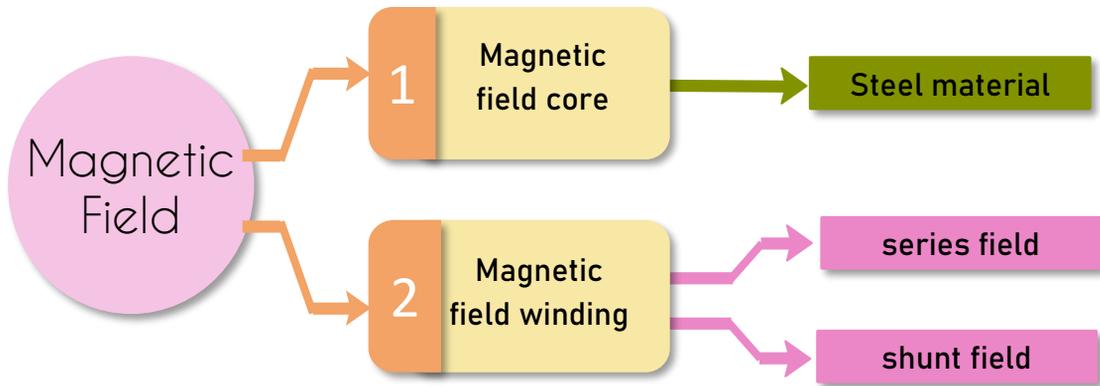


Figure 1.4: magnetic field construction charts

Its main function is to produce flux, divided into two main parts which are polar core and pole winding.

Pole Cores and Pole Shoes

The field magnets consist of pole cores and pole shoes.

The pole shoes serve two purposes:

- i. they spread out the flux in the air gap and also, being of larger cross-section, reduce the reluctance of the magnetic path
- ii. they support the exciting coils (or field coils)

There are **two main types of pole construction**.

- i. The pole core itself may be a solid piece made out of either cast iron or cast steel but the pole shoe is laminated and is fastened to the pole face by means of countersunk screws
- ii. In modern design, the complete pole cores and pole shoes are built of thin laminations of annealed steel which are riveted together under hydraulic pressure. The thickness of laminations varies from 1 mm to 0.25 mm

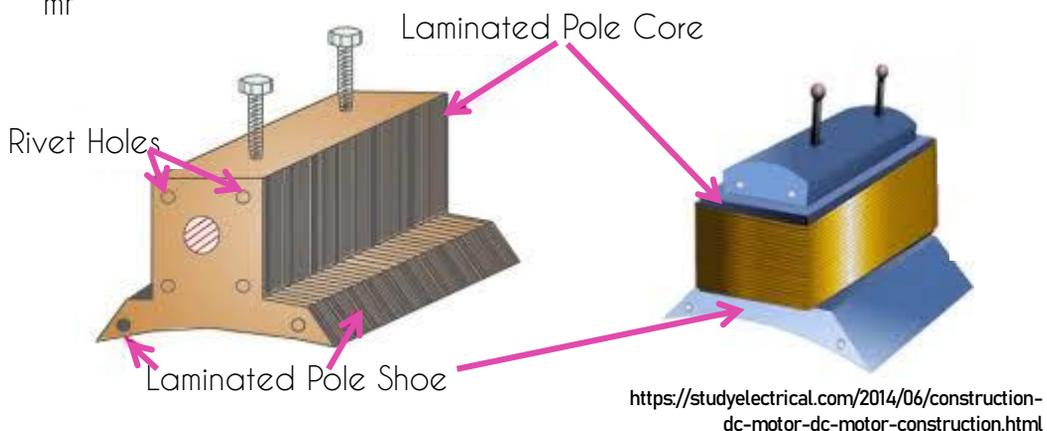


Figure 1.5: magnetic field circumference and magnetic field core

Magnetic Field

Pole winding.

There are two types of pole winding:

- i. series field- coarse wire size and small windings
- ii. shunt field- size of fine wire and many windings

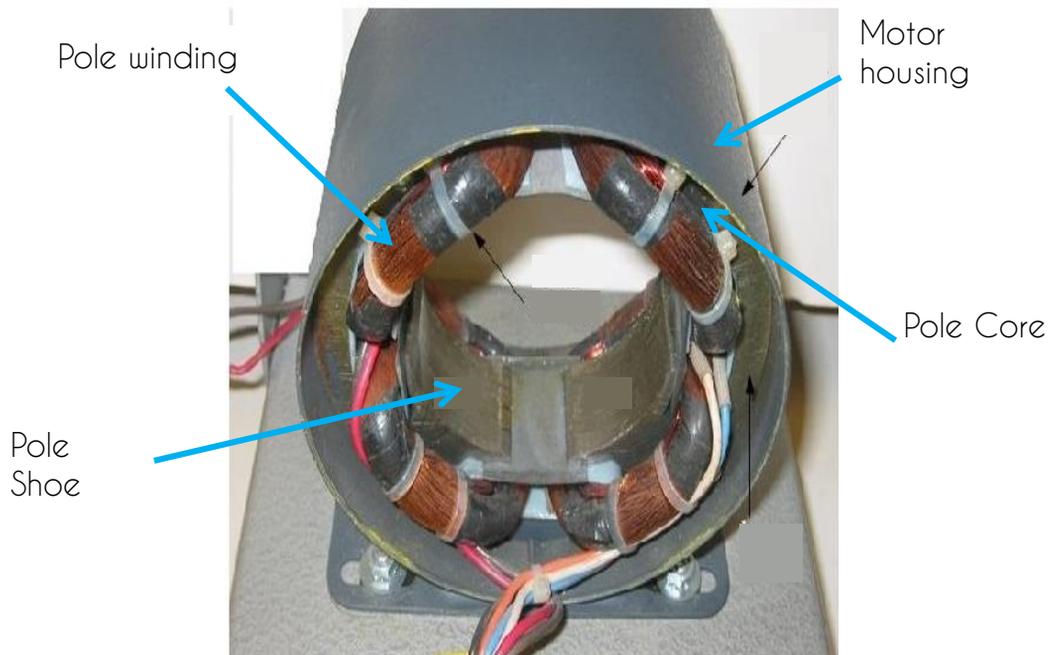


Figure 1.6: generator cross section

Main pole - Produces a magnetic field that will react with armature magnetic field

Intermediate pole - Prevents sparks and can improve reaction

Carbon Brush

Its main function is to collect current and as an intermediary regulator with external supply. Carbon brushes are located on the surface of the regulator. Made from a carbon mixture, where carbon has good electrical conductivity and high self-lubricity. Square shaped and placed on a handle that is connected to a variable spring.

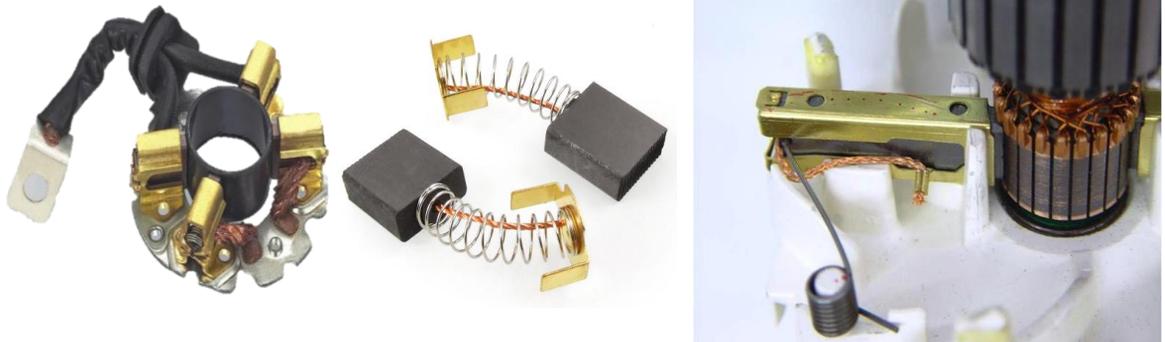


Figure 1.7: carbon brush

Commentator

The main function of the regulator is as a converter (rectifier) which converts alternating current to direct current. In addition, it is also a successor to the machine. The number of regulator segments is equal to the number of slotted holes in the armature. Made of copper sheet.

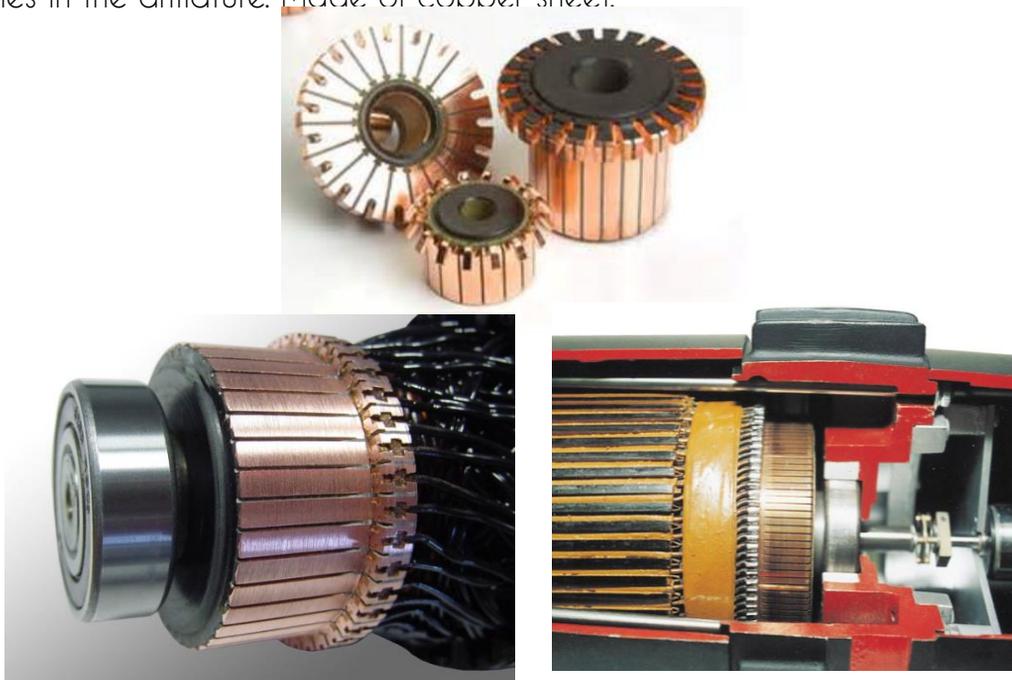


Figure 1.8: Commentator

Armature

Its main function is to collect current and as an intermediary regulator with external supply. Carbon brushes are located on the surface of the regulator. Made from a carbon mixture, where carbon has good electrical conductivity and high self-lubricity. Square shaped and placed on a handle that is connected to a variable spring.

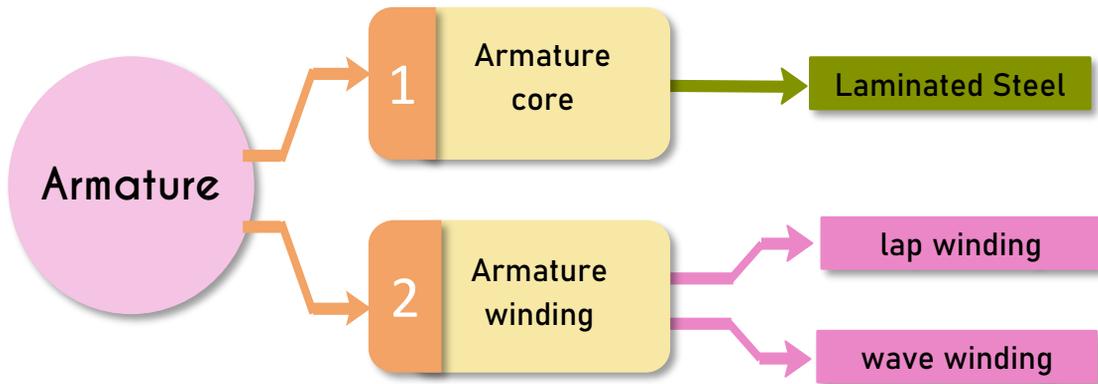
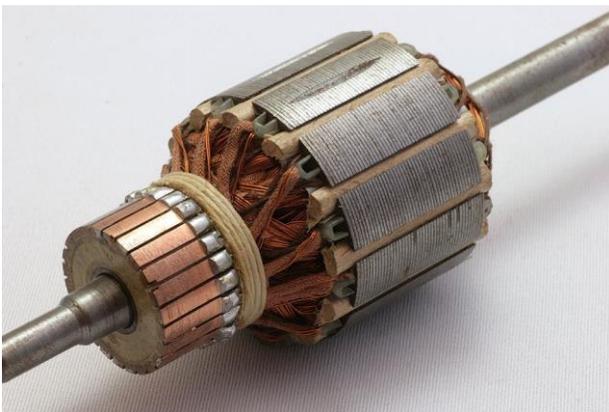


Figure 1.9: : armature construction charts

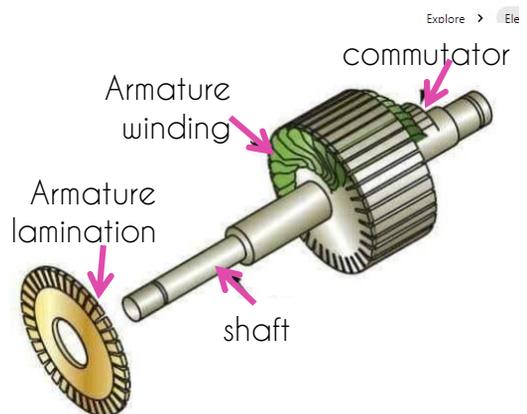
Its main function is to cut the flux, divided into two main parts which are: -

- **Armature core**
made of thin layers of steel for the purpose of reducing eddy current
- **Armature winding** : there are two types
 - series field- coarse wire size and few windings
 - field circuit- size of fine wire and many windings



<https://www.linquip.com/blog/parts-of-dc-generator-explanation-working/>

(a) Armature winding construction



(b) Armature core

Figure 1.10: Armature

Armature

The armature winding is the most important part of the rotating machine. It is the place where energy conversion takes place, i.e., the mechanical energy is converted into electrical energy, and the electrical energy is converted into mechanical energy. The armature winding is mainly classified into types, i.e., the lap winding and the wave winding.

The armature winding usually uses copper wire either round or square and it is neatly insulated as shown in figure 1.11. armature winding consists of **two types**, lap winding and wave winding. The difference between the two is in the connection of the base or the end connection of the coil with the regulator. While the appearance is basically the same. These two have different counts which are: -

Lap winding

Current path number: $a = mP$

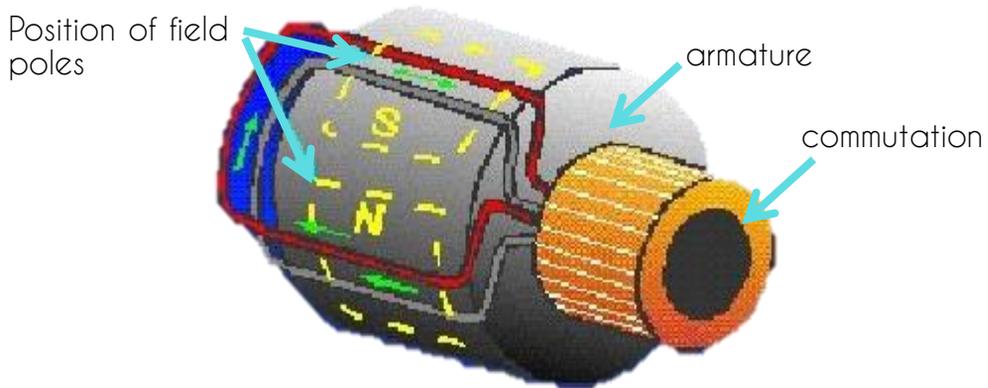
Wave winding (wave winding)

Current path number: $a = 2m$

Where: m : number of plex for winding (Simplex $m=1$, duplex $m=2$, triplex $m=3$)

P : number of poles for a machine

Lab Winding



<https://slidetodoc.com/e-lessons-student-module-for-c16-curriculum-state/>

Figure 1.11: lap winding

In lap winding, the finishing end of one coil is connected to a commutator segment. The starting of an adjacent coil situated under the same pole is also connected to the same commutator segment. Since there is an overlapping of successive coils, it is known as lap winding. It is shown in the following figure.

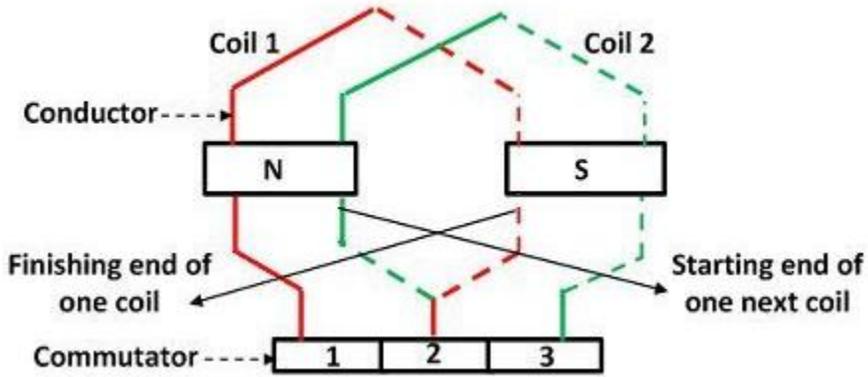


Figure 1.12: lap winding

The lap winding is mainly used in low voltage, high current machine applications. They are three types

- Simplex Lap Winding ($m = 1$)
 - Duplex Lap winding ($m = 2$)
 - Multiplex Lap winding (duplex, triplex, etc..)
- i. **Simplex lap winding** is a winding in which the number of parallel paths will be same as that of the poles.

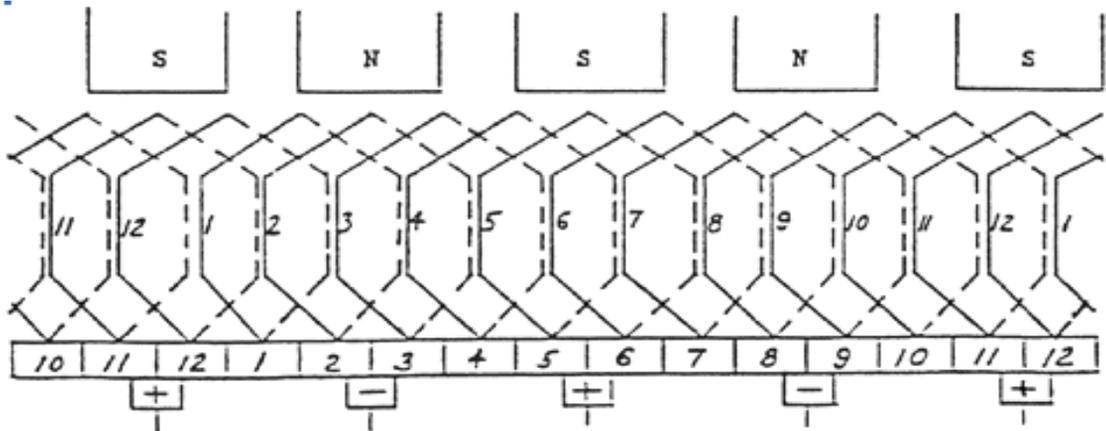
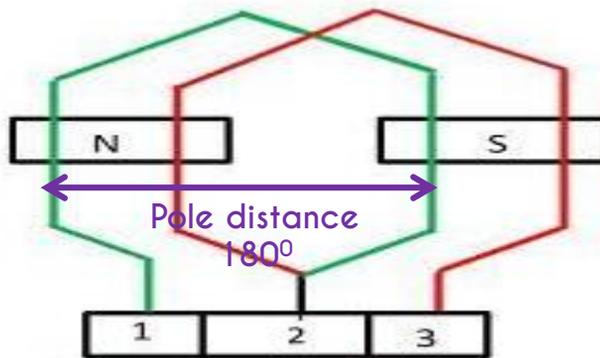


Figure 1.12: simplex lap winding

- ii. A **duplex winding** consists of two similar simplex winding placed in the armature slots and connected to the alternate commutator segments. Hence the number of parallel paths is twice the number of poles. In a similar way, the triplex winding is also connected. They have a number of parallel paths thrice the number of poles.

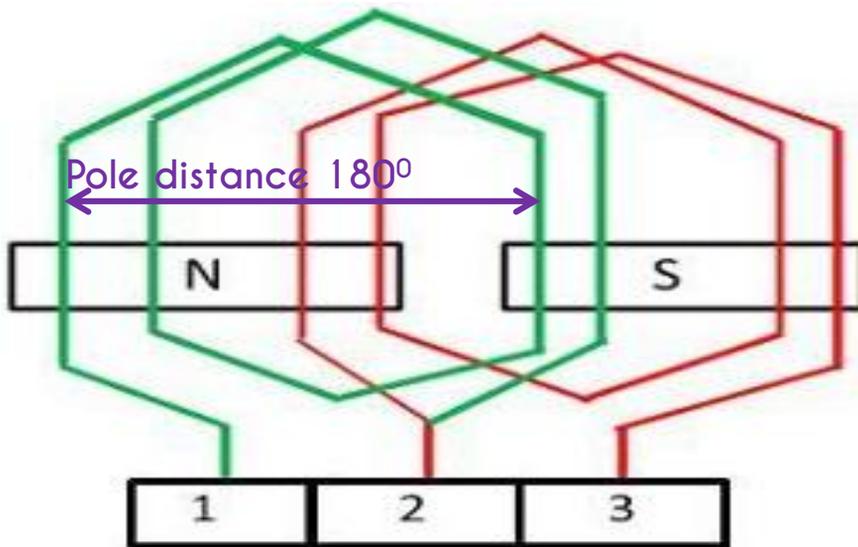


Figure 1.13: duplex lap winding

- iii. **Triplex Lap Winding:** In triplex lap winding the windings are connected to the one-third of the commutator bars. The lap winding has many paths and hence it is used for the larger current applications. The only disadvantage of the lap winding is that it requires many conductors which increase the cost of the winding.

Lap winding is also called as multiple or parallel winding and is used for applications with high current output..

Wave Winding



Figure 1.14: wave winding

In wave winding, the coil side is not connected back but progresses forward to another coil side. Each coil side pass through every N pole and S pole till it returns to the point where it was started. The winding is arranged, such that they progress in the same direction.

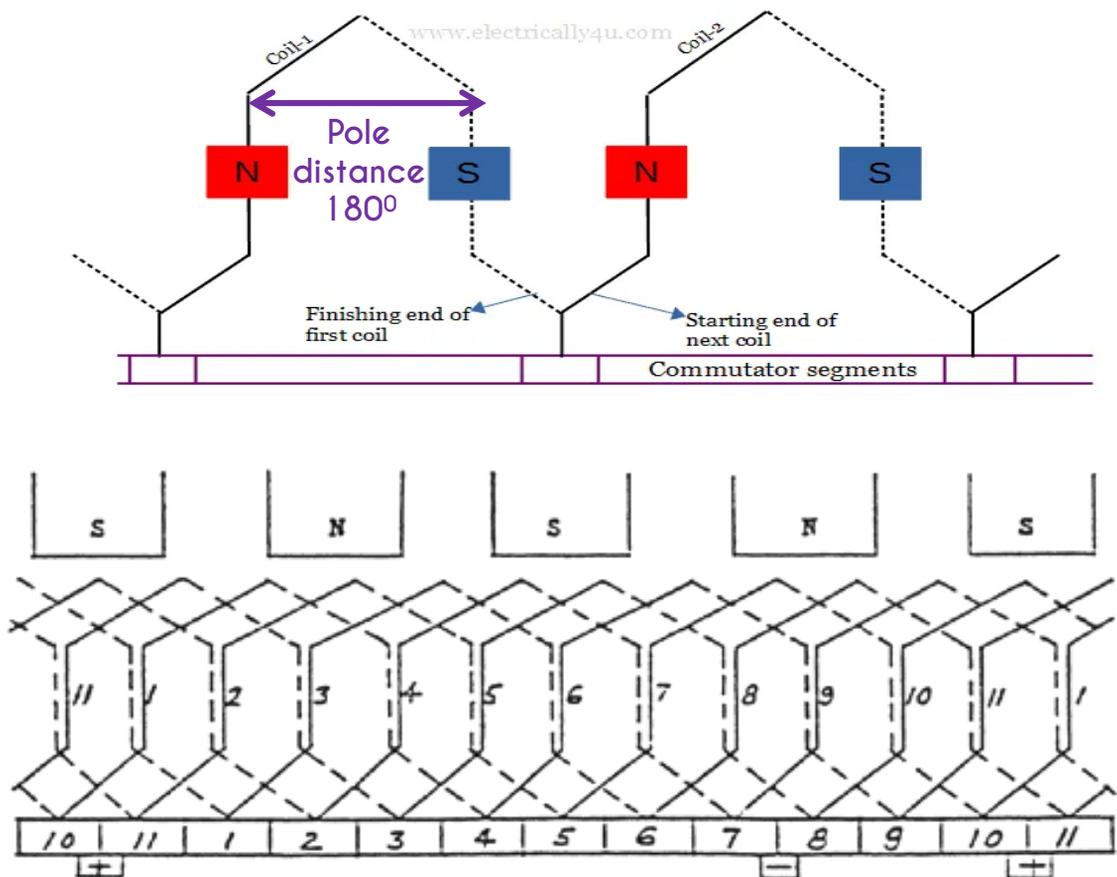
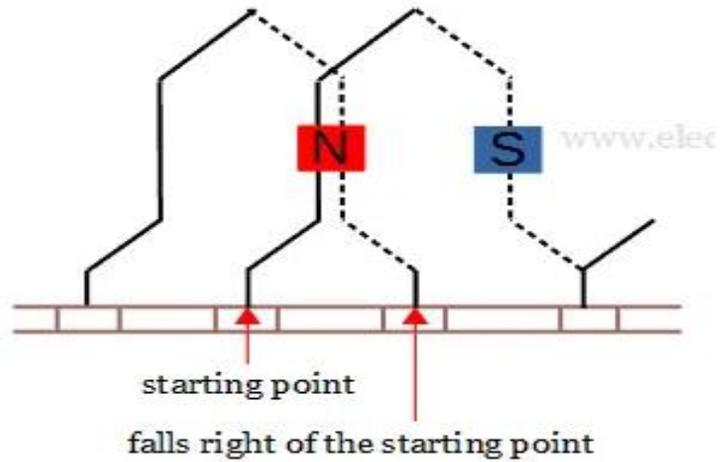


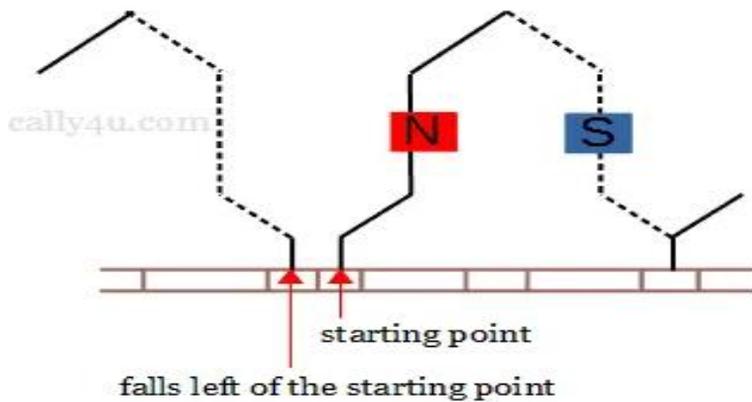
Figure 1.15: Wave winding

Since it looks like a wave-shaped structure, it is called wave winding. It is also known as series winding, as it forms a series of coils.

The winding after wound one round of the armature, if it falls in a slot to the right of its starting point, then it is said to be progressive wave winding. If it falls in a slot to the left of its starting point, it is retrogressive wave winding.



(a) progressive wave winding



(b) retrogressive wave winding

Figure 1.16: progressive and retrogressive wave winding

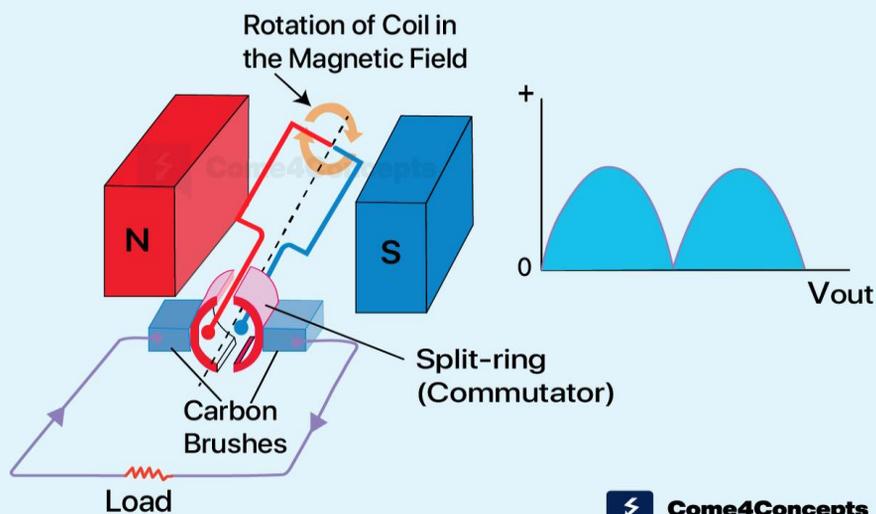
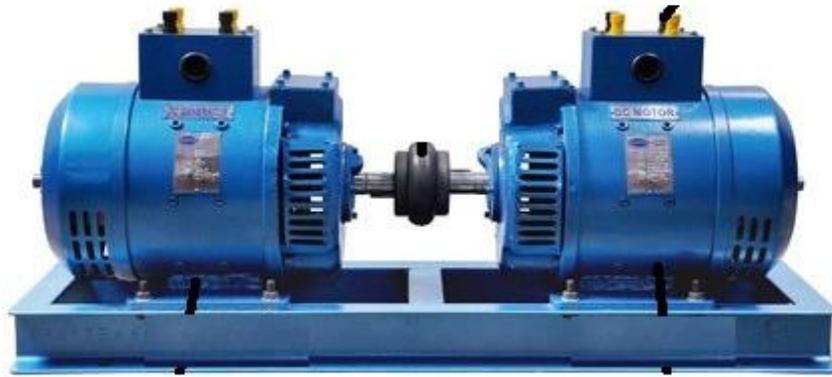
Comparison lap winding and wave winding

Table 1: : Comparison between lap winding and wave winding

Num	Lap winding	Wave winding
1	Coils are connect in parallel	Coils are connect in series
2	Parallel winding	series winding
3	Dummy coil are not required	May required Dummy coil
4	Used in low voltage high current machines	Used in high voltage low current machines
5	Generate less emf	Generate more emf
6	Number of parallel path (a) = pole (P)	Number of parallel path (a) = 2 always
7	Number of brush sets requires is equal to number of poles	Number of brush sets requires is always equal to two
8	Preferable for high current, low voltage capacity generators	Preferable for high voltage, low current capacity generators
9	The winding cost of the lap winding is High	The winding cost of the wave winding is Low
10	Normally used for generators of capacity more than 500A	Preferred for generators of capacity less than 500A
11	the types of lap winding are Simplex lap winding & Duplex lap winding.	The types of wave winding are Progressive & Retrogressive
12	The efficiency of the lap winding is Less	The efficiency of the wave winding is High

CHAPTER 2

DC GENERATOR



PRINCIPLES OF DC GENERATOR

Converts mechanics (motion) to electrical energy.

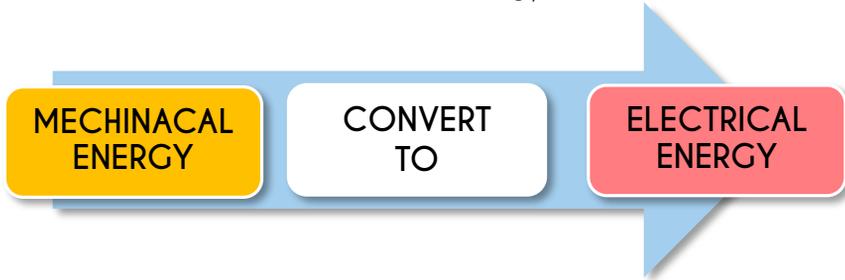


Figure 2.1 shows the form of a simple direct current generator that has a conducting loop ABCD and acts as an armature. It is in a dipole magnetic field. The end of the loop wire is connected to two segments of the commutator.

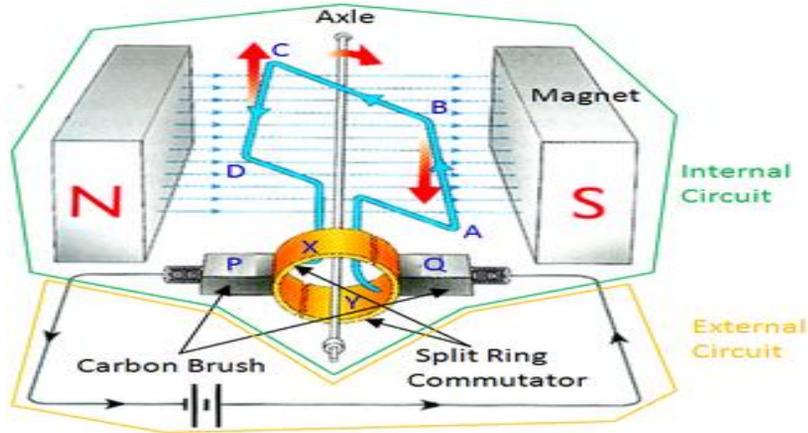


Figure 2.1: simple form of DC generator

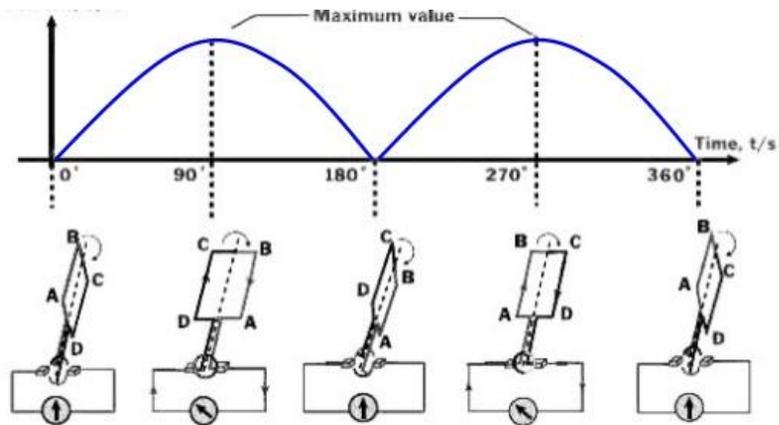


Figure 2.2: the output wave of the DC generator

PRINCIPLES OF DC GENERATOR

When the armature ABCD is rotated in a certain direction in the field, the flux supplied by the pole of the field will be cut by the armature and then e.m.f. induced. Because the rate of flux cutting changes according to the position of the conductor, the e.m.f. magnetism induced in it also changes. The resulting output wave is in the form of an alternating current, but with the presence of a slip ring and regulator, the output wave will be a direct current.

The direction of the induced current in the loop can be determined using Fleming's right-hand tip, figure 2.3 illustrates the tip. The magnitude e.m.f. of the inductance and the direction of current flow are determined by the position of the loop.

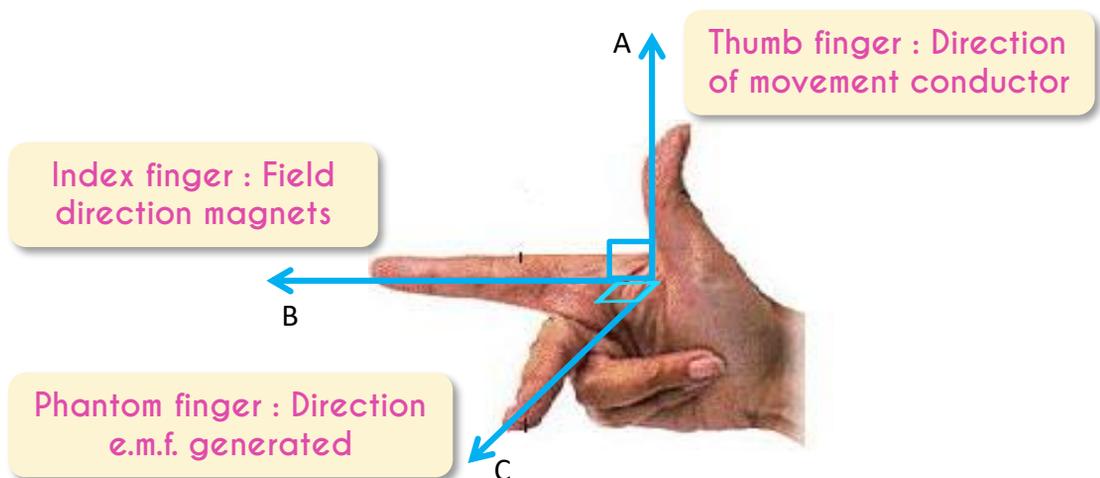


Figure 2.3: Fleming's right-hand rule

The magnitude e.m.f. produced by a single winding generator is small and unstable, so it is not suitable for commercial use.

Therefore e.m.f. produced by the at sponsor depends on the following factors:

- Main magnetic flux strength
- Number of wire loops on the armature
- The angle of the armature coil cuts the magnetic flux

TYPES OF DIRECT CURRENT GENERATORS

Direct current generators are classified according to the method of testing or producing the magnetic field. The two main methods of field excitation are self-excitation and separately-excitation.

The types of DC generators can be illustrated as in figure 2.3.



Figure 2.3: Type of DC generator

SEPARATELY-EXCITATION

Having a field winding connected to an external supply. This means that the voltage that produces the pole magnet is not supplied from the armature of the generator, the connection circuit of this motor is as shown in figure 2.4 and 2.5.

Armature current

$$I_a = I_L$$

Terminal Voltage

$$V_t = E_g - I_a R_a$$

Electric power develop

$$PE_b = E_g I_a$$

Power delivered to load

$$\begin{aligned} P_{out} &= E_g I_a - I_a^2 R_a \\ &= I_a (E_g - I_a R_a) \\ &= V_t I_a \end{aligned}$$

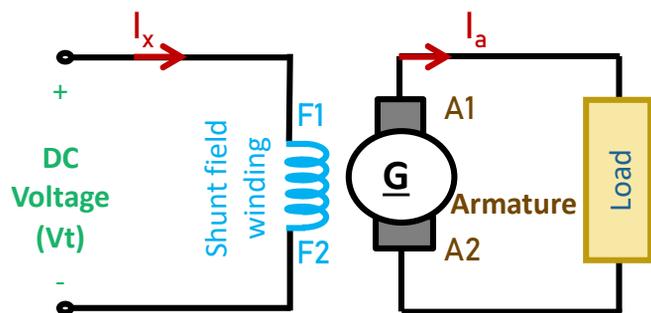


Figure 2.4: Shunt Winding

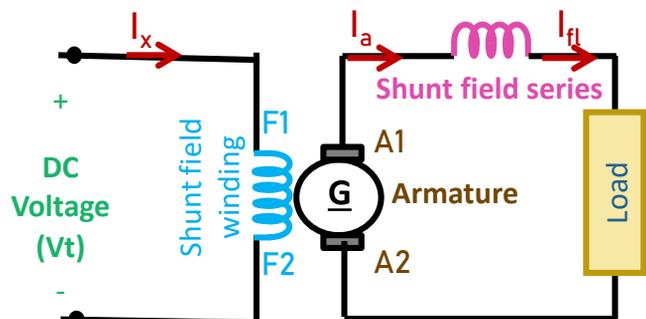


Figure 2.5: Compound Winding

Example

Example 2.1

Figure shows a separate excitation generator. This generator supplies 150A at 120V to a resistive load R_L while its speed is 1000 rpm. Calculate the value of the current when the armature speed decreases to 800rpm. Assume that the field excitation I_{sh} does not change. The armature resistance is 0.05Ω .

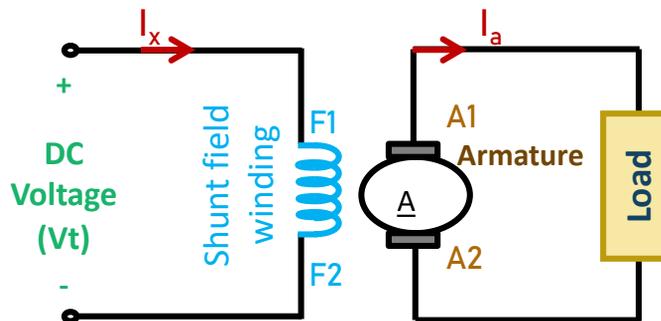


Figure 2.1

Solution 2.1

Given : $I_a = 180A$, $V_t = 140V$, $N_1 = 1500rpm$, $N_2 = 900rpm$, $R_a = 0.03\Omega$

$$R_L = \frac{V_t}{I_a} = \frac{120V}{150A} = \underline{0.8\Omega}$$

At 150rpm,

$$E_{g1} = V_t + I_{a1} R_a = 140V + (180A)(0.03\Omega) = \underline{145.4V}$$

From formulas
$$\frac{E_{g1}}{E_{g2}} = \frac{N_1}{N_2}$$

$$E_{g2} = E_{g1} \times \frac{N_2}{N_1} = 145.4V \times \frac{900}{1000} = \underline{130.86V}$$

$$I_{a2} = \frac{E_{g2}}{R_a + R_L} = \frac{130.86V}{0.03\Omega + 0.8\Omega} = \underline{157.7A}$$

SELF-EXCITATION

Having a field winding that is not connected to an external supply. The field winding of the generator gets its supply from the armature of the generator to produce a magnetic field. Generators are used in control systems that require large current changes without depending on the armature circuit such as the Ward- Leonard speed control system.

This machine has **three types** of self-excitation connections are :-

- i. Series field generator,
- ii. Shunt field generator,
- iii. Compound generator
 - long tributary
 - short tributary

Series field generator

The field winding of this generator is connected in series with the armature. A series connection must be connected with a load because it will cause a high current if there is no load. This generator is used for special purposes such as boosters.

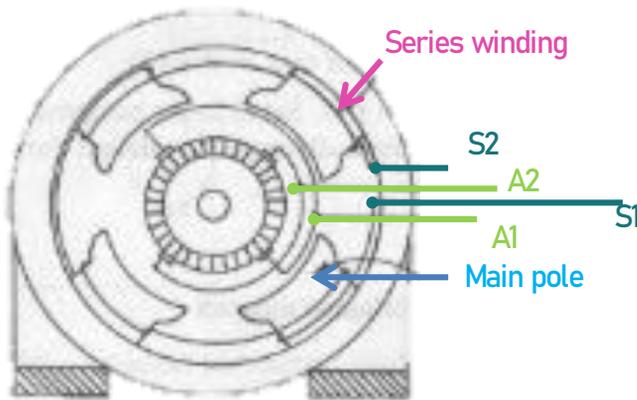


Figure 2.6(a): Series Field wiring diagram

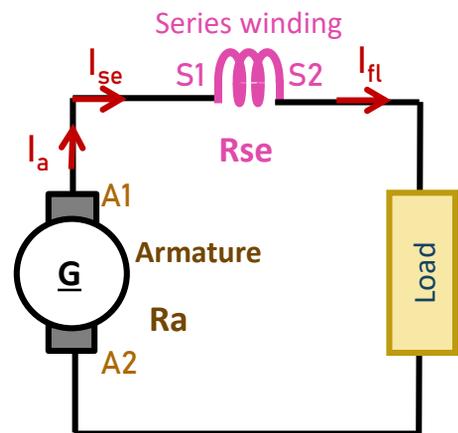


Figure 2.6(b): Series field circuit

The general voltage equation of generator : $V_t = E_g - V_a - V_{se} - V_{brush}$

For the series generator equation :

$$V_t = E_g - V_a - V_{se} - V_{brush}$$

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

V_{brush}

Armature current (I_a) = full load current (I_{fl}) = series current (I_{se}) : $I_a = I_{fl} = I_{se}$

Power develop in armature : $P_{eg} = E_g I_a$

Power is given to the load : $P_{out} = V_t I_a @ V_t I_{fl} = E_g I_a - I_a^2 (R_a + R_s)$

Shunt field generator

The field winding of this generator is connected in parallel with the armature. A shunt generator is used to supply power to a fixed load provided the load voltage changes are small.

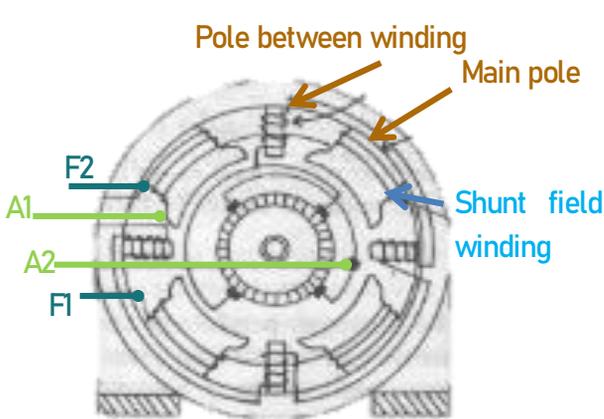


Figure 2.7(a): Shunt Field wiring diagram

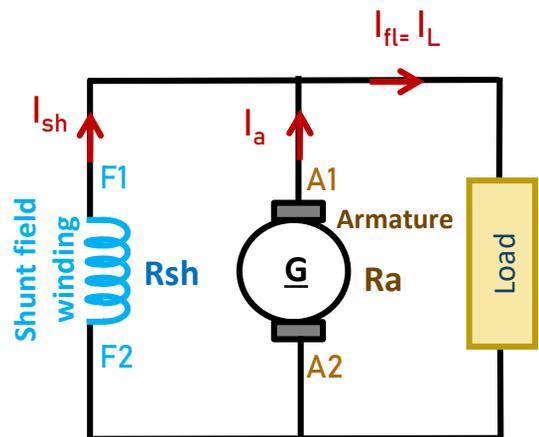


Figure 2.7(b): Shunt Field circuit

The general voltage equation for a generator : $V_t = E_g - V_a - V_{brush}$

For the shunt generator the equation : $V_t = E_g - I_a R_a - V_{brush}$

EMF generated equation : $E_g = V_t + I_a R_a + V_{brush}$

Armature current (I_a) = full load current (I_{fl}) + shunt current (I_{sh})

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

Power develop in armature : $P_{eg} = E_g I_a$

Power is given to the load : $P_{out} = V_t I_a @ V_{tfl} = E_g I_a - I_a^2 R_a$
 @ $P_L = V_L I_L$

Short compound field generator

The field winding of this generator is connected in parallel with the armature. A shunt generator is used to supply power to a fixed load provided the load voltage changes are small.

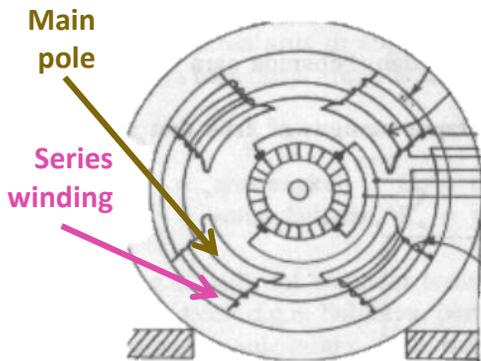


Figure 2.8(a): Short Compound Field wiring diagram

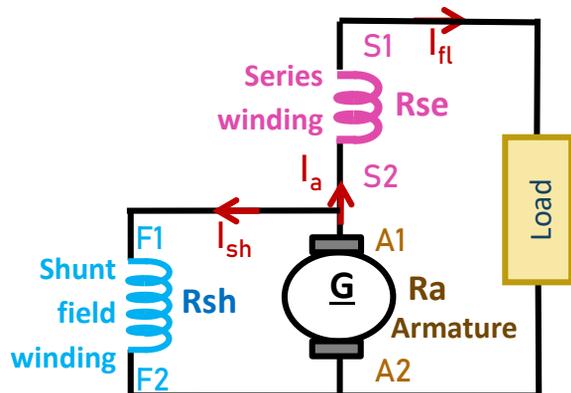


Figure 2.8(b): Short Compound Field circuit

For the short shunt compound generator, the equation:

$$V_t = E_g - V_a - V_s - V_{\text{brush}} = E_g - I_a R_a + I_{se} R_{se} - V_{\text{brush}}$$

$$\text{EMF generated : } E_g = V_t + I_a R_a + I_{se} R_{se} + V_{\text{brush}}$$

$$\text{Full load current : } I_{fl} = \frac{\text{Output Power}}{\text{Input Voltage}}$$

$$\text{Series voltage : } V_{R_{se}} = I_{fl} R_{se}$$

$$\text{Shunt current : } I_{sh} = \frac{\text{Input Voltage} + \text{Series Voltage}}{\text{Shunt Resistance}}$$

Armature current (I_a) = full load current (I_{fl}) + shunt current (I_{sh})

$$I_a = I_{fl} + I_{se}$$

$$\text{Power develop in armature : } P_{eg} = E_g I_a$$

$$\begin{aligned} \text{Power is given to the load : } P_{out} &= V_t I_a @ V_t I_{fl} = E_g I_a - I_a^2 R_a \\ &@ P_L = V_L I_L \end{aligned}$$

Long compound field generator

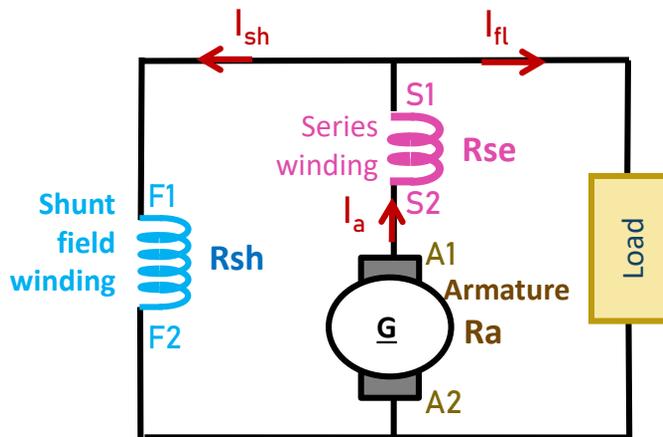


Figure 2.9: Long Compound Field circuit

For the short shunt compound generator, the equation becomes: -

$$\begin{aligned} V_t &= E_g - V_a - V_{se} - V_{brush} \\ &= E_g - I_a R_a + I_{se} R_{se} - V_{brush} \quad ; \text{ where; } \quad I_a = I_{se} \\ &= E_g - I_a (R_a + R_{se}) - V_{brush} \end{aligned}$$

EMF generated : $E_g = V_t + I_a (R_a + R_{se}) + V_{brush}$

Full load current : $I_{fl} = \frac{\text{Output Power}}{\text{Input Voltage}}$

Series voltage : $V_{Rse} = I_{fl} R_{se}$

Shunt current : $I_{sh} = \frac{\text{Input Voltage}}{\text{Shunt Resistance}}$

Armature current : $(I_a) = \text{full load current}(I_{fl}) + \text{shunt current}(I_{sh})$

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

Power develop in armature : $P_{eg} = E_g I_a$

Power is given to the load : $P_{out} = V_t I_a @ V_t I_{fl} = E_g I_a - I_a^2 R_a$
 @ $P_L = V_L I_L$

E.M.F & VOLTAGE EQUATION

The magnitude of e.m.f induced in an armature conductor rotating in a magnetic field, having a flux amounting to Φ weber is given as: -

$$e = \frac{d\Phi}{dt} \text{ V, a conductor}$$

The total flux ($d\Phi$) cut by one conductor in one full revolution of armature movement is: -

$$d\Phi = \Phi P \text{ weber}$$

The time (dt) taken by the armature to make one full revolution is: -

$$dt = \frac{60}{N} \text{ seconds}$$

Therefore the average e.m.f that will be induced in one armature conductor is: -

$$e = \Phi P \frac{N}{60} \text{ V}$$

Then the average e.m.f is induced in a parallel path containing a total $\frac{Z}{a}$ conductors connected in parallel are:-

$$E_g = \frac{\Phi P N Z}{60 a} \text{ V}$$

This equation can be summarized :

$$E_g = \frac{\Phi P N Z}{60 a} \text{ V item constant, } K = \frac{P Z}{60 a}$$

isolated makes an equation ; $E_g = \Phi N K \text{ Volt}$

Where : Φ = Polar flux in weber units

Z = Total number of armature conductors

P = Total number of poles

N = Armature rotation speed in rpm

E_g = E.m.f generated in a parallel path

V_t = Terminal voltage

a = where is the number of parallel paths

$a = mP$ for the armature type lap winding

$a = 2m$ for the armature type wave winding

If the polarizing flux for a generator is doubled while the speed is constant, then the generated (E_g) will be doubled. Conversely if the speed of the generator is doubled while the flux is constant, the generated (E_g) will double. For generators are usually constant speed and the generated (E_g) is adjusted by changing the field flux. To change the flux then the field current needs to be changed using a variable resistor.

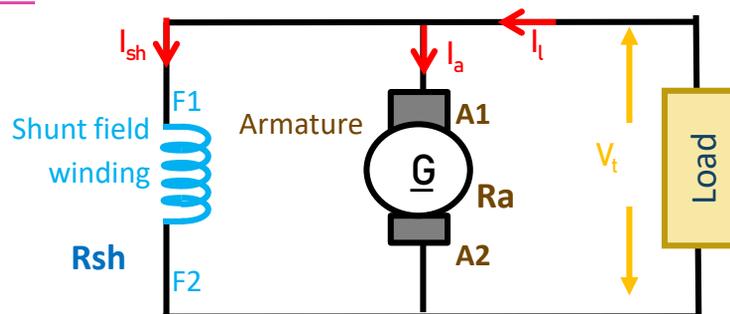
Example DC Generator

Example 2.2

A 14 pole AT generator has 420 armature coils containing 20 turns per coil driven at a speed of 60rpm. If the total useful flux of the pole is 0.042 Weber. Calculate e.m.f generated in the generator when the armature is wound type: -

- i. Lap winding triplex
- ii. Wave winding triplex type.

Solution 2.2



Use formula Energy Generator : $E_g = \frac{\phi PNZ}{60a} V$

Total number of conductors : $Z = 420 \times 20 \text{ winding/coil}$
 $= 8,400 \text{ conductor}$

i) Lap winding triplex type : $a = mP = (3) (14) = \underline{42}$

$$E_g = \frac{\phi PNZ}{60a} = \frac{(0.042)(14)(60)(8400)}{60(42)} = \underline{117.6 \text{ volt}}$$

ii) Wave winding triplex type : $a = 2m = (2) (3) = \underline{6}$

$$E_g = \frac{\phi PNZ}{60a} = \frac{(0.042)(14)(60)(8400)}{60(6)} = \underline{823.2 \text{ volt}}$$

Example

Example 2.3

An AT generator generated 125V when driven at a speed of 1,200psm. Calculate EMF generated when

- The flux is reduced by 10% but the speed is constant (no changed)
- Speed is reduced to 1,100psm with constant flux

Solution 2.3

i) The flux is reduced by 10% but the speed is constant (no changed)

Formula $E_g = \Phi N K \text{ Volt}$, for constant speed the equation becomes

Use formula : $E_g = \frac{\Phi P N Z}{60 a} V$ where : $\Phi_1 = 100$, $\Phi_2 = 90$ (reduce 10%)

Formula : $E_g = \Phi \text{ Volt}$

$$\begin{aligned} \frac{E_{g1}}{E_{g2}} &= \frac{\Phi_1}{\Phi_2} \quad \Rightarrow \quad E_{g2} = \frac{\Phi_2 E_{g1}}{\Phi_1} \\ &= \frac{(90)(125V)}{100} \\ &= \underline{\underline{112.5V}} \end{aligned}$$

ii) Speed is reduced to 1,100psm with constant flux ; $N_2 = 1100$ psm

The formula : $E_g = \Phi N K \text{ volt}$, for constant flux the equation becomes

formula : $E_g = \Phi \text{ volt}$

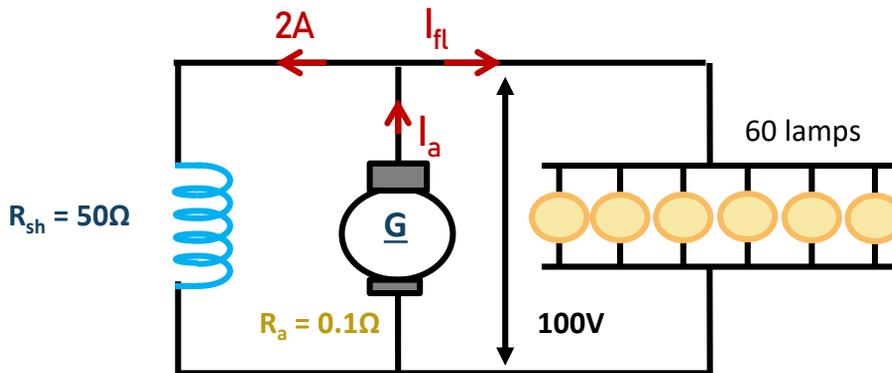
$$\begin{aligned} \frac{E_{g1}}{E_{g2}} &= \frac{N_1}{N_2} \quad \Rightarrow \quad E_{g2} = \frac{N_2 E_{g1}}{N_1} \\ &= \frac{(1100)(125v)}{1200} \\ &= \underline{\underline{114.6V}} \end{aligned}$$

Example

Example 2.4

A 4-pole shunt generator with an overlap type (wipe) connection has an armature resistance and a field resistance of 0.1Ω and 50Ω respectively, as many as 60 100V, 40 watt lamps are connected in parallel. Calculate the total armature current and EMF generated. Assume a brush drop voltage of 1 volt per brush.

Solution 2.4



Total wattage on the lamp = 60 watts \times 4W = 2400 watts

$$\text{Full load current, } I_{fl} = \frac{P_t}{V_t} @ I_L = \frac{P_L}{V_L} = \frac{2400W}{100V} = \underline{24 A}$$

$$\text{Shunt current, } I_{sh} = \frac{V_L}{R_{sh}} = \frac{100V}{50\Omega} = \underline{2 A}$$

$$\text{Armature current, } I_a = I_{fl} + I_{sh} = 24A + 2A = \underline{26A}$$

$$\begin{aligned} \text{Therefore, } E_g &= V_t + I_a R_a + V_{brush} \\ &= 100V + 26A (0.1\Omega) + 1V(2) \\ &= \underline{104.6 \text{ Volt}} \end{aligned}$$

Example

Example 2.5

A direct current generator has 4 poles, armature resistance of 10Ω . The generator output is 220V at a drive speed of 1500rpm without load and a total flux of 5mWb/pole. Calculate:-

- Output voltage when the generator drive speed is increased by 10% with constant flux
- Output voltage when the total flux speed is reduced to 4.5 mWb/pole but the speed is maintained at 1500 rpm
- The total number of parallel paths found in the armature windings that are superimposed simplex type
- Voltage regulation rectifier if the generator experiences a voltage drop of 20V when full load is applied.

Solution 2.5

The magnitude of E_g for the output voltage of the dc generator is given in the mathematical equation as, $E_g = k\Phi N$ volts, where: - k is constant, Φ is flux per pole, N is rotation speed

- From the mathematical equation above, when the speed N increases by 10% and the flux (Φ) is constant, but when E_g increases the speed will also increase by 10%. Suppose

E_{g1} - the output voltage in the first state, the speed is $N=1500$ rpm

E_{g2} - output voltage in second state, speed increased by 10%

$$E_{g2} = E_{g1} + \delta E_{g1} = 220V + 10\%(220V) = \underline{242 V}$$

$$E_{g2} = 110\% E_{g1} = 110\% \times 220V = \underline{242V}$$

- when the flux decreases by 4.5 mWb per pole

$$E_{g1} = E_{g1} - \delta E_{g1} = 220V - 10(220V) = \underline{198 V}$$

$$E_{g1} = 90\% E_{g1} = 90\% \times 220V = \underline{198 V}$$

$$\frac{E_{g2}}{E_{g1}} = \frac{\Phi_2}{\Phi_1} \Rightarrow E_{g2} = \frac{\Phi_2}{\Phi_1} \times E_{g1} = \frac{4.5mWb}{5mWb} \times 220V = \underline{198V}$$

- The number for the parallel paths in the armature of the simplex lap windings is

given as, $a = mP$, where: = number for multiplex, P = number of poles (poles)

$$a = (1)(4) = \underline{4}$$

- % voltage regulation** = $\frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\%$

$$V_{fl} = 20V \quad V_{nl} = 220V - 20V = 200V$$

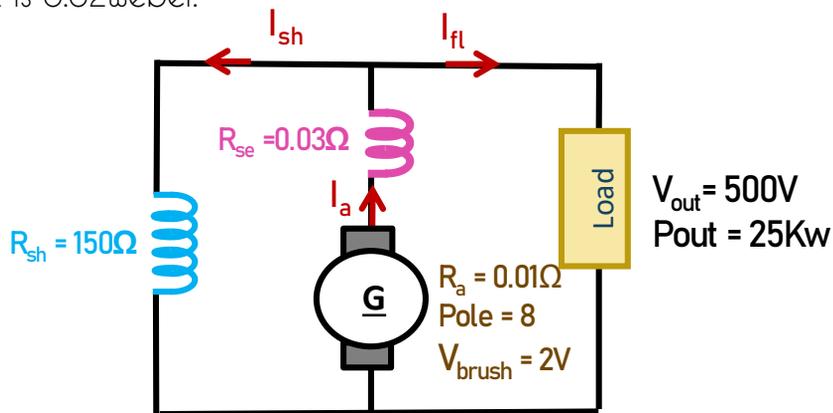
$$\% \text{ voltage regulation} = \frac{20V}{200V} \times 100\% = \underline{10\%}$$

Example

Example 2.6

A long shunt compound generator with over lapping windings, 8 poles supplies 25kW at a terminal voltage of 500V, armature resistance equal to 0.01Ω , series field resistance equal to 0.03Ω , while shunt field resistance equals 150Ω . If the brush drop is equal to 2V, find the generated and the number of conductors when the rotor speed is equal to 1200psm, the polarizing flux is 0.02weber.

Solution 2.6



i. Formula Generate e.m.f. : $E_g = V_t + V_a + V_{se} + V_{brush}$

Full load current : $I_{fl} = \frac{\text{output power}}{\text{input voltage}} = \frac{25Kw}{500V} = \underline{50 A}$

Shunt current : $I_{sh} = \frac{\text{Output Voltage}}{\text{Shunt Resistance}} = \frac{500V}{150\Omega} = \underline{3.33 A}$

Armature current : $I_a = I_{fl} + I_{sh} = 50A + 3.33A = \underline{53.33 A}$

Generate e.m.f. : $E_g = V_t + V_a + V_s + V_{brush}$
 $= 500V + 53.33A(0.01\Omega) + 53.33A(0.03\Omega) + 2V$
 $= \underline{504.13V}$

ii. Number of conductors = Z

formula : $E_g = \frac{\phi P n Z}{60 a}$ volt, Where : $a = mP = (1)(8) = \underline{8}$

$$Z = \frac{60 a E_g}{\phi P n} = \frac{(60)(8)(504.13V)}{(0.02)(8)(1200)}$$

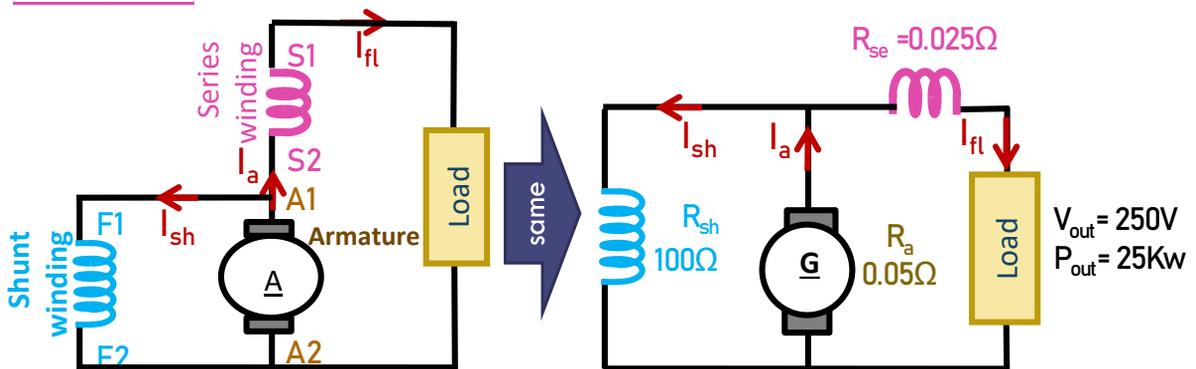
$$= \underline{1260 \text{ conductor}}$$

Example

Example 2.7

A 25kW compound generator produces a base voltage of 250V [at full load current]. The armature winding resistance, series field and shunt field are 0.05Ω, 0.025Ω and 100Ω respectively. Calculate e.m.f generated if the generator is connected in multiple short shunts.

Solution 2.7



i. formula Generate e.m.f : $E_g = V_t + V_a + V_s + V_{bruses}$

Full load current, : $I_{fl} = \frac{\text{output power}}{\text{input voltage}} = \frac{25Kw}{250V} = \underline{100 A}$

Series voltage : $V_s = I_{fl} R_s = (100A) (0.025\Omega) = \underline{2.5V}$

Shunt current, : $I_{sh} = \frac{\text{Output voltage + Series Voltage}}{\text{Shunt Resistance}}$
 $= \frac{500V + 2.5V}{150\Omega} = \underline{2.52 A}$

Armature current, : $I_a = I_{fl} + I_{sh}$
 $= 100A + 2.52A$
 $= \underline{102.525 A}$

Generate e.m.f : $E_g = V_t + V_a + V_s + V_{bruses}$
 $= 250 + 102.52(0.05) + 100(0.025)$
 $= \underline{257.63V}$

LOSS IN GENERATOR

The types of generator losses that occur in an AT generator can be divided into three categories: -

- i. loss of copper
 - armature loss
 - loss of magnetic field
 - loss of carbon brushes
- ii. magnetic loss
- iii. mechanical loss

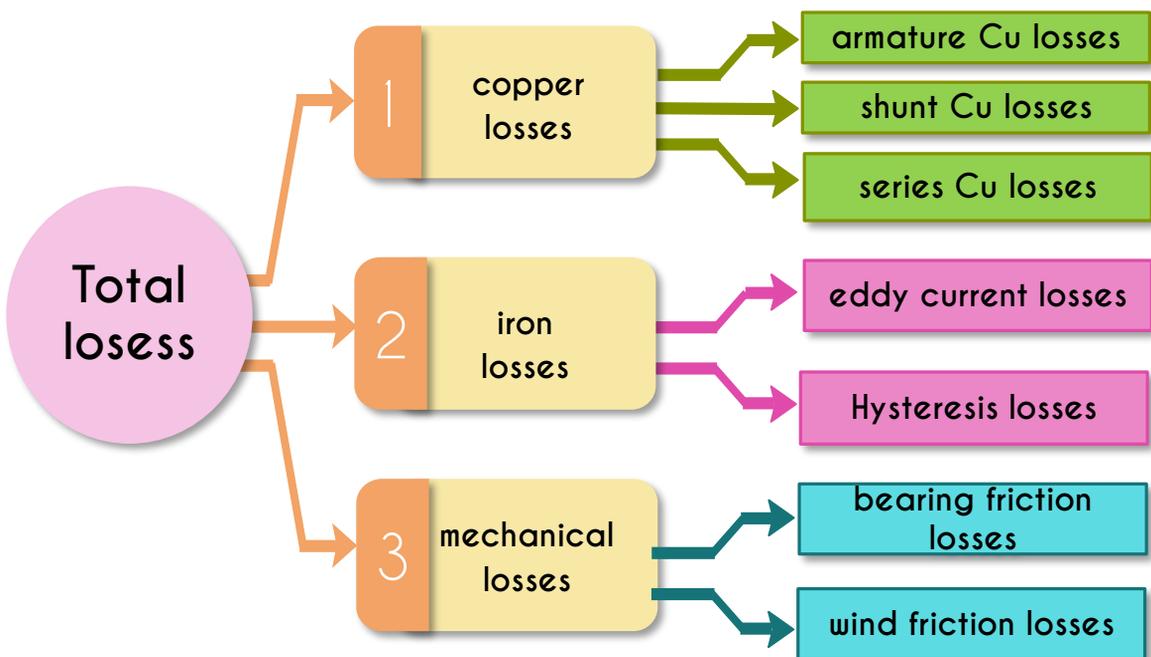


Figure 2.10 : DC generator loss configuration

Copper Losses

Armature copper loss

this loss is due to the resistance in the armature. Since the winding between the poles is always connected in series with the armature winding, the **copper loss of the armature** circuit can be given as,

$$P_{cu \text{ angker}} = I_a^2 R_a \text{ Watt}$$

Where R_a is the resistance of the armature winding and between the poles. This loss is 30-40% of the total full load loss.

Magnetic field copper loss

this loss is due to the resistance in the magnetic field winding. The armature circuit copper loss can be given as,

$$P_{cu \text{ field}} = I_{sh}^2 R_{sh} \text{ Watt} \quad : \text{ Shunt field generator}$$

$$P_{cu \text{ field}} = I_{se}^2 R_{se} \text{ Watt} \quad : \text{ Series field generator}$$

For a shunt generator, its field loss is constant. This loss is 20-30% of the total full load loss.

Loss of carbon brushes

Losses due to brush contact resistance are usually included as armature losses.

Magnetic/ Iron/ Core Losses

This loss is also known as iron loss or core loss. It is caused by hysteresis and eddy current. The iron loss of a shunt generator is constant and it is 20-30% of the total full load loss.

Mechanical Losses

This loss is divided into two namely: -

- i. friction on bearings and adjusters
- ii. wind friction and friction loss as the armature rotates

Is a loss of 10-20% of the total full load loss.

CHARACTERISTICS OF GENERATOR

The two important ones related to DC stimulation are the no-load characteristics and the external characteristics.

Saturation feature without load

Also known as the magnetic characteristic or the open circuit characteristic, it shows the relationship between the e.m.f generated in the armature at no load (E_o) and the field current (I_f) at a constant speed. The shape of the graph is almost the same for all types of generators, whether excited separately (separately exciting). or self-exciting.

External characteristics ($\frac{V}{I}$) @ voltage regulation

The relationship between supply voltage and load current (I_l) is very important and useful in making choices about the suitability of a generator for certain purposes or tasks. When the generator is loaded the base voltage will change (decrease) if there is no suitable step to increase it.

The change in base voltage from the no-load condition to the full-load condition is known as voltage regulation. The equation is as follows:-

$$\% \text{ Regulation} = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\%$$

EXCITATION IN THE GENERATOR

Separately Excited Generator

Graph for a separately exciting generator as in figure 2.12

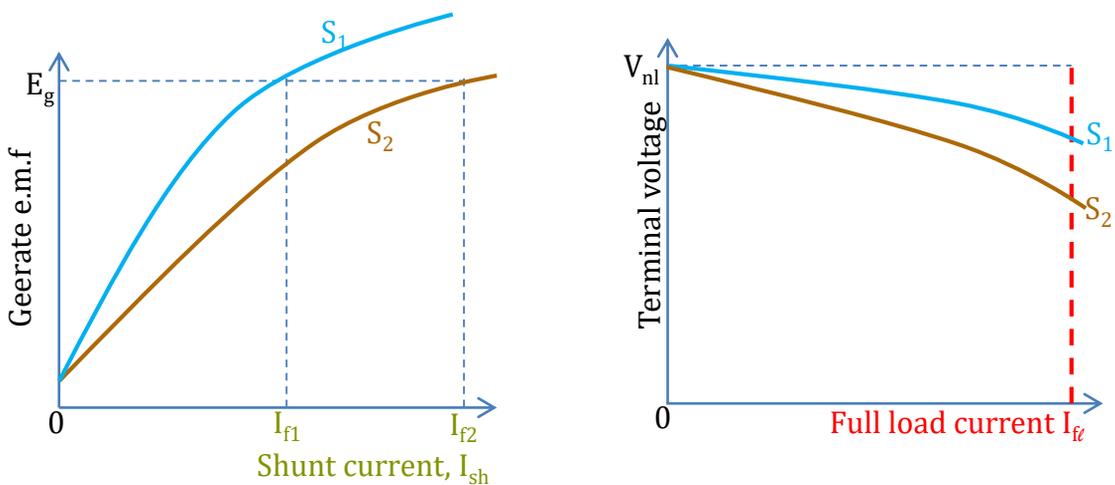


Figure 2.11: external characteristics of separately excited shunt generator

Where S_1 is the rated speed and S_2 is less than the rated speed.

From the graph it is found that when the field current increases the base voltage will decrease. This voltage drop is caused by armature circuit resistance and armature reaction effects. The advantage of an externally excited generator over a self-excited one is that it is more stable at any field excitation. The disadvantage is that it requires a separate power supply for the field, making its use limited.

Self-exciting Generator

The operation of a self-excited generator depends on the residual magnetism present at its field poles. When the generator starts to rotate, the armature conductor will cut off the remaining magnetic flux that will result.

Self-exciting series generator

The magnetic field is in series with the armature, so the current for both is the same. When this generator is supplied with no load, a small amount of e.m.f will result from the residual magnet. When an external load is applied, the current will flow to the field circuit and the base voltage will increase. This increase continues until saturation, as shown in figure 2.13.

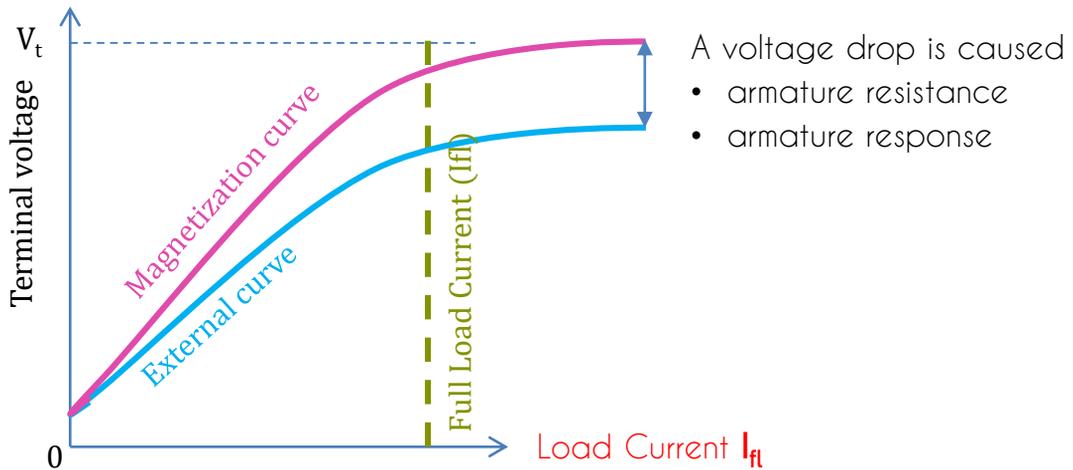


Figure 2.12: External features of series generators

Self-exciting shunt generator

The shunt field winding is connected in parallel with the armature winding, then the current will flow in it. If the direction of the current flows can strengthen the flux then a larger e.m.f will be generated in the armature conductor, further increasing the field current. This increase continues until the point of saturation, after which the increase in e.m.f generated becomes smaller and the current also decreases until the push process stops. The voltage curve of a self-excited shunt generator is shown graphically in figure 2.14.

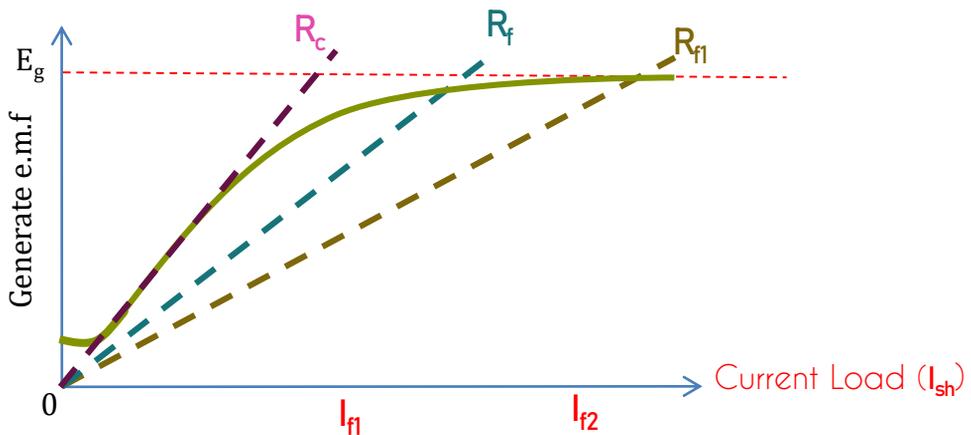


Figure 2.13: voltage build-up in a self-exciting shunt generator.

R_f is a fixed field resistance value, if this step is reduced (adjusting the rheostat) to the resistance value R_{f1} then the voltage spike will occur along the field resistance line. The shunt field resistance can be increased until it reaches a critical value, where any further increase will not produce a voltage spike. The critical resistance R_c is shown as tangent to the magnetization curve. Among the other reasons that can cause voltage spikes in self-excited shunt generators are:

- there are no more residual magnets at the field poles
- incorrect magnetic circuit connection where the flux produced by the generated current is opposite in direction to the residual magnetic flux.
- Armature rotation speed is too low

The external characteristics of the shunt generator as shown in figure 2.15 where this curve is similar to a separately excited shunt generator. But for self-excited generators the drop in base voltage is more significant if the load increases. This voltage drop causes the field current to decrease.

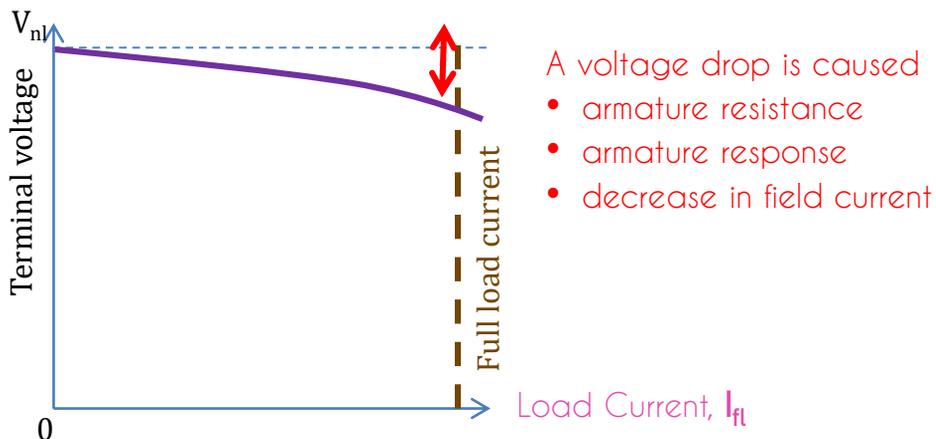


Figure 2.14: External features of shunt generators

Self-exciting Compound Generator

For shunt generators the shunt field is stronger than the series field. If the series field dgm helps the shunt field dgm, the generator is known as a compound generator. If it is the other way around, i.e. the direct field dgm is opposite to the shunt field dgm, the generator is known as a differential compound generator. There are three types of load characteristics possible for a shunt compound generator (either long or short shunt) and depend on the dgm strength of the series field.

- A compound generator where the base voltage increases when the load is added and the value of full load is higher than no load is known as over compound
- When the no-load base voltage equals the full-load value, this generator known as a flat compound.
- Reduced compound generator (low compound). has a base voltage full load is less than no-load base voltage, but characteristic the load is better than the shunt generator.

The external characteristics of the compound generator are shown in figure 2.16 together with the characteristics of the shunt generator for comparison.

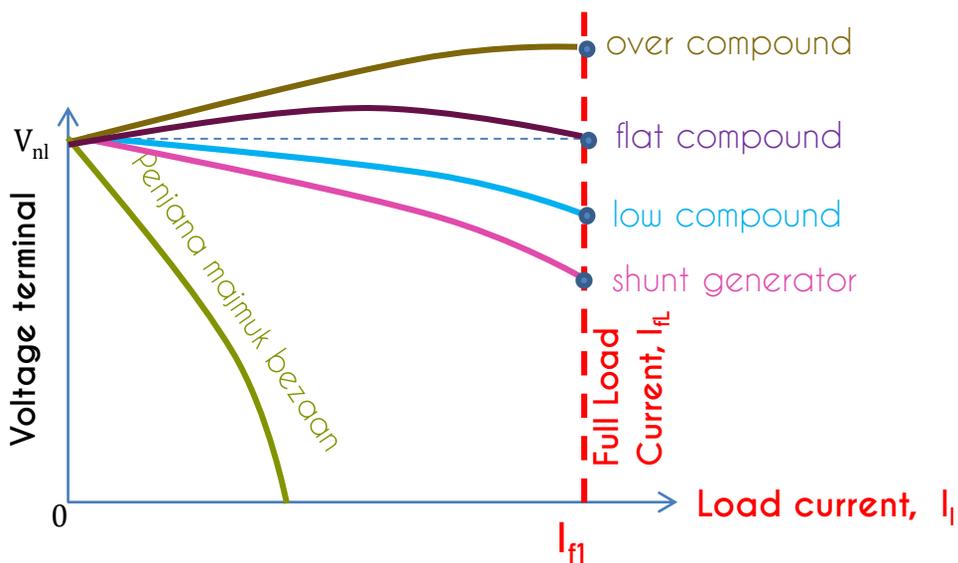


Figure 2.15: Characteristics of External compound generators

EFFICIENCY

The power stage in an DC generator is as shown in figure 2.16 below: -

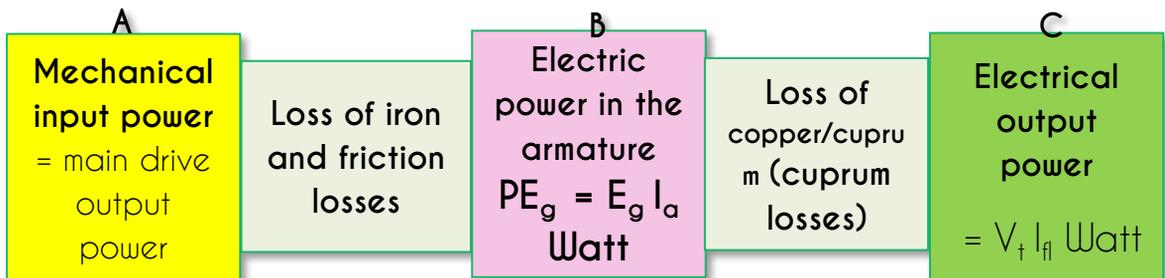


Figure 2.16: Power Level DC Generator

Based on figure 2.17 generator efficiency can be given as: -

Mechanical efficiency

$$\eta_m = \frac{B}{A} = \frac{\text{Total Develop Power in Armature}}{\text{Mechanical Input Power}}$$

Electrical efficiency

$$\eta_e = \frac{C}{B} = \frac{\text{Total Power in the Load Circuit}}{\text{Total Power Generated}}$$

Overall or commercial efficiency

$$\eta_c = \frac{C}{A} = \frac{\text{Total Power in the Load Circuit}}{\text{Mechanical Input Power}}$$

Usually the overall efficiency

$$\eta_c = \eta_m \times \eta_e$$

A good generator has an efficiency value of 95% and above.

APPLICATION OF DC GENERATOR

They are used as portable generators where low power supply is required. They are used in motorcycles as dynamos, in toys such as remote control cars and in appliances such as electric shavers

Generally type of DC generator more expensive especially type self-excited DC generators because of their requirement of separate excitation source. Because of that their applications are restricted

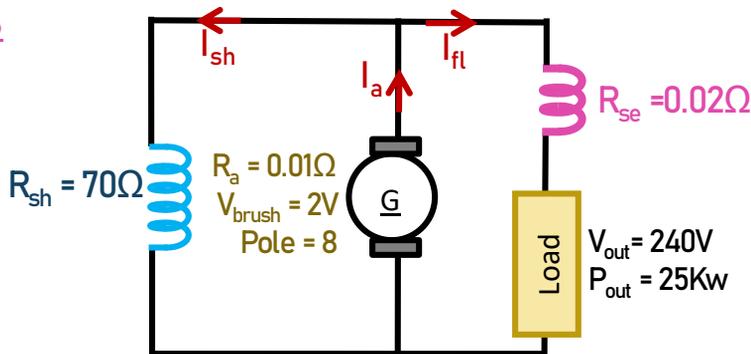
Motor type	Characteristics	Application
Shunt generator	Relatively constant base voltage	Used for power supply for lighting and general battery charging purposes
Series generator	Its voltage increases according to the load.	Not used to supply power for general use booster (booster).
Compound Wound	Has a good voltage setting	General power supply and those with sudden significant load changes.

Example

Example 2.8

A long shunt compound generator with overlapping windings, 8 poles supplies 25kW at a terminal voltage of 500V, armature resistance equal to 0.01Ω , series field resistance equal to 0.03Ω , while shunt field resistance equals 150Ω . If the brush drop is equal to 2V, find the e.m.f generated and the number of conductors when the rotor speed is equal to 1200psm, the polarizing flux is 0.02weber .

Solution 2.8



i. formula Generate e.m.f, : $E_g = V_t + V_a + V_{se} + V_{brush}$

$$\text{Full load current, } I_{fl} = \frac{\text{output power}}{\text{output voltage}} = \frac{25\text{KW}}{240\text{V}} = \underline{104.17\text{A}}$$

$$\text{Series voltage, } V_{se} = I_{fl} R_{se} = (104.17\text{A}) (0.02\Omega) = \underline{2.08\text{V}}$$

$$\text{Shunt current, } I_{sh} = \frac{\text{voltage terminal+series voltage}}{\text{shunt resistance}} = \frac{104.17+2.08}{70\Omega} = \underline{1.52\text{A}}$$

$$\text{Armature current, } I_a = I_{fl} + I_{sh} = 104.17 + 1.52 = \underline{105.69\text{A}}$$

$$\text{armature copper loss, } P_{cu \text{ armature}} = I_a^2 R_a = (105.69)^2 (0.01) = \underline{111.7\text{ Watt}}$$

$$\text{shunt field copper loss, } P_{cu \text{ shunt field}} = I_{sh}^2 R_{sh} = (1.52)^2 (70) = \underline{161.73\text{ Watt}}$$

$$\text{series field copper loss, } P_{cu \text{ series field}} = I_s^2 R_s = (104.17)^2 (0.02) = \underline{217.0\text{ Watt}}$$

$$\text{Total copper loss, } P_{cu \text{ total}} = 111.7\text{W} + 161.73\text{W} + 217\text{W} = \underline{490.46\text{ Watt}}$$

$$\text{Power input generator- Efficiency, } \zeta = \frac{P_{out}}{P_{in}},$$

$$P_{in} = \frac{P_{out}}{\zeta} = \frac{25000\text{W}}{0.88} = \underline{28,409.1\text{W}}$$

Iron losses & friction ;

$$P_{\text{total losses}} = P_{in} - P_{out} = 28,409.1\text{W} - 25000\text{W} = \underline{3,409.1\text{W}}$$

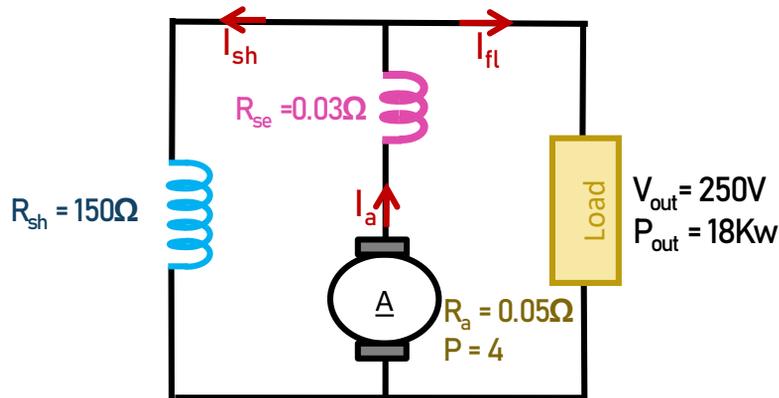
$$P_{\text{total losses\& friction}} = 3,409.1\text{W} - 2714.4\text{W} = \underline{694.7\text{W}}$$

Example

Example 2.9

A 20kW long shunt compound generator, 4 poles, 240V, has an armature winding resistance and a shunt winding resistance of 0.05Ω and 50Ω respectively, and a series field winding resistance of 0.03Ω . Calculate the generated e.m.f and total copper loss of the generator.

Solution 2.9



$$\text{Full load current, } I_{fl} = \frac{\text{output power}}{\text{output voltage}} = \frac{18Kw}{250V} = \underline{75A}$$

$$\text{Shunt current, } I_{sh} = \frac{\text{voltage terminal}}{\text{shunt resistance}} = \frac{250V}{150\Omega} = \underline{1.67 A}$$

$$\text{Armature current, } I_a = I_{fl} + I_{sh} = 75A + 1.67A = \underline{73.67A}$$

$$\begin{aligned} \text{Generate e.m.f, } E_g &= V_{out} + V_a + V_s + V_{berus} \\ &= 250V + (73.67A)(0.05\Omega + 0.03\Omega) = \underline{256V} \end{aligned}$$

$$\text{Armature copper loss, } P_{cu \text{ armature}} = I_a^2 R_a = (73.67)^2 (0.05) = \underline{281.25 \text{ Watt}}$$

$$\text{Shunt field copper loss, } P_{cu \text{ shunt field}} = I_{sh}^2 R_{sh} = (1.67)^2 (150) = \underline{418.34 \text{ Watt}}$$

$$\text{Series field copper loss, } P_{cu \text{ series field}} = I_a^2 R_s = (73.67)^2 (0.03) = \underline{168.75 \text{ Watt}}$$

$$\text{Total copper loss, } P_{cu \text{ total}} = 281.25 + 418.34 + 168.75 = \underline{868.34 \text{ Watt}}$$

$$\text{Power input generator- Efficiency, } \zeta = \frac{P_{out}}{P_{in}} \times 100\%$$

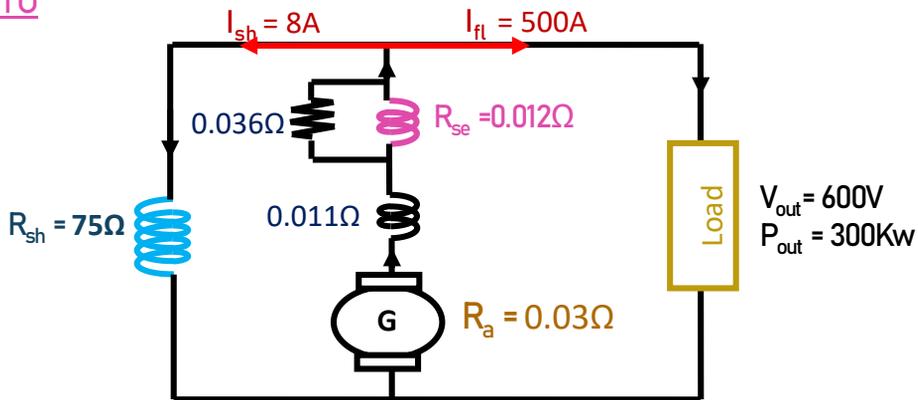
$$= \frac{18K}{250 \times 75} \times 100\% = \underline{96\%}$$

Example

Example 2.10

A long shunt compound generator has 300kW a, 600V.; shunt field resistance is 75Ω armature resistance including brush resistance 0.03Ω, commutating field resistance is 0.011Ω series field resistance is 0.012Ω, parallel resistance series resistance is 0.036Ω . When the machine is under full load, calculate the voltage and power produced by the armature.

Solution 2.10



$$\text{Full load current, } I_{fl} = \frac{\text{output power}}{\text{output voltage}} = \frac{18\text{Kw}}{250\text{V}} = \underline{75\text{A}}$$

$$\text{Shunt current, } I_{sh} = \frac{\text{voltage terminal}}{\text{shunt resistance}} = \frac{250\text{V}}{150\Omega} = \underline{1.67\text{A}}$$

$$\text{Armature current, } I_a = I_{fl} + I_{sh} = 75\text{A} + 1.67\text{A} = \underline{73.67\text{A}}$$

$$\begin{aligned} \text{Generate e.m.f, } E_g &= V_{out} + V_a + V_s + V_{berus} \\ &= 250\text{V} + (75\text{A})(0.05+0.03) = \underline{256\text{V}} \end{aligned}$$

$$\text{Armature copper loss, } P_{cu \text{ armature}} = I_a^2 R_a = (75\text{A})^2 (0.05) = \underline{281.25 \text{ Watt}}$$

$$\text{Shunt field copper loss, } P_{cu \text{ shunt field}} = I_{sh}^2 R_{sh} = (1.67\text{A})^2 (150) = \underline{418.34 \text{ Watt}}$$

$$\text{Series field copper loss, } P_{cu \text{ Series}} = I_a^2 R_{se} = (75\text{A})^2 (0.03) = \underline{168.75 \text{ Watt}}$$

$$\text{Total copper loss, } P_{cu \text{ total}} = 281.25\text{W} + 418.34\text{W} + 168.75\text{W} = \underline{868.34 \text{ Watt}}$$

Power input generator- Efficiency,

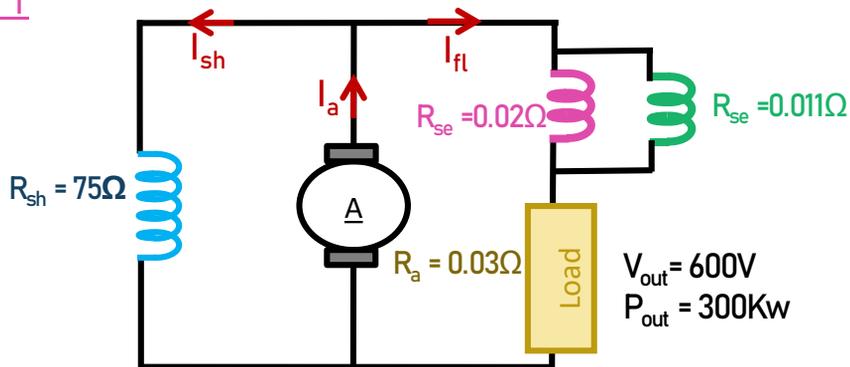
$$\zeta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{18\text{K}}{250\text{V} \times 75\text{A}} \times 100\% = \underline{96\%}$$

Example

Example 2.1 1

A 300kW, 600V long shunt generator has a shunt field resistance of 75Ω , armature resistance including brush resistance is 0.03Ω , regulator field winding resistance is 0.011Ω , series field resistance is 0.02Ω . When the generator delivers full power, calculate the voltage and power generated by the armature.

Solution 2.1 1



Output power of 300,000 watts,

$$\text{Full load current, } I_{fl} = \frac{\text{output power}}{\text{output voltage}} = \frac{30\text{Kw}}{600\text{V}} = \underline{500\text{A}}$$

$$\text{Shunt current, } I_{sh} = \frac{\text{terminal voltage}}{\text{shunt resistance}} = \frac{600\text{V}}{75} = \underline{8\text{A}}$$

$$\text{Armature current, } I_a = I_{fl} + I_{sh} = 500\text{A} + 8\text{A} = \underline{508\text{A}}$$

for resistance and series resistance opposite to the field connections as shown in the diagram and the total resistance is:-

$$R_{\text{total}} = \frac{0.012 \times 0.036}{0.012 + 0.036} = \frac{0.012\Omega \times 0.036\Omega}{0.048\Omega} = \underline{0.009\Omega}$$

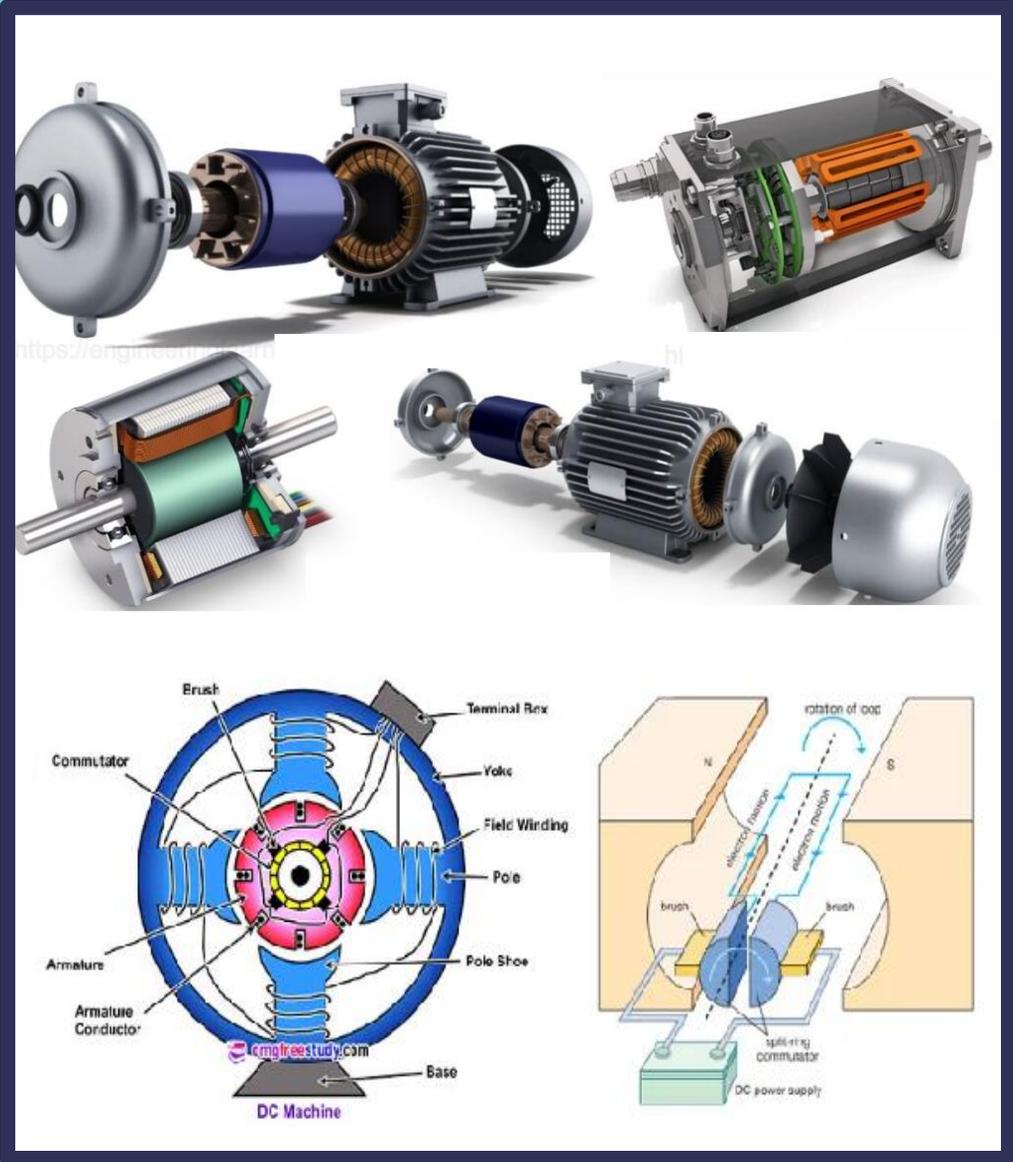
$$\text{Total armature resistance} = 0.03\Omega + 0.011\Omega + 0.009\Omega = \underline{0.05\Omega}$$

$$\text{Armature voltage drop} = 508\text{V} \times 0.05\Omega = \underline{25.4\text{V}}$$

$$\text{Voltage generated on the armature} = 600 \times 508 = \underline{317,700\text{ W}}$$

CHAPTER 3

DC MOTOR



INTRODUCTION

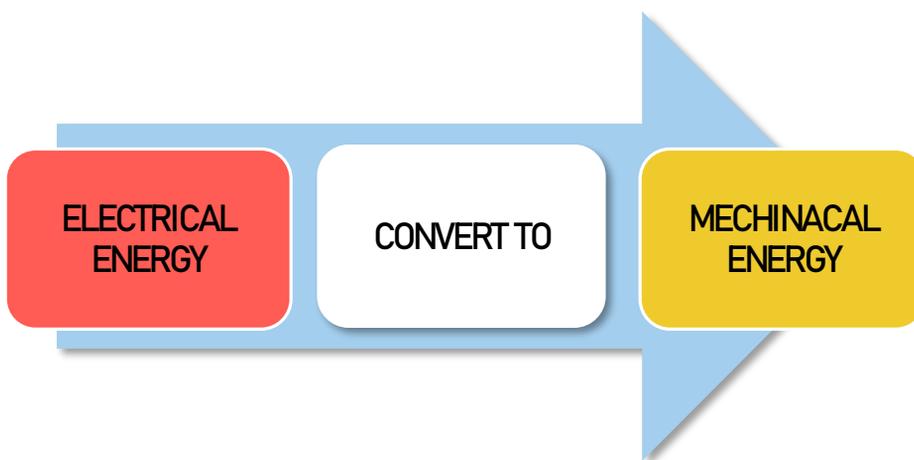
Basically, the operation of an AC motor depends on the interaction between two magnetic fields, namely the stationary magnetic field and the free -moving magnetic field. Its action is based on the principle that when a current -carrying conductor is placed in a magnetic field it will experience a mechanical force that has a direction given by Fleming's left-hand law and a magnitude that can be given as

$$F = B.I.L \text{ Newton}$$

Where : B = magnetic field in tesla (T)

I = current in the wire in amps (A)
L = length

DC power systems are not widely used, however DC motors are usually used in industries such as conveyors, elevators, extruders, marine applications, material handling, paper, plastics, rubber, steel, and textile applications, automobile, aircraft, and portable electronics, in speed control applications.



HOW A CURRENT MOTOR CONTINUES TO WORK

The attraction between dissimilar poles causes the armature loop to rotate clockwise. When current is passed through the carbon brush to the coil ABCD connected to the regulator the coil will rotate. This flowing current produces its own magnetic field around the conductor. This magnetic field has a direction opposite to the direction of the polar magnetic field.

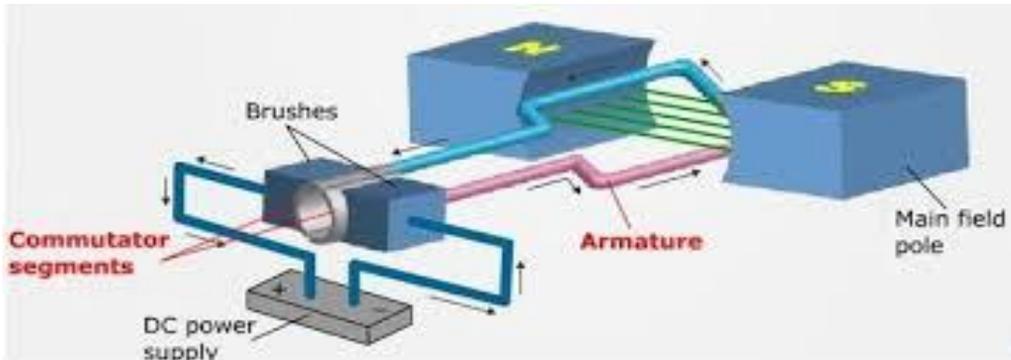


Figure 3.1: simple form of AT motor

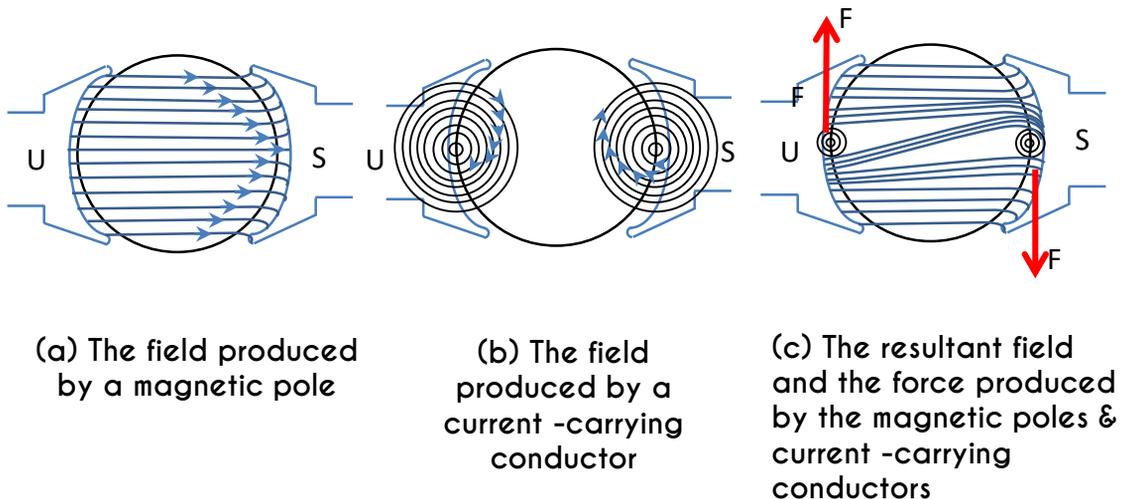


Figure 3.2: the process of interaction between the magnetic field produced by the main pole and the current-carrying conductor.

Figure 3.2 shows a pair of conductors placed across an armature core in the magnetic field of a 2-pole DC motor having uniform polarity as shown in figure 3.2 (a). When current is flowed in a conductor a concentric flux will result. Suppose the right conductor carries current in while the left conductor carries current out as shown in figure 3.2 (b). The combination of the two fluxes is shown in figure 3.2 (c). Figure 3.2 (c) this combination shows that the flux density is at the bottom of the U pole. While for the S pole the density is at the bottom. This imbalance will cause the conductor at the S pole to experience an inclined force to move it downwards. While the conductor on the U side tends to move upwards. Then this condition will cause the motor to rotate.

BACK EMF

When the motor rotates the armature conductor will cut off the flux. Based on the law of electromagnetic induction, e.m.f will be induced in it. According to Fleming's Right Hand rule, this e.m.f direction is opposite to the supply voltage direction as in figure 3.3. this condition is referred to as reversal. The production of this inverse e.m.f causes the exchange of electrical energy to mechanics to take place in the motor.

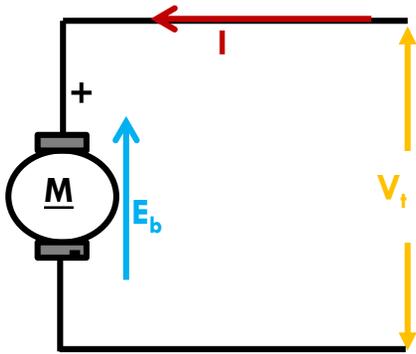


Figure 3.3: Back e.m.f in a dc motor

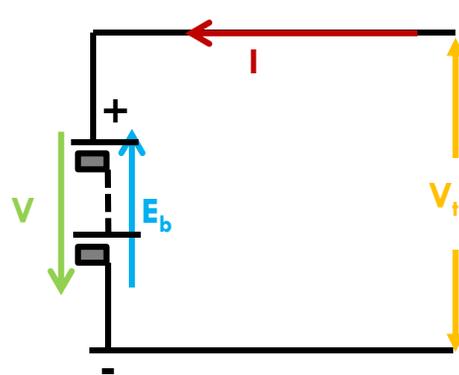


Figure 3.4: Equivalent circuit

The movement of the armature in producing the inverse e.m.f E_b is likened to placing a battery that has the as much as possible E_b across the supply of V_t volts as in the circuit of figure 3.3b. Production It must be V_t had to face the resistance of E_b .

The power required to face this resistance is like the formula :

$$P_m = E_b \times I_t \text{ watts.}$$

$$\text{It is equivalent to } = \frac{\text{voltage}}{\text{resistance}} = \frac{V_t - E_b}{R_a}$$

where R_a is the armature resistance.

The amount of reverse voltage depends on several factors such as armature speed. if the armature speed is high then the reverse voltage and armature current will increase.

TYPE OF DC MOTOR

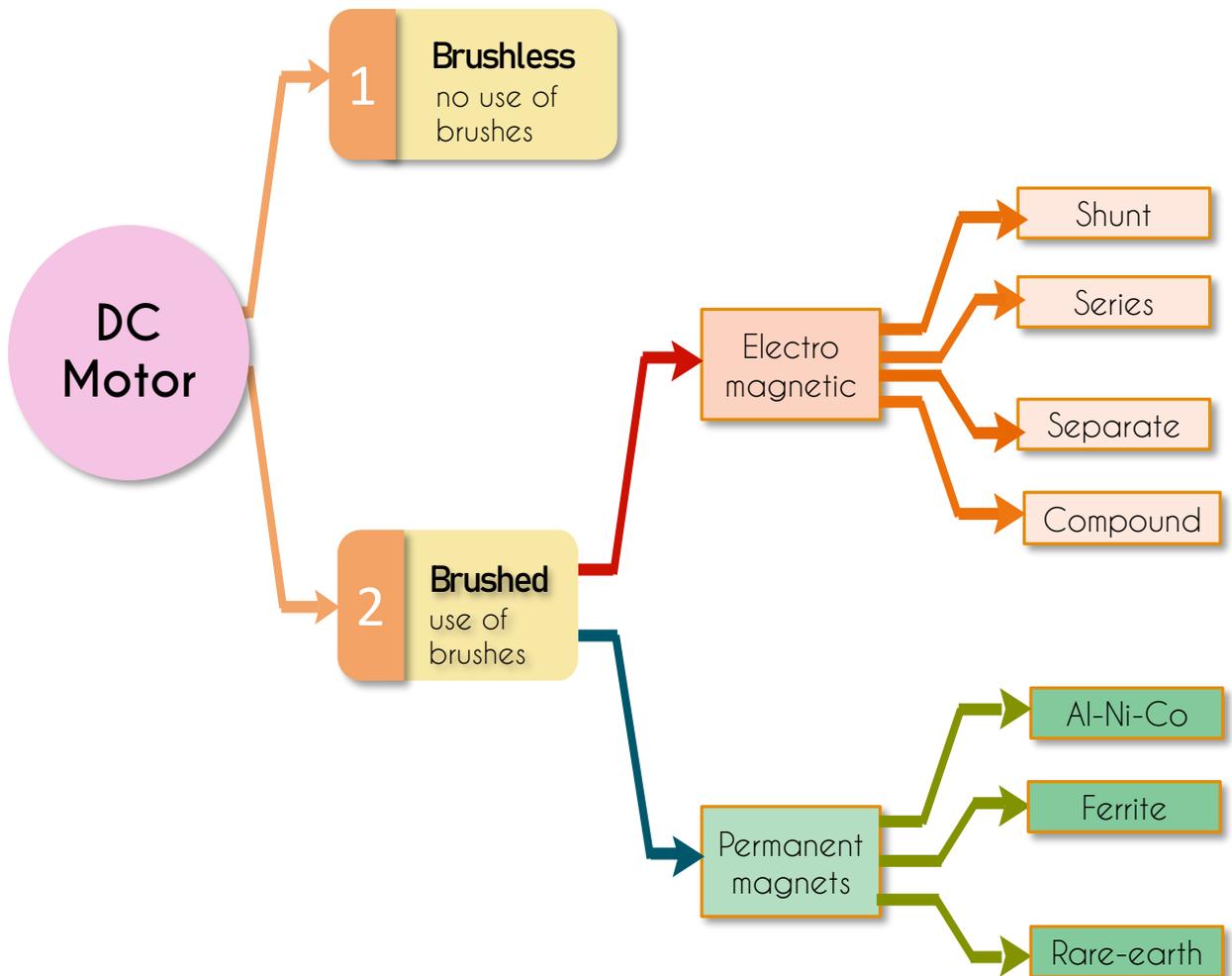


Figure 3.5: Type of DC motor

VOLTAGE EQUATION DC MOTOR

The armature resisting input voltage is for: -

- Overcome e.m.f back E_b
- Provides $I_a R_a$ ohm drop in armature circuit and brush resistance

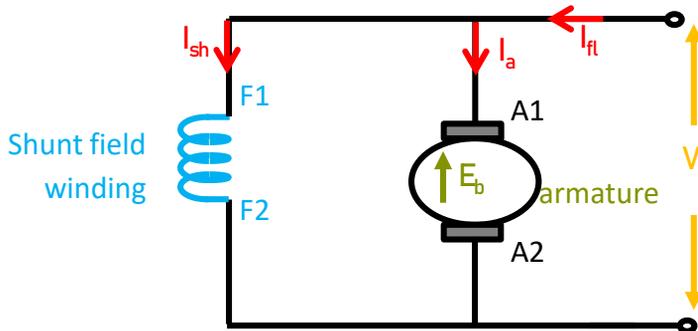


Figure 3.6: Circuit of DC motor

Therefore, the voltage equation of the AT motor is as follows:

$$V_t = E_b + I_a R_a$$

Multiply this equation by I_t will be:

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

Where :-

$V_t I_a$ - armature input power

$E_b I_a$ - electrical power equivalent to mechanical power generated in the armature

$I_a^2 R_a$ - copper power loss in the armature

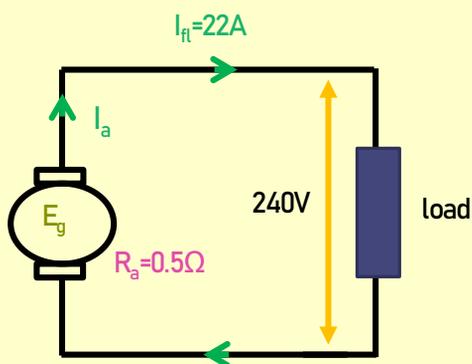
Some of power supplied to the armature will be lost as copper loss and brush voltage drop (if any). The rest will be converted to mechanical energy in the armature.

Example

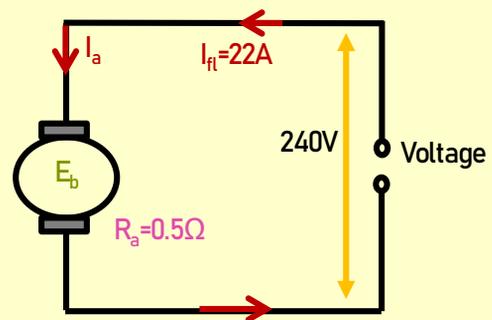
Example 3.1

A 240 volt direct current machine has an armature resistance of 0.5Ω . If the full load current is equal to 22A, calculate the induced e.m.f if the machine works as a Generator and a Motor

Solution 3.1



D.C generator



D.C motor

Generated e.m.f,

$$\begin{aligned} E_g &= V_t + I_a R_a \\ &= 240\text{V} + 22\text{A} (0.5\Omega) \\ &= \underline{251\text{V}} \end{aligned}$$

Back e.m.f,

$$\begin{aligned} E_b &= V_t - I_a R_a \\ &= 240\text{V} - 22\text{A} (0.5\Omega) \\ &= \underline{229\text{V}} \end{aligned}$$

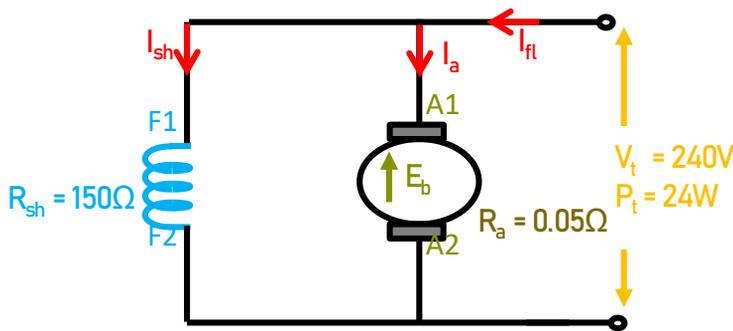
Example

Example 3.2

A 24kW, 240volt, direct current shunt machine has armature resistance and field resistance of 0.05Ω and 150Ω, respectively. Determine the total armature power if the machine works as:

- a generator that produces 24kW of output power
- a motor that uses 24kW input power

Solution 3.2



- A generator that produces 24kW of output power

$$\text{Full load current } (I_{fl}) = \frac{\text{output power}}{\text{input voltage}} = \frac{24\text{kW}}{240} = \underline{100\text{A}}$$

$$\text{Shunt field current } (I_{sh}) = \frac{\text{input voltage}}{\text{shunt resistance}} = \frac{240\text{V}}{150} = \underline{1.6\text{A}}$$

$$\text{Armature current } (I_a) = I_{fl} + I_{sh} = 100 + 1.6 = \underline{101.6\text{A}}$$

$$\text{Generate e.m.f : } E_g = V_t + I_a R_a = 240 + 101.6 (0.05) = \underline{245.08\text{V}}$$

$$\text{Total power in armature} = E_g I_a = 245.08 (101.6) = \underline{24.9\text{kW}}$$

- A motor that uses 24kW input power

$$\text{Full load current } (I_{fl}) = \frac{\text{output power}}{\text{input voltage}} = \frac{24\text{kW}}{240} = \underline{100\text{A}}$$

$$\text{Shunt field current } (I_{sh}) = \frac{\text{input voltage}}{\text{shunt resistance}} = \frac{240}{150} = \underline{1.6\text{A}}$$

$$\text{Armature current } (I_a) = I_{fl} - I_{sh} = 100 - 1.6 = \underline{98.4\text{A}}$$

$$\text{Back e.m.f : } E_b = V_t - I_a R_a = 240\text{V} - 98.4 (0.05) = \underline{235.08\text{V}}$$

$$\text{Total power in armature} = E_b I_a = 235.08 (98.4) = \underline{23.13\text{kW}}$$

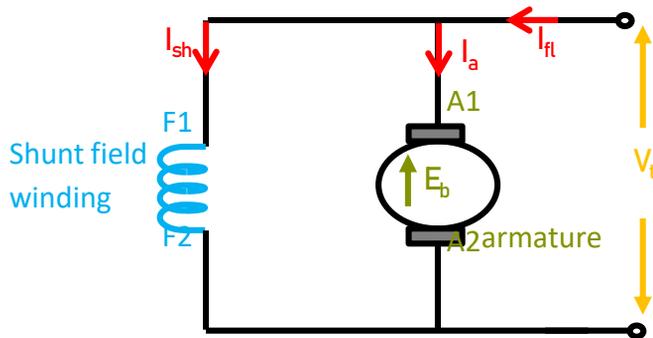
Example

Example 3.3

A motor is connected to a supply voltage of 415V and has an armature resistance value of 0.1Ω calculate: -

- The back e.m.f value when the current passing through the armature is 150A
- The value of the armature current when the back e.m.f is 410V

Solution 3.3



- The back e.m.f value when the current passing through the armature is 150A

$$\begin{aligned}\text{Back e.m.f, } E_b &= V_t - I_a R_a \\ &= 415 - 150 (0.1) \\ &= \underline{400V}\end{aligned}$$

- The value of the armature current when the back e.m.f is 410V

$$\begin{aligned}\text{Back e.m.f, } E_b &= V_t - I_a R_a \\ I_a &= \frac{V_t - E_b}{R_a} \\ &= \frac{415 - 410}{0.1} \\ &= \underline{50A}\end{aligned}$$

TORQUE

Torque is defined as the action of a force on a body that tends to move or rotate the body. Can be defined as rotation about an axis. Torque is measured as the product of the force and the radius where the force acts.

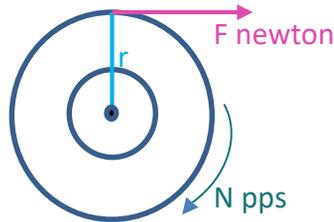


Figure 3.7: rotation on one axis

$$T = F \times r \text{ newton meters (Nm)}$$

$$\text{In one direction of revolution} = \text{Force} \times \text{distance} = F \times 2\pi r \text{ joule}$$

$$\text{Power generated} = F \times 2\pi r \times n \text{ joule/second} = F \times r \times 2\pi n \text{ joule/second}$$

Therefore the mechanical power of torque, $P_m = 2\pi n T$ joule/second or watt

ARMATURE TORQUE

Assume T_a is the torque produced in the armature when it rotates at a speed in seconds (rpm) and measured in units of Nm,

$$\text{Output power} = T_a \times 2\pi n \text{ watts}$$

known electrical power converted to mechanical in the armature = $E_b I_a$ watts
enter both equations into :-

$$T_a \times 2\pi n = E_b I_a \quad T_a = \frac{E_b I_a}{2\pi n} \text{ Nm}$$

Where: $E_b = \frac{\phi P n Z}{a}$

$$T_a = \frac{I_a}{2\pi n} \left(\frac{\phi P n Z}{a} \right) = \frac{I_a}{2\pi} \left(\frac{\phi P Z}{a} \right) = I_a \phi \left(\frac{P Z}{2\pi a} \right) \text{ Nm}$$

From this equation it is found that the torque is directly proportional to the flux

$T_a \propto I_a \phi$ where $\frac{P Z}{2\pi a}$ is constant. This situation is different for the type of motor that is,

- i. For a series motor (series motor) ϕ is directly proportional to I_a (before the condition saturated) because the field current carries all the armature current. **Therefore** the equation becomes, $T_a \propto I_a^2$
- ii. For a shunt motor ϕ is constant **therefore**, $T_a \propto I_a$

SHAFT TORQUE IN MOTOR

The torque from the armature will not all send out because it is necessary to overcome iron and friction loss in the motor. The output torque resulting from the armature torque minus with loss is known as the shaft torque (T_{sh}). The shaft torque can be given as:

$$T_{sh} = \frac{\text{output power}}{2\pi n} \text{ Nm}$$

The difference between armature torque and shaft torque ($T_a - T_{sh}$) is known as lost torque and its value is as,

$$T_a - T_{sh} = \frac{\text{iron loss and friction}}{2\pi n} \text{ Nm}$$

Example

Example 3.4

A motor has 8 poles, carrying 314 lap winding conductors. The armature current is 22A and produces a torque of 50Nm. Determine the required polar flux.

Solution 3.4

$$P = 8, \quad Z = 314, \quad I_a = 22\text{A}, \quad T_a = 50\text{Nm}, \quad a = mP = 8$$

$$T_a = \frac{I_a}{2\pi n} \left(\frac{\Phi P n Z}{a} \right) = \frac{I_a}{2\pi} \left(\frac{\Phi P Z}{a} \right) = I_a \Phi \left(\frac{P Z}{a 2\pi} \right)$$

$$\Phi = \frac{2\pi T_a}{P Z I_a} = \frac{2\pi(50)}{(22)(8)(314)}$$

$$\Phi = \underline{\underline{5.68\text{mWb}}}$$

Example

Example 3.5

A 240V direct current shunt motor rotates at a speed of 550 rpm when the armature current is 50A. Calculate the speed if the torque is doubled, given an armature resistance (R_a) of 0.2Ω.

Solution 3.5

$$V = 240V, N = 550\text{rpm}, I_a = 50A, T_{a2} = 2T_{a1}, R_a = 0.2\Omega$$

$T_a \propto I_a$ because Φ constant

$$\frac{T_{a1}}{T_{a2}} = \frac{I_{a1}}{I_{a2}} \Rightarrow \frac{1}{2} = \frac{50}{I_{a2}} \quad I_{a2} = \underline{100A}$$

$$E_{b1} = V_t - I_{a1}R_a = 240 - 50(0.2) = \underline{230V}$$

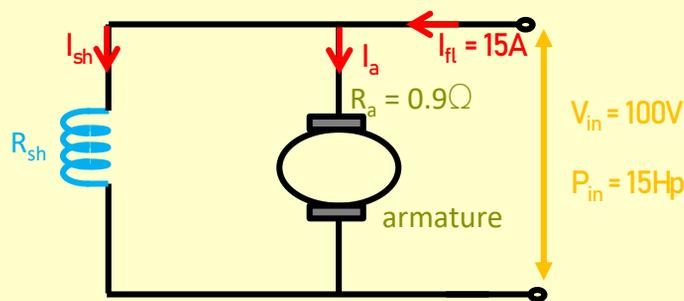
$$E_{b2} = V_t - I_{a2}R_a = 240 - 100(0.2) = \underline{220V}$$

$$\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2} \Rightarrow \frac{230}{220} = \frac{550}{N_2} \quad N_2 = \underline{526.1 \text{ rpm}}$$

Example 3.6

A 6-pole, 100V shunt motor has 540 lap winding. This motor takes a current of 15A from the input supply and a power of 1.5hp. The field winding takes as much as 0.5A. The armature resistance is 0.9Ω and the number of flux per pole is 20mWb. Calculate the speed of this motor and the shaft torque (output) in newton-meters.

Solution 3.6



$$\text{armature current, } I_a = I_{in} - I_{sh} = 15 - 1.5 = \underline{13.5A}$$

$$\text{back emf, } E_b = V_t - V_a - V_{brushes} = 100 - 15(0.9) = \underline{86.5V}$$

$$\text{speed, } N = \frac{aE_b}{\Phi PZ} = \frac{(6)(86.5)}{(20m)(6)(540)} = \underline{8.01 \text{ rpm}}$$

$$\text{Formula } T_{sh} = \frac{\text{output power}}{2\pi n} = \frac{1.5 \times 746}{2\pi(8.01)} = \underline{22.25Nm}$$

ROTATION SPEED

When the field flux is reduced the speed increases, the magnitude of the back e.m.f will decrease. The armature current and the torque also increase. An increase in torque causes the speed of the motor to increase, then the back e.m.f will increase again until the magnitude of the armature current and the torque is reduced to a value that is just sufficient to supply the load at a constant speed.

The combination of the formula $E_b = V_t - I_a R_a$ and $E_b = \frac{\Phi P n Z}{a}$ will produce a

$$E_b = \frac{\Phi P n Z}{a} \quad \Rightarrow \quad n = \frac{E_b (60 a)}{\Phi P Z} \quad \Rightarrow \quad \frac{E_b}{\Phi} \times \frac{60 a}{P Z}$$

where $\frac{60 a}{P Z}$ is constant, Then the equation becomes, $n = \frac{E_b}{\Phi}$ C rps

From the equation it can be stated that the speed is directly proportional to the back e.m.f and inversely proportional to the flux. It can be summarized that the factors that change the speed of the DC motor are:-

- i. Supply voltage
- ii. elective value of armature circuit resistance, R_a
- iii. Strength of magnetic field flux

N_1	speed at first state	N_2	speed at the second state
I_{a1}	armature current in the first state	I_{a2}	armature current in the second state
Φ_1	flux per pole in the first state	Φ_2	flux per pole in the second state

Where

Series DC motors, by using the relationship above found:-

$$N_1 = \frac{E_{b1}}{\Phi_1} \quad \text{where } E_{b1} = V_t - I_{a1} R_a \quad \Rightarrow \quad N_2 = \frac{E_{b2}}{\Phi_2} \quad \text{where } E_{b2} = V_t - I_{a2} R_a$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2}, \quad \text{before the magnetic field is saturated } \Phi \propto I_a$$

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

Shunt DC motors, by using the relationship above found:-

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2}, \quad \text{If } \Phi_1 = \Phi_2$$

Therefore:
$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

SPEED REGULATION

Speed regulation refers to the change in motor speed when the torque of the load changes while other conditions are constant (unchanged). The change in speed is not caused by the adjustment of tools or speed control devices but occurs by the nature of the motor itself.

Voltage regulation can be defined as the change in speed when the motor load is reduced from the rated value to zero and expressed as a percentage of the pin load speed. Can be defined as:-

$$\% \text{ Speed regulation} = \frac{N_{nl} - N_{fl}}{N_{fl}} \times 100\%$$

Where: N_{nl} = no load speed and N_{fl} = full load speed

Example

Example 3.7

A 240V direct current shunt motor rotates at a speed of 950psm and draws a current of 10A at no load. The total armature and field resistances are 0.2Ω and 120Ω. Calculate the speed when loaded and taking a current of 40A. Assume the flux is steady state.

Solution 3.7

$$I_{f1} = 10A, I_{f2} = 40A, V_t = 240V, N_1 = 950\text{psm}, R_a = 0.2\Omega, R_{sh} = 120\Omega$$

$$\text{Shunt current, } I_{sh} = \frac{E_b}{R_{sh}} = \frac{240V}{120\Omega} = \underline{2A}$$

$$\text{Armature current at no load, } I_{a1} = I_{f1} - I_{sh} = 10 - 2 = \underline{8A}$$

$$\text{Back e.m.f at no load, } E_{b1} = V_t - I_{a1}R_a = 240 - (8)(0.2) = \underline{238.4V}$$

$$\text{Armature current at full load, } I_{a2} = I_{f2} - I_{sh} = 40 - 2 = \underline{38A}$$

$$\text{Back e.m.f at full load, } E_{b2} = V_t - I_{a2}R_a = 240 - (38)(0.2) = \underline{232.4V}$$

$$\text{From formula } \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

$$\text{Therefore: } N_2 = \frac{E_{b2}}{E_{b1}} \times N_1 = \frac{232.4}{238.4} \times 950 = \underline{926.1 \text{ rpm}}$$

Example

Example 3.8

A 240V shunt motor DC, the armature resistance and field resistance are 0.5Ω and 125Ω . When there is no load, the speed is 1200rpm and the armature current is 2.5A. At a certain state the current will decrease by 1120rpm, calculate the line current and input power at this point.

Solution 3.8

$$N_1 = 1200\text{rpm}, N_2 = 1120, V_t = 240\text{V}, I_{a1} = \underline{2.5\text{A}}$$

$$\text{At no load, } E_{b1} = V_t - I_{a1}R_a = 240 - (2.5)(0.5) = \underline{238.75\text{V}}$$

$$\text{At current decrease, } E_{b2} = V_t - I_{a2}R_a = 240\text{V} - 0.5\Omega I_{a2}$$

$$\begin{aligned} \text{from formula } \frac{N_2}{N_1} &= \frac{E_{b2}}{E_{b1}} = \frac{1120\text{rpm}}{1200\text{rpm}} = \frac{240 - 0.5\Omega I_{a2}}{238.75}, \\ &= \frac{240 - 222.833}{0.5} \\ I_{a2} &= \underline{34.34\text{A}} \end{aligned}$$

Line current at second speed,

$$I_{fl2} = I_{a2} + I_{sh} = 34.34\text{ A} + \frac{240\text{ V}}{125} = \underline{36.26\text{A}}$$

Power enter on the second state,

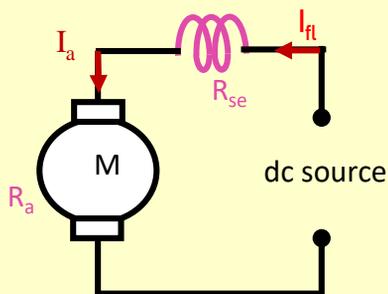
$$\begin{aligned} P_2 &= 240\text{V} \times 36.26\text{V} \\ &= \underline{8,702.4\text{W}} \end{aligned}$$

Example

Example 3.9

An at series motor has 1044 armature conductors with a wave connection. At a certain load, the flux value per pole is 34.6mWb and the total mechanical torque generated is 209 newton-meters. Calculate the line current drawn by the motor and the speed of the motor when rotating at a supply voltage of 500V. The total resistance value of this motor is 3Ω.

Solution 3.9



$$P = 8, Z = 1044, \Phi = 35\text{mWb},$$

$$T_a = 209\text{Nm}, V_t = 500\text{V},$$

$$R_{\text{tot}} = 3\Omega$$

$$\text{Formula, } T_a = \frac{E_b I_a}{2\pi n} \Rightarrow \frac{\Phi P n Z}{a} \times \frac{I_a}{2\pi n} \Rightarrow I_a = \frac{2\pi a T_a}{\Phi P Z}$$

$$= \frac{2\pi (2)(209)}{(35\text{m})(8)(1044)} = \underline{4.49\text{A}}$$

$$\text{back emf, } E_b = V_t - I_a(R_{\text{tot}}) - V_{\text{brushes}}$$

$$= 500 - 4.49(3)$$

$$= \underline{486.53\text{V}}$$

$$E_b = \frac{\Phi P n Z}{a} \quad \text{Where } n = \frac{a E_b}{\Phi P Z} = \frac{(2)(486.53)}{(35\text{m})(8)(1044)}$$

$$= \underline{3.33 \text{ rps}}$$

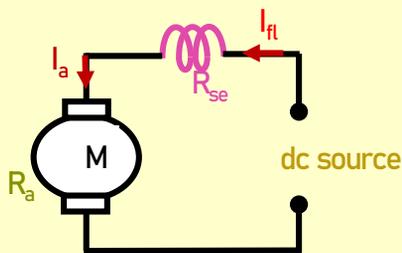
$$N = \text{rps} \times 60 = 3.33\text{rps} \times 60 = \underline{199.7 \text{ rpm}}$$

Example

Example 3.10

An 18kW, 200V shunt motor DC rotates at 1500rpm at full load. If the armature resistance of the motor is 0.3Ω and the voltage drop across the brush is 2V, calculate the Armature Current (I_a) when $E_b=225V$ and the shaft torque T_{sh} .

Solution 3.10



$$N = 1500\text{rpm}, V_{\text{brush}} = 2V$$

I_a when $E_b = 225V$, Formula $E_g = V_t - V_a - V_s - V_{\text{brushes}}$

$$V_a = V_t - E_g - V_{\text{brushes}}$$

$$I_a = \frac{V_t - E_b - V_{\text{brush}}}{R_a} = \frac{200 - 225 - 2}{0.3} = \underline{10A}$$

$$\text{shaft torque, } T_{sh} = \frac{\text{output power}}{2\pi N} = \frac{18\text{kW}}{2\pi(1500)} = \underline{115 Nm}$$

CHARACTERISTICS of DC MOTOR

The main characteristics of the AT motor are shown by using the curve for the relationship between the following quantities: -

- i. Torque and armature current $\frac{T_a}{I_a}$ - also known as electrical characteristics
- ii. Armature speed and current $\frac{N}{I_a}$
- iii. Speed and torque $\frac{N}{T_a}$ - known as mechanical characteristics

Note:- the following equation becomes the main title when discussing the characteristics of the motor $T_a \propto \Phi I_a$ and $N \propto \frac{E_b}{\Phi}$

Characteristics of Series DC Motor

The motor and generator connections are the same, the difference is that for the motor the voltage will enter at the terminal voltage. While the armature and field windings are connected in series. The field winding wire is made of coarse copper and is slightly twisted, to produce a small resistance

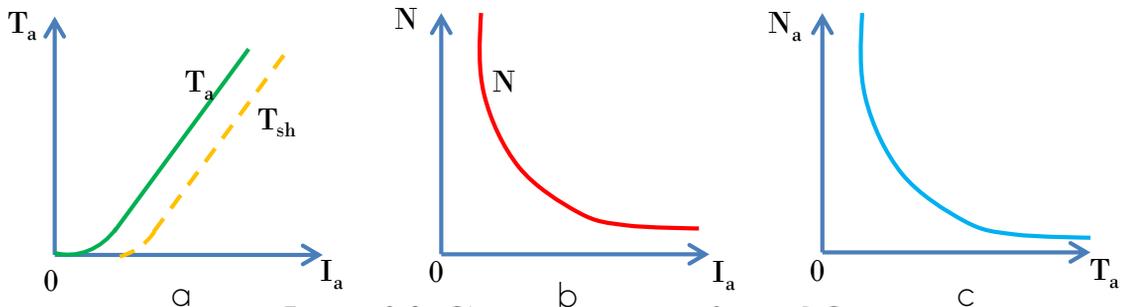


Figure 3.8: Characteristics of Series DC Motor

Torque and armature current $\frac{T_a}{I_a}$ - also known as electrical characteristics

From the $T_a \propto \Phi I_a$ equation, the series field current will carry the armature current $\Phi \propto I_a$, until it reaches a saturated state. Before saturation

$$T_a \propto \Phi I_a, T_a \propto I_a^2, \text{ (parabolic graph shape)}$$

Smaller series motor torque compares to shunt motor torque for small loads because it produces little flux, but the rated current is high (as in figure 3.8(a)).

Armature speed and current, $\frac{N}{I_a}$

Based on the formula $N \propto \frac{E_b}{\Phi}$, the change in E_b value for each load current change is small and will be ignored for certain conditions. When I_a increases Φ will also increase, because speed is inversely proportional to flux. When the load is large I_a will also increase, but the series motor needs to be loaded otherwise the current will be high and the speed will be too high (as in figure 3.8(b)).

Speed and torque $\frac{N}{T_a}$ - known as mechanical properties

When the speed is high the torque will be low and vice versa. This equation is illustrated as a graph in Figure 3.8(c).

Characteristics of Shunt DC Motor

The motor and generator connections are the same, the difference is that for the motor the voltage will enter at the terminal voltage. The armature and field windings are shunt-connected, where the voltage across the field windings is always constant. This means that the field flux is also constant.

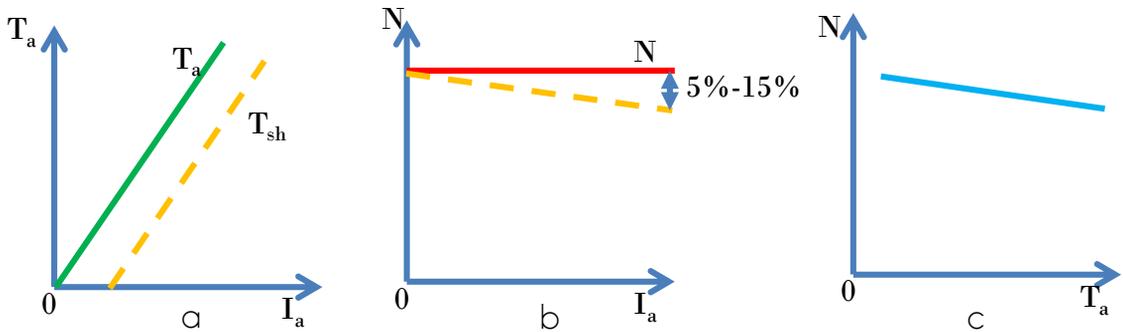


Figure 3.9: Characteristics of Shunt DC Motor

Torque and armature current $\frac{T_a}{I_a}$ - also known as electrical characteristics

The flux in this motor is constant therefore the equation $T_a \propto \Phi I_a$ will be $T_a \propto I_a$. This situation is shown as a graph in Figure 3.8(a), in practice it is a straight line. If the starting load is high then the starting current is also high, still the shunt motor should not have a high load at the start (as in figure 3.9(a)).

Armature speed and current, $\frac{N}{I_a}$

If it is considered a constant flux therefore $N \propto E_b$, as long as E_b is constant then the speed will be constant as in figure 3.9(b). When a load is applied to the armature shaft, the rotation speed will decrease, as will the reverse gear. The change in reverse gear only changes between 5%-15% only, then the speed also changes same rate as figure 3.8(b).

Speed and torque $\frac{N}{T_a}$ - known as mechanical properties

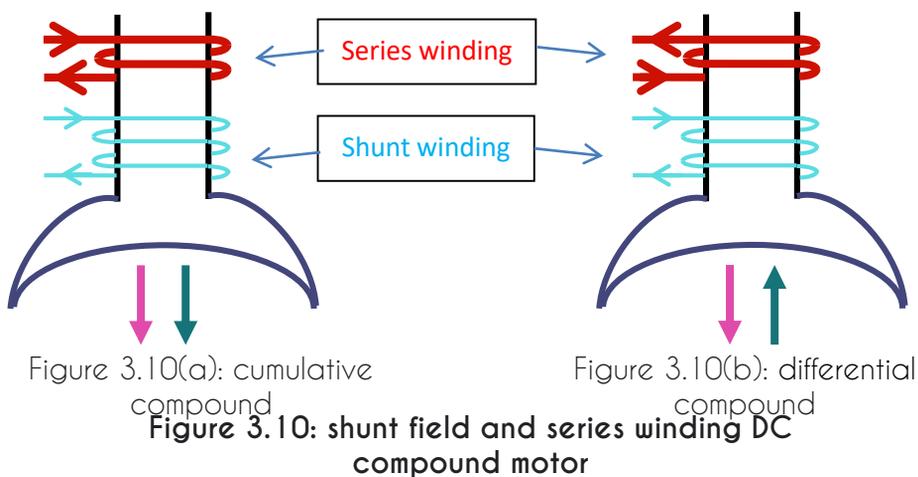
This feature is a combination of the two features above, shown as figure 3.9(c).

Characteristics of Compound DC Motor

This motor uses both field windings which are shunt field and series field. If the series field winding is connected to strengthen the shunt field, it is known as a cumulative compound. If the series winding is connected against the shunt field, it is known as a differential compound. These two connections are shown in figure 3.9 (a) and (b).

A compound motor characteristic is a combination of both shunt and series windings. The greater the influence of the shunt field, then this motor approaches the characteristics of a shunt motor. Conversely, if the influence of the series field is greater, the motor approaches the nature of a series motor.

A stepped compound motor produces high torque like a series motor, but the no-load speed is constant and controllable. Making it suitable for drive tasks that have high load fluctuations without experiencing extreme speeds. Differential compound motors are not used that much. But it has characteristics where its use becomes important in certain situations or for special tasks such as in experiments and research works.



Torque and armature current $\frac{T_a}{I_a}$ - also known as electrical characteristics

The current and also the flux in the shunt circuit (Φ_{sh}), for the compound motor is constant at the time of starting and during running, while the series field current (Φ_s) is a multiple of the armature current. The basic equation for the torque of a compound motor is:-

$$T = k(\Phi_{sh} + \Phi_s)I_a \text{ cumulative compound}$$

$$T = k(\Phi_{sh} - \Phi_s)I_a \text{ differential compound}$$

Assuming the no-load flux is equal to the magnetic field flux while the overall flux increases according to the increase in the armature current of the stepped compound motor, resulting in a torque curve that always exceeds the torque of the shunt motor.

For differential compound motors any increase in armature current will produce a series field e.m.f which will reduce the amount of flux and then torque. Therefore a differential compound motor produces a torque curve that is always less than the torque of a shunt motor. The second feature of this motor is shown in figure 3.11

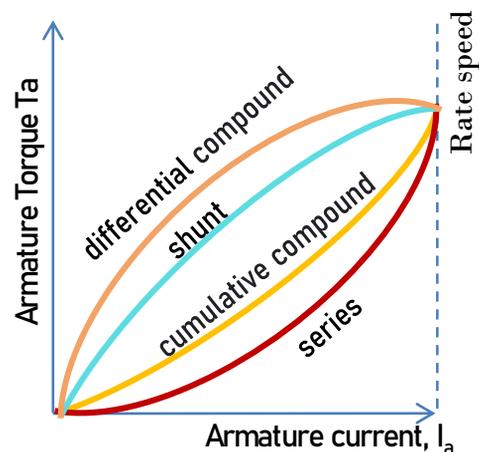
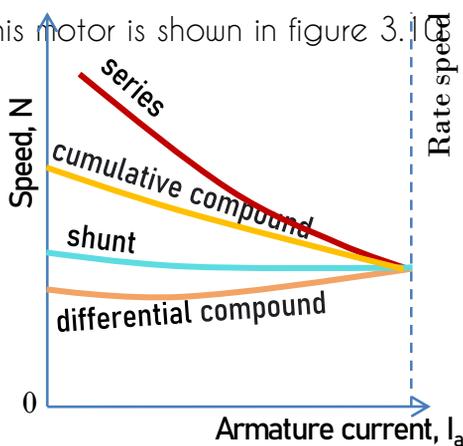


Figure 3.11(a) cumulative compound graph

Figure 3.11(b): differential compound graph

Figure 3.11: graph of speed and torque against armature current

Armature speed and current, $\frac{N}{I_a}$

The basic equation for the speed of a geared motor can be given as:

$$N = k \frac{E_b}{\Phi_{sh} + \Phi_s} = k \frac{V_t - I_a(R_a + R_s)}{\Phi_{sh} + \Phi_s}$$

When the load and armature current increase, the series field flux will also increase while the reverse will decrease. Therefore the carrier of the equation will increase while the peak will decrease at a higher rate compared to the shunt motor, as shown in figure 3.11 (a).

The basic equation for differential motor speed can be given as:

$$N = k \frac{E_b}{\Phi_{sh} - \Phi_s} = k \frac{V_t - I_a(R_a + R_s)}{\Phi_{sh} - \Phi_s}$$

When the load and armature current increase, the carrying capacity of the equation will decrease while the upper limit will increase. The speed will decrease slightly when the load is small but will increase when the load increases. This condition will produce dynamic instability, causing this motor to be rarely used. This speed characteristic can be illustrated as figure 3.10(b).

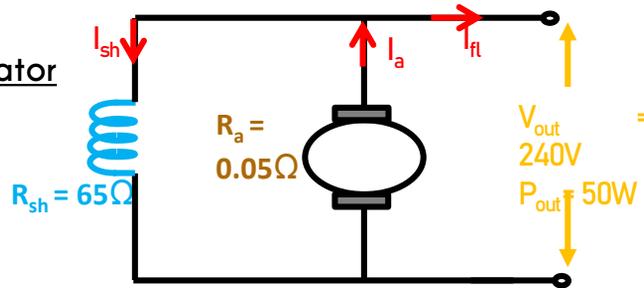
Example

Example 3.11

A shunt generator produces 50W at 240V and a speed of 450rpm. The armature resistance and field resistance amount to 0.05Ω and 65Ω , respectively. Calculate the speed of the machine when it rotates as a shunt motor and takes a power of 50Watt at 240V input. assume a brush voltage drop of 1V per brush.

Solution 3.11

Machine as a generator



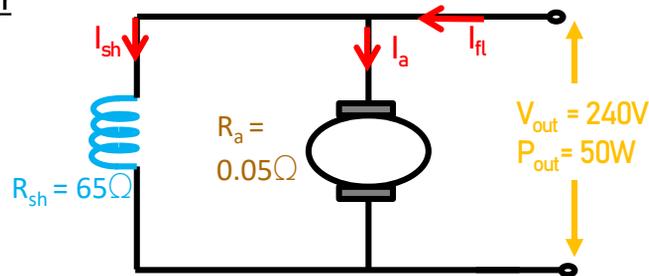
$$I_{fl} = \frac{\text{Power Output}}{\text{Voltage Output}} = \frac{50\text{kW}}{240} = \underline{208.3\text{A}} \quad I_{sh} = \frac{\text{Voltage output}}{\text{Shunt resistance}} = \frac{240\text{V}}{65} = \underline{3.69\text{A}}$$

$$I_{a1} = I_{fl} + I_{sh} = 208.3 + 3.69 = \underline{212.0\text{A}}$$

$$\text{Voltage drop at brushes } (V_b) = 2\text{V} \times 1 = \underline{2\text{V}}$$

$$\text{Generate e.m.f, } E_g = V_t + I_{a1}R_a + V_{\text{brush}} = 240\text{V} + 212.0(0.05) + 2\text{V} = \underline{248.1\text{V}}$$

Machine as a motor



$$I_{fl} = \frac{\text{Power output}}{\text{Voltage output}} = \frac{50\text{kW}}{240} = \underline{208.3\text{A}} \quad I_{sh} = \frac{\text{Voltage output}}{\text{Shunt resistance}} = \frac{240\text{V}}{65} = \underline{3.69\text{A}}$$

$$I_{a1} = I_{fl} - I_{sh} = 208.3\text{A} - 3.69\text{A} = \underline{204.6\text{A}}$$

$$\text{Voltage drop at brushes, } V_b = 2\text{V} \times 1 = \underline{2\text{V}}$$

$$\begin{aligned} \text{Back e.m.f, } E_b &= V_t - I_{a1}R_a - V_{\text{brush}} \\ &= 240\text{V} - 204.6\text{A}(0.05) - 2\text{V} = \underline{231.7\text{V}} \end{aligned}$$

Using formulas, $\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2}$, until $\Phi_1 = \Phi_2$ because I_{sh} is constant

$$N_2 = \frac{231.7}{248.1} \times 450 = \underline{413.9\text{rpm}}$$

Example

Example 3.12

The results below are taken from a test of an AT series motor. Sketch the speed versus torque graph for the machine when the supply voltage is a constant 460V. The value of the armature and field resistance is 0.5Ω, neglecting iron and friction losses.

Current (A)	20	30	40	50
Shunt torque (Nm)	128.8	230.5	349.8	469.2

Solution 3.12

By taking a current of 20A it is found: -

Enter the motor, $P_{in} = V I = 460V \times 20A = \underline{9200 \text{ Watt}}$

Copper loss in field and armature, $= 20^2 \times 0.5 = \underline{200 \text{ Watt}}$

Therefore by neglecting iron loss and friction then:

Output Power, $P_{out} = P_{in} - P_{aCu} = 9200 \text{ W} - 200\text{W} = \underline{9000 \text{ watt}}$

Now: $T_{sh} = \frac{P_{out}}{2\pi N}$

$$N = \frac{P_{out}}{2\pi T_{sh}} = \frac{9000 \text{ W}}{2\pi(128.8)} = 11.12 \text{ rpm} \times 60 = \underline{667.26 \text{ rpm}}$$

Current (A)	20	30	40	50
Shunt torque (Nm)	128.8	230.5	349.8	469.2
Input power	9200	13,800	18,400	23,000
Cuprum loss, I ² R	200	450	800	1250
Output power	9000	13,350	17,600	21,750
Speed (rpm)	667.26	553	480.7	442.89

LOSS AND EFFICIENCY

The losses that occur in an AT motor are the same as in an AT generator namely:-

- | | | |
|-------------------|-----------------------|----------------------|
| i) Loss of copper | ii) Loss of magnetism | iii) Mechanical loss |
|-------------------|-----------------------|----------------------|

Maximum power will be produced in the motor when: $I_a R_a = \frac{V_t}{2} = E_b$

Maximum efficiency occurs when the total copper loss equals the total fixed loss (magnetic and mechanical losses).

The power level in an AT motor is as shown in figure 3.12.

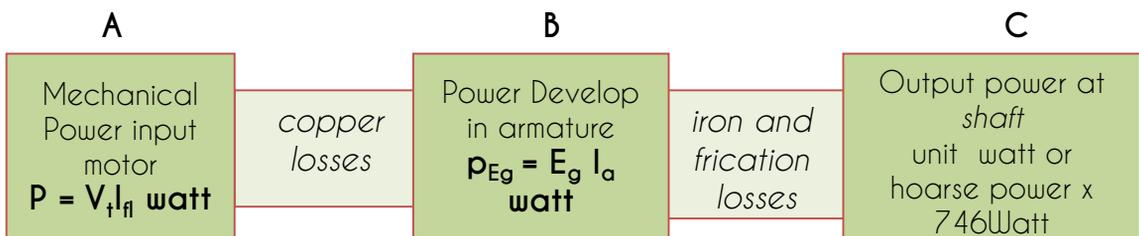


Figure 3.12: Power Rating DC Motor

based on figure 3.11 motor efficiency can be given as: -

- i. mechanical efficiency

$$\eta_m = \frac{C}{B} = \frac{\text{Output power at Shaft}}{\text{Power Develop in Armature}}$$

- ii. electrical efficiency

$$\eta_e = \frac{B}{A} = \frac{\text{Power Develop in Armature}}{\text{Mechanical Power input motor}}$$

- iii. overall or commercial efficiency

$$\eta_c = \frac{C}{A} = \frac{\text{Output power at Shaft}}{\text{Mechanical Power input motor}}$$

can be stated that :

A - B = copper losses and **B - C = iron and friction losses**

At no load motor loss is defined as:-

- i. Armature copper loss (armature Cu losses) = $I_a^2 R_a$ is variable
- ii. Fixed loss W_c it includes
 - shunt copper losses (shunt Cu losses)
 - loss of magnetic field (magnetic losses)
 - Mechanical losses (mechanical loss)

Example

Example 3.13

A 250V 4-pole series motor has 469 armature conductors that are wound over each other (wipe). The total polarizing flux is 22mWb and the total iron, wind and friction losses are 180W. The armature and series field resistances are 0.19ohm and 0.14ohm respectively. When the motor draws a current of 50A, calculate armature torque, rotational speed, output torque and efficiency.

Solution 3.13

Given: pole (P)=4, terminal voltage, $V_t = 250V$, number of armature conductors, $Z = 469$

polarized flux, $\Phi = 22mWb$, sum of iron loss, wind and friction = 180W,

$R_a = 0.19ohm$, $R_s = 0.14ohm$, armature current (I_a) = 50A, $\alpha = mP = (1)(4) = \underline{4}$

$$E_b = \frac{\Phi P n Z}{a} \quad , \quad T_a = \frac{E_b I_a}{2\pi n'}$$

$$T_a = \frac{\Phi P n Z}{a} \times \frac{I_a}{2\pi n'} = \frac{\Phi P Z}{a} \times \frac{I_a}{2\pi} = \frac{(22 \times 10^{-3})(4)(469)}{(2)} \times \frac{(50)}{2(3.14)} = \underline{82.15Nm}$$

$$E_b = V_t - I_a R_a = 250V - (50A)(0.19) = \underline{240.5V}$$

$$E_b = \frac{\Phi P n Z}{a} \quad \Rightarrow \quad N = \frac{E_b 60 a}{\Phi P Z} = \frac{(240.5)(60)(4)}{(22 \times 10^{-3})(4)(469)} = \underline{1,398.5 \text{ psm}}$$

$$\text{input power, } P_{in} = V_t I_{fl} = 250V \times 50A = \underline{12500 \text{ W}}$$

$$\text{armature winding copper loss } (P_{CUarmature}) = I_a^2 R_a = (50A)^2 (0.19\Omega) = \underline{475W}$$

$$\text{series field winding copper loss } (P_{CUseries}) = I_s^2 R_s = (50A)^2 (0.14\Omega) = \underline{350W}$$

$$\begin{aligned} \text{Fri. loss, } P_{total} &= P_{CUarmature} + P_{CUseries} + P_{iron\&friction} \\ &= 475 + 350 + 180 = \underline{1,005W} \end{aligned}$$

$$\text{Output power, } P_{out} = P_{in} - P_{total} = 12500 - 1,005 = \underline{11,495W}$$

$$\text{efficiency, } \% \zeta = \frac{P_{out}}{P_{in}} = \frac{11,495}{12500} \times 100 = \underline{92\%}$$

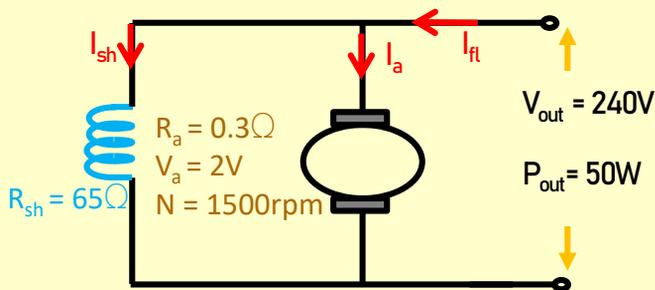
Example

Example 3.14

A shunt type direct current motor of 20HP, 240V rotates at a speed of 1500rpm at full load. If the armature resistance of this motor is 0.3Ω and the brush voltage drop is 2V. Calculate:

- Armature current if the voltage is 226V
- Output torque/shaft, T_{sh}
- The efficiency of this motor if the input current is 62A

Solution 3.14



Armature current if the voltage is 226V

$$V_a = V_t - E_g - V_{\text{brushes}}$$

$$I_a = \frac{V_t - E_g - V_{\text{brush}}}{R_a} = \frac{240V - 226V - 2V}{0.3\Omega} = \underline{40 \text{ Amp}}$$

Shunt torque T_{sh}

$$T_{sh} = \frac{\text{output power}}{2\pi N}, \quad 1\text{Hp} = 746 \text{ watt}$$

$$T_{sh} = \frac{V_t I_a \times 60}{2\pi N} = \frac{240V(40A) \times 60}{2\pi(1500\text{rpm})} = \underline{61 \text{ Nm}}$$

Motor efficiency when input current is 62A

$$\text{Input power, } P_{in} = V_t I_{fl} = 240V \times 40A = \underline{9600W}$$

$$\% \text{efficiency, } \% \zeta = \frac{\text{output power}}{\text{input power}} \times 100\% = \frac{240V(40A)}{240V(62a)} \times 100\% = \underline{64.5\%}$$

Example

Example 3.15

A motor at 450V, 35kk (hp) rotates at a speed of 1000psm. Calculate the torque of this motor in Nm. If the efficiency of this motor is 85%, calculate the current taken by the motor and the power cost absorbed if the load is constant for 10 hours. The estimated cost of electricity is RM 0.30 per kWh.

Solution 3.15

Output in watts (P_{out}) = 35 x 746W = 26110W

Motor torque in Nm

$$T_{sh} = \frac{P_{out}}{2\pi n} = \frac{26110 \times 60}{2\pi(1000)} = \underline{249.46Nm}$$

$$\% \text{efficiency, } \% \zeta = \frac{P_{out}}{P_{in}} \times 100\%, \quad P_{in} = \frac{P_{out}}{\text{efficiency}} = \frac{26110}{0.85} = \underline{30.72kW}$$

$$\text{Input power, } P_{in} = V_t I_{fl}, \quad I_{fl} = \frac{P_{in}}{V_t} = \frac{30.72kW}{450V} = \underline{68.26 A}$$

Energy absorbed in 10 hours = 30.72kW x 10 = 307.2kWh

Cost of the energy absorbed = RM307.2 x RM 0.30 = RM92.16

Example 3.16

A shunt motor at 480V, has armature resistance of 0.5Ω, field resistance of 150Ω. Find the value of the back emf when the power of this motor is 10 horsepower at 80% efficiency.

Solution 3.16

$$\% \text{efficiency, } \% \zeta = \frac{P_{out}}{P_{in}} \times 100\%, \quad P_{in} = \frac{P_{out}}{\text{efficiency}} = \frac{10 \times 746}{0.8} = \underline{9325kW}$$

$$\text{Input power, } P_{in} = V_t I_{fl},$$

$$\text{Input current, } I_{fl} = \frac{P_{in}}{V_t} = \frac{9325kW}{480V} = \underline{19.23 A}$$

$$I_{sh} = \frac{V_t}{R_{sh}} = \frac{480V}{150ohm} = \underline{3.2A}$$

$$I_a = I_{fl} - I_{sh} = 19.43A - 3.2A = \underline{16.23A}$$

$$\text{Back e.m.f, } E_b = V_t - V_a - V_{burses} = 480V - (16.23 \times 0.5) = \underline{471.9V}$$

APPLICATION OF DC MOTOR

Application of DC motors can be summarized as:

Type of motor	characteristics	application
shunt motor	<ul style="list-style-type: none"> • Almost constant (fixed) speed • Moderate torque which is not as high as a series motor for the same amount of current 	or constant speed use in any load condition <ul style="list-style-type: none"> • Centrifugal pump • Fans and blowers • Lathe machine • Reciprocating pump
series motor	Variable speed <ul style="list-style-type: none"> • High starting torque • Low speed when the load is large 	For the use of traction work where the load starts to be high <ul style="list-style-type: none"> • electric locomotives, • rapid transit, Trolley cars • cranes and hoists • conveyors
cumulative compound motor	Variable speed <ul style="list-style-type: none"> • Speed changes when adjusted • High starting torque For high torque 	<ul style="list-style-type: none"> • Lathe and lathe • Elevators • Conveyors • Heavy planers • Rolling mills

Advantages of DC motor

- i. Easy to control the speed whether fast or slow. Causing most push motors (traction) and servo motors use AT, such as the motor to move the LRT (high-speed train).
- ii. High starting torque: AT series motors are best for use electrical traction ie can carry heavy loads when starting work. AT series motor torque can reach 500% compared to normal torque. Therefore, the AT series motor is suitable for use in electric trains (LRT) and cranes.
- iii. Constant torque at any speed
- iv. Easy to turn on, turn off, change direction and more precision.
- v. Harmonic free, reactive power consumption and many other factors make AT motors better than AU motors.

Disadvantages of DC motor

- i. High cost
- ii. Increased operating costs and disruption due to carbon brushes and commutator.
- iii. Cannot operate in explosive and hazardous conditions due to AT motor easy to produce flowers (sparks) on the carbon brush (because of the risk on the regulator)

Example

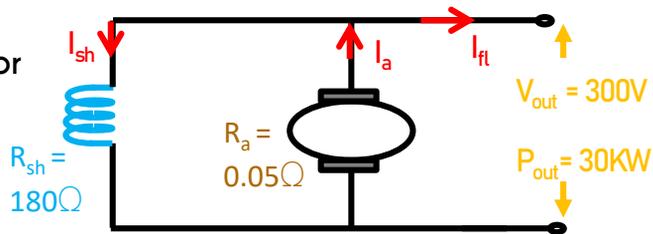
Example 3.17

A 30kW, 300V shunt type machine has armature resistance and field resistance of 0.05Ω and 180Ω respectively. Determine the total armature power when the machine works as: -

- Generator with 30kW output power
- Motor with 30kW input power

Solution 3.17

Machine as a generator



$$\text{Output current, } I_{fl} = \frac{P_{out}}{V_t} = \frac{30 \times 1000}{300} = 100 \text{ A}$$

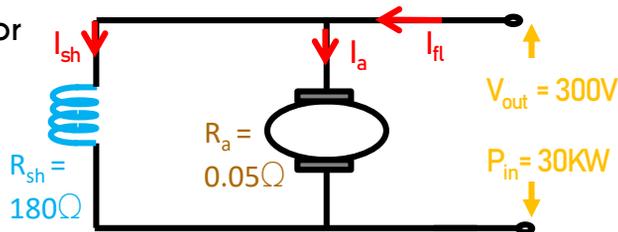
$$\text{Shunt field current, } I_{sh} = \frac{V_t}{R_{sh}} = \frac{300}{180} = 1.67 \text{ A}$$

$$\text{Armature current, } I_a = I_{out} + I_{sh} = 100 + 1.67 = 101.67 \text{ A}$$

$$\text{Generate e.m.f, } E_g = V_t + V_a + V_{brushes} = 300 + 101.67(0.05) = 305.1 \text{ V}$$

$$\text{Power develop in armature, } E_g I_a = 305.1(101.67) = 31.02 \text{ kW}$$

Machine as a motor



$$\text{Output current, } I_{fl} = \frac{P_{out}}{V_t} = \frac{30 \times 1000}{300} = 100 \text{ A}$$

$$\text{Shunt field current, } I_{sh} = \frac{V_t}{R_{sh}} = \frac{300}{180} = 1.67 \text{ A}$$

$$\text{Armature current, } I_a = I_{out} - I_{sh} = 100 - 1.67 = 98.33 \text{ A}$$

$$\text{Back e.m.f, } E_b = V_t + V_a + V_{brushes} = 300 - 98.33(0.05) = 295.08 \text{ V}$$

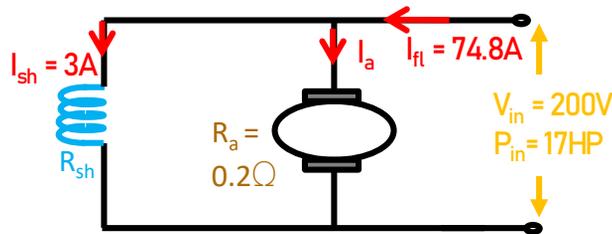
$$\text{Power develop in armature, } E_g I_a = 295.08(98.33) = 29.02 \text{ kW}$$

Example

Example 3.18

A shunt motor AT 17hp, 200V, 1150 psm, 4 poles has a conductor of 620 wave windings and an armature resistance of 0.2Ω . when it provides rated power at rated speed it will produce a line current of 74.8A and a field current of 3A. calculate flux per pole, armature torque, rotational loss and total loss.

Solution 3.18



$$\text{Armature current, } I_a = I_{fl} - I_{sh} = 74.8\text{A} - 3\text{A} = \underline{71.8\text{A}}$$

$$E_b = V_t - I_a R_a = 200 - 71.8 (0.2) = \underline{185.7\text{V}}$$

$$a = 2m \text{ (wave winding), } n = \frac{N}{60} = \frac{1150}{60} = 19.17$$

Flux per pole

$$E_b = \frac{\Phi P n Z}{a}, \quad \Phi = \frac{a E_b}{P n Z} = \frac{(2)(185.7)}{(4)(19.17)(620)} = \underline{7.8\text{mWb}}$$

Armature torque

$$T_a = \frac{E_b I_a}{2\pi n} = \frac{(185.7)(71.8)}{2\pi(19.17)} = \underline{110.75\text{ Nm}}$$

Rotor losses

$$E_b I_a = (185.7)(71.8) = \underline{13,333.3\text{ watt}}$$

$$\text{Output power, } P_{out} = 17\text{hp} \times 746\text{w} = \underline{12,682\text{ watt}}$$

$$\text{Rotor losses} = E_b I_a - P_{out} = 13,333.3 - 12,682 = \underline{651\text{ watt}}$$

Total losses

$$\text{Input power, } P_{in} = V_t I_{fl} = 200 \times 74.8 = \underline{14,960\text{ watt}}$$

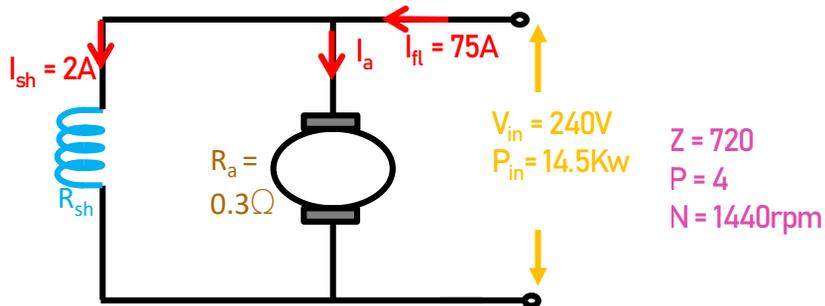
$$\text{Total losses} = P_{in} - P_{out} = 14,960 - 12,682 = \underline{2,278\text{ watt}}$$

Example

Example 3.19

A 14.5kW, 4-pole AT shunt motor contains a total of 720 conductors arranged in 2 parallel paths. This motor rotates at a speed of 1440rpm when supplied with 240V and receives 75Amperes. If the resistance of the armature is 0.3Ω and the field takes 2 Ampere, the iron and friction losses are 500W, calculate the following flux per pole produced, the Torque (torque) produced in the armature, the total loss of the motor, the electrical efficiency of the motor.

Solution 3.19



$$\text{Armature current, } I_a = I_{fl} - I_{sh} = 75\text{A} - 2\text{A} = \underline{73\text{ A}}$$

$$E_b = V_t - I_a R_a = 240\text{V} - 73(0.3) = \underline{229.1\text{ V}}$$

Flux per pole

$$E_b = \frac{\Phi P n Z}{a}, \quad \Phi = \frac{a E_b (60)}{P n Z} = \frac{(2)(229.1)(60)}{(4)(1440)(720)} = \underline{6.63\text{mWb}}$$

Armature torque

$$T_a = \frac{E_b I_a}{2\pi n} = \frac{(229.1)(73)(60)}{2\pi(1440)} = \underline{110.97\text{ Nm}}$$

Total loss

$$P_{\text{CUarmature}} = I_a^2 R_a = 73^2(0.3) = \underline{799.4\text{W}}$$

$$P_{\text{CUseries}} = I_{sh} V_t = 2(240) = \underline{480\text{W}}$$

$$P_{\text{CUtotal}} = 799.4 + 480 = \underline{1,279.35\text{W}}$$

$$P_{\text{loss total}} = P_{\text{CUtotal}} + P_{\text{iron+friction}} = 1,279.35 + 500 = \underline{1,779.35\text{W}}$$

The electrical efficiency of the motor

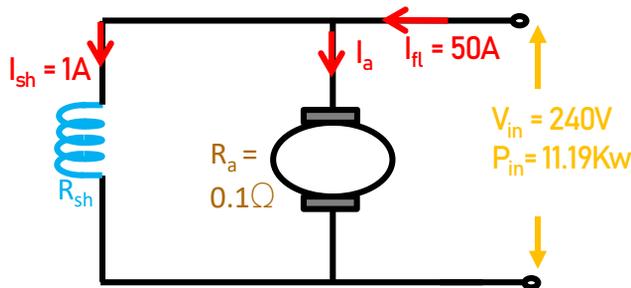
$$\% \text{ efficiency} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% = \frac{P_{\text{in}} - P_{\text{loss total}}}{P_{\text{in}}} = \frac{143.5\text{K} - 1.779\text{K}}{143.5\text{K}} = \underline{98.76\%}$$

Example

Example 3.20

A 4-pole, 240 V wave-wound shunt motor with a simplex type winding arrangement supplies a power of 11.19kW when rotating at a speed of 1000psm. The armature current and the field current in that condition are 50A and 1A respectively. If the armature contains as many as 540 conductors with a total resistance of 0.1 ohm and assuming a brush drop of 1V/brush calculate the total torque produced, T_a , the total useful torque, T_{sh} , the efficiency.

Solution 3.2 0



$$\begin{aligned}
 P &= 4 \\
 N_r &= 10 \\
 &00\text{pm} \\
 V_{\text{brush}} &= 1\text{v/brush} \\
 a &= 2m = 2z
 \end{aligned}$$

$$\text{Armature current, } I_a = I_{fl} - I_{sh} = 75\text{A} - 2\text{A} = \underline{73\text{ A}}$$

$$E_b = V_t - I_a R_a = 240\text{V} - 50\text{A} (0.1) - 2\text{V} = \underline{233\text{V}}$$

Armature torque

$$T_a = \frac{E_b I_a}{2\pi n} = \frac{(233)(50)(60)}{2\pi(1000)} = \underline{111.3\text{Nm}}$$

Shaft torque

$$T_a = \frac{P_{out}}{2\pi n} = \frac{11,190(60)}{2\pi(1000)} = \underline{106.8\text{Nm}}$$

The electrical efficiency of the motor

$$\begin{aligned}
 \% \text{ efficiency} &= \frac{P_{out}}{P_{in}} \times 100\% \\
 &= \frac{11,190}{12,240} \times 100\% \\
 &= \underline{91.4\%}
 \end{aligned}$$

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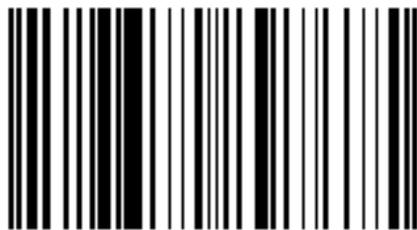
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