جمهورية العراق

وزارة التعليم العالي والبحث العلمي

كلية المأمون الجامعة

قسم هندسة تقنيات القدرة الكهربائية

DC Machine

مكائن التيار المستمر

المرحلة الثانية

المحاضرة (3)

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I. Armature Reaction

When a DC generator is loaded, a current flow through the armature conductor in the same direction as that of the induced (or generated) emf the armature conductors carrying current, produce their own magnetic field called armature field.

The effect of armature field produced by the armature current carrying conductors on the main magnetic field is known as **armature reaction**.

Let us see the effect of armature field on the main magnetic field when the generator is loaded.

Consider a bipolar generator. At no-load, no current flows through the armature conductors and the flux distribution in the armature is shown in **Fig. 1**. The vector OF_m represents the m.m.f. produced by the main field. It is observed that the Magnetic Neutral Axis (MNA), which are vertical to the main field passing through the armature, and the Geometrical Neutral Axis (GNA) coincide with each other. The brushes (B1 and B2) are always placed at MNA. Here, they are shown as touching the armature conductors directly, but in reality, they touch the commutator segments connected to these conductors.

Geometrical Neutral Axis: The line passing through the geometrically central point between the two adjacent opposite magnetic poles is called geometrical neutral axis (GNA).

Magnetic Neutral Axis: The line passing through the magnetically neutral position between the two adjacent opposite magnetic poles is called magnetic neutral axis (MNA). When a conductor (or coil) passes through these axis, no emf is induced in the conductor (or coil).

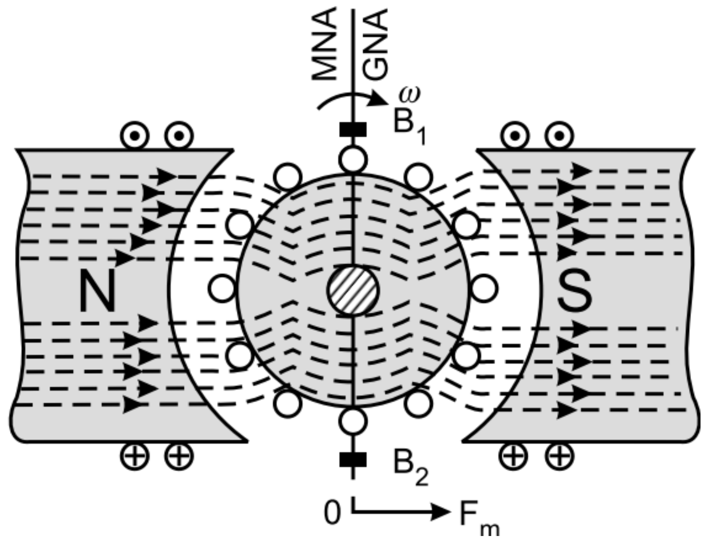

Figure 1. Main field produced by main poles.

When load is applied to the generator, current* flows through the armature conductors which sets up armature field as shown in **Fig. 2**. The vector OF_A represents the m.m.f. produced by the armature field.

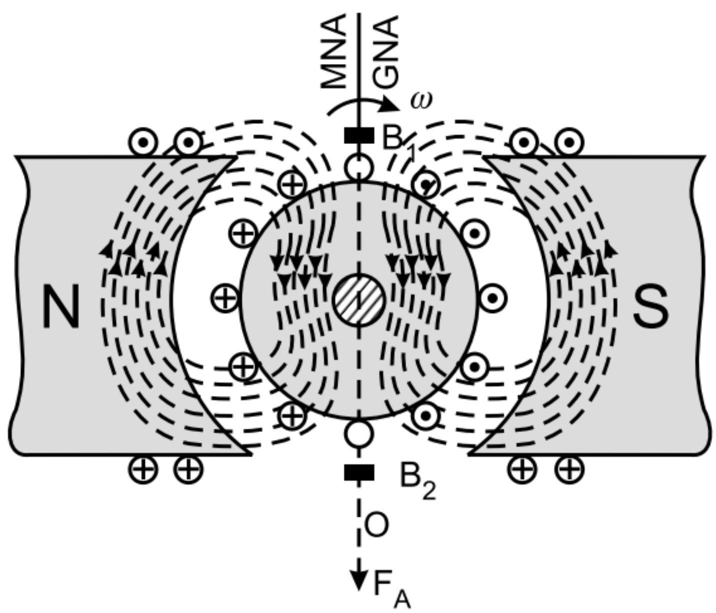

Figure 2. Field produced by armature conductors.

This armature flux interacts with the main flux and a resultant flux is set up in the armature as shown in **Fig. 3(a)**. It can be observed that the resultant flux is no longer uniform. It is concentrated (becomes stronger) at the trailing pole tips and is rare (becomes weaker) at the leading pole tips.

The resultant m.m.f. is shown by the vector OF which is the vector sum of OF_m and OF_A. Thus, the MNA are shifted to new position displaced from its original position by an angle Ɵ.

The new position of magnetic neutral axis i.e., the shifting of axis by an angle Ɵ depends upon the magnitude of load applied on the generator. Larger the load, larger will be the shift or larger will be the value of angle Ɵ. It means the shifting of MNA is not constant, it varies and depends upon the magnitude of load applied on the machine. Moreover, the shift is in the direction of rotation. (In generating action).

As per the new position of MNA, the distribution of armature flux is shown in **Fig. 3(b)**. The vector OF_{AR} represents the new position of m.m.f. producing resultant armature field. This armature field has two component (i) OF_C which is perpendicular to the main m.m.f. OF_m and produces the cross-magnetizing effect. (ii) OF_D which opposes the main m.m.f. OF_m and produces the demagnetizing effect.

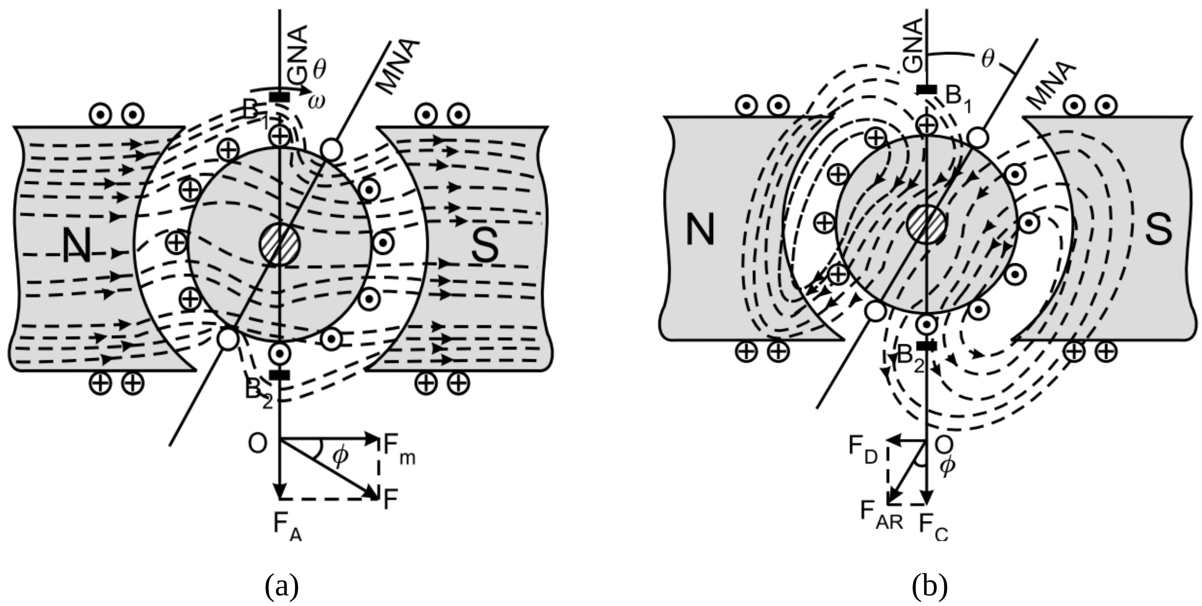

Figure 3. (a) Resultant field (b) New position of MNA.

Thus, the armature magnetic field produces.

i. Cross magnetizing effect which creates a magnetic field in between the two adjacent opposite poles where brushes are placed for commutation.
ii. Demagnetizing effect which weakens the main magnetic field and changes the flux distribution such that at trailing pole tips the flux is strengthened and at leading pole tips the flux is weakened.

Effects of armature reaction

The above two effects caused by the armature reaction **led to poor commutation** (increases sparking at the brushes or at the commutator surface) and **increases iron losses**. Let us see how it happens;

Sparking at brushes: During commutation i.e., when a coil is short circuited by the brushes through commutator segments should have zero emf induced in it. That is why the brushes are usually placed along the interpolar axis where the flux cut by the coil is zero and no emf is induced in it. But due to armature reaction the magnetic neutral axis (MNA) are shifted and the coil which undergoes commutation induces some emf causing sparking at the brushes. At heavy loads, the induced emf in the commutating coil may be so high that it may produce a spark that may spread around the commutator surface forming a ring of fire. By all means, it has to be avoided otherwise it would damage the commutator surface and brushes.

Iron losses: The flux density in the leading and trailing pole tips is changing due to change in load on the generator or due to armature reaction. This change in flux density causes more iron losses in the pole shoes.

II. Commutation

In a DC machine, one of the major functions is the delivery of current from the armature (rotating part) to the external circuit (stationary part) or vice versa. This operation is conducted with the help of brushes and a commutator.

During this operation one of the armature coil moves from the influence of one pole to the other and consequently the current in this coil is reversed. While moving from one pole to the other the coil is short circuited by the brushes through commutator segments for fraction of a second (say about 1/500 the process). This operation is called commutation.

Thus, *the process in which a coil is short circuited by the brushes through commutator segments while it passes from the influence of one pole to the other is called* ***commutation****. In this process the current in the coil is reversed.*

*The duration for which a coil remains short circuited is called **commutation period**.*

Explanation

For better understanding, consider a machine having ring winding, a part of which is shown in **Fig. 4**. Assume that the width of brush is equal to the width of commutator segment and the insulation between the segments is very thin (negligibly small). The current per conductor is I_C and the armature is rotating in such a direction, that coils are moving from left to right. Let the coil 'B' undergoes commutation. Stepwise explanation in given below:

1. As shown in **Fig. 4(a)**, the brush is in contact with commutator segment 'a' and collects current $2I_C$ coming equally from both the sides.
2. As the armature is moving, in the first step as shown in **Fig. 4(b)**, the brush contact with segment 'b' starts increasing and contact with segment 'a' starts decreasing. Consequently, the current flowing towards the brush via segment 'b' starts increasing* and through segment 'a' starts decreasing.

It may be noted that current in coil 'B' decreases from I_C to x.

3. At the next instant, as shown in **Fig. 4(c)**, the brush is at the center of both the segments 'b' and 'a' and covers half of the area of both the segments. At this instant brush is drawing equal current (I_C) from both the segments 'b' and 'a' and its total value is $2I_C$.
4. Further at the next instant, as shown in **Fig. 4(d)**, larger area of segment 'b' has come in contact with the brush than segment 'a'. Accordingly, brush

draws more current (I_C + y) from segment ‘b’ and draws smaller current (I_C – y) * from segment ‘a’.

It may be noted that current in the coil ‘B’ has reversed and starts increasing.

5. At the next (final) instant, as shown in **Fig. 4(e)**, the brush completely comes in contact with segment ‘b’ and draws equal current I_C from both the sides.

It may be noted that current in the coil ‘B’ has totally reversed and obtains its rated value I_C.

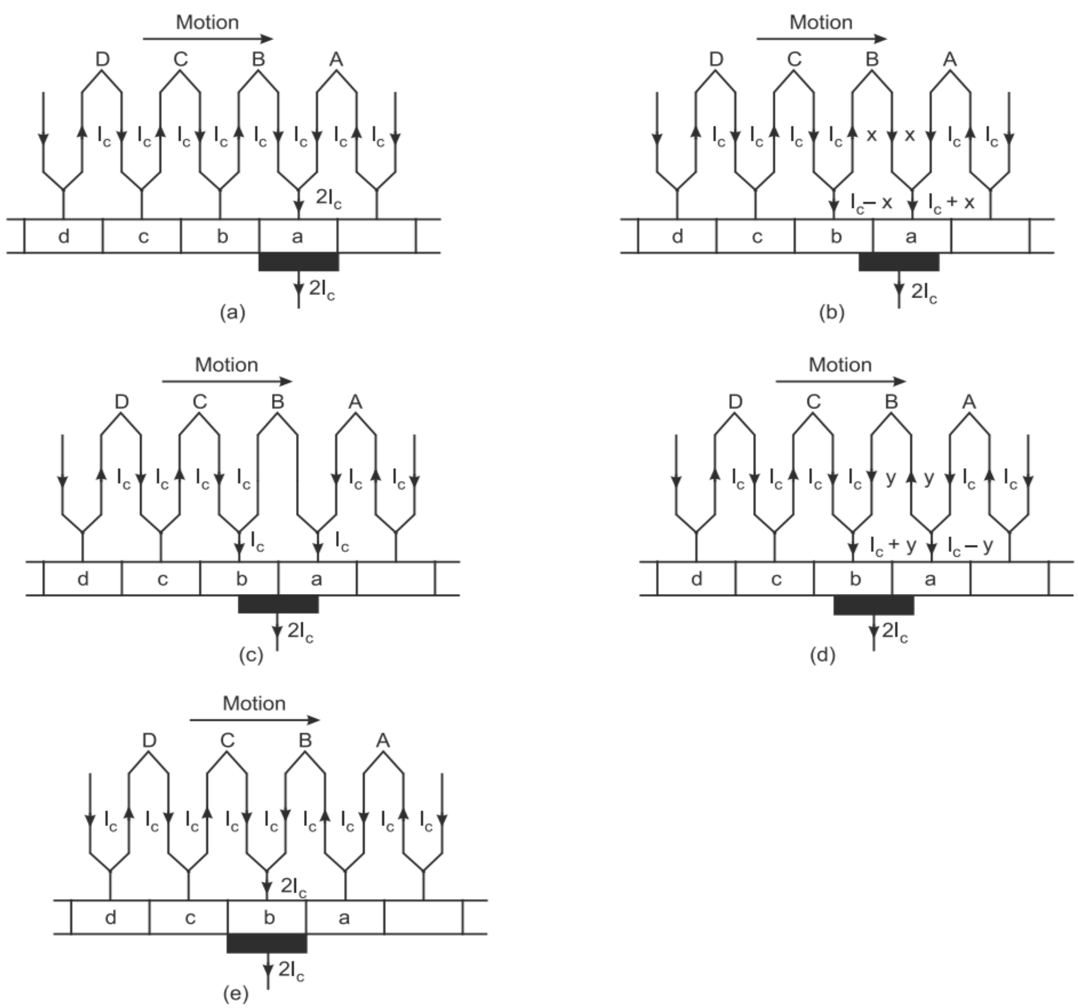

Figure 4. Commutation during brush shifts from segment ‘a’ to ‘b’.

Good Commutation

Good commutation means no sparking at the brushes and the commutator surface remains unaffected during continuous operation of DC machines. Efforts are made to obtain good commutation.

Poor Commutation (Causes of sparking at brushes)

A machine is said to have poor commutation if there is sparking at the brushes and the commutator surface gets damaged during its operation. Sparking at the brushes results in overheating at the commutator brush contact and pitting of commutator.

Poor commutation may be caused by mechanical or electrical conditions.

- The mechanical conditions for poor commutation may be due to uneven surface of the commutator, non-uniform brush pressure or vibrations of brushes in the brush holder etc. By making proper mechanical arrangements, the sparking due to mechanical conditions can be avoided (or eliminated)
- The electrical condition for poor commutation is development of emf in the coils undergoing commutation which may be due to armature reaction or inductance effect of the coil.

Methods of Improving Commutation

- **By use of high resistance brushes**. High resistance carbon brushes help the current to be reversed in the coil undergoing commutation and reduces sparking at the brushes.
- **By use of interpoles or commutating poles**. In this method, narrow poles are placed in between the main poles of a DC machine which re-energized to such an extent that they neutralize the field produced by the armature under load. Hence, no emf is induced in the coil which undergoes commutation.
- **By shifting of brushes**. In this method, brushes are shifted to the new position of MNA so that no emf be induced in the coil undergoing commutation. Thus, the sparking at the brushes is eliminated. But in this case, the position of MNA changes with the change in load on the machine and simultaneously the position of brushes cannot be changed. Hence, this method is employed in the machine which we do not have interpoles and the load on the machine remain almost constant.
- **By use of compensating winding.** In this method, a number of conductors or coils are embedded in the slots provided at the pole shoes faces and carry current of such a magnitude and direction that field produced by them neutralises the armature field and improve commutation.

III. EMF Equation

Generated e.m.f. E_g = e.m.f. generated in any one of the parallel paths (E).

Average e.m.f. generated/conductor $= \frac{d\Phi}{dt}$ volt ($\because n = 1$)

Now, flux cut/conductor in one revolution $d\Phi = dP$ Wb

No. of revolutions/second $= \frac{N}{60}$

∴ Time for one revolution, $dt = 60/N$ second Hence, according to Faraday's Laws of Electromagnetic Induction,

E.M.F. generated/conductor $= \frac{d\Phi}{dt} = \frac{\Phi PN}{60}$ volt

The number of conductors connected in series in each

parallel path = Z/A.

∴ Average induced emf across each parallel path or across the armature terminals,

$$E_g = \frac{P\phi N}{60} \times \frac{Z}{A} = \frac{PZ\phi N}{60A} \text{ volt}$$

or

$$E_g = \frac{PZ\phi n}{A} \text{ where } n \text{ in speed in r.p.s.}$$

where,

Φ is flux/pole in weber

Z is total number of armature conductors or (No. of slots × No. of conductors/slot)

P is No. of generator poles

A is No. of parallel paths in armature

N is armature rotation in revolutions per minute (r.p.m.)

n is armature rotation in revolutions per minute (r.p.s.)

E is e.m.f. induced in any parallel path in armature

For a given machine, the number of poles and number of conductors per parallel path (Z/A) are constant

∴ $E_g = K\phi n$ where $K = \frac{PZ}{A}$ is a constant or $E_g \propto \phi n$

or $E_g = K_1\phi N$ where $K_1 = \frac{PZ}{60A}$ is another constant or $E_g \propto \phi N$

or $E_g \propto \phi\omega$ where $\omega = \frac{2\pi N}{60}$ is the angular velocity in radian/second

For a simplex wave-wound generator

No. of parallel paths (A) = 2

No. of conductors (in series) in one path = Z/2

$$E_g = \frac{P\phi N}{60} \times \frac{Z}{2}$$

For a simplex lap-wound generator

No. of parallel paths (A) = 2

No. of conductors (in series) in one path = Z/P

$$E_g = \frac{P\phi N}{60} \times \frac{Z}{P} » \frac{Z\phi N}{60}$$

IV. Torque Equation

Average force on each conductor, $F = Bil$ newton

Torque due to one conductor (T) = $F\ r$

Total torque developed in the armature, $T = ZFr$

Now, current in each conductor, $i = \frac{I_a}{A}$

Average flux density, $B = \frac{\phi}{a}$

where 'a' is the X- sectional area of flux path at radius r.

Obviously, $a = \frac{2\pi rl}{P}$ m^2 $\therefore B = \frac{\phi P}{2\pi rl}$ tesla

$$T = Z \times \frac{\phi p}{2\pi rl} \times \frac{I_a}{A} \times l \times r \text{ or } T = \frac{PZ\phi I_a}{2\pi A} \quad \text{Nm}$$

Example

A six-pole machine has an armature with 90 slots and 8 conductors per slot, the flux per pole is 0.05 Wb and rms at 1000 rpm. Determine induced emf if winding is (i) lap connected (ii) wave connected.

Solution:

Here, $P = 6$; $\phi = 0.05$ Wb; $N = 1000$ rpm

No. of slots = 90 each slot with 8 conductors

$$\therefore \qquad Z = 90 \times 8 = 720$$

(*i*) *When lap connected*: $A = P = 6$

$$\text{Induced emf, } E_g = \frac{\phi ZNP}{60A} = \frac{0.05 \times 720 \times 1000 \times 6}{60 \times 6} = \mathbf{600\ V}\ (Ans.)$$

(*ii*) *When wave connected*: $A = 2$

$$\text{Induced emf, } E_g = \frac{\phi ZNP}{60A} = \frac{0.05 \times 720 \times 1000 \times 6}{60 \times 2} = \mathbf{1800\ V}\ (Ans.)$$

Example

A DC generator carries 600 conductors on its armature with lap connections. The generator has 8 poles with 0.06 Wb useful flux. What will be the induced emf at its terminals if it is rotated at 1000 rpm? Also determine the speed at which it should be driven to induce the same voltage with wave connections?

Solution:

Here, $P = 8$; $Z = 600$; $\phi = 0.06$ Wb; $N = 1000$ rpm.

$$A = P = 8 \text{ (when lap wound)}$$

$$\text{Induced emf, } E_g = \frac{\phi ZNP}{60A} = \frac{0.06 \times 600 \times 1000 \times 8}{60 \times 8} = \mathbf{600\ V}\ (Ans.)$$

when wave wound, let the speed be N′ rpm but $E_g = 600$ V

$$\text{Now, } N' = \frac{E_g \times 60A}{\phi ZP} = \frac{600 \times 60 \times 2}{0.06 \times 600 \times 8} = \mathbf{250\ rpm}\ (Ans.)$$

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Example

A six-pole lap wound armature rotating at 350 rpm is required to generate 260 V. The effective flux per pole is about 0.05 Wb. If the armature has 120 slots, determine the suitable number of conductors per slot and hence determine the actual value of flux required to generate the same voltage.

Solution:

Here, $P = 6$; $A = P = 6$; $N = 350$ rpm; $E_g = 260$ V; $\phi = 0.05$ Wb

Now, $E_g = \dfrac{\phi ZNP}{60A}$ or $260 = \dfrac{0.05 \times Z \times 350 \times 6}{60 \times 6}$

or $Z = \dfrac{260 \times 60 \times 6}{0.05 \times 350 \times 6} = \dfrac{260 \times 24}{7}$

$$\text{No. of conductors/slot} = \frac{Z}{\text{No. of slots}} = \frac{260 \times 24}{7 \times 120} = 7.43 \cong 8 \text{ (an integer)}$$

For 8 conductors/slot, $Z = 120 \times 8 = 960$

$$\text{Actual value of flux required, } \phi = \frac{E_g \times 60A}{ZNP} = \frac{260 \times 60 \times 6}{960 \times 350 \times 6} = \mathbf{0.0464\ Wb}\ (Ans.)$$

Example

The emf generated by a 4 pole DC generation is 400 V, when the armature is driven at 1200 rpm. Calculate the flux per pole if the wave wound generator has 39 slots having 16 conductors per slot.

Solution:

Induced emf, $E_g = \dfrac{\phi ZNP}{60A}$

where, $P = 4$; $E_g = 400$ V; $N = 1200$ rpm; $Z = 39 \times 16 = 624$; $A = 2$ (wave winding)

$$\therefore \quad \textit{Flux per pole, } \phi = \frac{E_g \times 60A}{ZNP} = \frac{400 \times 60 \times 2}{624 \times 1200 \times 4} = 0{\cdot}016 \text{ Wb} = \mathbf{16\ mWb}\ (Ans.)$$

Example

A four-pole generator has an induced emf of 250 V when driven at 500 rpm. The armature is lap wound and has 600 conductors. The radius of the pole shoe is 20 cm and it subtends an angle of 60°. Calculate the flux density in the air-gap if the length of pole shoe is 18 cm.

Solution:

Here, $P = 4$; $E_g = 250$ V; $N = 500$ rpm; $A = P = 4$; $Z = 600$

$$\text{Flux per pole, } \phi = \frac{E_g \times 60A}{ZNP} = \frac{250 \times 60 \times 4}{600 \times 500 \times 4} = 0.05 \text{ Wb}$$

$$\text{Pole shoe arc} = 2\pi r \times \frac{\theta}{360} = 2\pi \times 0.2 \times \frac{60}{360} = 0.21 \text{ m}$$

$$\text{Pole shoe area} = \text{Pole shoe arc} \times l = 0.21 \times 0.18 = 0.0378 \text{ m}^2$$

$$\text{Flux density in air gap} = \frac{\phi}{\text{area}} = \frac{0.05}{0.0378} = \mathbf{1.323\ tesla}\ (Ans.)$$

LECTURE 3

V. Types of DC Generators

Generators are usually classified according to the way in which their fields are excited. Generators may be divided into (a) **separately excited generators** and (b) **self-excited generators**.

a) **Separately excited generators** are those whose field magnets are energized from an independent external source of D.C. current. It is shown diagrammatically in **Fig. 5.**

b) **Self-excited generators** are those whose field magnets are energized by the current produced by the generators themselves. Due to residual magnetism, there is always present some flux in the poles. When the armature is rotated, some e.m.f. and hence some induced current is produced which is partly or fully passed through the field coils thereby strengthening the residual pole flux.

There are three types of self-excited generators named according to the manner in which their field coils (or windings) are connected to the armature.

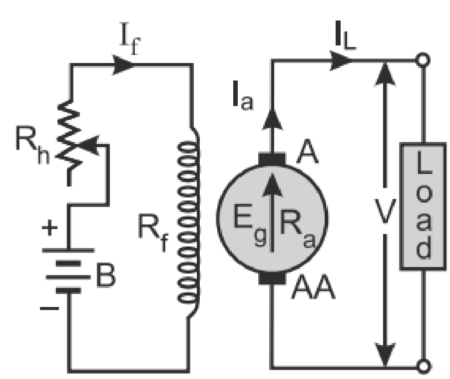


Figure 5. Circuit diagram for separately excited DC generator.

i. **Shunt wound** The field windings are connected across or in parallel with the armature conductors and have the full voltage of the generator applied across them (**Fig. 6a**).

Important relations:

Shunt field current, $I_{sh} = V/R_{sh}$

Where R_{sh} is the shunt field winding resistance. The field current I_{sh} is practically constant at all loads, therefore, the DC shunt machine is considered to be constant flux machine.

Armature current, $I_a = I_L + I_{sh}$

Terminal voltage, $V = E_g - I_a R_a$

Including brush contact drop, $V = E_g - I_a R_a - 2V_b$

Power developed = $E_g I_a$: Power output = VI_L

ii. **Series Wound** In this case, the field windings are joined in series with the armature conductors (**Fig. 6b**). As they carry full load current, they consist of relatively few turns of thick wire or strips. Such generators are rarely used except for special purposes.

Important relations:

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

Series field winding resistance = R_{se}

Terminal voltage, $V = E_g - I_a R_a - I_{se} R_{se} = E_g - I_a(R_a + R_{se})$

Including brush contact drop, $V = E_g - I_a(R_a + R_{se}) - 2V_b$

Power developed = $E_g I_a$: Power output = VI_L = VI_a

iii. **Compound Wound** It is a combination of a few series and a few shunt windings and can be either short-shunt or long-shunt as shown in **Fig. 6 (c)** and **(d)** respectively. In a compound generator, the shunt field is stronger than the series field. When series field aids the shunt field, generator is said to be commutatively compounded. On the other hand, if series field opposes the shunt field, the generator is said to be differentially compounded. Various types of DC generators have been shown separately in **Fig. 7**.

Important relations for long shunt:

Shunt field current, $I_{sh} = V/R_{sh}$

Series field current, $I_{se} = I_a = I_L + I_{sh}$

Terminal voltage, $V = E_g - I_a R_a - I_{se} R_{se} = E_g - I_a(R_a + R_{se})$

Including brush contact drop, $V = E_g - I_a(R_a + R_{se}) - \; 2V_b$

Power developed = $E_g I_a$: Power output = VI_L

Important relations for short shunt:

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

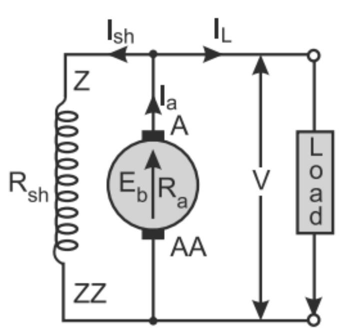
Shunt field current, $I_{sh} = \frac{V + I_L R_{se}}{R_{sh}} \; or \; \frac{E_g - I_a R_a}{R_{sh}}$

Where $I_a = I_L + I_{sh}$

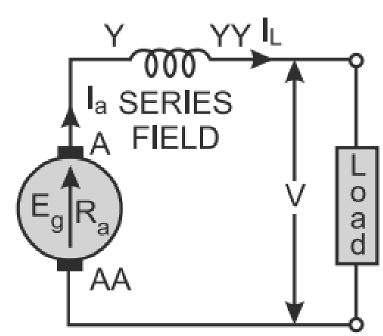
Terminal voltage, $V = E_g - I_a R_a - I_L R_{se}$

Including brush contact drop, $V = E_g - I_a R_a - I_L R_{se} - 2V_b$

Power developed = $E_g I_a$: Power output = VI_L



(a)



(b)

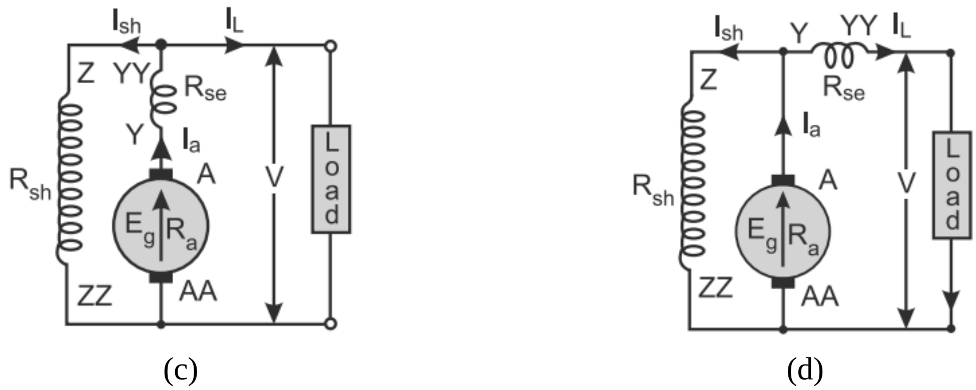


Figure 6. Circuit diagram (a) for DC shunt generator (b) for DC series generator (c) for long shunt DC compound generator (d) for short shunt DC compound generator.

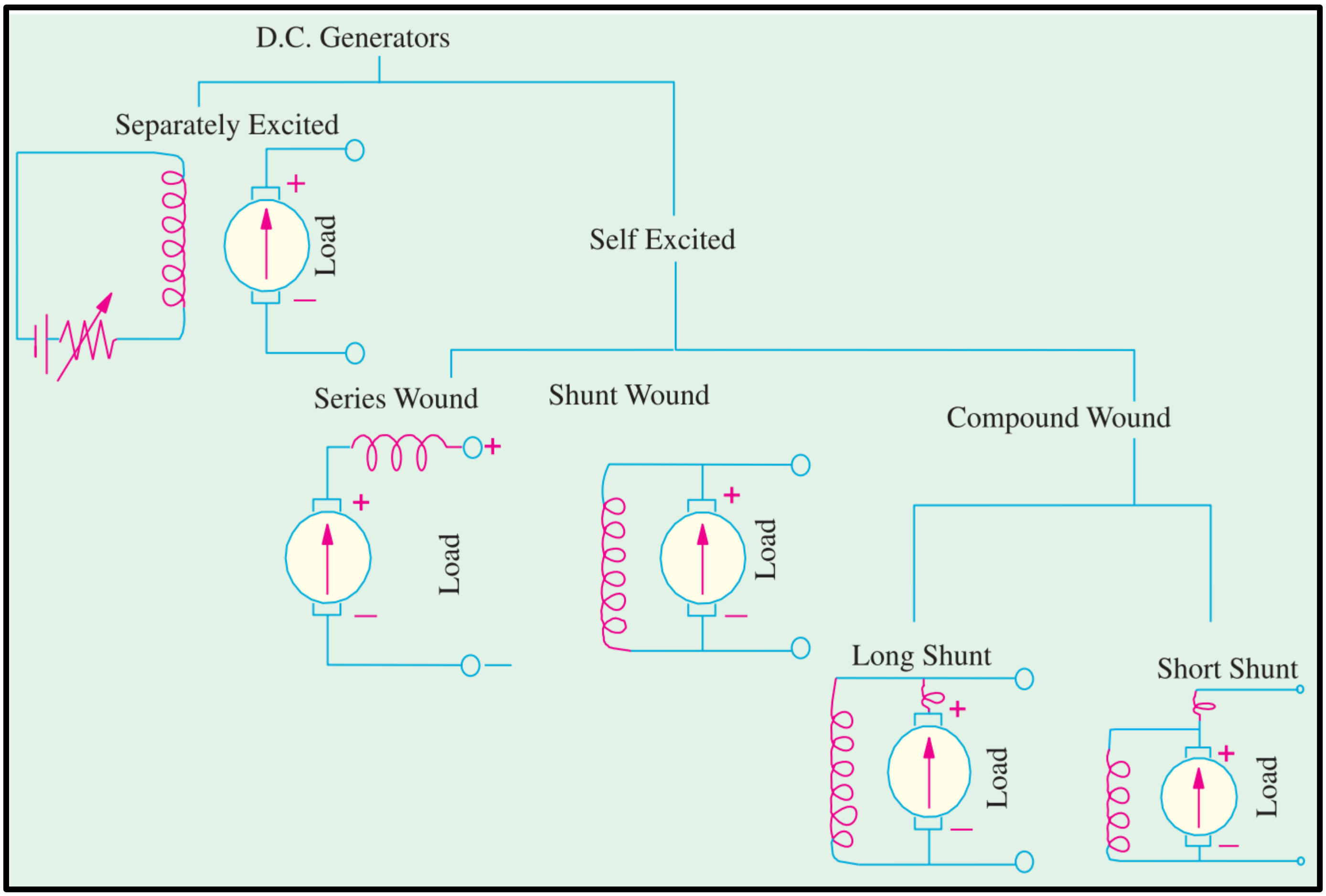


Figure 7. Various types of DC generators.

LECTURE 3

Voltage Regulation of a DC Shunt Generator

At no-load, the voltage at the terminals of a shunt generator is maximum and is called no-load generated emf. When load is applied on the generator, the terminal voltage decreases due to a drop in the armature circuit.

Generated voltage or voltage at the terminals at no-load

$$E_g = E_0 \frac{P\phi ZN}{60A}$$

At full load, the terminal voltage is $V = E_g - I_{a(fl)}R_a - V_b$

Where $I_{a(fl)}$= Full-load armature current

R_a = Armature resistance

V_b = Total voltage drop at the brushes

The rise in terminal voltage from full-load to no-load at constant speed of a DC generator is called its voltage regulation. It is expressed as a percentage of full-load terminal voltage.

$$\%\text{ Voltage regulation } = \frac{E_0 - V}{V} \times 100$$

Example

A 12 kW, six-pole DC generator develops an emf of 240 at 1500 rpm. The armature has a lap connected winding. The average flux density over the pole pitch is 1.0 T. The length and diameter of the armature is 30 cm and 25 cm respectively. Calculate flux per pole, total number of active armature conductors. Power generated in the armature and torque developed when the machine is delivering 50 A current to the load.

Solution:

Here, $P = 6$; $V = 240$ V; $N = 1500$ rpm; $A = P = 6$;

$B = 1.0$ T; $D = 0.25$ m; $l = 0.3$ m; $I_a = I_L = 50$ A

Flux per pole, $\phi = B \times \frac{\pi D}{P} \times l = 1.0 \times \frac{\pi \times 0.25}{6} \times 0.3 = \mathbf{0.0393\ Wb}$ (*Ans.*)

Now, $E_g = \frac{\phi ZNP}{60\ A}$

$\therefore$ $Z = \frac{E_g \times 60A}{\phi \times N \times P} = \frac{240 \times 60 \times 6}{0.0393 \times 1500 \times 6} = \mathbf{244}$ (*Ans.*)

Power developed in the armature, $P_g = E_g I_a = 240 \times 50 = \mathbf{12000\ W}$ (*Ans.*)

Torque developed, $T = \frac{P_g}{\omega} = \frac{P_g}{2\pi N / 60} = \frac{12000 \times 60}{2\pi \times 1500} = \mathbf{76.4\ Nm}$ (*Ans.*)

LECTURE 3

Example

A four-pole shunt generator with lap connected armature has field and armature resistance of 50 Ω and 0.1 Ω respectively. The generator is supplying a load of 2.4 kW at 100 V. Calculate the armature current, current in each conductor and generated emf.

Solution:

$$\text{Load current, } I_L = \frac{2.4 \times 1000}{100} = 24 \text{ A}$$

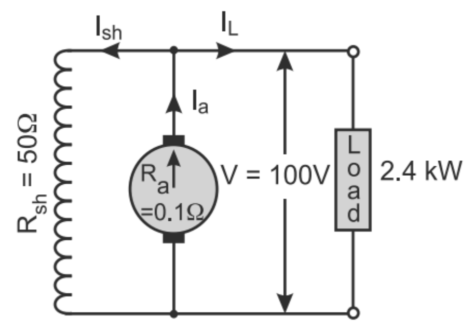
$$\text{Shunt field current; } I_{sh} = \frac{V}{R_{sh}} = \frac{100}{50} = 2\text{A}$$

$$\text{Armature current, } I_a = I_L + I_{sh} = 24 + 2 = \mathbf{26\ A}\ (Ans.)$$

$$\text{Current in each conductor, } I_c = \frac{I_a}{A} = \frac{26}{6} = \mathbf{4.33\ A}\ (Ans.)$$

$$\text{Generated emf, } E_g = V + I_a R_a$$

$$= 100 + 26 \times 0.1 = \mathbf{102.6\ V}\ (Ans.)$$



Circuit diagram

Example

A load of 20 kW at 230 V is supplied by a compound DC generator. If the series, shunt field and armature resistances are 0·05, 115 and 0.1 ohm respectively. Calculate the generated emf when the generator is connected as long shunt.

Solution:

$$\text{Load} = 20 \text{ kW} = 20 \times 10^3 \text{ W}$$

$$V = 230 \text{ V}; R_a = 0{\cdot}1\ \Omega; R_{se} = 0{\cdot}05\ \Omega; R_{sh} = 115\ \Omega$$

Line current, $$I_L = \frac{20 \times 10^3}{230} = 86 \cdot 96 \text{ A}$$

Shunt field current, $$I_{sh} = \frac{V}{R_{sh}} = \frac{230}{115} = 2\text{A}$$

Armature current, $$I_a = I_L + I_{sh} = 86{\cdot}96 + 2 = 88{\cdot}96 \text{ A}$$

Generated emf, $$E_g = V + I_a R_a + I_a R_{se}$$

$$= 230 + 88{\cdot}96 \times 0{\cdot}1 + 88{\cdot}96 \times 0{\cdot}05$$

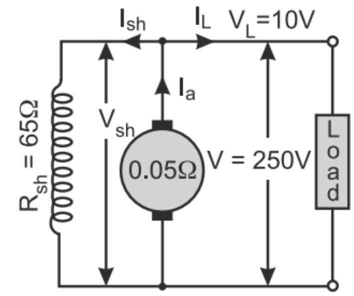
$$= \mathbf{243{\cdot}3\ V}\ (Ans.)$$

Example

A four-pole DC shunt generator with a wave wound armature having 390 conductors has to supply a load of 500 lamps each of 100 W at 250 V. Allowing 10 V for the voltage drop in the connecting leads between the generator and the load and brush drop of 2 V. Calculate the speed at which the generator should be driven. The flux per pole is 30 m Wb and the value of $R_a = 0{\cdot}05\ \Omega$ *and* $R_{sh} = 65\ \Omega$.

Solution:

The conventional circuit diagram of the DC shunt generator is shown in Fig. 4.64.



Circuit diagram

$$\text{Total load} = 500 \times 100 \text{ W}$$

$$I_L = \frac{500 \times 100}{250} = 200 \text{ A}$$

Voltage drip in leads, $V_L = 10$ V

Voltage across shunt field winding,

$$V_{sh} = V + V_L = 250 + 10 = 260 \text{ V}$$

$$I_{sh} = V_{sh}/R_{sh} = 260/65 = 4 \text{ A}$$

$$I_a = I_L + I_{sh} = 200 + 4 = 204 \text{ A}$$

$$\text{Armature drop} = I_a R_a = 204 \times 0{\cdot}05 = 10{\cdot}2 \text{ V}$$

Total brush drop, $2\upsilon_b = 2$ V

Generated emf, $E_g = V + I_a R_a + V_L + 2\upsilon_b$

$$= 250 + 10{\cdot}2 + 10 + 2 = 272{\cdot}2 \text{ V}$$

Now, $$E_g = \frac{P\phi NZ}{60\,A} \text{ or } 272{\cdot}2 = \frac{4 \times 30 \times 10^{-3} \times N \times 390}{60 \times 2}$$

or $$N = \frac{272 \cdot 2 \times 60 \times 2}{4 \times 30 \times 10^{-3} \times 390} = \mathbf{698\ rpm}\ (Ans.)$$

VI. Characteristics of DC Generators

1. **No-load characteristics**. It is also known as magnetic characteristics or open-circuit characteristics (O.C.C.). It shows the relation between the no-load generated emf in the armature (E_0) and the field current (i.e., exciting current) I_f, at a specified speed.

To obtain this characteristic, proceed as follows: Open the field winding of the generator and connect it to a separate DC source through a rheostat as shown in **Fig. 8**. Connect an ammeter in the field circuit and a voltmeter across the armature. Reduce the field current to zero and run the armature at a specified speed. Get the reading of voltmeter and mark the point 'a' on the graph. To plot the characteristics, take field current I_f along X-axis and no-load generated emf (E_0) along Y-axis. Increase the field current in steps and get the corresponding voltmeter readings. The curve thus obtained (shown in **Fig. 9**) shows the no-load characteristics or open circuit characteristics (O.C.C.) of the generator.

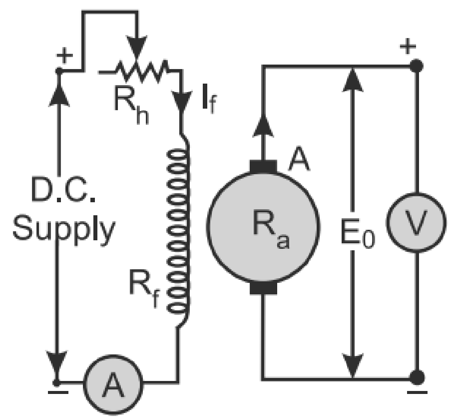


Figure 8. Circuit diagram.

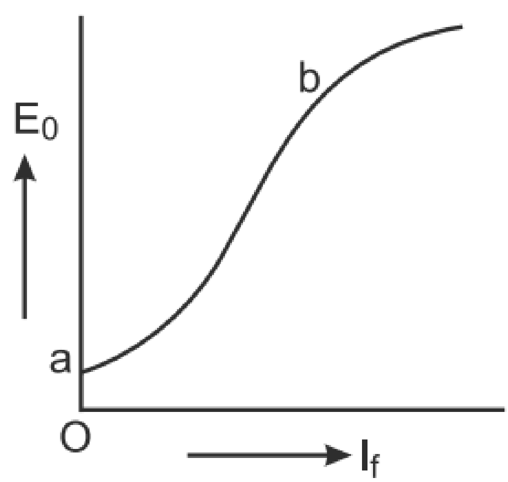


Figure 9. No-load characteristics.

Analysis of the curve

1) The curve starts from point ‘a’ instead of ‘O’ when the field current is zero. It is because of the residual magnetism of the poles.
2) The initial part of the curve (ab) is almost a straight line because at this stage the magnetic material is unsaturated, and it has high permeability.
3) After point ‘b’ the curve bends and the generated emf (E_0) becomes almost constant. It is because after point ‘b’, the poles (magnetic material) start getting saturated.

2. **External characteristics**. It is also called the performance characteristics. It shows the relation between the terminal voltage (V) and the load current I_L.

I. *External characteristics of Shunt Generator*

To obtain this characteristic, proceed as follows: Connect an ammeter A1 and rheostat in the field circuit and an ammeter A2 and voltmeter V on the load side as shown in **Fig. 10**. Apply a variable load across the terminals. At the start switch off the load and run the generator at rated speed. No-load emf (generated voltage E_g) will appear across the voltmeter. Then switch on the load through switch S and increase the load gradually keeping field current (ammeter reading A1) constant with the help of rheostat R_h. The curve so obtained is shown in **Fig. 11**.

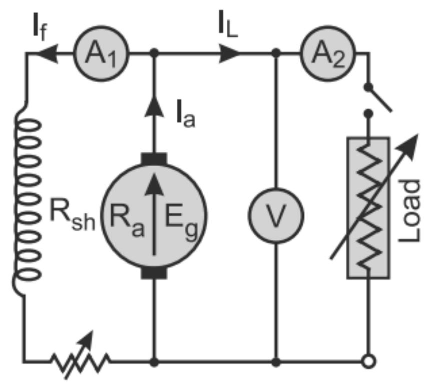


Figure 10. Circuit diagram.

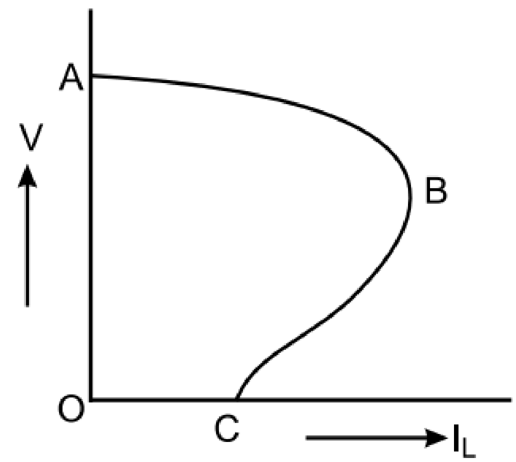


Figure 11. Curve between V and I_L

Analysis of the curve

1) At no-load, the voltage across the terminals is maximum and is equal to generated emf E_g.
2) As the load is increased gradually, the load current I_L increases but the terminal voltage decreases. The decrease in voltage is because of the following reasons:
   - ♦ Due to increase in voltage drop in the armature resistance $(I_a R_a)$
   - ♦ Due to armature reaction, when load current or armature current I_a increases, the demagnetizing effect of the armature field increases on the main field which reduced the induced emf Consequently the terminal voltage decreases.

- ♦ The drop in terminal voltage further causes decreases in field current. This will, in turn, causes the decrease in induced emf which reflects the drop in terminal voltage. However, the field current can be kept constant by adjusting the rheostat connected in the field circuit.

3) During the initial portion of curve AB, the tendency of the voltage drop due to armature resistance is more than armature reaction.
4) At point B these two effects neutralize each other.
5) After point B, armature reaction dominates, and the curve turns back (BC portion of the curve).
6) The point C at which the external characteristic cuts the current axis corresponds to a gradual short circuit.

II. External characteristics of Series Generator

In this generator, the field winding is connected in series with the armature and load. Therefore, full armature current I_a flows through it. When load increases, I_a increases which increases flux and consequently generated emf is also increased. This correspondingly increases the terminal voltage V. Thus, a series generator has a rising characteristic (curve OA) as shown in **Fig. 12**. However, at higher loads, the terminal voltage begins to reduce because of the excessive demagnetizing effects of armature reaction. Ultimately, the terminal voltage reduces to zero at load current OB as shown in **Fig. 12**.

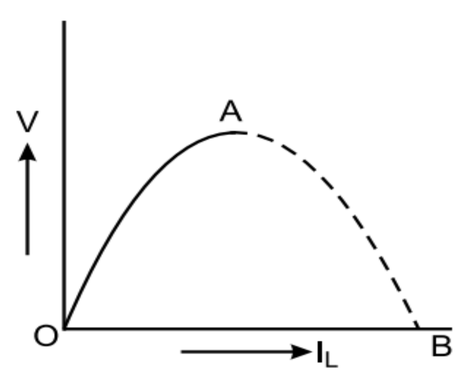


Figure 12. Curve between V and I_L.

LECTURE 3

3. **Internal Characteristics.** It is also known as total characteristics. It gives the relation between the emf actually induced in the armature (E_g) and the armature current I_a.

VII. Losses in a DC Generator

While conversion of mechanical energy into electrical energy, a part of energy dissipated in the form of heat in surrounding air is called losses in the generator.

These losses affect the efficiency of the generator. A reduction in these losses leads to higher efficiency. Thus, the major objective in the design of a DC machine is the reduction of these losses. The various losses occurring in a DC machine can be sub-divided as:

1. **Copper losses**. The various windings of the DC machine, made of copper, have some resistance. When current flows through them, there is power loss proportional to the square of their respective currents. These power losses are called copper losses.

In general, the various copper losses in a DC machine are:

i. Armature copper loss = ${I_a}^2 R_a$
ii. Shunt field copper loss = ${I_{sh}}^2 R_{sh}$
iii. Series field copper loss = ${I_{se}}^2 R_{se}$
iv. Brush contact loss = ${I_a}^2 R_b$

The brush contact drop is generally included in armature copper losses.

2. **Iron losses.** The losses which occur in the iron parts of a DC generator are known as iron losses or core losses or magnetic loss. These losses consist of the following:

   i. *Hysteresis loss*. Whenever a magnetic material is subjected to reversal of magnetic flux, this loss occurs. It is due to the retentivity property of the material. It occurs in the rotating armature. To minimize this loss, the armature core is made of silicon steel which has low hysteresis constant.

   ii. *Eddy current loss*. When flux linking with the magnetic material changes (or flux is cut by the magnetic material) an emf is induced in it which circulates eddy currents through it. These eddy currents produce eddy current loss in the form of heat. A major part of this loss occurs in the armature core. To minimize this loss, the armature core is laminated into thin sheets (0.3 to 0.5 mm) since this loss is directly proportional to the square thickness of the laminations.

3. **Mechanical losses.** As the armature of a DC machine is a rotating part, some power is required to overcome:

   i. Air friction of rotating armature (windage loss)

   ii. Friction at the bearing and friction between brushes and commutator (friction loss).

   These losses are known as mechanical losses. To reduce these losses proper lubrication is done at the bearings.

VIII. Constant and Variable Losses

The losses in a DC generator may also be sub-divided into:

1. **Constant losses.** The losses in a DC machine which remain the same at all loads are called constant losses. The constant losses in a DC machine are: (i) Iron losses; (ii) Mechanical losses; (iii) Shunt field copper losses.
2. Variable losses. The losses in DC machines which vary with load are called variable losses. The variable losses in a DC machine are: (i) Armature copper loss; (ii) Series field copper loss.

The sum of the iron losses and mechanical losses in a DC machine are known as **stray losses.**

Stray losses = Iron losses + Mechanical losses.

IX. Power Flow Diagram

The mechanical power ($\omega\ T_m$) is supplied to the generator which is converted into electrical power ($V\ I_L$). During conversion, various losses occur in the machine. The power flow diagram for a DC generator is shown in **Fig. 13**.

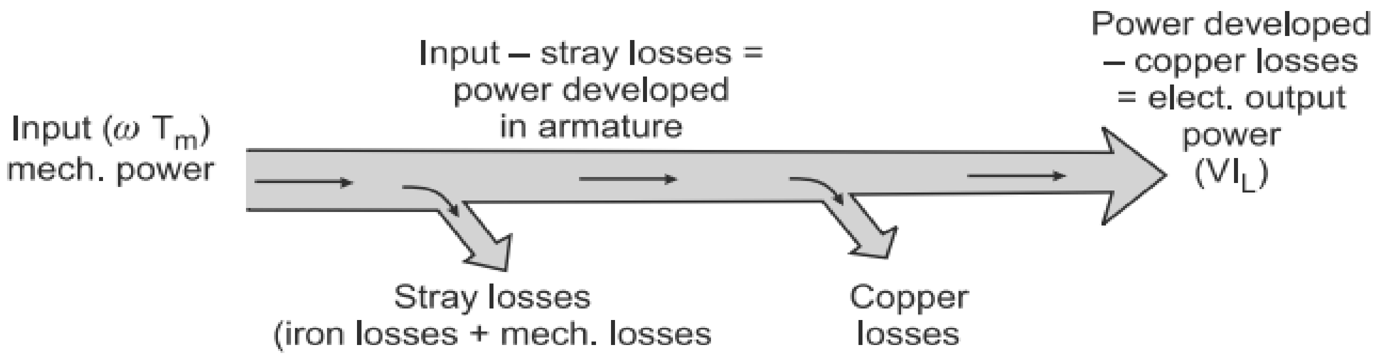


Figure 13. Power flow diagram of a DC generator.

X. Efficiency of a DC Generator

The ratio of output power to the input power of a DC generator is called its *efficiency*.

Efficiency, $\eta = \frac{Output}{Input} * 100\%$

where, Power output = $V\, I_L$ watt;

Power input = Power output + Variable losses + Constant losses

Since the shunt field current I_{sh} is very small as compared to line current, therefore, $I_L \cong I_a$(neglecting I_{sh})

Variable losses = ${I_L}^2 R_a$

Constant losses = P_C

Then, power output = $V\, I_L + {I_L}^2 R_a + P_C$

$$\boldsymbol{\eta = \frac{V\, I_L}{V\, I_L + {I_L}^2 R_a + P_C}}$$

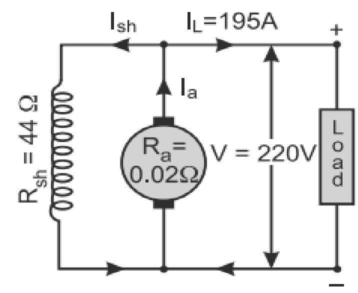
Now, efficiency will be maximum when the line current is such that constant loss is equal to the variable loss. $I_L = \sqrt{\frac{P_C}{R_a}}$

Example

A shunt generator supplies 195 A at 220 V. Armature resistance is 0.02 ohm, shunt field resistance is 44 ohm. If the iron and friction losses amount to 1600 watt, find (i) emf generated; (ii) copper losses;

Solution:

The conventional circuit is shown



Circuit diagram

Shunt field current,

$$I_{sh} = \frac{V}{R_{sh}} = \frac{220}{44} = 5\text{A}$$

Armature current, $I_a = I_L + I_{sh} = 195 + 5 = 200$ A

Generated or induced emf,

$$E_g = V + I_aR_a = 220 + 200 \times 0.02 = \mathbf{224\ V}\ (Ans.)$$

Armature copper loss;

$$= I_a^2\, R_a = (200)^2 \times 0.02 = 800\ \ \text{W}$$

$$\text{Shunt field copper loss} = I_{sh}^2\ R_{sh} = (5)^2 \times 44 = 1100\,\text{W}$$

$$\text{Total copper losses} = 800 + 1100 = \mathbf{1900\ W}\ (Ans.)$$

$$\text{Output power} = VI_L = 220 \times 195 = 42900\ \text{W}$$

$$\text{Input power} = 42900 + 1600 + 1900 = 46400\ \text{W}$$

Example

A DC generator is connected to a 220 V DC mains. The current delivered by the generator to the mains is 100 A. The armature resistance is 0.1 ohm. The generator is driven at a speed of 500 rpm Calculate (i) the induced emf (ii) the electromagnetic torque (iii) the mechanical power input to the armature neglecting iron, winding and friction losses, (iv) Electrical power output from the armature, (v) armature copper loss.

Solution:

(*i*) The induced emf, $E_g = V + I_aR_a = 220 + 0.1 \times 100 = \mathbf{230\ V}$ (*Ans.*)

(*ii*) Using the relation, $\omega T = E_gI_a$

Electromagnetic torque, $$T = \frac{E_gI_a}{\omega} = \frac{E_gI_a}{2\pi N} \times 60 \qquad \left[\because\ \omega = \frac{2\pi N}{60}\right]$$

$$= \frac{230 \times 100 \times 60}{2\pi \times 500} = \mathbf{439.27\ Nm}\ (Ans.)$$

(*iii*) Neglecting iron, winding and friction losses,

Input to armature $= \omega T$ (or E_gI_a)

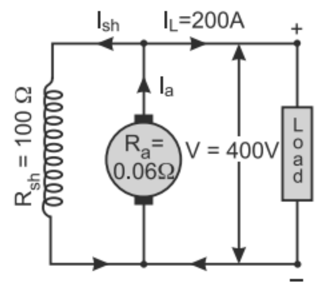
$$= \frac{2\pi\ NT}{60} = \frac{2\pi \times 500 \times 439.27}{60} = \mathbf{23000\ W}\ (Ans.)$$

(*iv*) Electrical power output = $VI_a = 220 \times 100 = \mathbf{22000\ W}$ (*Ans.*)

(*v*) Armature copper losses = $I_a^2 R_a = (100)^2 \times 0.1 = \mathbf{1000\ W}$ (*Ans.*)

Example

A 400 V shunt generator has full-load current of 200 A. Its armature resistance is 0.06 ohm, field resistance is 100 ohm and the stray losses are 2000 watt. Find the h.p. of prime-mover when it is delivering full load, and find the load for which the efficiency of the generator is maximum.



Circuit diagram

Solution:

The conventional circuit is shown

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{400}{100} = 4\text{A}$$

$$\text{Armature current, } I_a = I_L + I_{sh} = 200 + 4 = 204 \text{ A}$$

$$\text{Armature copper loss; } = I_a^2 R_a = (204)^2 \times 0.06 = 2497 \text{ W}$$

$$\text{Shunt field copper loss } = I_{sh}^2 R_{sh} = (4)^2 \times 100 = 1600 \text{ W}$$

$$\text{Total losses} = 2497 + 1600 + 2000 = 6097 \text{ W}$$

$$\text{Output power} = VI_L = 400 \times 200 = 80000 \text{ W}$$

$$\text{Input power} = \text{Output power} + \text{losses}$$

$$= 80000 + 6097 = 86097 \text{ W}$$

$$\text{Horse power of prime-mover} = \frac{\text{Input power}}{735.5} = \frac{86097}{735.5} = \mathbf{17.06\ H.P.}\ (Ans.)$$

Constant losses = stray losses + shunt field copper loss = 2000 + 1600 = 3600 W

Condition for maximum efficiency is,

Variable losses = constant losses.

Let, I_L' be the load current at which the efficiency is maximum and armature current is I_a'

$$\therefore \quad I_a'^2 R_a = 3600 \quad \text{or} \quad I_a' = \sqrt{\frac{3600}{0.06}} = 245 \text{ A}$$

Load current, $I_L' = I_a' - I_{sh} = 245 - 4 = 241$ A

Load for which the efficiency is maximum = $I_L'V = 241 \times 400 = \mathbf{96.4\ kW}$ (*Ans.*)

XI. Applications of DC Generators

Depending upon the characteristics of various types of DC generators, their important applications are given below:

1. **Separately excited DC generators**. Although, these generators are more costly than self-excited generators as they require a separate source for their field excitation. But their response to the change in field resistance is quicker and more precise. Therefore, these are employed where quick and definite response to control is important such as Ward–Leonard System of speed control.
2. **Shunt-wound DC generators**. As they provide constant terminal voltage, they are best suited for battery charging. Along with field regulators, they are also used for light and power supply purposes.
3. **Series-wound DC generators.** These generators have very few applications. Their best application is in the DC locomotives, where they supply field current for regenerative braking. They are also employed in series arc lighting. Another application of these generators is as series boosters for increasing DC voltage across the feeders.