Chapter 2

DC Machines

3.1 Introduction

Converters that are used to continuously translate electrical input to mechanical output or vice versa are called *electric machines.* The process of translation is known as *electromechanical energy conversion.* An electric machine is therefore a link between an electrical system and a mechanical system. In these machines the conversion is reversible. *If the conversion is from mechanical to electrical energy, the machine is said to act as a* ***generator****. If the conversion is from electrical to mechanical energy, the machine is said to act as a* ***motor****.* These two effects are shown in Fig.3.21. In these machines, conversion of energy from electrical to mechanical form or vice versa results from the following two electromagnetic phenomena:

١. *When a conductor moves in a magnetic field, voltage is induced in the conductor. (**Generator action**)*

٢. *When a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. (**Motor action**)*

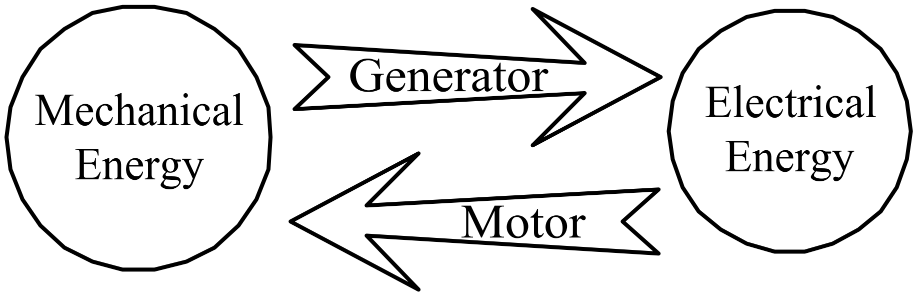


Fig.3.1 The Energy directions in generator and motor actions.

These two effects occur simultaneously whenever energy conversion takes place from electrical to mechanical or vice versa. In *motoring action*, the electrical system makes current flow through conductors that are placed in the magnetic field. A force is produced on each conductor. If the conductors are placed on a structure free to rotate, an electromagnetic torque will be produced, tending to make the rotating structure rotate at some speed. If the conductors rotate in a magnetic field, a voltage will also be induced in each conductor. *In generating action*, the process is reversed. In this case, the rotating structure, the rotor, is driven by a prime mover (such as a steam turbine or a diesel engine). A voltage will be induced in the conductors that are rotating with the rotor. If an electrical load is connected to the winding formed by these conductors, a current i will flow, delivering electrical power to the load. Moreover, the current flowing through the conductor will interact with the magnetic field to produce a reaction torque, which will tend to oppose the torque applied by the prime mover.

Note that in both motor and generator actions, the coupling magnetic field is involved in producing a torque and an induced voltage.

3.2 Induced Voltage

An expression can be derived for the voltage induced in a conductor moving in a magnetic field. As shown in Fig.3.2a, if a conductor of length *l* moves at a linear speed *v* in a magnetic field *B,* the induced voltage in the conductor can be obtained with the help of fraday's law as shown in the following equation:

$$e = Blv \tag{3.1}$$

where *B, l*, and *v* are mutually perpendicular. The polarity (Direction) of the induced voltage can be determined from the so-called *Fleming's Right-Hand Rule* as explained in the previous chapter. The direction of this force is shown in Fig.3.2(b).

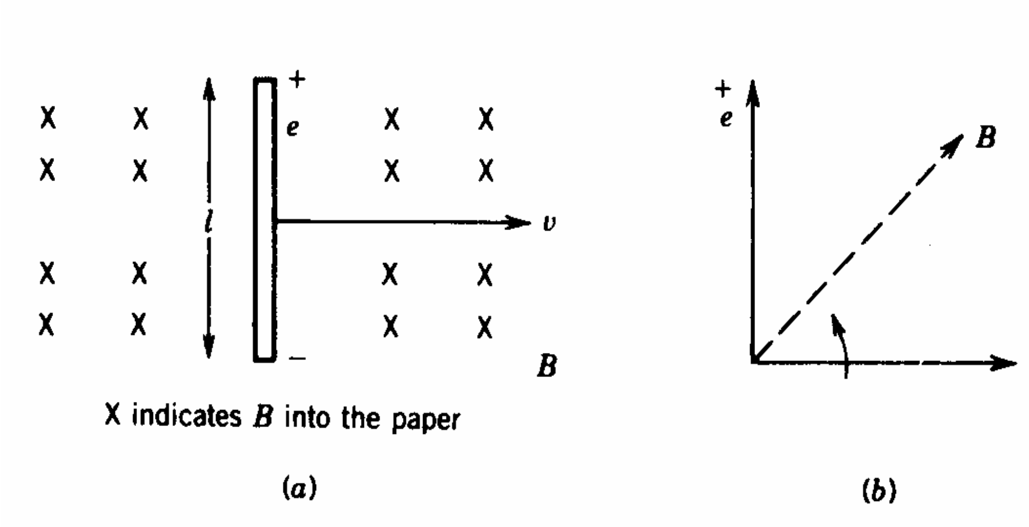


Fig.3.2 Motional voltage , (a) Conductor moving in the magnetic field. (b) Right hand screw rule.

Fleming's Right-Hand Rule

"Hold out your right hand with forefinger, second finger, and thumb at right angles to one another. If the forefinger represents the direction of the field, and the thumb represents the direction of the motion then, the second finger represents the direction of the induced emf in the coil".

3.3 Electromagnetic Force, *f*

For the current-carrying conductor shown in Fig.3.3(a), the force (known as *Lorentz force*) produced on the conductor can be determined from the following equation:

$$f = Bli \qquad (3.2)$$

where B, l, and i are mutually perpendicular. The direction of the force can be determined by using the *Fleming's Left Hand Rule or right-hand screw rule* as explaind in the previous chapter and are stated in the following. The direction of the force is illustrated in Fig.3.3(b).

Fleming's Left Hand Rule:

"*Hold out your left hand with forefinger, second finger and thumb at right angles to one another. If the forefinger represents the direction of the field, and the second finger that of the current, then thumb gives the direction of the motion or force*."

Right-Hand Screw Rule:

Turn the current vector i toward the flux vector B. If a screw is turned in the same way, the direction in which the screw will move represents the direction of the force f.

Note that in both cases (i.e., determining the polarity of the induced voltage and determining the direction of the force) the moving quantities (v and i) are turned toward B to obtain the screw movement.

Equations (3.1) and (3.2) can be used to determine the induced voltage and the electromagnetic force or torque in an electric machine. There are, of course, other methods by which these quantities *(e* and *f)* can be determined.

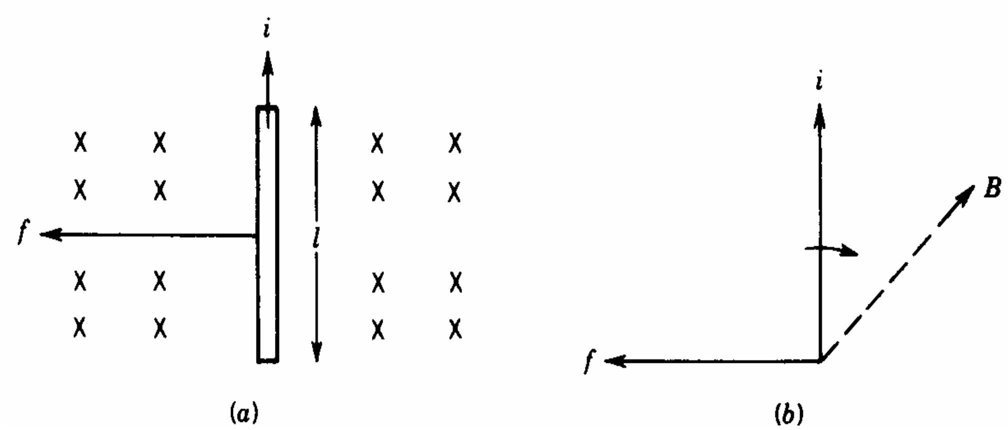


Fig.3.3 Electromagnetic force. (a) Current-carrying conductor moving in a magnetic field. (b) Force direction.

3.4 Simple Loop Generator

In Fig.3.4 is shown a single turn rectangular copper coil **ABCD** moving about its own axis, a magnetic field provided by either permanent magnets or electromagnets. The two ends of the coil are joined to two slip-rings or discs *a* and *b* which are insulated from each other and from the central shaft. Two collecting brushes (of carbon or copper) press against the slip rings. Their function is to collect the current induced in the coil and to convey it to the external load resistance *R*.

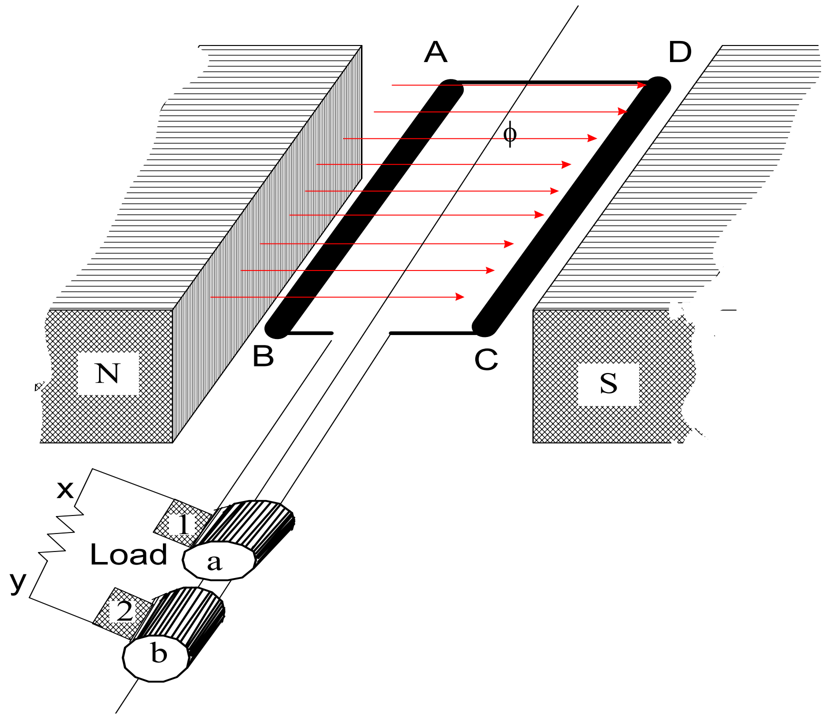
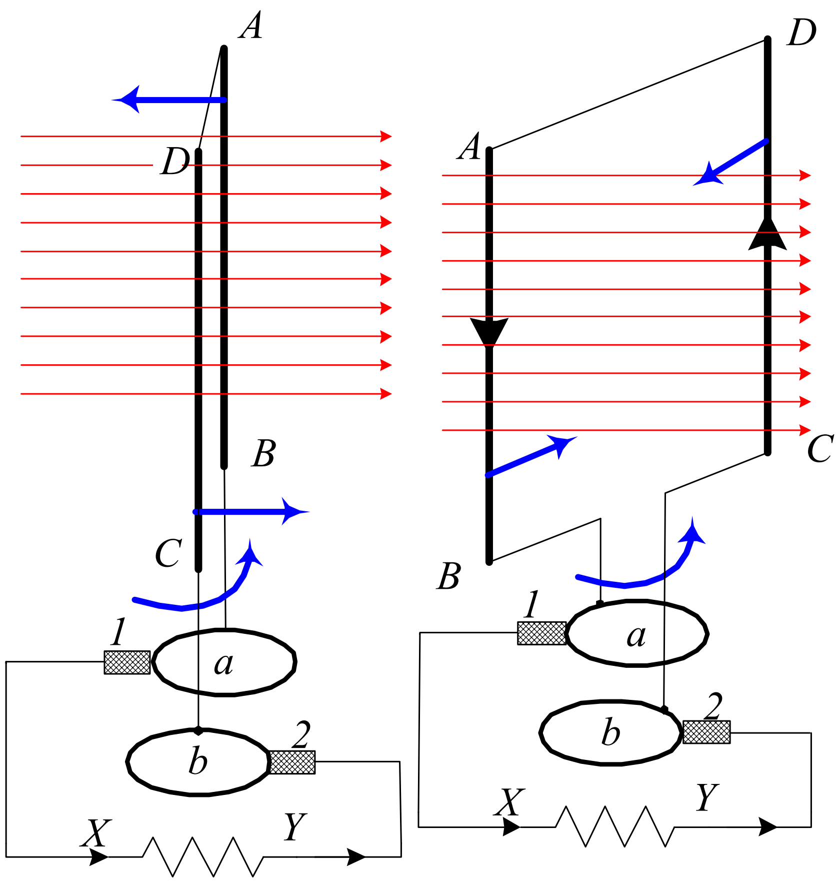


Fig.3.4 Simple loop generator.

3.4.1 Working Theory:

Imagine the coil to be rotating in clockwise direction (Fig:3.5). As the coil assumes successive positions in the field, the flux linktd with it changes. Hence, an *EMF* is induced in it which is proportional to the rate of change of flux linkages $(e = -N\frac{d\phi}{dt})$.

When the plane of the coil is at right angles to the lines of flux as shown in Fig.3.5 (a), then, the direction of velocity of both sides of the coil is parallel to the direction of the field lines so, there is no cutting for the field lines. Then flux linkages with the coil is minimum. Hence; there is no inducxd *EMF* in the coil. Let us take this no *emf* on vertical position of the coil as the starting position. The angle of rotation or time will be measured from this position so we can determine the first point (angle 0^{o}) of Fig.3.6.



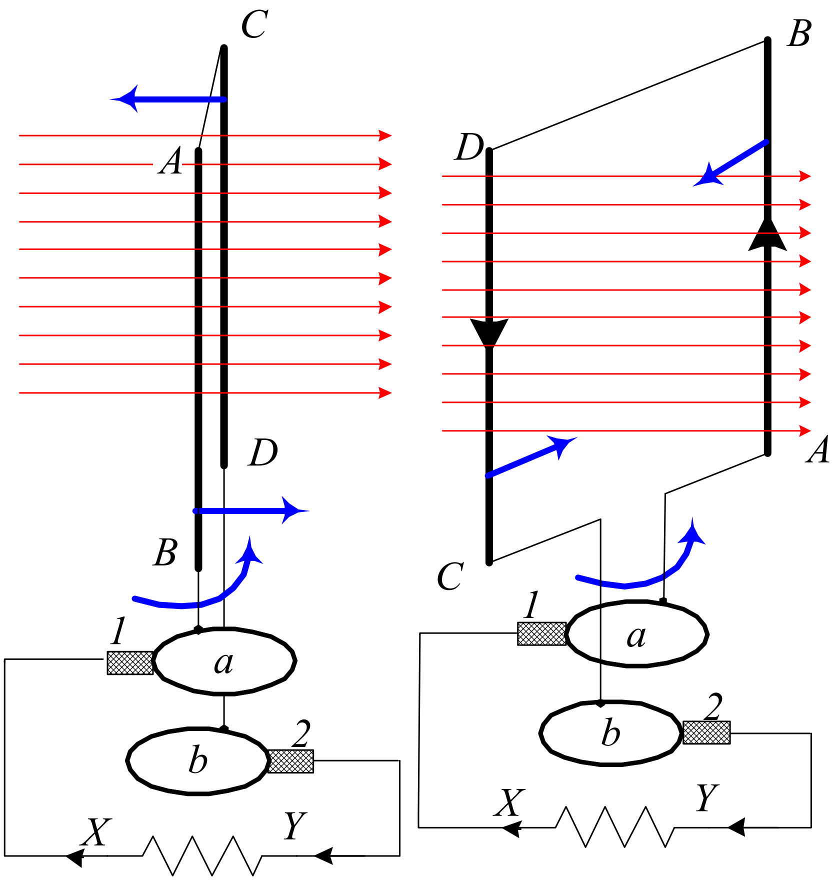


Fig.3.5

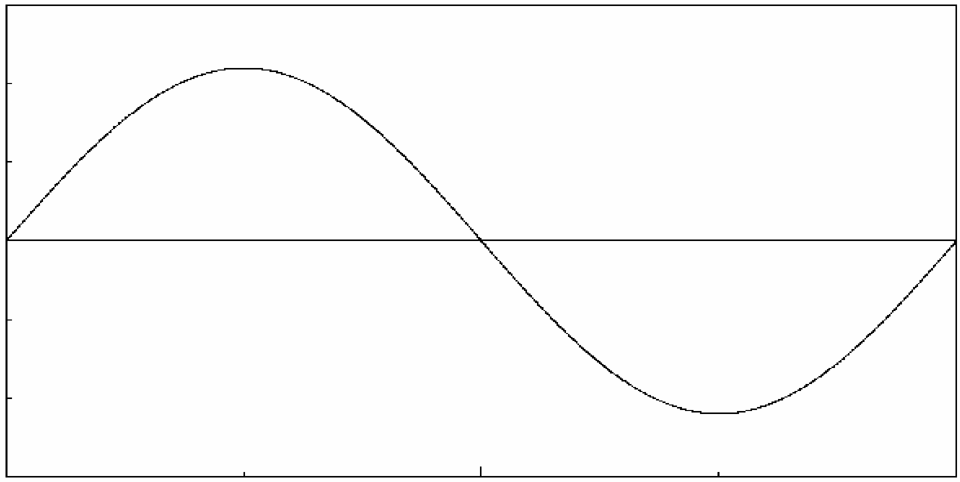


Fig.3.6

As the coil continues rotating further, the rate of change of flux linkages (and hence induced *EMF* in it) increases, till position 2, Fig.3.5 (b) is reached at 90 degrees. Here the coil plane is horizontal i.e. parallel to the lines of flux. As seen, the *rate of change* of flux *linkages is maximum.* Hence, maximum *EMF* is induced in the coil as shown in Fig.3.6 at 90 degrees and the direction of current flow is **ABXYCD as shown in Fig.3.5 (b)**.

In the next quarter revolution *i.e.* from 90^o *to* 180^o, the rate of change of flux linkages *decreases.* Hence, the induced *EMF* decreases gradually till in position 4 Fig.3.5(c) of the coil, it is reduced to zero value and the direction of current flow is **ABXYCD as shown in Fig.3.5 (b)**.

Note that:

The direction of this induced *EMF* can be found by applying *Fleming's Right hand rule. So,* the current through the load resistance *R* flows from **X** to **Y** during the first half revolution of the coil.

In the next half revolution *i.e.* from 180 to 360 degrees, the variations in the magnitude of *EMF* are similar to those in the first half revolution but it will be found that the direction of the induced current is from **D** to **C** and **B** to **A**. Hence, the path of current flow is along **DCYXBA** which is just the reverse of the previous direction of flow. Therefore, we find that the current the resistive load, R which we obtain from such a simple generator reverses its direction after every half revolution as shown in Fig.3.5 and Fig.3.6. Such a current undergoing periodic reversals is known as alternating current. It is, obviously, different from a direct current which continuously flows in one and the same direction which we need to generate from the DC generator. So, we sould make some modification to get unidirection current in the load which will be explained soon. It should be noted that alternating current not only reverses its direction, it does not even keep its magnitude constant while flowing in any one direction. The two halfcycles may be called positive and negative half cycles respectively (Fig.3.6).

For making the flow of current unidirectional in the *external* circuit, the slip rings are replaced by split rings which shown in Fig.3.7. The splitrings are made out of a conducting cylinder which is cut into two halves or segments insulated from each other by a thin sheet of mica or some other insulating material. As before, the coil ends are joined to these segments on which rest the carbon or copper brushes. In the practical genertor which has more than two poles and more than one coil the split rings has not just two halves but has many parts as shown in Fig.3.7 (b).

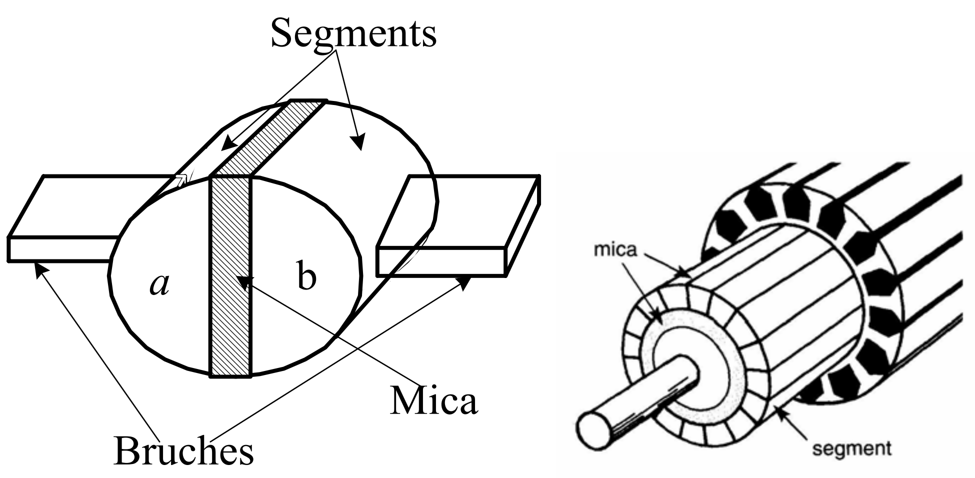


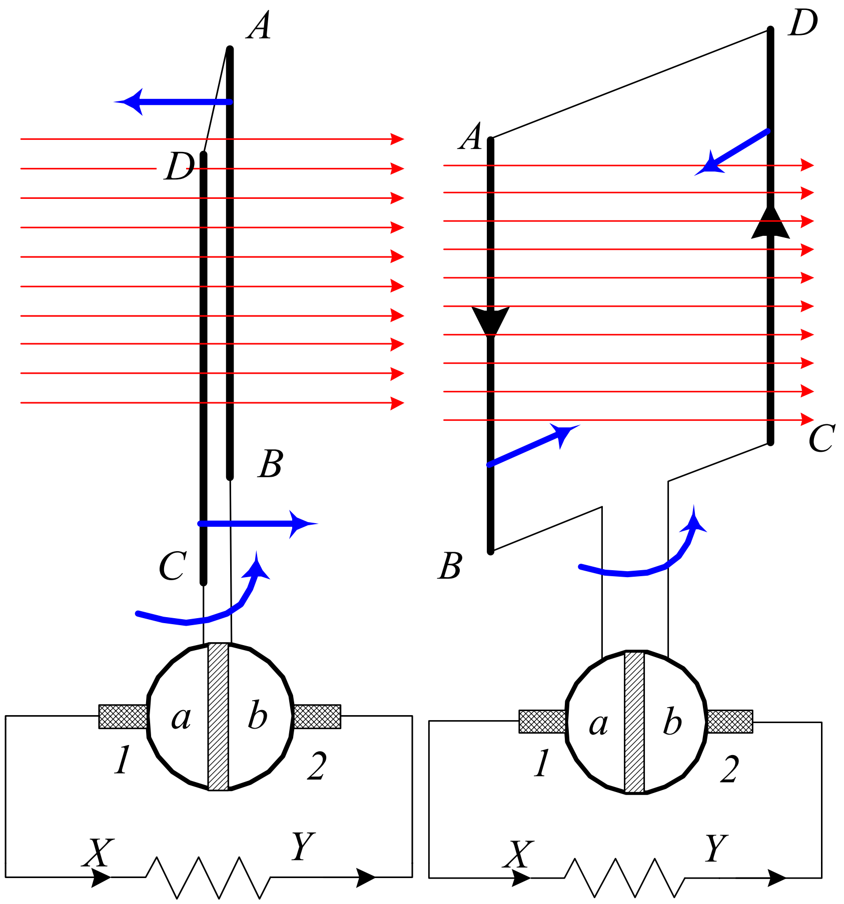
Fig.3.7

(a) Two segments split rings in simple generator loop.

(b) Many segments split rings in Practical generator loop.

It is seen (Fig.3.8(a) to Fig.3.8 (b)) that in the first half revolution current flows along **ABXYCD** i.e. the brush No. 1 in contact with segment ***a*** acts as the positive end of the supply and ***b*** as the negative end. In the next half revolution (Fig.3.8 (c) to Fig.3.8 (d)), the direction of the induced current in the coil has reversed. But at the same time, the positions of segments ***a*** and ***b*** have also reversed with the result that brush No. 1 comes in touch with that segment which is positive *i.e* segment ***b*** in this case. Hence, the current in the load resistance again flows from **X** to **Y**. The waveform of the current through the external circuit is as shown in Fig.3.9. This current is unidirectional but not continuous like pure direct current.

It should be noted that the position of brushes is so arranged that the changeover of segments ***a*** and ***b*** from one brush to the other takes place when the plane of the rotating coil is at right angles to the plane of the flux lines. It is so because in that position, the induced *EMF* in the coil is zero.


A
D
B
C
a
b
1
2
X
Y
A
D
C
B
a
b
1
2
X
Y

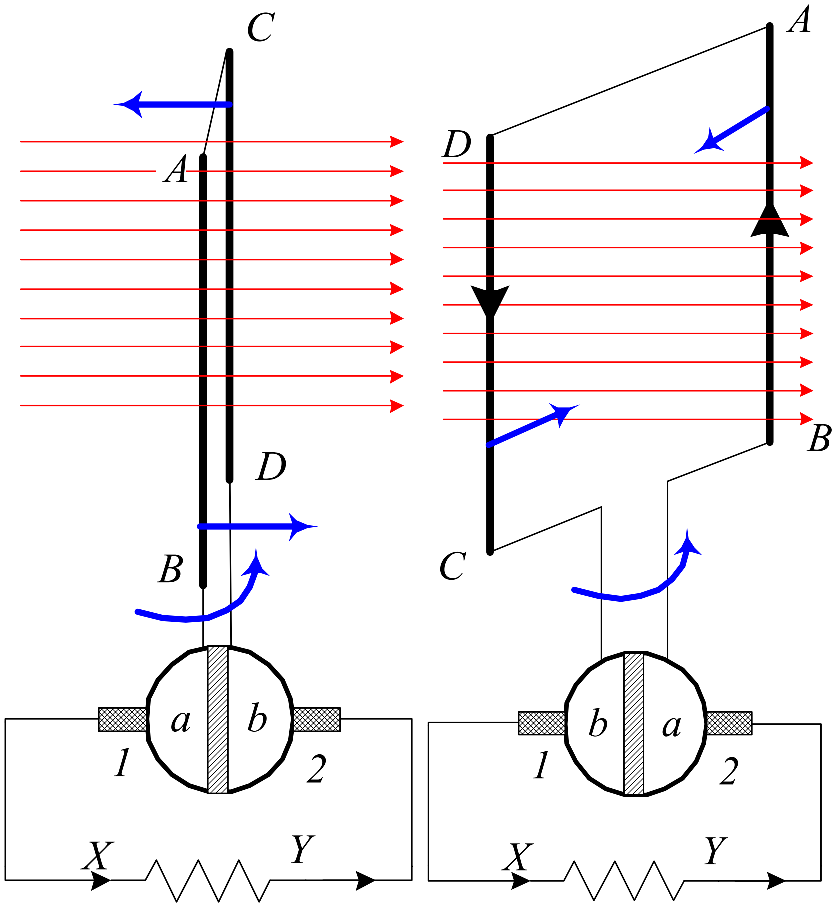


Fig.3.8

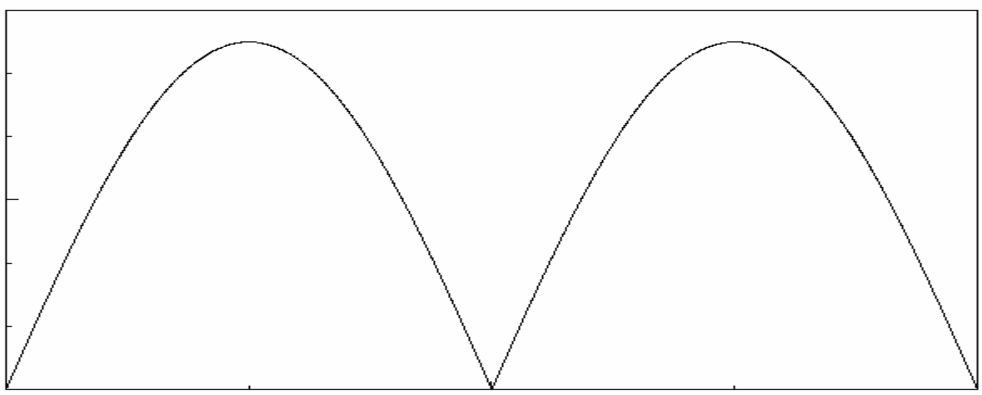


Fig.3.9

Commutator

The function of the commutator is to facilitate collection of current from the armature conductors i.e. converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit. It is of cylindrical structure and is built up of wedge-shaped:segments of high conductivity hard-drawn or drop-forged

3.5 Practical Generator

The simple loop generator has been considered in detail merely to bring out the basic principle underlying the construction and working of as actual generator illustrated in Fig.3.10 which consists of the following essential parts:

(i) Magnetic Frame or Yoke (ii) Pole-cores and Pole-shoes
(iii) Pole Coils or Field Coils (iv) Armature Core
(v) Armature Windings or (vi) Commutator
(vii) Brushes and Bearings

Of these, the yoke, the pole cores, the armature core and air gaps between the poles and the armature core form the magnetic circuit whereas the rest form the electrical circuit.

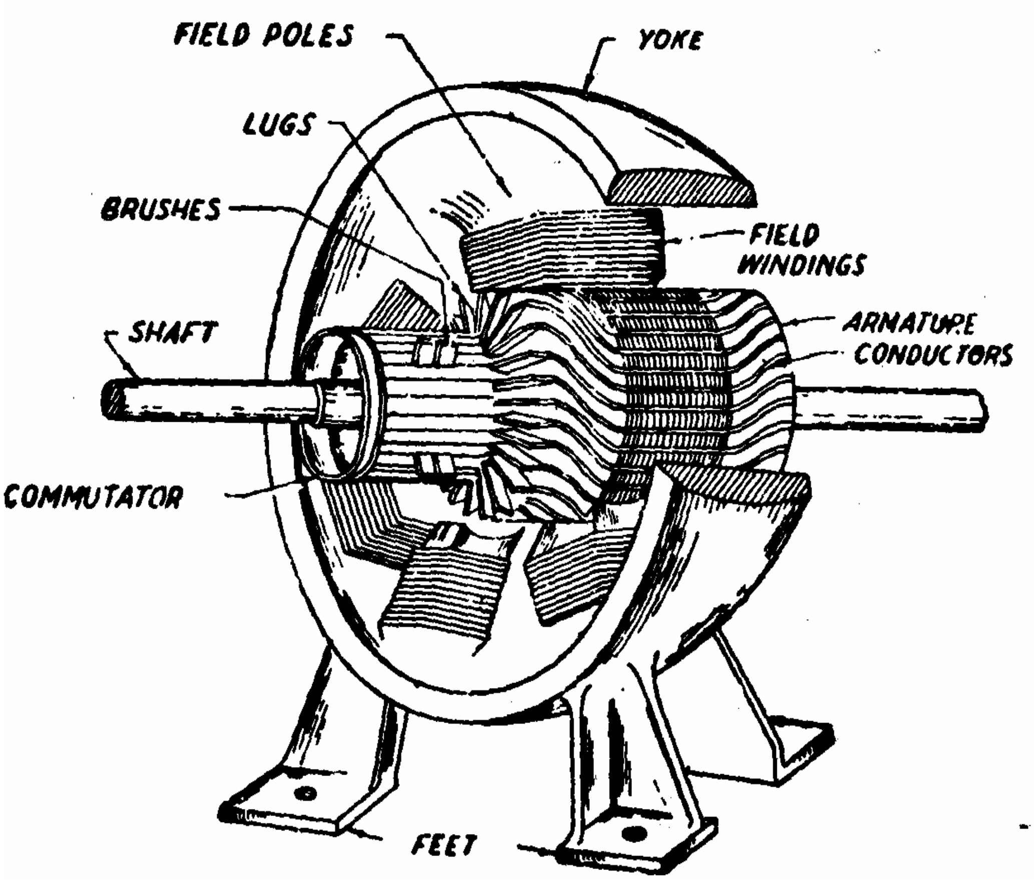


Fig.3.10 Practical DC machine parts .

Armature Windings

Two types of windings mostly employed for the armatures of DC machines are known as *Lap Winding* and *Wave Winding*. The difference between the two is merely due to the different arrangement of the end connections at the front or commutator end of armature. The following rules, however, apply to both types of the windings:

In a lap winding, the number of parallel paths (a) *is always equal to the number of poles (b) and also to the number of brushes.*

In wave windings, the number of parallel paths (a) *is always two and there may be two or more brush positions.*

The coils of rotor part or armature are arranged in many options which inflounce the performance of DC machines. Now, we will briefly discuss the winding of an actual armature. But before doing this, we have to explain many terms as shown in the following items.

Pole-pitch

The periphery of the armature divided by the number of poles of the generate.

i.e. the distance between two adjacent poles

It is equal to the number of armature conductors (or armature slots) per pol. If there are 400 conductors and 4 poles, then pole pitch is 400/4= 100 conductor.

Coil span or Coil pitch

It is the distance, measured in terms of armature slots (or armature conductors), between two sides of a coil. It is, in fact, the periphery of the armature spanned by the two sides of the coil as shown in Fig.3.11.

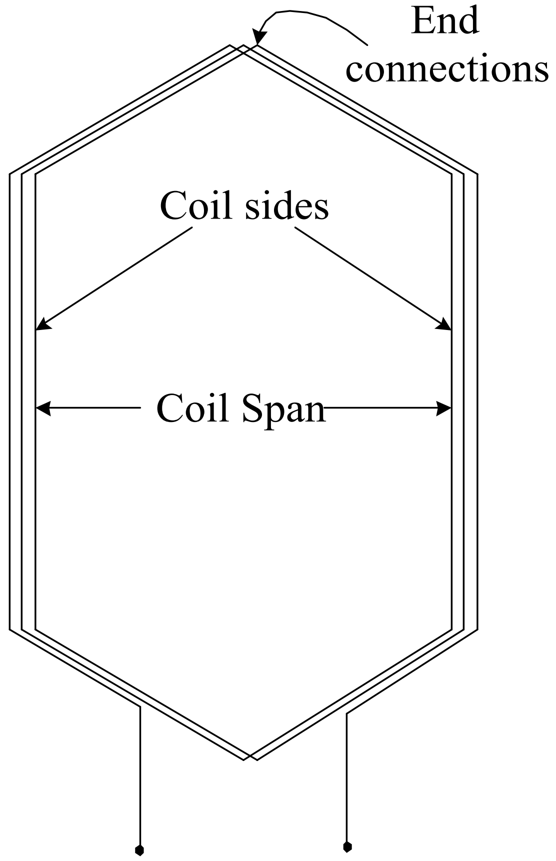


Fig.3.11 One armature coil.

Back Pitch

The distance, measured in terms of the armature conductors. ***which a coil* advances on** the back of the armature is called back pitch and is denoted by Y_b. It is equal'to the *number difference* of the conductors connected to a given segment of the commutator.

Front Pitch

The number of armature conductors or elements spanned by a coil on the front (or commutator end of an armature) is called the front pitch and is designated by Y_f as shown in Fig.3.12.

Alternatively, the front pitch may be defined as the distance (in terms of armature conductors) between the second conductor of one coil and the first conductor of the next coil which are connected together to commutator end of the armature. In other words, it is the *number difference* of the conductors connected together at the back end of the armature. Both front and back pitches for lap and wave-winding are shown in Fig. 3.12 and Fig.3.13 respectively.

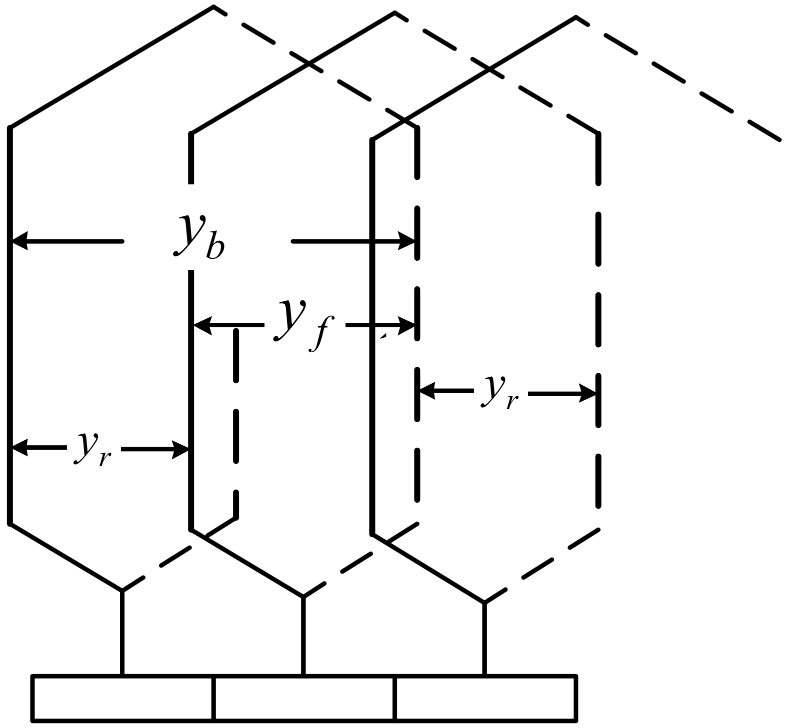


Fig.3.12

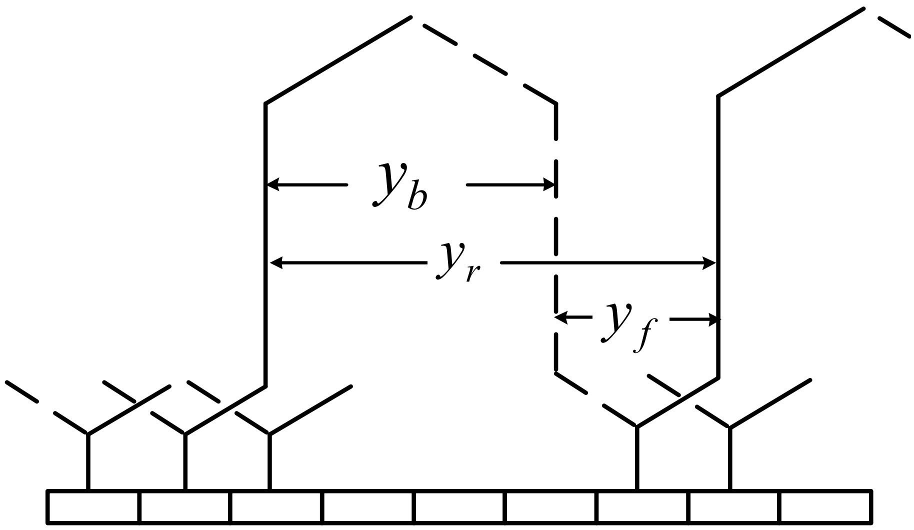


Fig.3.13

Resultant Pitch

It is the distance between the beginning of one coil and the beginning of the next coil to which it is connected as shown in Fig.3.12 and Fig.3.13.

As a matter of precaution, it should be kept in mind that all these pitches, though normally stated in terms of armature conductors, are also sometimes given in terms of armature slots or commutator bars.

Commutator Pitch (Y_c)

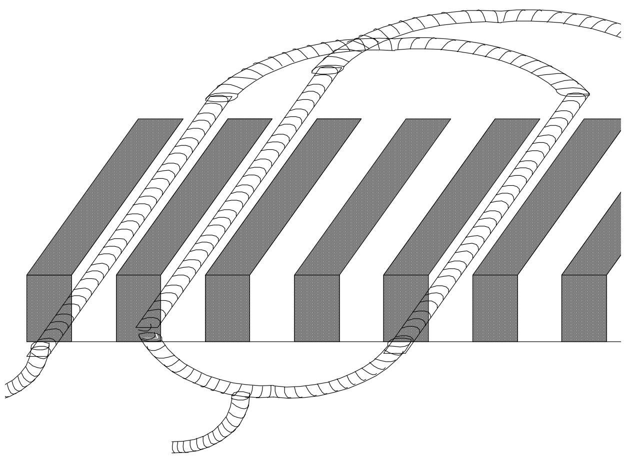
It is the distance (measured in commutator bars or segments) between the segments to which the two ends of a coil are connected as shown in Fig.3.12 and Fig.3.13. From these figures it is clear that for lap winding, Y_c is the difference of Y_b and Y_f whereas for wavewinding it is the sum of Y_b and Y_f .

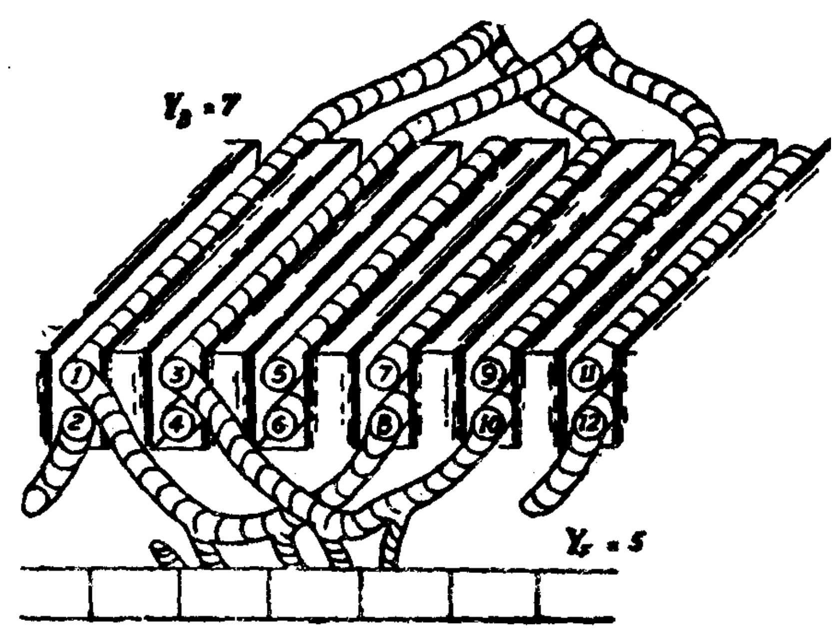
21-2t, Single-layer Winding

It is that winding in which one conductor or one coil side is placed in each armature slot as shown in Fig.3.14. Such a winding is not much used.

2t-2Z. Two-Layer Winding

In this type of winding,' there are two conductors or coil sides-per slot arranged in two layers. Usually, one side of every coil lies in the upper half of one slot and other side lies in the lower half of some other slot at a distance of approximately one pitch away (Fig.3.15). 1 he transfer of , the coil from one slot to another is usually made in a radial plane by means of a peculiar bend or twist at the back





Lap and wave windings

The winding types of the armature of the DC machines can be devided to two main types, Lap and Wave windings. The main difference between them is the method of connecting the terminals of coils to the commutator segments.

In case of lap wound there are two kinds, the simplex lap winding and multiple lap winding.

For simple lap winding the two terminals of one coil is connected to adjusent two commutator segments as shown in Fig.3.12 and Fig.3.16.

3.7 Generated EMF Equation of a Generator.

Let ϕ =flux/pole in weber.

Z=total number of armature conductors = No. of slots*No. of conductors/slot.

P=No. of poles.

A= No. of parallel paths in armature.

N=armature rotation in *rpm*

E=*EMF* induced in any parallel path in armature.

Generated *EMF=e.m.f.* generated in one of the parallel paths.

Average EMF generated/conductor= $\frac{d\phi}{dt}$ *volt* (3.3)

Now, flux cut/conductor in one revolution,

$$d\phi = \phi * P \ \ web. \tag{3.4}$$

Number of revolution per second =N/60;

Then, time for one revolution, dt=60/N second

Hence according to *Faraday's laws* of electromagnetic induction,

EMF generated/conductor= $\frac{d\phi}{dt} = \frac{\phi PN}{60} Volt$ (3.5)

For a wave-wound generator

No. of parallel paths is 2

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

Then, *EMF* generated/path= $\frac{\phi PN}{60} * \frac{Z}{2} = \frac{\phi ZPN}{120} Volt$ (3.6)

For a lap-wound generator

No. of parallel paths =P

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

Then, EMF generated/path$=\frac{\phi PN}{60}*\frac{Z}{P}=\frac{\phi ZN}{60}\ Volt$ (3.7)

In general, generated $EMF=\frac{\phi PN}{60}*\frac{Z}{A}\ \ Volt$ (3.8)

Where A=2 *for wave-winding.*

And A= P *for lap-winding.*

3.8 Classification Of DC Machines

The field circuit and the armature circuit can be interconnected in various ways to provide a wide variety of performance characteristics an outstanding advantage of DC machines. Also, the field poles can be excited by two field windings, a shunt field winding and a series field winding as shown in Fig.3.9. The shunt winding has a large number of turns and takes only a small current (less than 5% of the rated armature current). This winding can be connected across the armature (i.e., parallel with it), hence the name shunt winding. The series winding has fewer turns but carries a large current. It is connected in series with the armature, hence the name series winding. If both shunt and series windings are present, the series winding is wound on top of the shunt winding, as shown in Fig.3.9.

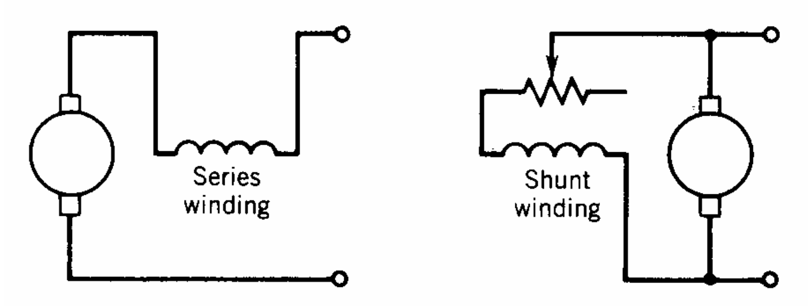


Fig.3.9 Series and shunt field winding DC generators.

The various connections of the field circuit and armature circuit are shown in Fig.3.10. In the *separately excited* DC machine (Fig.3.10 *a),* the field winding is excited from a separate source. In the *self-excited* DC machine, the field winding can be connected in three different ways. The field winding may be connected in series with the armature (Fig.3.10*b),* resulting in a series DC machine; it may be connected across the armature (i.e., in shunt), resulting in a *shunt machine* (Fig.3.10*c);* or both shunt and series windings may be used (Fig.3.10*d*), resulting in a compound machine. If the shunt winding is connected across the armature, it is known as *short-shunt* machine. In an alternative connection, the shunt winding is connected across the series connection of armature and series winding, and the machine is known as *long-shunt* machine. There is no significant difference between these two connections, which are shown in Fig.3.10d. In the compound machine, the series winding *mmf* may aid or oppose the shunt winding *mmf*, resulting in different performance characteristics.

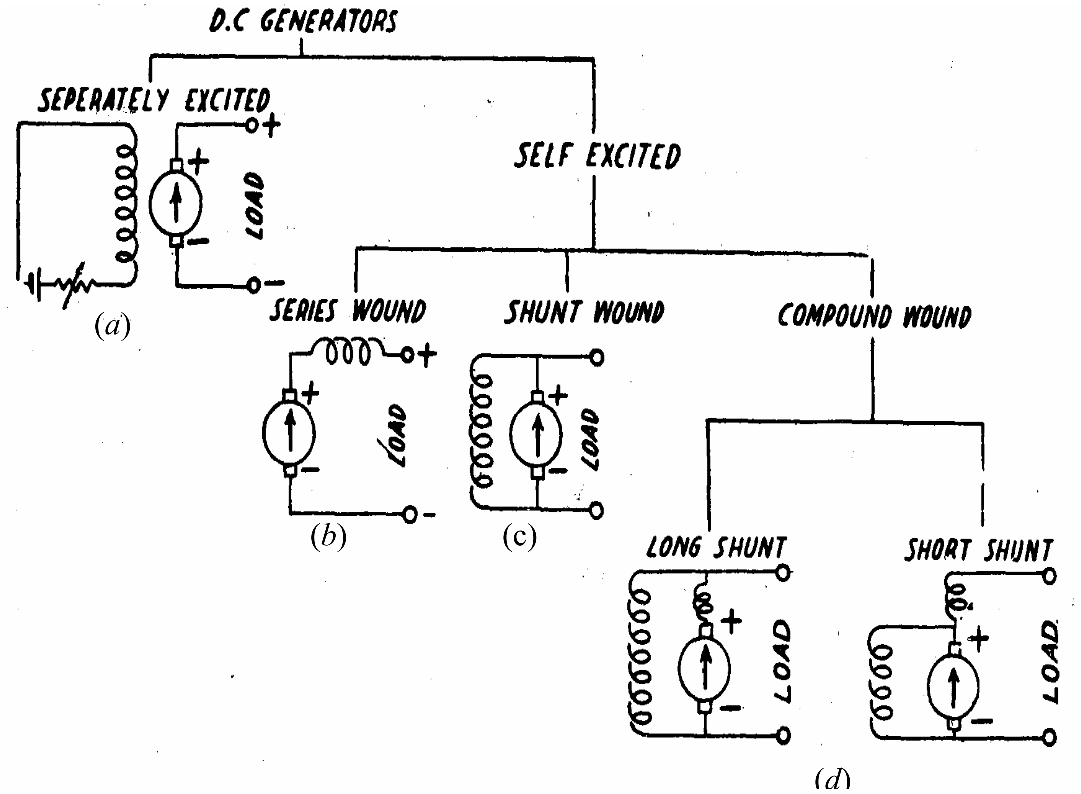


Fig.3.10 Different connections of DC machines. (a) Separately excited DC machine. (b) Series DC machine. (c) Shunt DC machine. (d) Compound DC machine.

A rheostat is normally included in the circuit of the shunt winding to control the field current and thereby to vary the field *mmf*.

Field excitation may also be provided by permanent magnets. This may be considered as a form of separately excited machine, the permanent magnet providing the separate but constant excitation.

Example 3.1 *A 4 pole, long-shunt, compound gaterator supplys 100 A at a terminal voltage of 500 V. If armature resistance is 0.02Ω, series field resistance it 0.04 Ω and shunt field resistance 100Ω, find the generated EMF. Take drop per brush as 1 V, Neglect armature reaction.*

Solution:

Generator circuit is shown in Fig.3.11

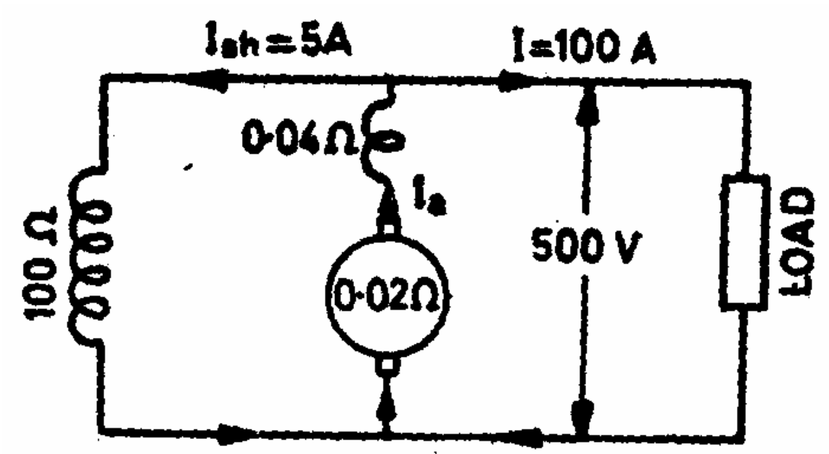


Fig.3.11

$$I_{sh} = \frac{500}{100} = 5\,A$$

Current through armature and series field winding is:

=100+5=105 A

Voltage drop on series field windings=105*0.04=4.2V

Armature voltage drop= 105 * 0.02=3.1 volt

Drop at brushes= 2 * 1= 2 V

Now,

$$EMF = V + I_a R_a + series\,drop + brush\,drop \qquad (3.9)$$

$$= 500 + 4.2 + 2.1 \qquad + 2 \qquad = 508.3\,Volt$$

Example 3.2 *A 20 kW compound generator works on full load with a terminal voltage of 250 V. The armature, series and shunt windings have resistances of 0.05Ω, 0.025Ω and 100 Ω respectively. Calculate the total EMF generated in the armature when the machine is connected as short shunt.*

Solution:

Generator voltage is shown in Fig. 3.12

Load current =20000/250=80 A

Voltage drop in the series windings =80*0.025=2V

Voltage across shunt winding=252 V.

$$I_{sh} = \frac{252}{100} = 2.52A$$

$$I_a = 80 + 2.52 = 82.52A$$

$$I_a R_a = 82.52 * 0.05 = 4.13V$$

Then the generated *EMF*=250+4.13+2=256.13V

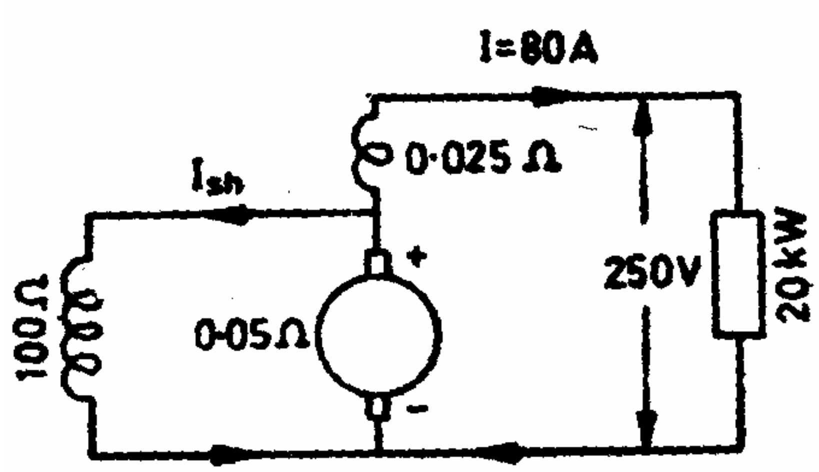


Fig.3.12

Example 3.3 *The following information is given for a 300 kW, 600 V, long-shunt compound generator: Shunt field resistance=75Ω, armature resistance including brush resistance= 0.03 Ω, commutating field winding resistance=0.011Ω, series field resistance=0.012 Ω, divertor resistance =0.036 Ω. When the machine is delivering full load, calculate the voltage and power generated by the armature.*

Solution:

Generator voltage is shown in Fig. 3.13

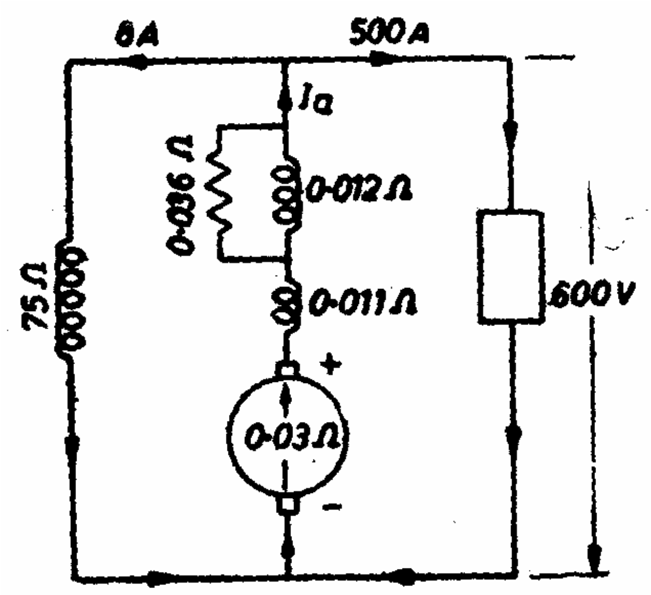


Fig.3.13

Power output= 300,000 W

Output current =300,000/600=500 A

I_{sh} =600/75=8 A

I_a =500+8=508 A

Since the series field resistance and divertor resistance are in parallel (Fig.3.13) their combined resistance is :

0.012 * 0.036/0.048=0.009 Ω

Total armature circuit resistance

=0.03+0.011+0.009=0.05 Ω

Voltage drop =508*0.05=25.4 V

Voltage generated by armature=600+25.4=625.4 V

Power generated= 625.4*508=317,700 W=317.7 kW

Example 3.4 *A 4 pole, lap;wound, DC shunt generator has a useful flux per pole of 0.07 Wb. The armature winding consists of 220 turns each of 0.004 Ω resistance. Calculate the terminal voltage when running at 900 rpm if the armature current is 50 A.*

Solution:

Since each turn has two sides,

Z=220 x 2 =440 ; N=900 *rpm* ;

ϕ=0.07 Wb ; P=A=4

$$E = \frac{\phi ZN}{60} * \left(\frac{P}{A}\right) = \frac{0.07 * 440 * 900}{60} * \left(\frac{4}{4}\right) = 462 Volt$$

Total resistance of 220 turns or 440 conductors=220*0.004=0.88*Ω*

Since, there are 4 parallel paths in armature, .

Resistance of each path=0.88/4=0.22 *Ω*

There are four such resistances in parallel each of value 0.22*Ω*

Armature resistance, R_a=0.22/4=0.055 *Ω*

Armature drop $=I_a R_a$ =50*0.055=2.75 volt

Now, terminal voltage $V = E - I_a R_a$,=462-2.75=459.25 volt

Example 3.5 *A 4 pole, DC shunt generator with a shunt field resistance of 100 Ω and an armature resistance of 1 Ω has 378 wave-connected conductors in its armature. The flux per pole is 0.01 Wb. If a load resistance of 10 Ω is connected across the armature terminals and the generator is driven at 1000 rpm, calculate the power absorbed by the load.*

Solution:

Induced *EMF*. in the generator is:

$$E = \frac{\phi ZN}{60} * \left(\frac{P}{A}\right) = \frac{0.02 * 378 * 1000}{60} * \left(\frac{4}{2}\right) = 252 Volt$$

Now let *V* be the terminal voltage i.e. the voltage available across the load as well as the shunt resistance (Fig.3.14).

Load current= V/10 ampere and shunt current= V/100 ampere

Armature current= $\frac{V}{10} + \frac{V}{100} = \frac{11V}{100}$

Now, *V*=*E*−armature drop

Then, $V = 252 - 1 * \frac{11V}{100} = 227 Volt$

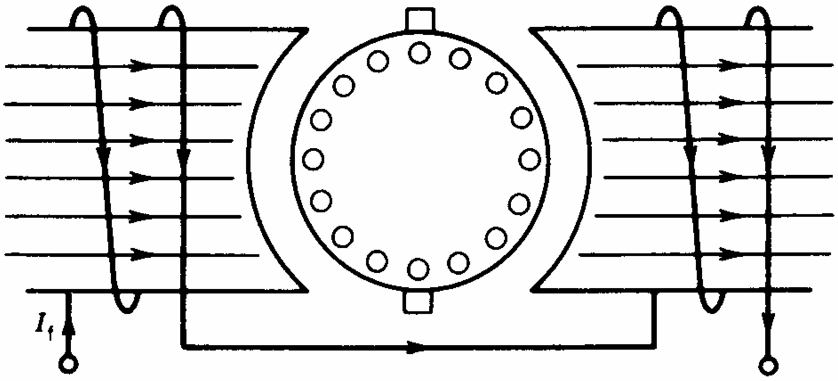
Load current =227/10=22.7A;

Power absorbed by the load is 227*22.7=5 153 W.

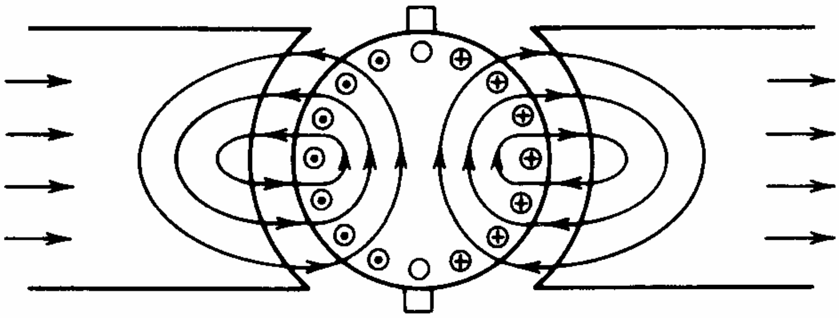
3.9 Armature Reaction (AR)

With no current flowing in the armature, the flux in the machine is established by the *mmf* produced by the field current (Fig.3.14a). However, if the current flows in the armature circuit it produces its own *mmf* (hence flux) acting along the q-axis. Therefore, the original flux distribution in the machine due to the field current is disturbed. The flux produced by the armature *mmf* opposes flux in the pole under one half of the pole and aids under the other half of the pole, as shown in Fig.3.14b. Consequently, flux density under the pole increases in one half of the pole and decreases under the other half of the pole. If the increased flux density causes magnetic saturation, the net effect is a reduction of flux per pole. This is illustrated in Fig.3.14c.

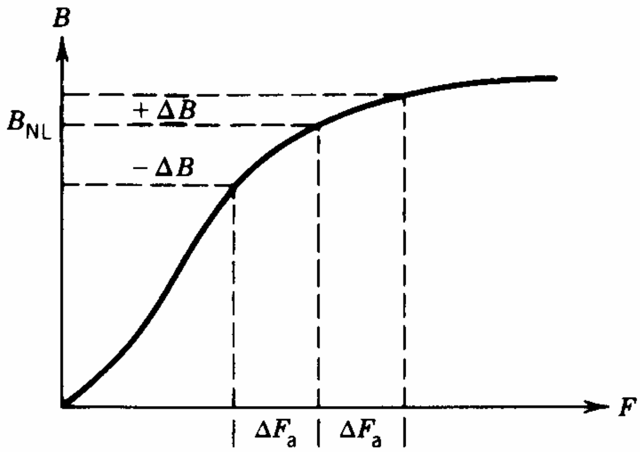
At no load $(I_a = I_t = 0)$ the terminal voltage is the same as the generated voltage $(V_{t0} = E_{a0})$. As the load current flows, if the flux decreases because of armature reaction, the generated voltage will decrease (Equation (3.6) and (3.8)). The terminal voltage will further decrease because of the $I_a R_a$ drop (Equation (3.9)).



(a)



(b)



(c)

Fig.3.14 Armature reaction effects.

In Fig.3.14d, the generated voltage for an actual field current $I_{f(actual)}$ *is* E_{a0}. When the load current I_a, flows the generated voltage is $E_a = V_t + I_a R_a$ *If* $E_a < E_{ao}$, the flux has decreased (assuming the speed remains unchanged) because of armature reaction, although the actual field current $I_{f(actual)}$ in the field winding remains unchanged. In Fig.3.14b, the generated voltage E_a is produced by an effective field current $I_{f(eff)}$. The net effect of armature reaction can therefore be considered as a reduction in the field current. The difference between the actual field current and effective field current can be considered as armature reaction in equivalent field current. Hence,.

$$I_{f(eff)} = I_{f(actual)} - I_{f(AR)} \qquad (3.10)$$

where $I_{f(AR)}$ is the armature reaction in equivalent field current.

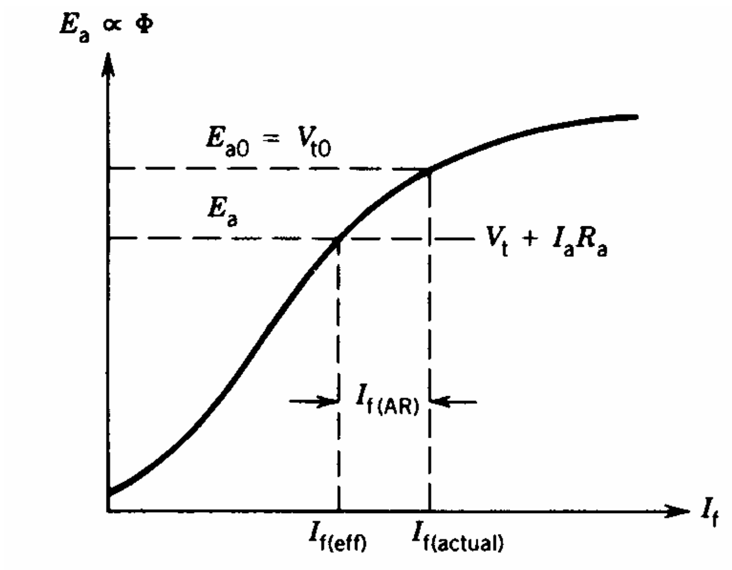


Fig. 3.14d Effect of armature reaction.

3.9.1 Demagnetizing AT per Pole ,

Since armature demagnetising ampere-turns are neutralized by adding extra amperetures to the main field winding, it is essential to calculate their number. But before proceeding further, it should be remembered that the number of turns is equal to half the number of conductors because two conductors constitute one turn.

Let Z= total number of armature conductors

I = current in each armature conductor

$$I = \frac{I_a}{2} \quad \text{for wave winding} \qquad (3.11)$$

$$I = \frac{I_a}{P} \quad \text{for lap winding} \qquad (3.12)$$

θ_m forward lead in mechanical or geometrical or angular degrees.

Total number of conductors in these angles= $\frac{4\theta_m}{360} * z$ (3.13)

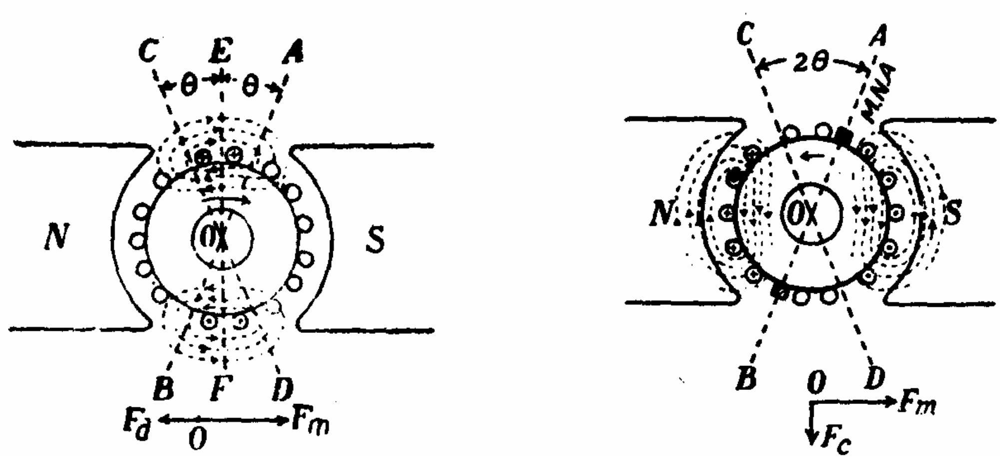


Fig.3.15

As two conductors constitute one turn,

Then total number of turns in these angels $= \frac{2\theta_m}{360} * Z$ (3.14)

Demagnetising amp-turns per pair of poles $= \frac{2\theta_m}{360} ZI$ (3.15)

Demagnetising amp-turns/pole $= \frac{\theta_m}{360} ZI$ (3.16)

AT_d per pole $= \frac{\theta_m}{360} ZI$. (3.17)

3.9.2 Cross-magnetizing AT per Pole

The conductors lying between angles **AOD** and **BOC** constitute what are known as distorting or cross conductors. Their number is found as under:

Total armature conductors/pole bath cross and demagnetising $= Z/P$

Demagnetising conductors/pole $= \frac{2\theta_m}{360} Z$ (found above)

Then, cross-magnetising conductors/pole

$$= \frac{Z}{P} - \frac{2\theta_m}{360} Z = Z\left(\frac{1}{P} - \frac{2\theta_m}{360}\right) \quad (3.18)$$

Cross-magnetising amp-condurtors/pole $= ZI\left(\frac{1}{P} - \frac{2\theta_m}{360}\right)$

Cross-magnetising amp-turns/pole $= ZI\left(\frac{1}{2P}-\frac{\theta_m}{360}\right)$

(remembering that two conductors make one turn)

$$AT_c/pole = ZI\left(\frac{1}{2P}-\frac{\theta_m}{360}\right) \quad (3.19)$$

Note. (i) For neutralizing the demagnetising effect of armature-reaction, an extra number of turns may be put on each pole.

No. of extra turns/pole $=\frac{AT_d}{I_{sh}}$ for shunt generator

$=\frac{AT_d}{I_a}$ for series generator

If the leakage coefficient a is given, then multiply each of the above expression by it.

(ii) If lead angle is given in electrical degrees, it should be converted into mechanical degrees by the following relation

$$\theta_{(mechanical)} = \frac{\theta_{(electrical)}}{pair\ of\ pole} \text{ or } \theta_m = \frac{\theta_e}{P/2} = \frac{2\theta_e}{P} \quad (3.20)$$

3.9.3 Compensating Windings

These are used for large direct current machines which are subjected to large fluctuations in load i.e. rolling mill motors and turbo-generators etc. Their function is to neutralize the cross-magnetizing effect of armature reaction. In the absence of compensating windings, the flux will be suddenly shifting backward and forward with every change in load. This shifting of flux will induce statically induced *EMF*. in the armature coils. The magnitude of this *EMF* will depend upon the rapidity of changes in load and the amount of change. It may be so high as to strike an arc between the consecutive commutator segments across the top of the mica sheets separating them. This may further develop into a flash-over around the whole commutator thereby shortcircuiting the whole armature.

These windings are embedded in slots in the poleshoes and are connected in series with armature in such a way that the current in them flows in opposite direction to that flowing in armature conductors directly below the poleshoes. An elementary scheme of compensating winding is shown in Fig.3.16.

Owing to their cost and the room taken up by them, the compensating windings are used in the case of large machines which are subject to violent fluctuations in load and also for generators which have to deliver their full-load output at considerably low induced voltages.

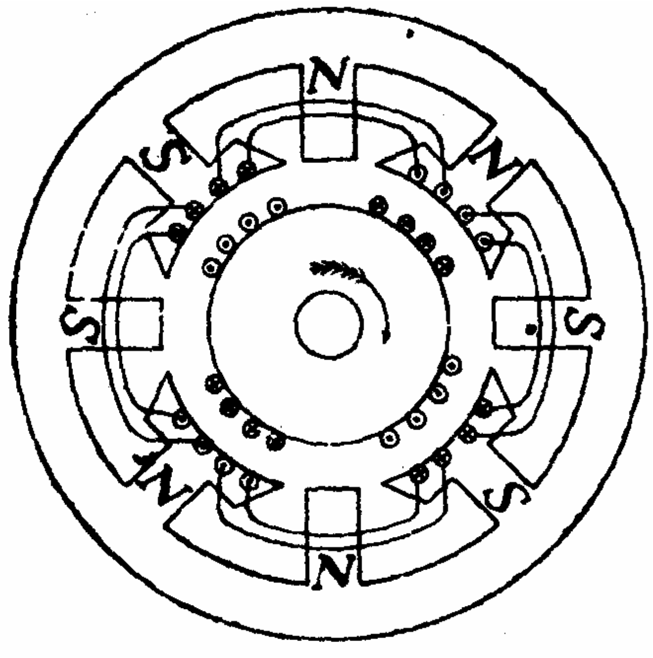


Fig.3.16

3.9.4 No. of Compensating Windings

No. of armature conductors/pole $= \dfrac{Z}{P}$ (3.21)

No. of armature turns/pole $= \dfrac{Z}{2P}$ (3.22)

Then, No. of armature-turns immediately under one pole

$$= \frac{Z}{2P} * \frac{Pole\,arc}{Pole\ pitch} \cong 0.7 * \frac{Z}{2P} \quad (3.23)$$

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

$$= 0.7 * \frac{ZI}{2P} = 0.7 * armature\,amper - Turn\,/\,pole \quad (3.24)$$

Example 3.6 *A 4 pole, DC shunt generator has a simple weve-wound armature with 35 slots and 12 conductors per slot and delivers 35 A on full-load. If the brush lead is 10 space degrees, calculate the demagnetising and cross-magnetising ampere-turns per pole at full-load.*

Solution. Z=35 * 12=420; $\theta_m = 10^o$, $I = \frac{I_a}{2} = \frac{35}{2} = 17.5A$

$$AT_d/\text{ pole} = \frac{\theta_m}{360} ZI = 420 * 17.5 * \frac{10}{360} = 204 At$$

$$AT_c/pole = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right) = 420 * 17.5 * \left(\frac{1}{2*4} - \frac{10}{360}\right) = 715\ At$$

Example 3.7 A *250 V, 500 kW, 8 pole DC generator has a lap-wound armature with 480 conductors. Calculate the demagnetising and cross-magnetising ampere-turns per pole at full-load if the brushes are given a forward lead of 7.5 mechanical.*

Solution:. Output current =500,000/250=2,000 A

$$I_a = 2000A, I = \frac{2000}{8} = 250A, \quad Z = 480, \quad \theta_m = 7.5^o$$

$$AT_d/\text{ pole} = \frac{\theta_m}{360} ZI = 480 * 250 * \frac{7.5}{360} = 2500 .At$$

$AT_c/pole = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right) = 480*250*\left(\frac{1}{2*8} - \frac{7.5}{360}\right) = 5000\,At$

Example 3.8 *A 4 pole, wave-wound motor armature has 880 conductors and delivers 120 A. The brushes have been displaced through 3 angular degrees from the geometrical axis. Calculate (a) demagnetising amp-turns/pole (b) cross-magnetising amp-turns/pole (c) the additional field current for neutralizing the demagnetisation if the field winding has 1100 turns/pole.*

Solution:.

Z=880 ; $I = \frac{120}{2} = 60A,\ \theta = 3^o$

(a) $AT_d/\text{ pole} = \frac{\theta_m}{360} ZI = 880*60*\frac{3}{360} = 440\ At$

(b) $AT_c/pole = 880*60*\left(\frac{1}{8} - \frac{3}{360}\right) = 6160$

Or total $AT_d/pole = \frac{880}{2}*\frac{60}{4} = \frac{Z}{2}*\frac{I_a}{P} = 6600\,\text{At}$

Hence $AT_c/pole$=Total $AT/pole$ -$AT_d/pole$ =6600-440=6160

(c) Additional field current= 440/1100=0.4 A

Example 3.9 *A 4 pole generator supplies a current of 143 A. It has 492 armature conductors (a) wave-wound (b) lap-connected. When delivering full load, the brushes are given an actual lead of*

10^o. *Calculate the demagnetising amp-turns/pole. This field winding is shunt connected and takes 10 A: Find the number of extra shunt field turns necessary to neutralize this demagnetisation.*

Solution.:

Z=492 ; $\theta = 10^o$; $AT_d/pole = ZI * \frac{\theta}{360}$

$I_a = 143 + 10 = 153$ A ;

I=153/2 ...when wave wound

I=153/4 ...when lap-wound

(a) $AT_d/$ pole $= 492 * \frac{153}{2} * \frac{10}{360} = 1046\ At$

Extra shunt field turns =1046/10=105 approx.

(b) $AT_d/pole = 492 * \frac{153}{4} * \frac{10}{360} = 523$

Extra shunt field turns =523/10=52 (approx.)

Example 3.10. *A 4 pole, 50-kW, 250-V wave-wound shunt generator has 400 armature conductors. Brushes are given a lead of 4 commutator segments. Calculate the demagnetisation amp-turns/pole if shunt field resistance is* 50Ω. *Also calculate extra shunt field turns/pole to neutralize the demagnetisation.*

Solution.

Load current supplied=50,000/250=200 A

$$I_{sh} = \frac{250}{50} = 5A$$

Then $I_a = 200 + 5 = 205A$

Current in each conductor I=205/2=102.5 A

No. of commutator segments =Z/A where A=2 .for wave winding

Then, No. of segments =400/2=200 segments

$$\theta_m = \frac{no.of segments * 360}{200} = \frac{4*360}{200} = \frac{36}{5} \deg rees$$

AT_d/ pole $= 400 * \frac{205}{2} * \frac{36}{5*360} = 820\ At$

Extra shunt turns/pole$= \frac{AT_d}{I_{sh}} = \frac{820}{5} = 164$ turns

Example 3.11 A *30 h.p. (British) 440 V, 4 pole, wave-wound DC shunt motor has 840 armature conductors and 140 commutator segments. Its full load efficiency is 88% and the shunt field current is 1.8 A. If brushes are shifted backwards through 1.5 segment from the geometrical neutral axis, find the demagnetising and distorting amp-turns/pole.*

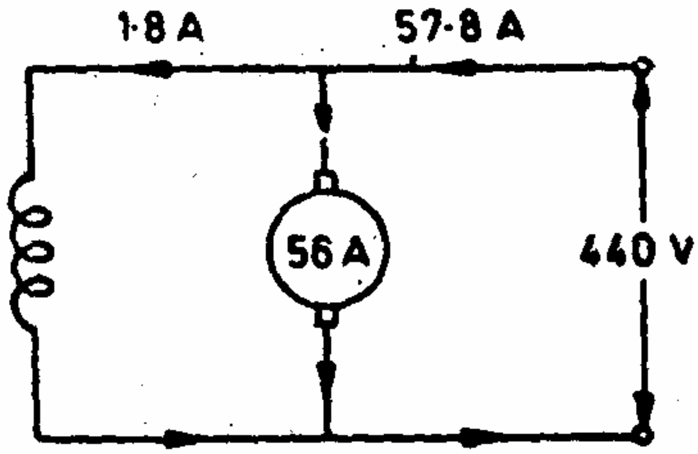


Fig.3.17

Solution:

The shunt motor is shown diagrammatically in Fig.3.17

Motor output=30 * 746 W, - $\eta = 0.88\%$

Motor input $= \frac{30*746}{0.88} = 25432W$

Motor input current$= \frac{25432}{440} = 57.8A$

$I_{sh} = 1.8A,\ I_a = 57.8 - 1.8 = 56A$

Current in each conductor = 56/2=28 A

$\theta_m = 1.5*360/140 = 27/7 \text{ deg} rees$

AT_d/ pole $= 840*28*\frac{27}{7*360} = 252At$

$AT_c/pole = 840*28*\left(\frac{1}{8} - \frac{27}{7*360}\right) = 2688\ At$

3.10 Shifting The Brushes To Improve Commutation

Due to the shift in the neutral zone (Fig.3.18) when the generator is under load, we could move the brushes to reduce the sparking.

For generators, the brushes are shifted to the new neutral zone by moving them in the direction of rotation. For motors, the brushes are shifted against the direction of rotation.

As soon as the brushes are moved, the commutation improves, meaning there is less sparking. However, if the load fluctuates, the armature *mmf* rises and falls and so the neutral zone shifts back and forth between the no load and full load positions. We would therefore have to move the brushes back and forth to obtain sparkless commutation. This procedure is not practical and other means are used to resolve the problem. For small DC machines, however, the brushes are set in an intermediate position to ensure reasonably good commutation at all loads.

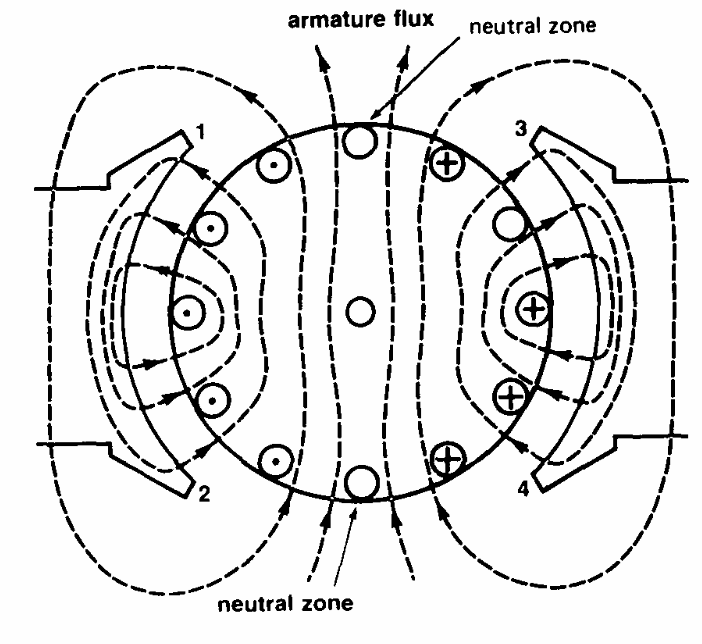


Fig.3.18 (a) Magnetic field produced by the current flowing in the armature conductors.

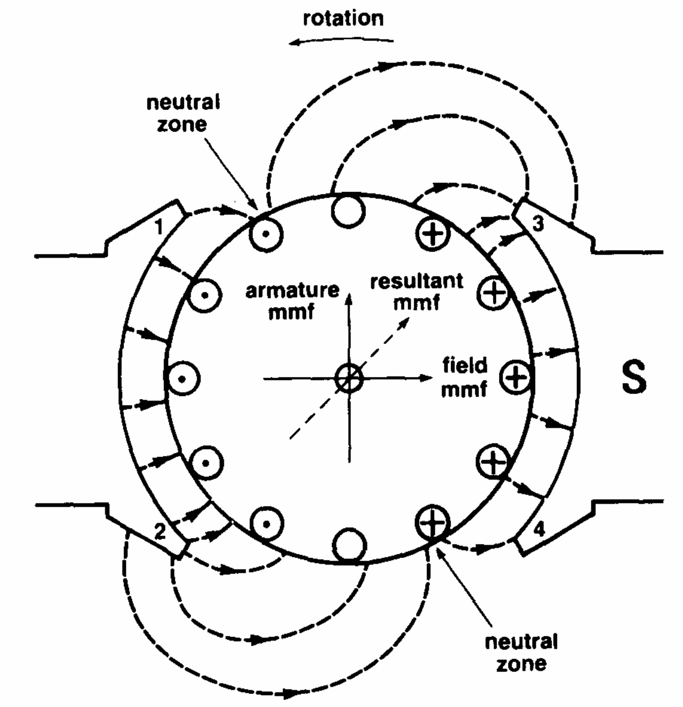


Fig.3.18 (b) Armature reaction distorts the field produced by the N, S poles.

3.11 Commutating Poles (Interpoles Windings)

To counter the effect of armature reaction in medium and large-power DC machines, we always place a set of *commutating poles* (Sometimes called interpoles windings) between the main poles (Fig.3.19). These narrow poles carry windings that are connected in series with the armature. The number of turns on the windings is designed so that the poles develop a magnetomotive force mmf_c equal and opposite to the magnetomotive force mmf_a of the armature. As the load current varies, the two magnetomotive forces rise and fall together, exactly bucking each other at all times. By nullifying the armature *mmf* in this way, the flux in the space between the main poles is always zero and so we no longer have to shift the brushes. In practice, the *mmf* of the commutating poles is made slightly greater than the armature *mmf*. This creates a small flux in the neutral zone, which aids the commutation process.

Fig.3.19 shows how the commutating poles of a 2-pole machine are connected. Clearly, the direction of the current flowing through the windings indicates that the *mmf* of the commutating poles acts opposite to the *mmf* of the armature and, therefore, neutralizes its effect. However, the neutralization is restricted to the narrow brush zone where commutation takes place. The distorted flux distribution under the main poles, unfortunately, remains the same.

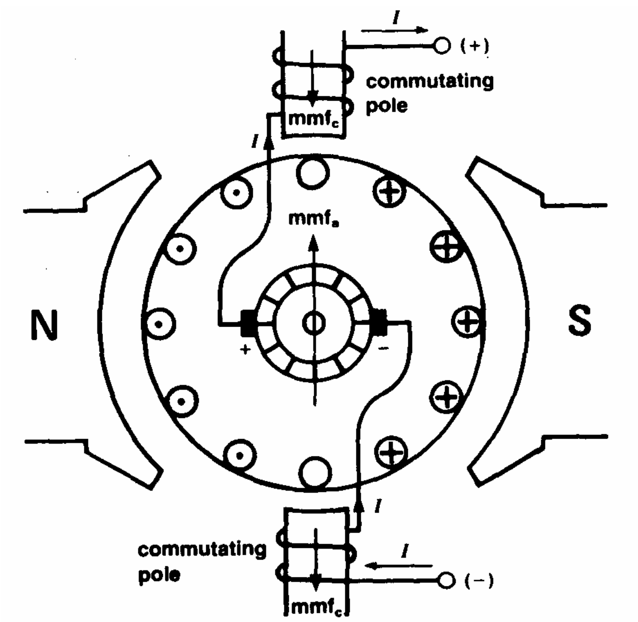


Fig.3.19 Commutating poles produce an mmf_c that opposes the mmf_a of the armature.

3.12 Separately Excited Generator

Now that we have learned some basic facts about DC generators, we can study the various types and their properties. Thus, instead of using permanent magnets to create the magnetic field, we can use a pair of electromagnets, called field poles, as shown in Fig.3.20. When the DC field current in such a generator is supplied by an independent source (such as a storage battery or another generator, called an exciter), the generator is said to be separately excited. Thus, in Fig.3.20 the DC source connected to terminals ***a*** and ***b*** causes an exciting current I_X to flow. If the armature is driven by a motor or a diesel engine, a voltage E_o appears between brush terminals **x** and **y**.

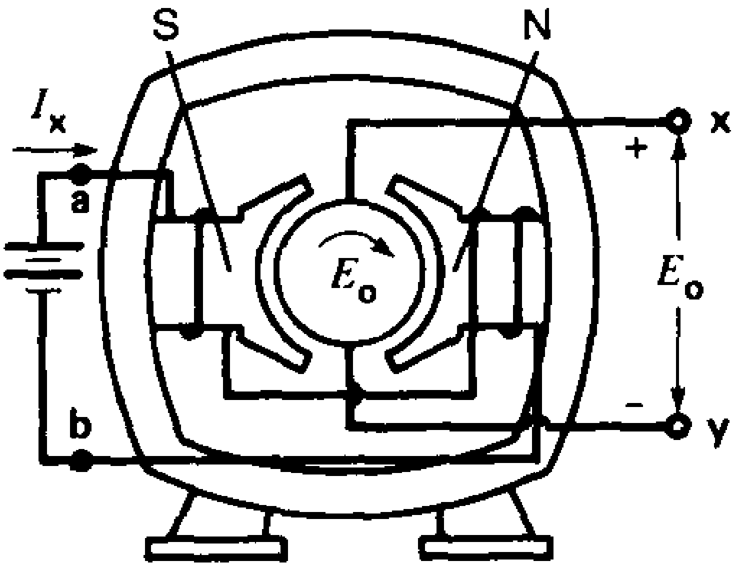


Fig.3.20 Separately excited 2-pole generator. The N, S field poles are created by the current flowing in the field windings.

3.1 No-Load Operation And Saturation Curve

When a separately excited DC generator runs at no load (armature circuit open), a change in the exciting current causes a corresponding change in the induced voltage. We now examine the relationship between the two.

3.13.2 Field flux vs. exciting current.

Let us gradually raise the exciting current I_X, so that the *mmf* of the field increases, which increases the flux (ϕ per pole). If we plot ϕ as a function of I_X, we obtain the saturation curve of Fig.3.21a. This curve is obtained whether or not the generator is turning.

When the exciting current is relatively small, the flux is small and the iron in the machine is unsaturated. Very little *mmf* is needed to establish the flux through the iron, with the result that the *mmf* developed by the field coils is almost entirely available to drive the flux through the air gap. Because the permeability of air is constant, the flux increases in direct proportion to the exciting current, as shown by the linear portion **0a** of the saturation curve.

However, as we continue to raise the exciting current, the iron in the field and the armature begins to saturate. A large increase in the *mmf* is now required to produce a small increase in flux, as shown by portion **bc** of the curve. The machine is now said to be saturated. Saturation of the iron begins to be important when we reach the so-called "*knee*" **ab** of the saturation curve.

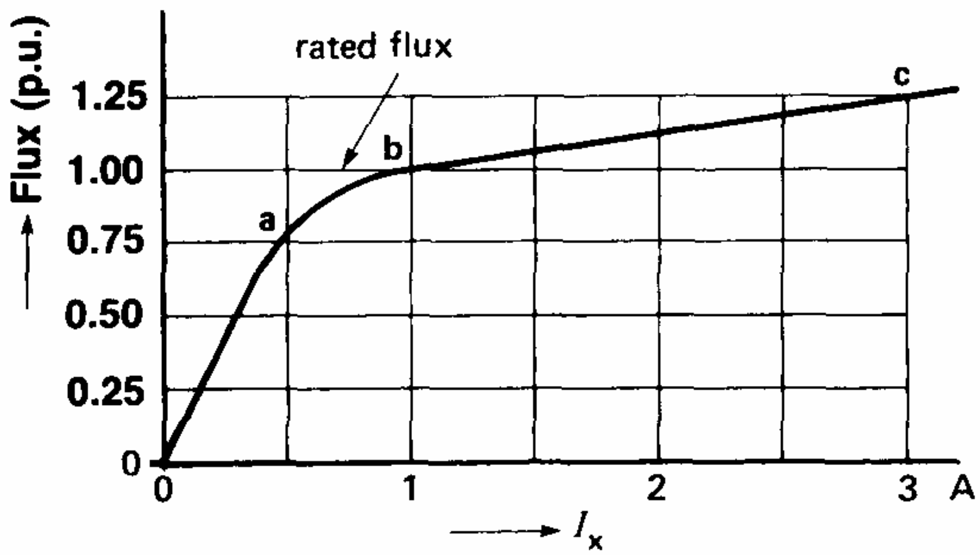


Fig.3.21a Flux per pole versus exciting current.

The output voltage varies to the field current for separately excited DC generator is shown in Fig.3.21b.

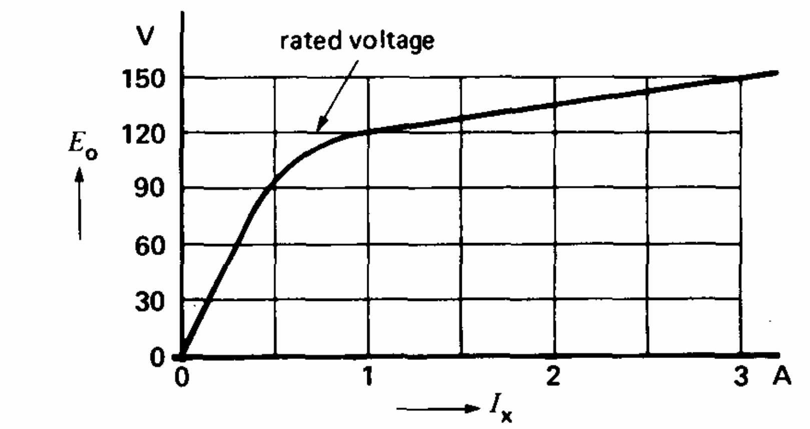


Fig.3.21b Saturation curve of a DC generator.

3.13 Shunt Generator

A shunt-excited generator is a machine whose shunt field winding is connected in parallel with the armature terminals, so that the generator can be self-excited (Fig.3.22). The principal advantage of this connection is that it eliminates the need for an external source of excitation.

How is self-excitation achieved? When a shunt generator is started up, a small voltage is induced in the armature, due to the remaining flux in the poles. This voltage produces a small exciting current I_X in the shunt field. The resulting small *mmf* acts in the same direction as the remaining flux, causing the flux per pole to increase. The increased flux increases E_0 which increases I_X, which increases the flux still more, which increases E_0 even more, and so forth. This progressive buildup continues until E_0 reaches a maximum value determined by the field resistance and the degree of saturation. See next section.

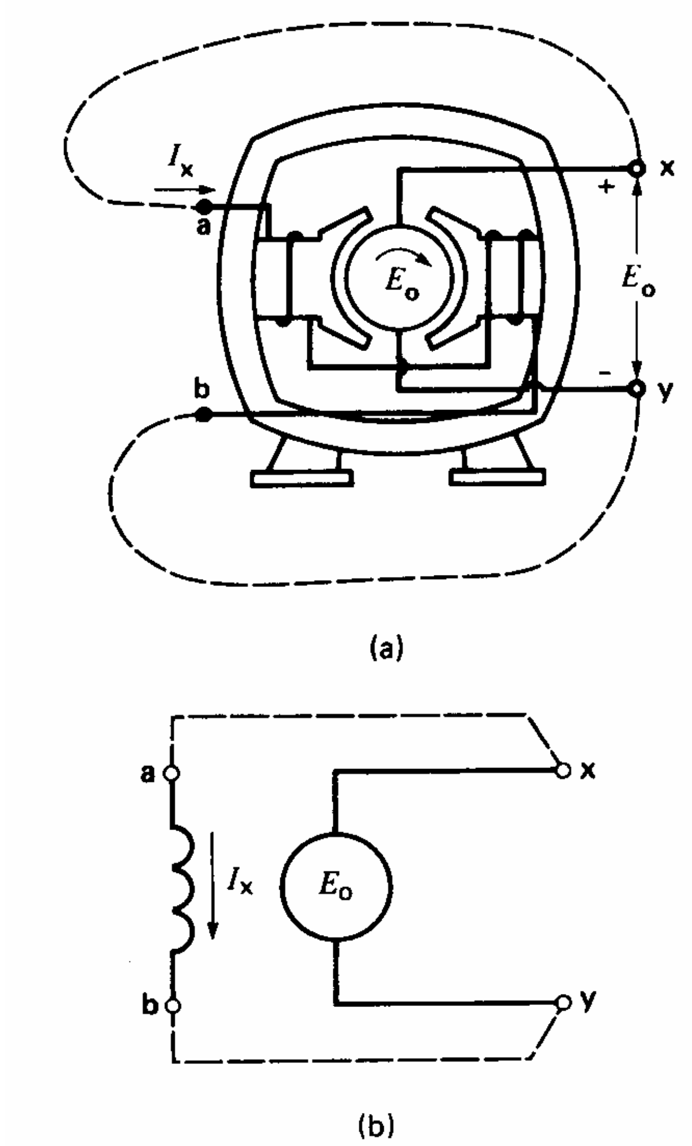


Fig.3.22 a. Self-excited shunt generator.

b. Schematic diagram of a shunt generator. A shunt field is one designed to be connected in shunt (alternate term for parallel) with the armature winding.

3.13.1 Controlling The Voltage Of A Shunt Generator

It is easy to control the induced voltage of a shunt-excited generator. We simply vary the exciting current by means of a rheostat connected in series with the shunt field (Fig.3.23).

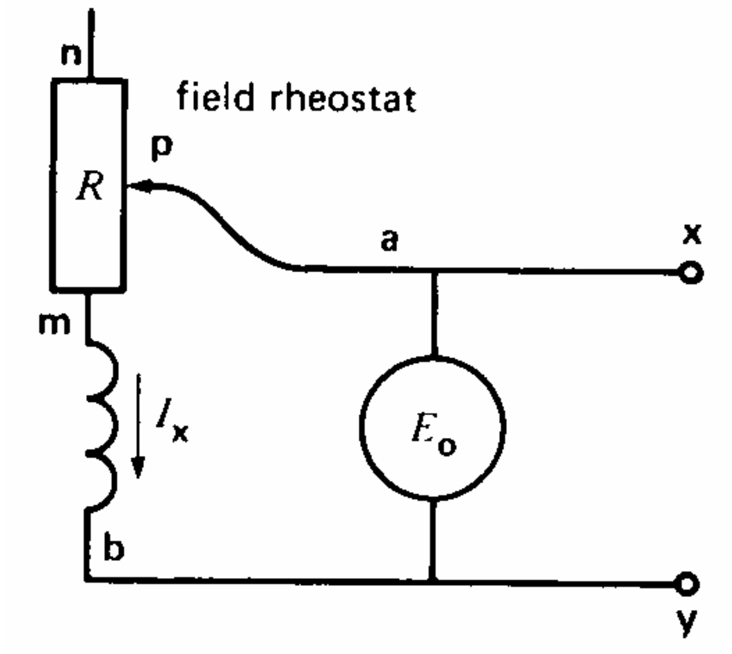


Fig.3.23 Controlling the generator voltage with a field rheostat. A rheostat is a resistor with an adjustable sliding contact.

To understand how the output voltage varies, suppose that E_0 is 120 V when the movable contact p is in the center of the rheostat.

If we move the contact toward extremity **m**, the resistance R_t between points **p** and **b** decreases, which causes the exciting current to increase. This increases the flux and, consequently, the induced voltage E_0. On the other hand, if we move the contact toward extremity **n**, R_t increases, the exciting current decreases, the flux decreases, and so E_0 will fall.

We can determine the no-load value of E_0 if we know the saturation curve of the generator and the total resistance R_t of the shunt field circuit between points **p** and **b**. We draw a straight line corresponding to the slope of R_t and superimpose it on the saturation curve (Fig. 4.24). This dotted line passes through the origin, and the point where it intersects the curve yields the induced voltage.

For example, if the shunt field has a resistance of 50 Ω and the rheostat is set at extremity m, then R_t = 50 Ω. The line corresponding to R_t must pass through the coordinate point E = 50 V, I = 1 A. This line intersects the saturation curve where the voltage is 150 V (Fig.3.24). That is the maximum voltage the shunt generator can produce.

By changing the setting of the rheostat, the total resistance of the field circuit increases, causing E_0 to decrease progressively. For example, if R_t is increased to 120 Ω, the resistance line cuts the saturation curve at a voltage E_0 of 120 V

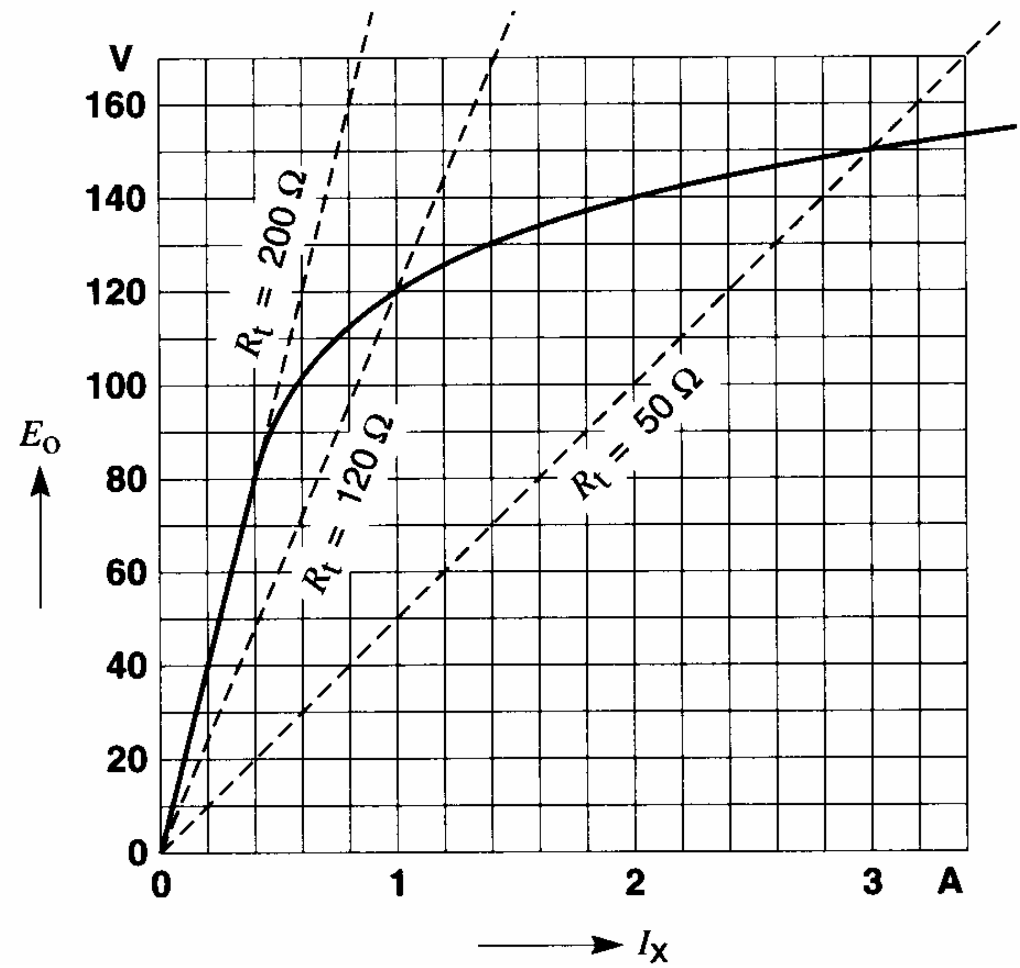


Fig3.24 The no-load voltage depends upon the resistance of the shunt-field circuit.

If we continue to raise R_t, a critical value will be reached where the slope of the resistance line is equal to that of the saturation curve in its unsaturated region. When this resistance is attained, the induced voltage suddenly drops to zero and will remain so for any R_t greater than this critical value. In Fig.3.24 the critical resistance corresponds to 200Ω.

We have seen that the armature winding contains a set of identical coils, all of which possess a certain resistance. The total armature resistance R_a is that which exists between the armature terminals when the machine is stationary. It is measured on the commutator surface between those segments that lie under the (+) and (-) brushes. The resistance is usually very small, often less than one hundredth of an ohm. Its value depends mainly upon the power and voltage of the generator. To simplify the generator circuit, we can represent R_a as if it were in series with one of the brushes. If the machine has interpoles, the resistance of these windings is included in R_a.

The equivalent circuit of a generator is thus composed of a resistance R_a in series with a voltage E_0 (Fig.3.25). The latter is the voltage induced in the revolving conductors. Terminals 1, 2 are the external armature terminals of the machine, and F_1, F_2 are the field winding terminals. Using this circuit, we will now study the more common types of direct-current generators and their behavior under load.

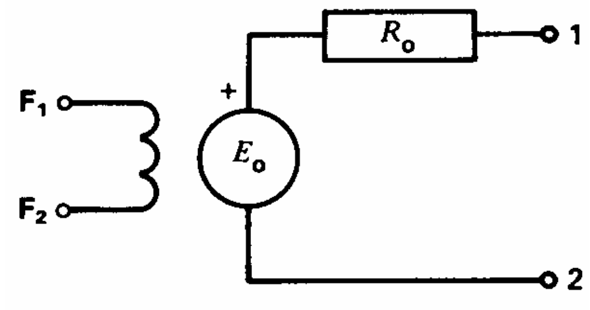


Fig.3.25 Equivalent circuit of a DC generator.

3.14 Separately Excited Generator Under Load

Let us consider a separately excited generator that is driven at constant speed and whose field is excited by a battery (Fig.3.26). The exciting current is constant and so is the resultant flux. The induced voltage E_o is therefore fixed. When the machine operates at no load, terminal voltage E_{12} is equal to the induced voltage E_o because the voltage drop in the armature resistance is zero. However, if we connect a load across the armature (Fig.3.26), the resulting load current I produces a voltage drop across resistance R_a. Terminal voltage E_{12} is now less than the induced voltage E_o. As we increase the load, the terminal voltage decreases progressively, as shown in Fig.3.27. The graph of terminal voltage as a function of load current is called the load curve of the generator. In practice, the induced voltage E_o also decreases slightly with increasing load, because pole-tip saturation tends to decrease the field flux. Consequently, the terminal voltage E_{12} falls off more rapidly than can be attributed to armature resistance alone.

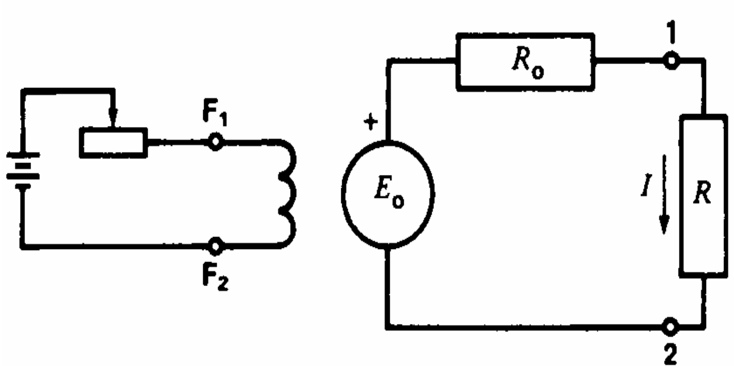


Fig.3.26 Separately excited generator under load.

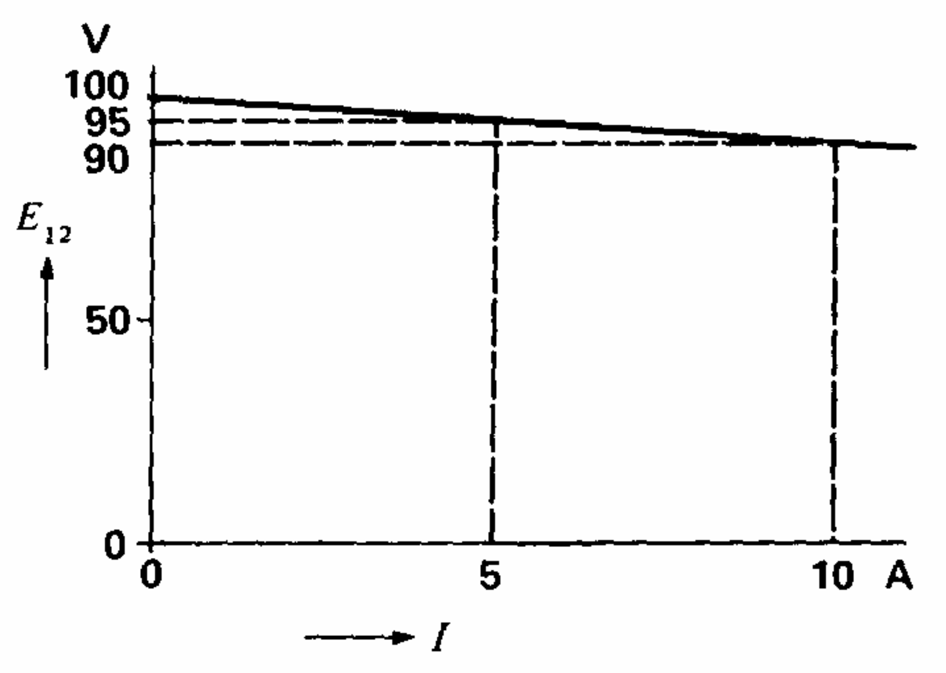


Fig.3.27 Load characteristic of a separately excited generator

3.15 Shunt generator under load

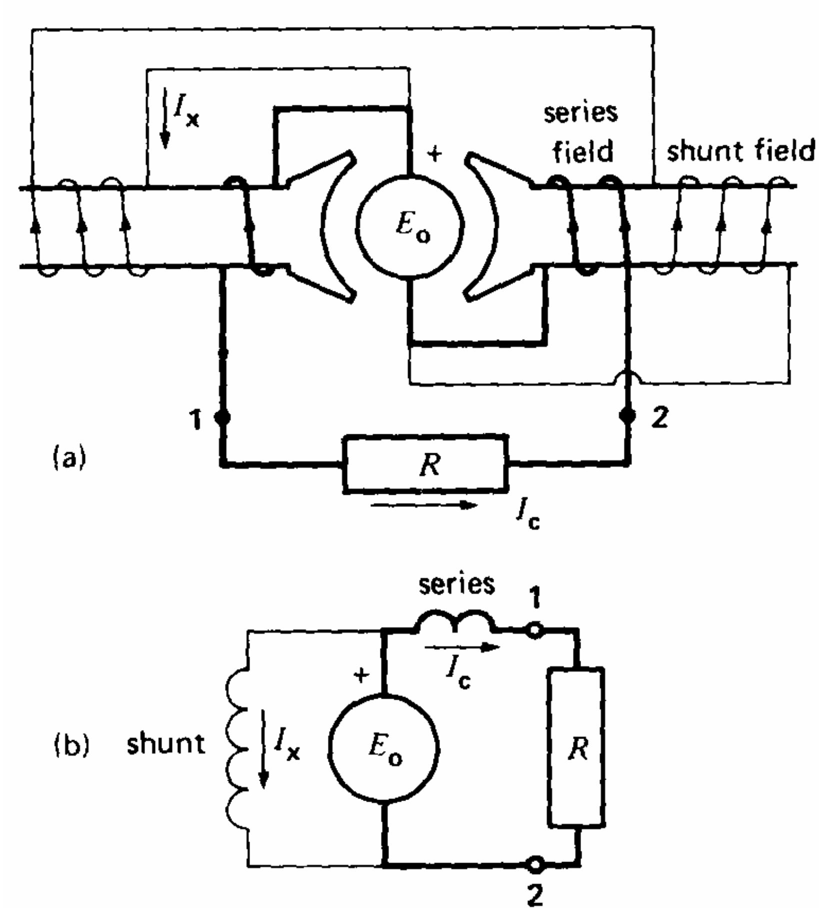
The terminal voltage of a self-excited shunt generator falls off more sharply with increasing load than that of a separately excited generator (Fig.3.27). The reason is that the field current in a separately excited machine remains constant, whereas in a self-excited generator the exciting current falls as the terminal voltage drops. For a self-excited generator, the drop in voltage from no load to full load is about 15 percent of the full-load voltage, whereas for a separately excited generator it is usually less than 10 percent. The voltage regulation is said to be 15% and 10%, respectively.

3.16 Compound Generator

The compound generator was developed to prevent the terminal voltage of a DC generator from decreasing with increasing load. Thus, although we can usually tolerate a reasonable drop in terminal voltage as the load increases, this has a serious effect on lighting circuits. For example, the distribution system of a ship supplies power to both DC machinery and incandescent lamps. The current delivered by the generator fluctuates continually, in response to the varying loads. These current variations produce corresponding changes in the generator terminal voltage, causing the lights to flicker. Compound generators eliminate this problem.

A compound generator (Fig.3.28a) is similar to a shunt generator, except that it has additional field coils connected in series with the armature. These series field coils are composed of a few turns of heavy wire, big enough to carry the armature current.

The total resistance of the series coils is, therefore, small. Fig.3.28b is a schematic diagram showing the shunt and series field connections.



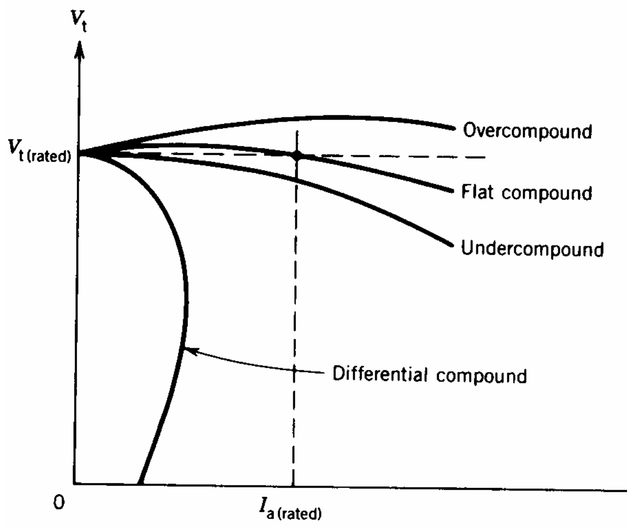


Fig.3.28 (*a*). Compound generator under load. (*b*). Schematic diagram. (*c*) *V-I* characteristics.

When the generator runs at no-load, the current in the series coils is zero. The shunt coils, however, carry exciting current I_X which produces the field flux, just as in a standard self-excited shunt generator. As the generator is loaded, the terminal voltage tends to drop, but load current I_c now flows through the series field coils. The *mmf* developed by these coils acts in the same direction as the *mmf* of the shunt field. Consequently, the field flux under load rises above its original no-load value, which raises the value of E_o. If the series coils are properly designed, the terminal voltage remains practically constant from no-load to full-load. The rise in the induced voltage compensates for the armature drop.

In some cases we have to compensate not only for the armature voltage drop, but also for the *I R* drop in the feeder line between the generator and the load. The generator manufacturer then adds one or two extra turns on the series winding so that the terminal voltage increases as the load current rises. Such machines are called over compound generators. If the compounding is too strong, a low resistance can be placed in parallel with the series field (The name of this resistance is diverter resistance). This reduces the current in the series field and has the same effect as reducing the number of turns. For example, if the value of the diverter resistance is equal to that of the series field, the current in the latter is reduced by half.

3.17 Differential Compound Generator

In a differential compound generator the *mmf* of the series field acts opposite to the shunt field. As a result, the terminal voltage falls drastically with increasing load as shown in Fig.3.28c. We can make such a generator by simply reversing the series field of a standard compound generator. Differential compound generators were formerly used in DC arc welders, because they tended to limit the short-circuit current and to stabilize the arc during the welding process.

3.18 DC Motor

The DC machine can operate both as a generator and as a motor. This is illustrated in Fig.3.29. When it operates as a generator, the input to the machine is mechanical power and the output is electrical power. A prime mover rotates the armature of the DC machine, and DC power is generated in the machine. The prime mover can be a gas turbine, a diesel engine, or an electrical motor. When the DC machine operates as a motor, the input to the machine is electrical power and the output is mechanical power. If the armature is connected to a DC supply, the motor will develop mechanical torque and power. In fact, the DC machine is used more as a motor than as a generator. DC motors can provide a wide range of accurate speed and torque control.

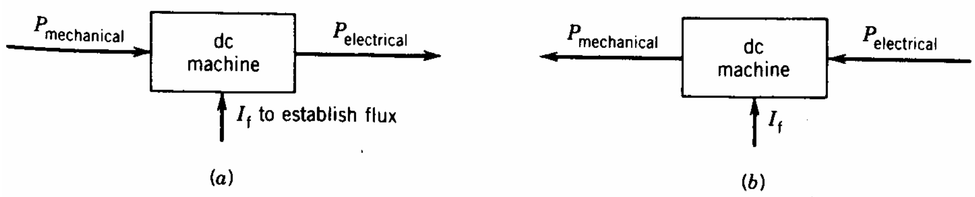


Fig.3.29 Reversibility of a DC machine. (a) Generator. (b) Motor.

In both modes of operation (generator and motor) the armature winding rotates in the magnetic field and carries current. Therefore, the same basic equations (3.5), (3.6) and (3.8) hold good for both generator and motor action.

3.18.1 Shunt Motor

A schematic diagram of a shunt field DC motor is shown in Fig.3.30. The armature circuit and the shunt field circuit are connected across a DC source of fixed voltage V_t. An external field rheostat (R_{fc}) is used in the field circuit to control the speed of the motor. The motor takes power from the DC source, and therefore the current I_t flows into the machine from the positive terminal of the DC source. As both field circuit and armature circuit are connected to a DC source of fixed voltage, the connections for separate and shunt excitation are the same. The behavior of the field circuit is independent of the armature circuit.

The governing equations for steady-state operation of the DC motor are as follows:

$$V_t = I_a R_a + E_a \tag{3.25a}$$

$$I_t = I_a + I_f \tag{3.25b}$$

$$E_a = K_a \phi \omega_m = \frac{\phi z N}{60} * \frac{p}{A} \tag{3.25c}$$

$$E_a = V_t - I_a R_a \tag{3.25d}$$

where K_a is the machine constant.

The armature current I_a and the motor speed ω_m depend on the mechanical load connected to the motor shaft.

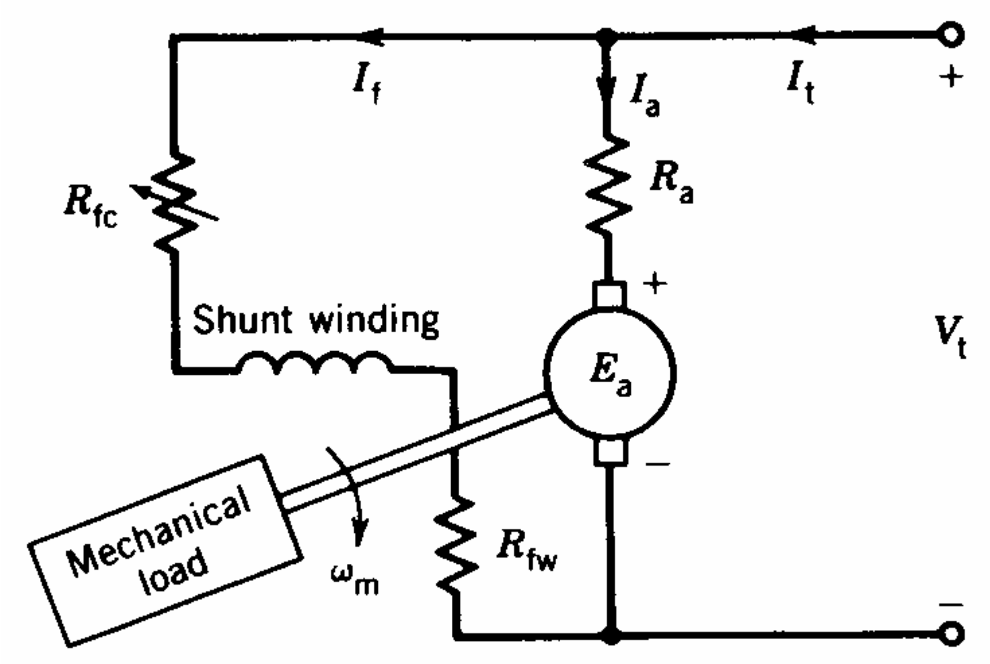


Fig.3.30 Shunt DC motor equiva lent circuit.

3.19 Power Flow and Efficiency

The power flow in a DC machine is shown in Fig.3.31. The various losses in the machine are identified and their magnitudes as percentages of input power are shown. A short-shunt compound DC machine is considered as an example (Fig.3.31a).

With the machine operating as a generator (Fig.3.31b), the input power is the mechanical power derived from a prime mover. Part of this input power is lost as rotational losses required to rotate the machine against windage and friction (rotor core loss is also included in the rotational loss). The rest of the power is converted into electrical power $E_a I_a$. Part of this developed power is lost in R_a (which includes brush contact loss), part is lost in $R_f = R_{fc} + R_{fw}$, and part is lost in R_{sr}. The remaining power is available as the output electrical power. Various powers and losses in a motoring operation are shown in Fig.3.31c.

The percentage losses depend on the size of the DC machine. The range of percentage losses shown in Fig.3.31 is for DC machines in the range 1 to 100 kW or 1 to 100 hp. Smaller machines have a larger percentage of losses, whereas larger machines have a smaller percentage of losses.

The efficiency of the machine is:

$$efficiency = \frac{P_{output}}{P_{input}} \tag{3.26}$$

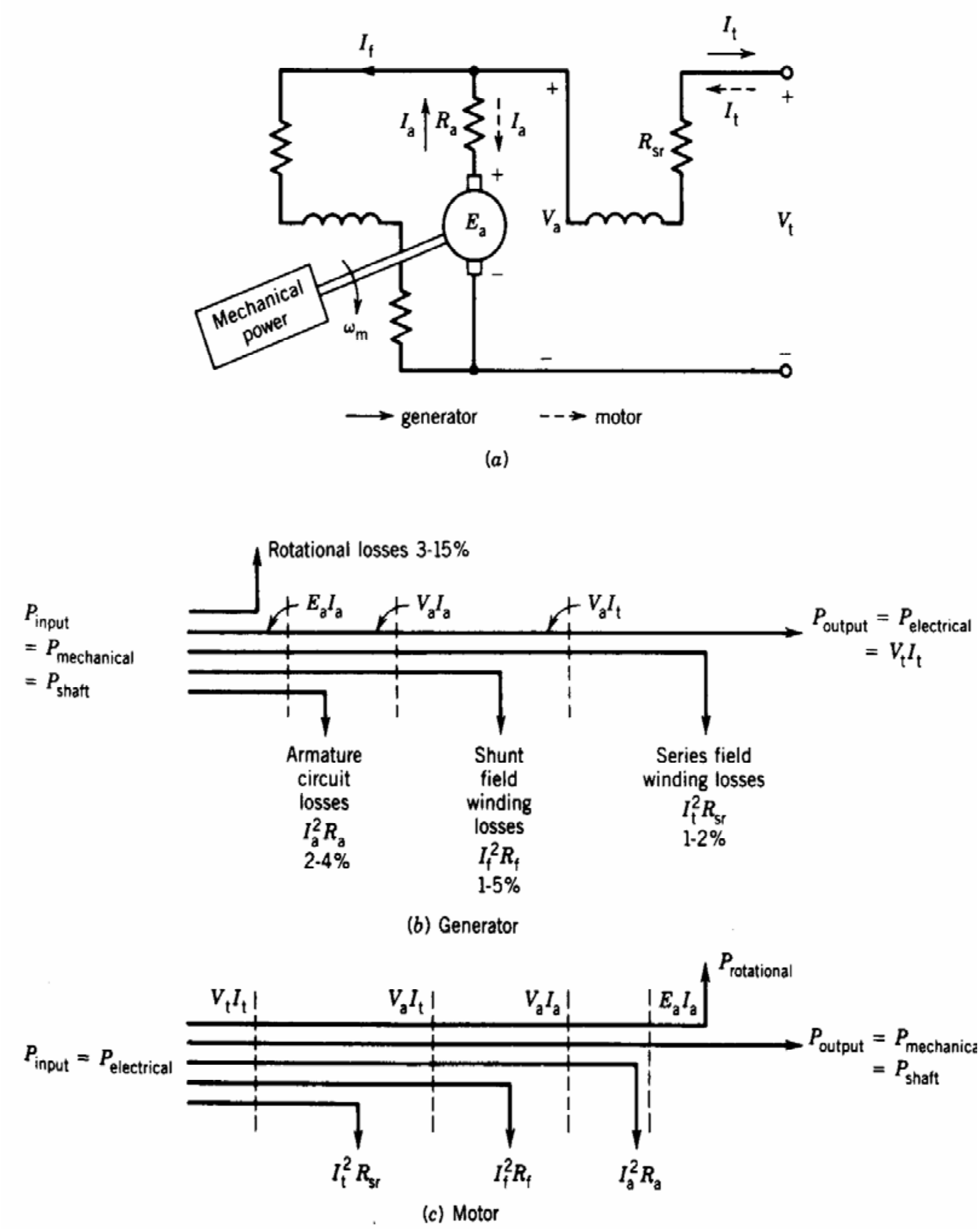


Fig.3.31 Power losses in a DC machine.

3.20 Condition for Maximum Power

The mechanical power developed by a motor is:

$$P_m = V_t * I_a - I_a^2 R_a \qquad (3.27)$$

Differentiating both sides with respect to I_a we get:

$$\frac{dP_m}{dI_a} = V_t - 2I_a R_a = 0 \qquad (3.28)$$

Then, $I_a R_a = V_t / 2$ (3.29)

As $V_t = E_a + I_a R_a \;\; and \;\; I_a * R_a = V_t / 2$

Then $E_a = V_t / 2$ (3.30)

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

3.21 Torque

By the term torque is meant the turning or twisting moment of a force about an axis. It is measured by the product of the force and the radius at which this force acts.

Consider a pulley of radius *r* meters acted upon by a circum ferential force of *F* Newton which causes it to rotate at *N rps*

Then, torque $T = F * r$ Newton meter (N-m)

Work done by this force in one revolution

=Force * distance $= F * 2\pi r$

Power developed $= F * 2\pi r * N$ joule/second

$= (F * r) * 2\pi N$ joule/second

Now $2\pi N =$ angular velocity ω in rad/second

power developed = $T * \omega$ joule/second or watt (3.31)

Series-wound DC motor

In series DC motor field & armature circuits are connected in series, as shown in the Figure below; so $I_a = I_f$. Assuming linear dependence of flux on the field current (approximately), we have:

- Note, there is no voltage drop across the inductance in a steady-state regime (because Ia=const in time)

3.22 Armature Torque of a Motor

Let T_a be the torque developed by the armature of a motor running at N *rps* If T_a is in N-m, then power developed, $P_{dev} = T_a * 2\pi N$ watt (3.32)

We also know that electrical power converted into mechanical power in the armature is $E_a * I_a$ (3.33)

Equating (3.32) and (3.33), we get $T_a * 2\pi N = E_a I_a$

Since $E_a = \phi ZN \frac{P}{A}$ volt, we have:

$$T_a * 2\pi N = \phi ZN \frac{P}{A} * I_a \quad (3.34)$$

Then, $T_a = \frac{1}{2\pi} \phi Z I_a \frac{P}{A}$ N-m (3.35)

or $T_a = 0.159 \phi Z I_a \frac{P}{A}$ N.m (3.36)

Note. From the above equation for the torque, we find that

$T_a \alpha \phi I_a$

(a) 1n the case of a series motor, ϕ is directly proportional to I_a (before saturation) because field windings carry full armature current. $\therefore T_a \alpha I_a^2$.

(b) For shunt motors, ϕ is practically constant, hence $\therefore T_a \alpha I_a$

It is also seen from (3.34) above that,

$$T_a = \frac{1}{2\pi} \frac{E_a I_a}{N} N.m \quad (3.37)$$

3.23 Shaft Torque

The whole of the armature torque, as calculated above, is not available for doing useful work, because a certain percentage of this is required for supplying iron and friction losses in the motor.

The torque which is available for doing useful work is known as *shaft torque* T_{sh}. It is so called because it is available at the shaft. The horse-power obtained by using the shaft torque is called *Brake Horse-Power* (*B.H.P.*) because it is the horse-power available at the brake.

$$B.H.P._{(meteric)} = \frac{T_{sh} * 2\pi N}{735.5} \qquad (3.38)$$

$$T_{sh} = \frac{735.5 * B.H.P._{(meteric)}}{2\pi N} \qquad (3.39)$$

The difference $T_a - T_{sh}$ is known as lost torque (3.40)

Example 3.12 *A 500V, 50 b.h.p. (37.3 kW), 1000 rpm DC shunt motor has on full-load an efficiency of 90 percent. The armature circuit resistance is 0.24 Ω and there is total voltage drop of 2 V at the brushes. The field current is 1.8 A. Determine (i) full-load line current (ii) full-load shaft torque in N-m and (iii) total* *resistance in motor, starter to limit the starting current to 1.5 times the full-load current.*

Solution: *(i)* Motor input=37,300/0.9=41,444 *W*;

Full load line current =41,444/500=82.9 *A*

$$(ii)\, T_{sh} = \frac{output}{\omega} = \frac{37300}{2\pi\left(\frac{1000}{60}\right)} = 356\, N.m$$

(iii) Starting line current =1.5*82.9=124.3 A

Armature current at starting =124.3 –1.8=122.5 A

If *R* is the starter resistance (which is in series with armature); then

$$122.5 * (R + 0.24) + 2 = 500$$

Then, *R*=3.825 Ω

Example 2.13 *A 4-pole, 220-V shunt motor has 340 lap-wound conductors. It takes 32 A from the supply mains and develops 7.5 h. p. (5.595 kW). The field winding takes 1 A. The armature resistance is 0.09 Ω and the flux per pole is 30 mWb. Calculate (i) the speed and (ii) the torque developed in newton-metere.*

$$I_a = 32 - 1 = 31A$$

$$E_b = V - I_a R_a = 220 - (0.09 * 31) = 217.2V$$

$$Now,\ E_b = \frac{\phi Z N}{60}\left(\frac{P}{A}\right)$$

$$217.2 = \frac{30*10^{-2}*540*N}{60}\left(\frac{4}{4}\right)$$

(i) $\therefore N = 804.4\ rpm = 13.4\, rps$

(ii) $T_{sh} = \frac{output\, in\, watt}{\omega} = \frac{5595}{2\pi*13.4} = 66.5\ N.m$

Example 3.14 *A DC series motor takes 40 A at 220 V and runs at 800 rpm If the armature and field resistances are 0.2 Ω and 0.1Ω respectively and the iron and friction losses are 0.5 k W, find the torque developed in the armature. What will be the output of the motor?*

Solution:

Armature torque is given by $T_a = \frac{E_a I_a}{2\pi N}$ *N.m*

Now

$$E_a = V - I_a\left(R_a + R_{se}\right) = 220 - 40*\left(0.2 + 0.1\right) = 208V$$

$$N = \frac{800}{60} = \frac{40}{3} rps$$

$$\therefore T_a = \frac{1}{2\pi}\frac{E_a I_a}{N} N.m = \frac{1}{2\pi}*\frac{208*40}{(40/3)} = 99.3\ N.m$$

Cu loss in armature and series-field resistance:

$$= 40^2 * 0.3 = 480W$$

Iron and friction losses= 500 W,

Total losses=480+500=980 W

Motor power input =220 * 40=8,800 W

Motor output=8,800-980 =7,820 W =7.82 kW

Example 3.15 *A 4-pole, 240 V, wave-connected shunt motor gives 11.19 kW when running at 1000 rpm and drawing armature an field-currents of 50 A and 1.0 A respectively. It has 540 conductors. Its resistance is 0.1Ω. Assuming a drop of 1 volt per brush, find (a) total torque (b) useful torque (c) useful flux/pole (d) rotational losses and (e) efficiency.*

Solution:

$$E_a = V - I_a R_a - Brush\,drop = 240 - 50 * 0.1 - 2 = 233V$$

Also, $I_a = 50A$

(a) Armature Torque:

$$T_a = \frac{0.159 * E_a I_a}{N} = \frac{0.159 * 233 * 50}{50/3} = 111 N.m$$

(b) $T_{sh} = \frac{Output}{2\pi N} = \frac{11190}{2\pi * 50/3} = 106.9\ N.m$

(c) $E_a = \phi Z N \frac{P}{A}$

Then, $233 = \phi 540 * 50 / 3 * \frac{4}{2}$

Then, $\phi = 12.9\, mWb.$

(d) Armature Input =$V * I_a = 240 * 50 = 12000W$

Armature Cu loss $= I_a^2\, R_a = 50^2 * 0.1 = 250\,W$

Brush contact loss= 50 * 2= 100 W

Power developed= 12,000- 350=11,650 W;

Output=11.19 kW=11,190 W

Rotational losses=11,650 - 1,190=460 W

(e) Total motor input = VI= 240 * 51=12,240 W;

Motor output= 11,190 W

$$\therefore Effeciency = \frac{output}{Input} = \frac{11190}{12240} * 100 = 91.4\%$$

Example 3.16 *A 460 V series motor runs at 500 rpm taking a current of 40 A. Calculate the speed and percentage change in torque if the load is reduced so that the motor is taking 30 A. Total resistance of the armature and field circuits is 0.8 Ω. Assume flux is proportional to the field current.*

Solution*:*

Since $\phi\, \alpha\, I_a$ hence $T \alpha\, \phi\, I_a\, \alpha\, I_a^2$

$T_1\, \alpha\, 40^2$ *and* $T_2\, \alpha\, 30^2$

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

Percentage change in torque is

$$= \frac{T_1 - T_2}{T_1} * 100 = \frac{7}{16} * 100 = 43.75\%$$

Now $E_{a_1} = 460 - (40 * 0.8) = 428V$

$$E_{a_2} = 460 - (30 * 0.8) = 436V$$

$$\frac{N_2}{N_1} = \frac{E_{a_2}}{E_{a_1}} * \frac{I_{a_1}}{I_{a_2}}$$

Then, $\frac{N_2}{500} = \frac{436}{428} * \frac{40}{30}$

Then, $N_2 = 679\,rpm$

3.24 Speed of a DC Motor

From the voltage equation of a motor we get,

$$E_a = V - I_a * R_a \quad Or \quad \phi ZN\left(\frac{P}{A}\right) = V - I_a R_a \tag{3.41}$$

$$N = \frac{V - I_a R_a}{\phi} * \left(\frac{A}{ZP}\right) \; rps \tag{3.42}$$

Now $V - I_a R_a = E_a$ (3.43)

Then, $N = \frac{E_a}{\phi} * \left(\frac{A}{ZP}\right) rps \quad or \quad N = k\frac{E_a}{\phi}$ (3.44)

It shows that speed is directly proportional to back *EMF*. E_a and

inversely-to the flux ϕ or $N \alpha \frac{E_a}{\phi}$ (3.45)

For Series Motor

Let N_1speed in the 1st case;

I_{a_1} =armature current in the 1st case

ϕ_1 =flux/pole in the first case :

N_1, I_{a_2}, ϕ_2 =corresponding quantities in the 2nd case.

Then using the above relation, we get:

$$N_1 \alpha \frac{E_{a_1}}{\phi_1}, \; Where \;\; E_{a_1} = V - I_{a_1} R_a \quad (3.46)$$

$$N_2 \alpha \frac{E_{a_2}}{\phi_2}, \; Where \;\; E_{a_2} = V - I_{a_2} R_a \quad (3.47)$$

$$\therefore \frac{N_2}{N_1} = \frac{E_{a_2}}{E_{a_1}} * \frac{\phi_1}{\phi_2} \quad (3.48)$$

Prior to saturation of magnetic poles ; $\phi \, \alpha \, I_a$

$$\therefore \frac{N_2}{N_1} = \frac{E_{a_2}}{E_{a_1}} * \frac{I_{a_1}}{I_{a_2}} \quad (3.49)$$

For Shunt Motor

In this case the same equation applies,

$$\therefore \frac{N_2}{N_1} = \frac{E_{a_2}}{E_{a_1}} * \frac{\phi_1}{\phi_2}, \; If \;\; \phi_2 = \phi_1 \;\; Then, \; \frac{N_2}{N_1} = \frac{E_{a_2}}{E_{a_1}} \qquad (3.50)$$

3.25 Speed Regulation

The term speed regulation refers to the change in speed of a motor with change in applied load torque, other conditions remaining constant. By change in speed here is meant the change which occurs under these conditions due to inherent properties of the motor itself and not those changes which are affected through manipulation of rheostats or other speed-controlling devices.

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

$$\therefore \% Speed\ regulation = \frac{N.L\,speed - F.L\,Speed}{F.L\,Speed} * 100 \qquad (3.51)$$

Example 3.17 *A shunt generator delivers 50 kW at 250 V and 400 rpm The armature and field resistances are 0.02 Ω and 50 Ω respectively. Calculate the speed of the machine running as a* *shunt motor and taking 50 kW input at 250 V. Allow 1 volt per brush for contact drop.*

Solution:

As Generator [Fig.3.32*(a)*]

Load current, I=50,000/250=200 A;

Shunt current, I_{sh} 250/50=5 A

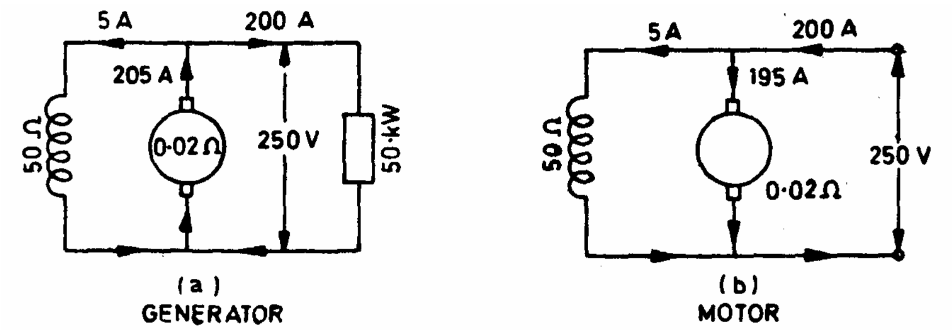


Fig.3.32

$I_a = I + I_{sh} = 205\text{A},$

$I_a R_a = 205 * 0.02 = 4.1$ V;

Brush drop=2 * 1 =2V

Induced *EMF* in armature =250 + 4.1 +2=256.1 V

Obviously, if this machine were to run as a motor at 400 *rpm*, it would have a back *EMF* of 256.1 V induced in its armature.

$\therefore E_{a_1} = 256.1V,\ N_1 = 400\ \ rpm$

As Motor [Fig. 3.32 *(b)*]

Input line current *I*=50,000/250=200 A

$I_{sh} = 250/50 = 5$ A;

$I_a = 200 - 5 = 195$ A

$I_a R_a = 195 * 0.02 = 3.9\ V$

Brush drop=2 * 1 =2V

$E_{a_2} = 25 - (3.9 + 2) = 244.1V$

$\frac{N_2}{N_1} = \frac{E_{a_2}}{E_{a_1}} * \frac{\phi_1}{\phi_2}$, $Since\ \phi_2 = \phi_1$

$Then,\ \frac{N_2}{N_1} = \frac{E_{a_2}}{E_{a_1}}$ $Then,\ \frac{N_2}{400} = \frac{244.1}{256.1}$

Then, $N_2 = 381.4\ rpm$

Example 3.18 *The input to a 220 V, DC shunt motor is 11 kW. Calculate (a) the torque developed (b) the efficiency (c) the speed at this load. The particulars of the motor are as follows:*

No-load current =5 A ;

No-load speed= 1150 rpm.

Arm. resistance =0.5Ω

shunt field resistance =110Ω

Solution.

No-load input = 220 * 5 =1,100 W ;

$I_{sh} = 220/110 = 2$ A

$I_{a0} = 5\text{-}2 = 3$A

No-load armature Cu loss=$3^2 * 0.5 = 4.5\ W$

Then, Constant losses=1,100-4.5=1095.5 W

When input is 11 kW

Input current=11,000/220=50 A ;

Armature current=50-2=48 A

Arm. Cu loss=48^2*0.5=1,152 W

Total loss=Arm. Cu loss + constant losses:

=1152- 1095.5=2248 W

Output=11,000-2,248=8,752 W

(b) Efficiency= 8,752 * 100/11,000=79.6%

(c) Back *EMF* at no-load=220-(3 * 0.5)=218.5 V

Back *EMF* at given load=220-(48 * 0.5)=196 V

Then, Speed *N*=1150* 196/218.5=1,031 *rpm*

(d) Power developed in armature=$E_a I_a = 196*48$ W

$T_a * 2\pi * 1031/60 = 196 * 48,$

Then, $T_a = 196 * 48 * 60/2\pi * 1031 = 87.1 N.m$

Example 3.19 *A 220 V, series motor in which the total armature and field resistance is 0.1Ω is working with unsaturated* *field, taking 100 A and running at 800 rpm Calculate at what speed the motor will run when developing half the torque ?*

Solution:

$$\therefore \frac{N_2}{N_1} = \frac{E_{a_2}}{E_{a_1}} * \frac{\phi_1}{\phi_2} = \frac{E_{a_2}}{E_{a_1}} * \frac{I_{a_1}}{I_{a_2}}$$

Since field is unsaturated, $T_a \,\alpha\, \phi\, I_a \,\alpha\, I_a^2$

Then, $T_1 \,\alpha\, I_{a1}^2 \quad and \quad T_2 \,\alpha\, I_{a2}^2$

Or,

$$\frac{T_2}{T_1} = \left(\frac{I_{a2}}{I_{a1}}\right)^2$$

$$Then,\ \frac{1}{2} = \left(\frac{I_{a2}}{I_{a1}}\right)^2$$

Then, $I_{a2} = I_{a1} / \sqrt{2} = 1000 / \sqrt{2} = 70.7\ A$

$$E_{a_1} = 220 - 100 * 0.1 = 210V$$

$$E_{a_2} = 220 - 70.7 * 0.1 = 212.9\ V$$

$\therefore \frac{N_2}{800} = \frac{212.9}{210} * \frac{100}{70.7}$, Then, $N_2 = 1147\ rpm$

Problems

1- A DC machine (6 kW, 120 V, 1200 rpm) has the following magnetization characteristics at 1200 rpm.

I_f, A	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.2
E_a, V	5	20	40	60	79	93	102	114	120	125

The machine parameters are $R_a = 0.2\Omega$, $R_{fw} = 100\ \Omega$. The machine is driven at 1200 rpm and is separately excited. The field current is adjusted at $I_f = 0.8$ A. A load resistance $R_L = 2\ \Omega$ is connected to the armature terminals. Neglect armature reaction effect.

(a) Determine the quantity $K_a\phi$ for the machine. (b) Determine E_a and I_a. (c) Determine torque T and load power P_L

2- Repeat Problem 1 if the speed is 800 rpm.

3-The DC generator in Problem 1 rotates at 1500 rpm and it delivers rated current at rated terminal voltage. The field winding is connected to a 120 V supply.

(a) Determine the value of the field current.

(b) Determine the value of Rf, required.

4- The DC machine in Problem 1 has a field control resistance whose value can be changed from 0 to 150 Ω. The machine is driven at 1200 rpm. The machine is separately excited and the field winding is supplied from a 120 V supply.

(a) Determine the maximum and minimum values of the no-load terminal voltage.

(b) The field control resistance R_{fc} *is adjusted to provide a no-load terminal voltage of 120 V. Determine the value of* R_{fc}*,. Determine the terminal voltage at full load for no armature reaction and also if* $I_{f(AR)}$*= 0.1 A.*

5-Repeat Problem 4 if the speed is 1500 rpm.

6- The DC machine in Problem 1 is separately excited. The machine is driven at 1200 rpm and operates as a generator. The *rotational loss is 400 W at 1200 rpm and the rotational loss is proportional to speed.*

(a)For a field current of 1.0 A, with the generator delivering rated current, determine the terminal voltage, the output power, and the efficiency. (b)Repeat part (a) if the generator is driven at 1500 rpm.

7-The DC machine in Problem 4 is self-excited.

(a) Determine the maximum and minimum values of the no-load terminal voltage.

(b) R_{fc} *is adjusted to provide a no-load terminal voltage of 120 V. Determine the value of* R_{fc}.

(i)Assume no armature reaction. Determine the terminal voltage at rated armature current. Determine the maximum current the armature can deliver. What is the terminal voltage for this situation?

(ii) Assume that $I_{f(AR)} = 0.1$ *A at* $I_a = 50$ *A and consider armature reaction proportional to armature current. Repeat part (i).*

8- A DC machine (10 kW, 250 V, 1000 rpm) has $R_a = 0.2\ \Omega$ *and* $R_{fw} = 133\ \Omega$. *The machine is self-excited and is driven at 1000 rpm. The data for the magnetization curve are*

I_f	0	0.1	0.2	0.3	0.4	0.5	0.75	1.0	1.5	2.0
E_a	10	40	80	120	150	170	200	220	245	263

(a) Determine the generated voltage with no field current.

(b) Determine the critical field circuit resistance.

(c) Determine the value of the field control resistance (RfJ if the no-load terminal voltage is 250 V.

(d) Determine the value of the no-load generated voltage if `the generator is driven at 800 rpm and $R_{fc} = 0$.

(e) Determine the speed at which the generator is to be driven such that no-load voltage is 200 V with $R_{fc} = 0$.

9- The self-excited DC machine in Problem 8 delivers rated load when driven at 1000 rpm. The rotational loss is 500 watts.

(a) Determine the generated voltage.

(b) Determine the developed torque.

(c) Determine current in the field circuit. Neglect the armature reaction effect.

(d) Determine the efficiency.

10- A DC shunt machine (24 kW, 240 V, 1000 rpm) has $R_a = 0.12\ \Omega$, $N_f = 600$ *turns/pole. The machine is operated as a separately excited DC generator and is driven at 1000 rpm. When* $I_f = 1.8$ *A,* *the no-load terminal voltage is 240 V. When the generator delivers full-load current, the terminal voltage drops to 225 V.*

(a) Determine the generated voltage and developed torque when the generator delivers full load.

(b) Determine the voltage drop due to armature reaction.

(c) The full-load terminal voltage can be made the same as the no-load terminal voltage by increasing the field current to 2.2 A or by using series winding on each pole. Determine the number of turns per pole of the series winding required if If is kept at 1.8 A.

11- A DC series machine (9.25 kW, 185 V, 1500 rpm) has $R_a + R_{sr} = 0.3\ \Omega$. The data for the magnetization curve are;

$I_a(a)$	0	10	20	30	40	50	60
$E_a(v)$	10	50	106	156	184	200	208

Determine the terminal voltage at (a) $I_a = 20$ A. (b) $I_a = 40$ A. (c) I_a =60 A. if the DC series machine operates as a generator.

12- A separately excited DC motor has the following nameplate data: 100 hp, 440 V, 2000 rpm. (a) Determine the rated torque. (b) Determine the current at rated output if the efficiency of the motor is 90% at rated output.

13- The DC machine of Problem 1 is operated at If = 1.0 A. The terminal voltage of the DC machine is 220 V and the developed *torque is 100 N. m. Determine the speed of the DC machine when it operates (a) As a motor. (b) As a generator.*

14 The DC machine in Problem 1 is operated as a DC shunt motor. Determine the minimum and maximum no-load speeds if R_{fc} is varied from 0 to 200 Ω.

15- Repeat Problem 4.18 for the full-load condition if $R_{fc} = 0\Omega$.

(a) Assume no armature reaction.

(b) Assume a 10% reduction of flux at full load.

16- The DC shunt machine in Problem 1 is provided with a series field winding of $N_s = 5$ turns/pole and $R_S = 0.05\Omega$. It is connected as along-shunt compound machine. If $R_{fc} = 50\ \Omega$ and the machine is operated as a cumulative compound motor

(a) Determine its no-load speed.

(b) Determine its full-load speed. Assume no armature reaction.

17-Repeat Problem 4.20 if the DC motor is connected as a differentially compounded motor.

18- The compound DC machine in Problem 16 is operated as a series motor by not using the shunt field winding. Determine the speed and torque at (a) 50% rated current. (b) 100% rated current.

19- A DC machine is connected across a 240-volt line. It rotates at 1200 rpm and is generating 230 volts. The armature current is 40 amps. (a) Is the machine functioning as a generator or as a motor? (b) Determine the resistance of the armature circuit. (c) Determine power loss in the armature circuit resistance and the electromagnetic power. (d) Determine the electromagnetic torque in newton-meters. (e) If the load is thrown off, what will the generated voltage and the rpm of the machine be, assuming
(i) No armature reaction. (ii)10% reduction of flux due to armature reaction at 40 amps armature current.

20- The DC shunt machine in Problem 4.13 is used as a motor to drive a load
which requires a constant power of 15.36 kW. The motor is connected to a 300 V DC supply.
(a) Determine the speed range possible with a field rheostat of 200 Ω.
(b) Determine the efficiency at the lowest and highest speeds. For this part, assume a constant rotational loss of 300 W over the speed range.

21-A permanent magnet DC motor drives a mechanical load requiring a constant torque of 25 N . m. The motor produces 10 N.m with an armature current of 10 A. The resistance of the armature circuit is 0.2 Ω. A 200 V DC supply is applied to the armature terminals. Determine the speed of the motor.

22- A DC shunt motor drives an elevator load which requires a constant torque of 300 N.m. The motor is connected to a 600 V DC supply and the motor

rotates at 1500 rpm. The armature resistance is 0.5 Ω.

(a) Determine the armature current.

(b) If the shunt field flux is reduced by 10%, determine the armature current and the speed of the motor.

23- A DC shunt motor (50 hp, 250 V) is connected to a 230 V supply and delivers power to a load drawing an armature current of 200 amperes and running at a speed of 1200 rpm. $R_a = 0.2\ \Omega$.

(a) Determine the value of the generated voltage at this load condition.

(b) Determine the value of the load torque. The rotational losses are 500 watts.

(c) Determine the efficiency of the motor if the field circuit resistance is 115 Ω.

24 A DC shunt machine (23 kW, 230 V, 1500 rpm) has R. = 0.1 Ω.

1. The DC machine is connected to a 230 V supply. It runs at 1500 rpm at no-load and 1480 rpm at full-load armature current.

(a) Determine the generated voltage at full load.

(b)Determine the percentage reduction of flux in the machine due to armature reaction at full-load condition.

2. The DC machine now operates as a separately excited generator and the field current is kept the same as in part 1. It delivers full load at rated voltage.

(a) Determine the generated voltage at full load.

(b) Determine the speed at which the machine is driven.

(c) Determine the terminal voltage if the load is thrown off.

25 A DC shunt machine (10 kW, 250 V, 1200 rpm) has Ra = 0.25 S2. The machine is connected to a 250 V DC supply, draws rated armature current, and rotates at 1200 rpm.

(a) Determine the generated voltage, the electromagnetic power developed, and the torque developed.

(b) The mechanical load on the motor shaft is thrown off, and the motor draws 4 A armature current.

(i) Determine the rotational loss. (iii)Determine speed, assuming 10% change in flux due to armature reaction, for a change of armature current from rated value to 4 A.

26 A 240 V, 2 hp, 1200 rpm DC shunt motor drives a load whose torque varies directly as the speed. The armature resistance of the motor is 0.75 SZ. With If = 1 A, the motor draws a line current of 7 A and rotates at 1200 rpm.

Assume magnetic linearity and neglect armature reaction effect. (a) The field current is now reduced to 0.7 A. Determine the operating speed of the motor.

(b) Determine the line current, mechanical power developed, and efficiency for the operating condition of part (a). Neglect rotational losses.

27- Repeat Problem 26 if the load torque is constant. Determine the torque.