MODULE – 3

Transformers (continuation): Cause and effects of harmonics, Current inrush intransformers, noise in transformers. Objects of testing transformers, polarity test, Sumpner'stest.

Direct current Generator – Review of construction, types, armature windings, relation between no load and terminal voltage (No question shall be set from the review portion).Armature reaction, Commutation and associated problems, no load and full load characteristics. Reasons for reduced dependency on dc generators.

Synchronous generators- Review of construction and operation of salient & non-salient pole synchronous generators (No question shall be set from the review portion). Armature windings, winding factors, emf equation. Harmonics – causes, reduction and elimination. Armature reaction, Synchronous reactance, Equivalent circuit. **10 Hours**

Harmonics

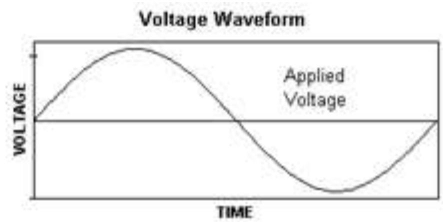
Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate (e.g. 50Hz or 60 Hz).

Harmonics are simply a technique to analyze the current drawn by computers, electronic ballasts, variable frequency drives and other equipment which have modem "transformer-less" power supplies.

There are two important concepts to bear in mind with regard to power system harmonics.

The first is the nature of harmonic-current producing loads (non-linear loads) and the second is the way in which harmonic currents flow and how the resulting harmonic voltages develop.

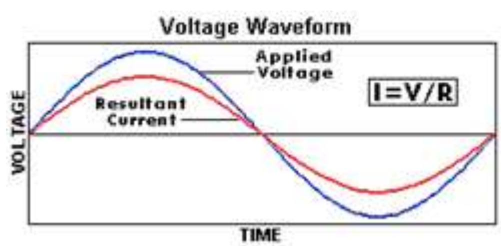
There is a law in electrical engineering called Ohm’s Law. This basic law states that when a voltage is applied across a resistance, current will flow. This is how all electrical equipment operates. The voltage we apply across our equipment is a sine wave which operates 60 Hertz (cycles per second).



To generate this voltage sine wave. It has (relatively) constant amplitude and constant frequency.

Once this voltage is applied to a device, Ohm’s Law kicks in. Ohm’s Law states that current equal’s voltage divided by resistance. Expressed mathematically $I=V/R$

Expressed graphically, the current ends up being another sine wave, since the resistance is a constant number. Ohm’s Law dictates that the frequency of the current wave is also 60 Hertz. In the real world, this is true; although the two sine waves may not align perfectly (as a power factor) the current wave will indeed be a 60 Hertz sine wave.



Since an applied voltage sine wave will cause a sinusoidal current to be drawn, systems which exhibit this behaviour are called linear systems. Incandescent lamps, heaters and motors are linear systems.

Some of our modem equipment however does not fit this category. Computers, variable frequency drives, electronic ballasts and uninterruptable power supply systems are non-linear systems. In these systems, the resistance is not a constant and in fact, varies during each sine wave. This occurs because the resistance of the device is not a constant. The resistance in fact, changes during each sine wave

Linear and non-linear loads (motors, heaters and incandescent lamps):

A linear element in a power system is a component in which the current is proportional to the voltage.

In general, this means that the current wave shape will be the same as the voltage (See Figure 1). Typical examples of linear loads include motors, heaters and incandescent lamps.

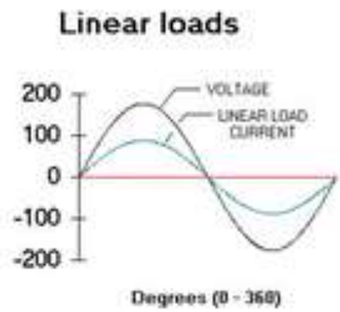


Figure 1. Voltage and current waveforms for linear

Non-Linear System (Computers, VFDS, Electronic Ballasts):

As in Figure As we apply a voltage to a solid state power supply, the current drawn is (approximately) zero until a critical "firing voltage" is reached on the sine wave. At this firing voltage, the transistor (or other device) gates or allows current to be conducted.

This current typically increases over time until the peak of the sine wave and decreases until the critical firing voltage is reached on the "downward side" of the sine wave. The device then shuts off and current goes to zero. The same thing occurs on the negative side of the sine wave with a second negative pulse of current being drawn. The current drawn then is a series of positive and negative pulses, and not the sine wave drawn by linear systems.

Some systems have different shaped waveforms such as square waves. These types of systems are often called non-linear systems. The power supplies which draw this type of current are called switched mode power supplies. Once these pulse currents are formed, we have a difficult time analyzing their effect. Power engineers are taught to analyze the effects of sine waves on power systems. Analyzing the effects of these pulses is much more difficult.

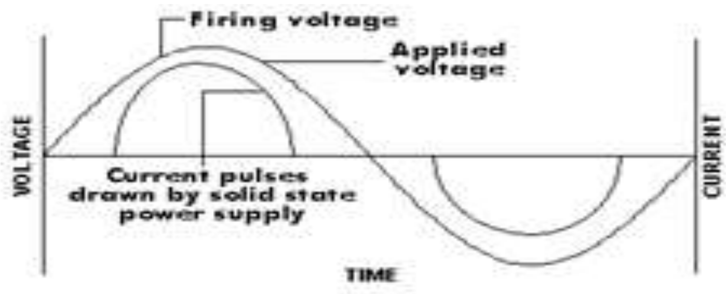


Figure 2. Voltage and current waveforms for linear

The current drawn by non-linear loads is not sinusoidal but it is periodic, meaning that the current wave looks the same from cycle to cycle. Periodic waveforms can be described mathematically as a series of sinusoidal waveforms that have been summed together.

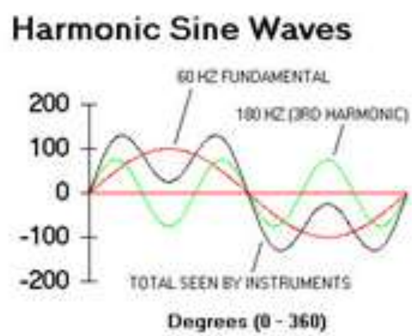


Figure 3. Waveform with symmetrical harmonic components

The sinusoidal components are integer multiples of the fundamental where the fundamental, in the United States, is 60 Hz. The only way to measure a voltage or current that contains harmonics is to use a true-RMS reading meter. If an averaging meter is used, which is the most common type, the error can be Significant.

Each term in the series is referred to as a harmonic of the fundamental. The third harmonic would have a frequency of three times 60 Hz or 180 Hz. Symmetrical waves contain only odd harmonics and un-symmetrical waves contain even and odd harmonics.

A symmetrical wave is one in which the positive portion of the wave is identical to the negative portion of the wave. An un-symmetrical wave contains a DC component (or offset) or the load is such that the positive portion of the wave is different than the negative portion. An example of un-symmetrical wave would be a half wave rectifier.

Most power system elements are symmetrical. They produce only odd harmonics and have no DC offset.

Harmonic current flow

When a non-linear load draws current that current passes through all of the impedance that is between the load and the system source (See Figure 4). As a result of the current flow, harmonic voltages are produced by impedance in the system for each harmonic.

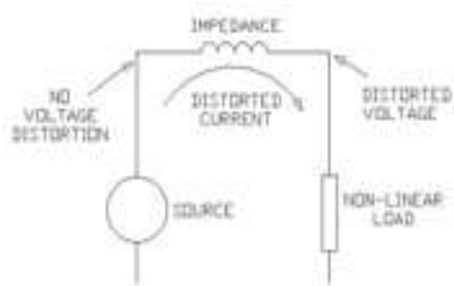


Figure 4 – Distorted-current induced voltage distortion

These voltages sum and when added to the nominal voltage produce voltage distortion. The magnitude of the voltage distortion depends on the source impedance and the harmonic voltages produced.

If the source impedance is low then the voltage distortion will be low. If a significant portion of the load becomes non-linear (harmonic currents increase) and/or when a resonant condition prevails (system impedance increases), the voltage can increase dramatically.

Harmonic currents can produce a number of problems:

Equipment heating

Equipment malfunction

Equipment failure

Communications interference

Fuse and breaker mis-operation

Process problems

Conductor heating.

How harmonics are generated

In an ideal clean power system, the current and voltage waveforms are pure sinusoids. In practice, non-sinusoidal currents are available due to result of the current flowing in the load is not linearly related to the applied voltage.

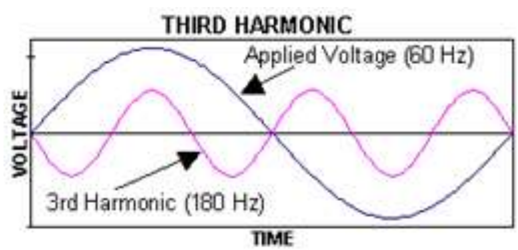
In a simple circuit containing only linear circuit elements resistance, inductance and capacitance. The current which flows is proportional to the applied voltage (at a particular frequency) so that, if a sinusoidal voltage is applied, a sinusoidal current will flow. Note that where there is a reactive element there will be a phase shift between the voltage and current waveforms the power factor is reduced, but the circuit can still be linear.

But in The situation where the load is a simple full-wave rectifier and capacitor, such as the input stage of a typical switched mode power supply (SMPS). In this case, current flows only when the supply voltage exceeds that stored on the reservoir capacitor, i.e. close to the peak of the voltage sine wave, as shown by the shape of the load line.

Any cyclical waveform can be de constructed into a sinusoid at the fundamental frequency plus a number of sinusoids at harmonic frequencies. Thus the distorted current waveform in the figure can be represented by the fundamental plus a percentage of second harmonic plus a percentage of third harmonic and so on, possibly up to the thirtieth harmonic.

For symmetrical waveforms, i.e. where the positive and negative half cycles are the same shape and magnitude, all the even numbered harmonics is zero. Even harmonics are now relatively rare but were common when half wave rectification was widely used.

The frequencies we use are multiples of the fundamental frequency, 60 Hz. We call these multiple frequencies harmonics. The second harmonic is two times 60 Hertz, or 120 Hz. The third harmonic is 180 Hertz and so on. In our three phase power systems, the “even” harmonics (second, fourth, sixth, etc.) cancel, so we only need deal with the “odd” harmonics.



This figure shows the fundamental and the third harmonic. There are three cycles of the third harmonic for each single cycle of the fundamental. If we add these two waveforms, we get a non-sinusoidal waveform.

This resultant now starts to form the peaks that are indicative of the pulses drawn by switch mode power supplies. If we add in other harmonics, we can model any distorted periodic waveform, such as square waves generated by UPS of VFD systems. It is important to remember these harmonics are simply a mathematical model. The pulses or square waves, or other distorted waveforms are what we actually see if we were to put an oscilloscope on the building’s wiring systems.

These current pulses, because of Ohm’s Law, will also begin to distort the voltage waveforms in the building. This voltage distortion can cause premature failure of electronic devices.

On three phase systems, the three phases of the power system are 120’ out of phase. The current on phase B occurs 120 deg (1/3 cycle) after the current on A. Likewise, the current on phase C occurs 120’ after the current on phase B. Because of this, our 60 Hertz (fundamental) currents actually cancel on the neutral. If we have balanced 60 Hertz currents on our three phase conductors, our neutral current will be zero. It can be shown mathematically that the neutral current (assuming only 60 Hertz is present) will never exceed the highest loaded phase conductor. Thus, our over current protection on our phase conductors also protects the neutral conductor, even though we do not put an over current protective device in the neutral conductor. We protect the neutral by the mathematics. When harmonic currents are present, this math breaks down. The third harmonic of each of the three phase conductors is exactly in phase. When these harmonic currents come together on the neutral, rather than cancel, they actually add and we can have more current on the neutral conductor than on phase conductors. Our neutral conductors are no longer protected by mathematics!

These harmonic currents create heat. This heat over a period of time will raise the temperature of the neutral conductor. This rise in temperature can overheat the surrounding conductors and cause insulation failure. These currents also will overheat the transformer sources which supply the power system. This is the most obvious symptom of harmonics problems; overheating neutral conductors and transformers. Other symptoms include:

Nuisance tripping of circuit breakers

Malfunction of UPS systems and generator systems

Metering problems

Computer malfunctions

Over voltage problems

Problems caused by harmonics

Harmonic currents cause problems both on the supply system and within the installation.

The effects and the solutions are very different and need to be addressed separately; the measures that are appropriate to controlling the effects of harmonics within the installation may not necessarily reduce the distortion caused on the supply and vice versa.

Harmonic problems within the installation

Problems caused by harmonic currents:

overloading of neutrals

overheating of transformers

nuisance tripping of circuit breakers

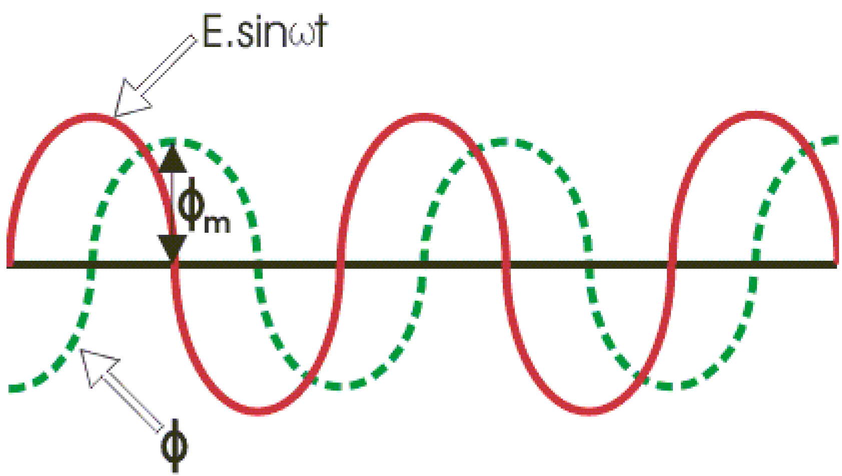
over-stressing of power factor correction capacitors

skin effect

Magnetizing Inrush Current in Power Transformer

When an electrical power transformer is switch on from primary side, with keeping its secondary circuit open, it acts as a simple inductance. When electrical power transformer runs normally, the flux produced in the core is in quadrature with applied voltage as shown in the figure below. That means, flux wave will reach its maximum value, 1/4 cycle or $\pi/2$ angle after, reaching maximum value of voltage wave. Hence as per the waves shown in the figure, at the instant when, the voltage is zero, the corresponding steady state value of flux should be negative maximum. But practically it is not possible to have flux at the instant of switching on the supply of transformer. This is because, there will be no flux linked to the core prior to switch on the supply. The steady state value of flux will only reach after a finite time, depending upon how fast the circuit can take energy. This is because the rate of energy transfer to a circuit cannot be infinity. So the flux in the core also will start from its zero value at the time of switching on the transformer.

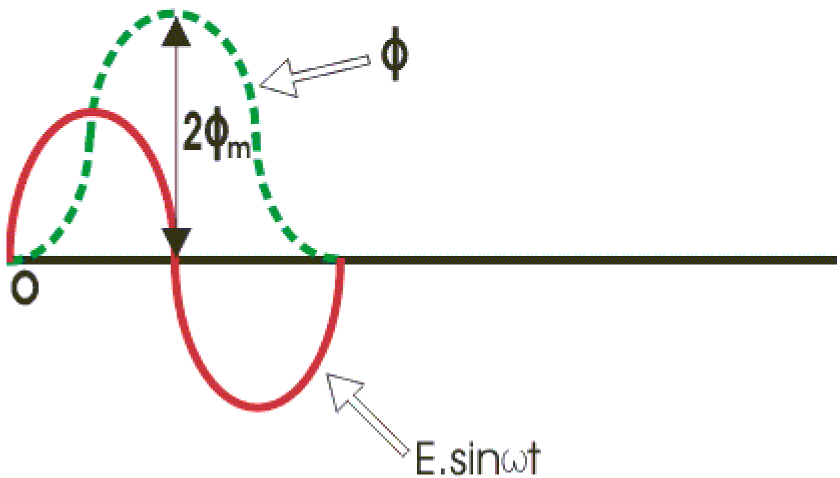
According to Faraday's law of electromagnetic induction the voltage induced across the winding is is given as e = dφ/dt. Where φ is the flux in the core. Hence the flux will bintegral of the voltage wave.



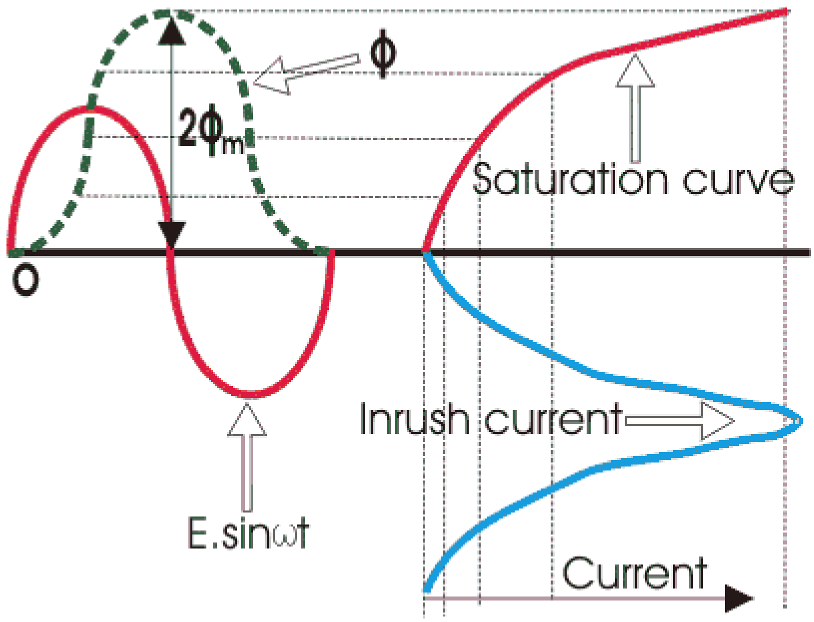
$$e = E.\sin\omega t = d\varphi/dt \Rightarrow \varphi = \int e.dt = E \int \sin\omega t.dt$$

If the transformer is switched on at the instant of voltage zero, the flux wave is initiated from the same origin as voltage waveform, the value of flux at the end of first half cycle of the voltage waveform will be,

$$\varphi_m' = (E/\omega) \int_0^\pi \omega.\sin\omega t.dt = \varphi_m \int_0^\pi \sin\omega t.d(\omega t) = 2\varphi_m$$



Where φm is the maximum value of steady state flux. The transformer core are generally saturated just above the maximum steady state value of flux. But in our example, during switching on the transformer the maximum value of flux will jump to double of its steady state maximum value. As, after steady state maximum value of flux, the core becomes saturated, the current required to produced rest of flux will be very high. So transformer primary will draw a very high peaky current from the source which is called magnetizing inrush current in transformer or simply inrush current in transformer.



Magnetizing inrush current in transformer is the current which is drown by a transformer at the time of energizing the transformer. This current is transient in nature and exists for few milliseconds. The inrush current may be up to 10 times higher than normal rated current of transformer.

Although the magnitude of inrush current is so high but it generally does not create any permanent fault in transformer as it exists for very small time. But still inrush current in power transformer is a problem, because it interferes with the operation of circuits as they have been designed to function. Some effects of high inrush include nuisance fuse or breaker interruptions, as well as arcing and failure of primary circuit components, such as switches. High magnetizing inrush current in transformer also necessitate over-sizing of fuses or breakers. Another side effect of high inrush is the injection of noise and distortion back into the mains.

Testing of Transformers

The structure of the circuit equivalent of a practical transformer is developed earlier. The performance parameters of interest can be obtained by solving that circuit for any load conditions. The equivalent circuit parameters are available to the designer of the transformers from the various expressions that he uses for designing the transformers. But for a user these are not available most of the times. Also when a transformer is rewound with different primary and secondary windings the equivalent circuit also changes. In order to get the equivalent circuit parameters test methods are heavily depended upon. From the analysis of the equivalent circuit one can determine the electrical parameters. But if the temperature rise of the transformer is required, then test method is the most dependable one. There are several tests that can be done on the transformer; however a few common ones are discussed here.

Winding resistance test

This is nothing but the resistance measurement of the windings by applying a small d.c voltage to the winding and measuring the current through the same. The ratio gives the winding resistance, more commonly feasible with high voltage windings. For low voltage windings a resistance-bridge method can be used. From the d.c resistance one can get the a.c. resistance by applying skin effect corrections.

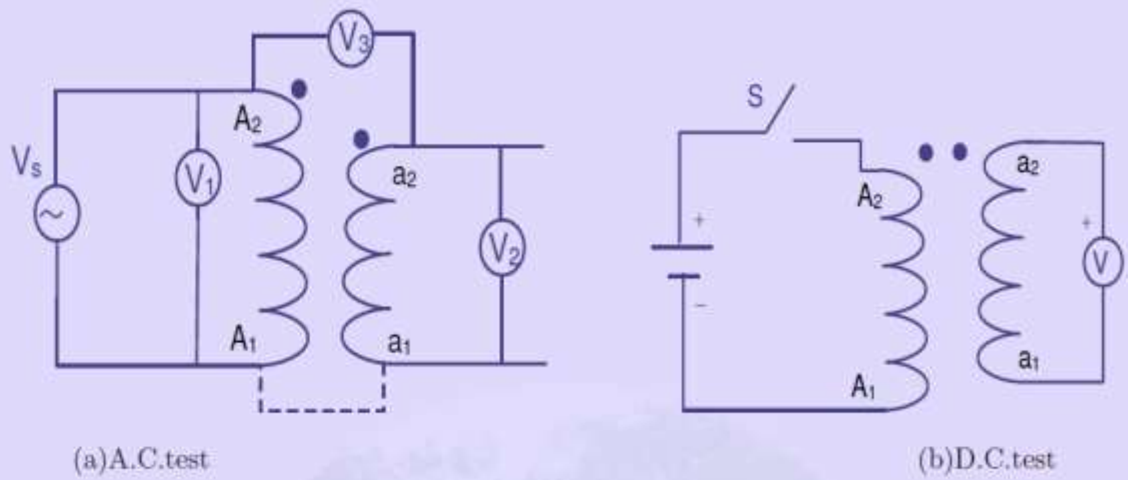


Figure 18: Polarity Test

Polarity Test

This is needed for identifying the primary and secondary phasor polarities. It is a must for poly phase connections. Both a.c. and d.c methods can be used for detecting the polarities of the induced emfs. The dot method discussed earlier is used to indicate the polarities. The transformer is connected to a low voltage a.c. source with the connections made as shown in the fig. 18(a). A supply voltage Vs is applied to the primary and the readings of the voltmeters V1, V2 and V3 are noted. V1 : V2 gives the turns ratio. If V3 reads V1−V2 then assumed dot locations are correct (for the connection shown). The beginning and end of the primary and secondary may then be marked by A1 −A2 and a1 −a2 respectively.

If the voltage rises from A1 to A2 in the primary, at any instant it does so from a1 to a2 inthe secondary. If more secondary terminals are present due to taps taken from the windings they can be labeled as a3, a4, a5, a6. It is the voltage rising from smaller number towards larger ones in each winding. The same thing holds good if more secondaries are present.

Fig. 18(b) shows the d.c. method of testing the polarity. When the switch S is closed if the secondary voltage shows a positive reading, with a moving coil meter, the assumed polarity is correct. If the meter kicks back the assumed polarity is wrong.

Sumpner's Test (Back to Back Test)

The Sumpner's test is another method of determining efficiency, regualtion and heating under load conditions. The O.C. and S.C. tests give us the equivalent circuit parameters but ca not give heating information under various load conditions. The Sumpner's test gives heating information also. In O.C. test, there is no load on the transformer while in S.C. circuit test also only fractional load gets applied. In all in O.C. and S.C. tests, the loading conditions are absent. Hence the results are inaccurate. In Sumpner's test, actual loading conditions are simulated hence the results obtained are much more accurate. Thus Sumpner;s test is much improved method of predetermining regulation and efficiency than O.C. and S.C. tests.

The Sumpner's test requires two identical transformers. Both the transformers are connected to the supply such that one transformer is loaded on the other. Thus power taken from the supply is that much necessary for supplying the losses of both the transformers and there is very small loss in the control circuit.

While conducting this test, the primaries of the two identical transformers are connected in parallel across the supply V1. While the secondaries are connected in series opposition so that induced e.m.f.s in the two secondaries oppose each other. The secondaries are supplied from another low voltage supply are connected in each circuit to get the readings. The connection diagram is shown in the Fig. 1.

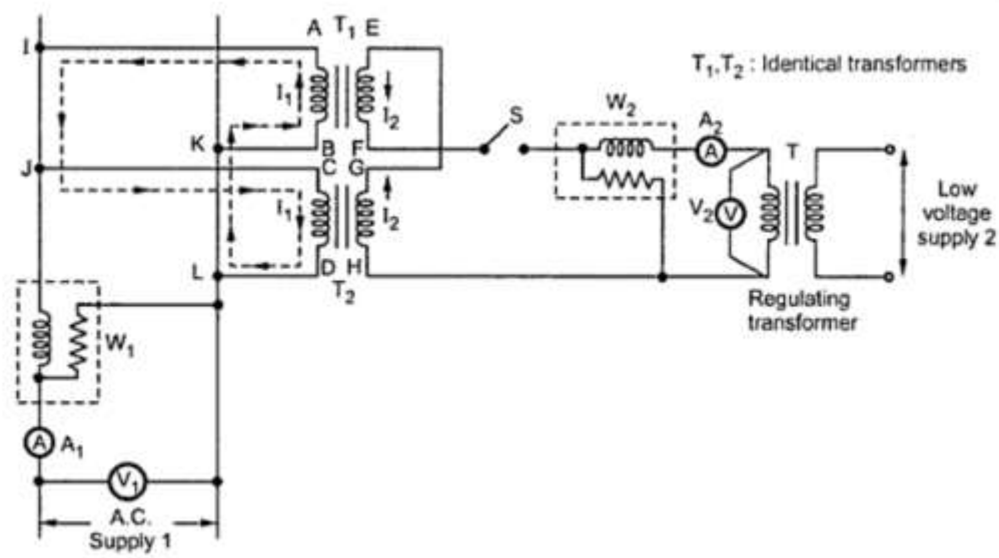


Fig 1 Connection diagram for Sumpner's test

T1 and T2 are two identical transformers. The secondaries of T1 and T2 are connected in series opposition. So EEF = EGH i.e. induced in two secondaries are equal but the secondaries are connected such that E is connected to G and F is connected to H. Due to such series opposition, two e.m.f.s act in opposite direction to each other and cancel each other. So net voltage ion the local circuit of secondaries is zero, when primaries are excited by supply 1 of rated voltage and frequency. So there is no current flowing in the loop formed by two secondaries. The series opposition can be checked by another voltmeter connected in the secondary circuit as per polarity test. If it reads zero, the secondaries are in series opposition and if it reads double the induced e.m.f. in each secondary, it is necessary to reverse the connections of one of the secondaries.

As per superposition theorem, if V2 is assumed zero then due to phase opposition to current flows through secondary and both the transformers T1, T2 are as good as on no load. So O.C. test gets simulated. The current drawn from source V1 in such case is 2 Io where Io is no load current of each transformer. The input power as measured by wattmeter W1 thus reads the iron losses of both the transformers.

Pi per transformer =W1 /2 as T1, T2 are identical

Then a small voltage V2 is injected into the secondary with the help of low voltage transformer, by closing the switch S. With regulation mechanism, the voltage V2 is adjusted so that the rated secondary current I2 flows through the secondaries as shown. I2 flows from E to F and then from H to G. The flow of I1 is restricted to the loop B A I J C D L K B and it does not pass through W1. Hence W1 continues to read core losses. Both primaries and secondaries carry rated current so S.C. test condition gets simulated. Thus the wattmeter W2 reads the total full load copper losses of both the transformers.

(Pcu) F.L.per transformer = W2 /2

Key Point : Thus in the sumpner's test without supplying the load, full iron loss occurs in the core while full copper loss occurs in the windings simultaneously. Hence heat run test can be conducted on the two transformers. In O.C. and S.C. test, both the losses do not occur simultaneously hence heat run test can not be conducted. This is the advantage of Sumpner's test.

From the test results the full load efficiency of each transformer can be calculated as,

$$\boxed{\% \, \eta_{F.L.} \text{ of each transformer} = \frac{\text{Output}}{\text{Output} + \frac{W_1}{2} + \frac{W_2}{2}} \times 100}$$

where output = VA rating x cos Φ2

Key Point : As all the voltage, currents and powers are measured during the test, the equivalent circuit parameters also can be determined. Hence the regulation at any load and load power factor condition can be predetermined.

The only limitation is that two identical transformers are required. In practice exact identical transformers can not be obtained. As two transformers are required, the test is not economical.

DC Generator

Introduction:

An Electrical generator is a machine which converts mechanical energy (or power) into electrical energy (or power).

The energy conversion is based on the principal of the production of dynamically (or motionally) induced emf. Whenever a conductor cuts magnetic flux, dynamically induced emf is produced in it according to Faraday's Laws of Electromagnetic Induction. This Emf causes a current to flow if the conductor circuit is closed.

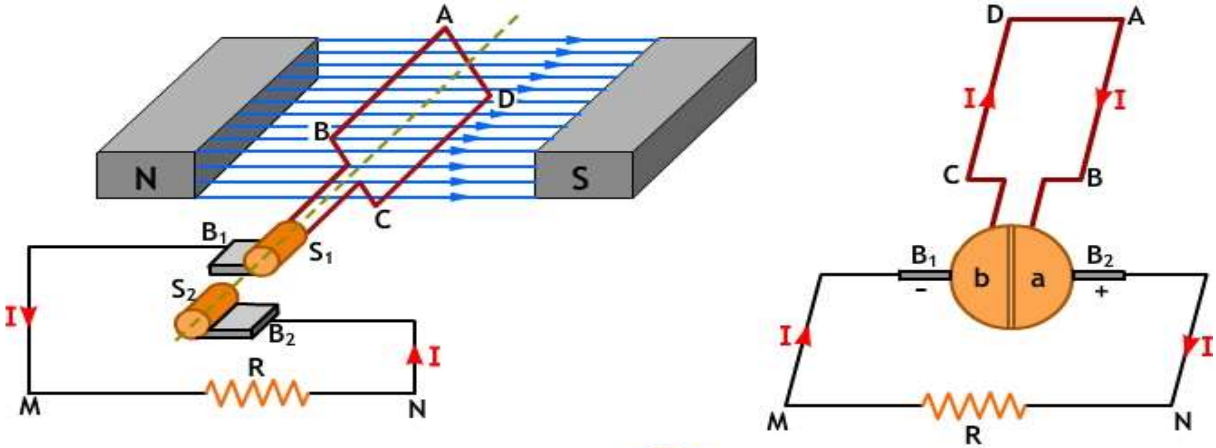
Hence, two basic essential parts of an electrical generator are

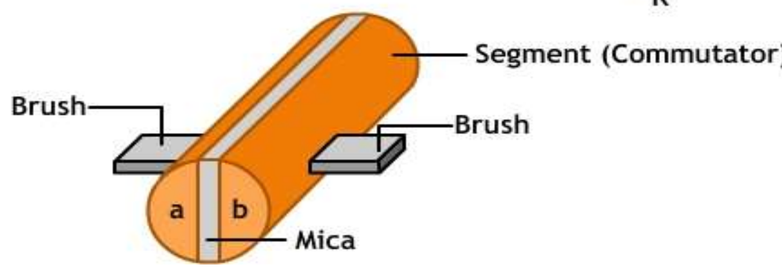
i) a magnetic field and
ii) a conductor or conductors which can so move as to cut the flux.

Principle of Operation:

D.C generator is a machine that converts **mechanical energy** into **DC electrical energy**. It works on the principle of dynamically induced emf viz., whenever a conductor cuts flux, an emf is induced in the conductor. The direction of the induced emf is given by Fleming's right hand rule.

Simple Loop Generator:



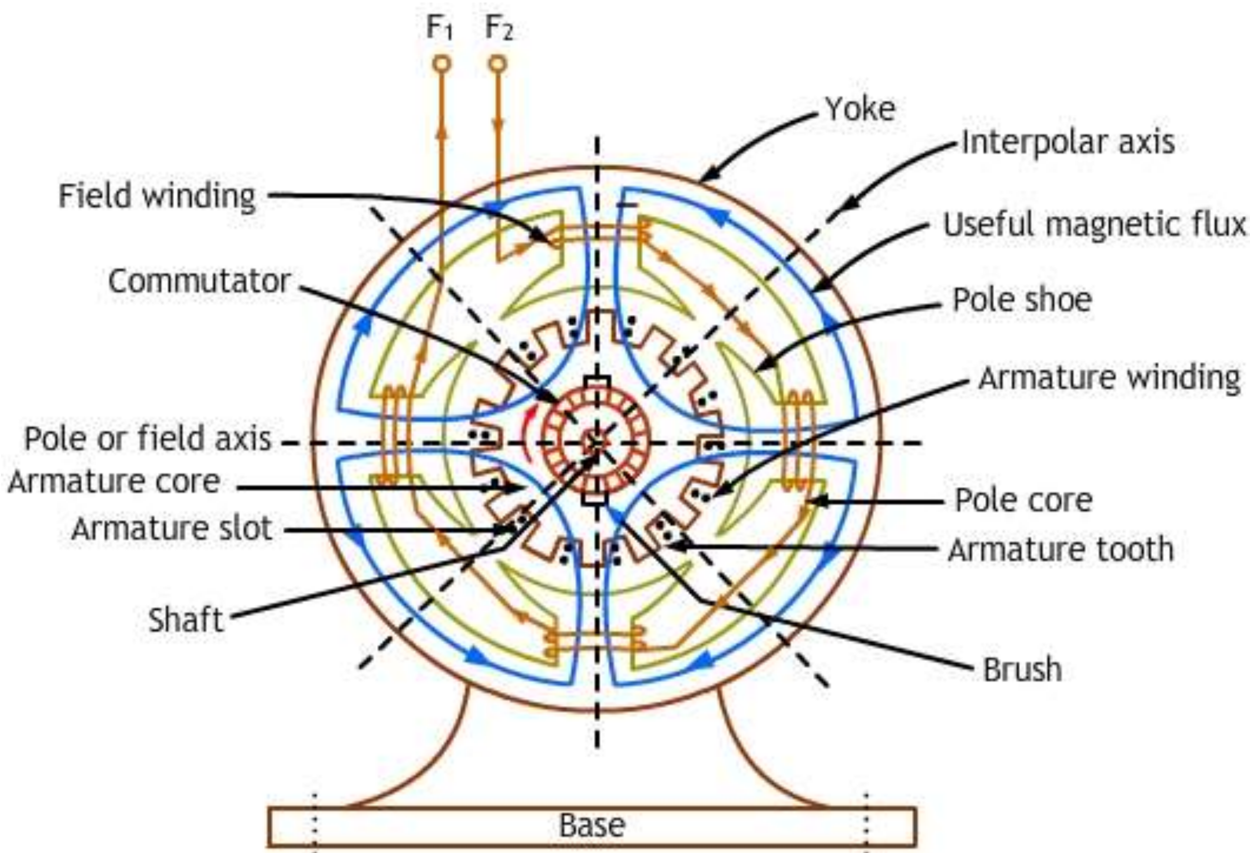


Consider rectangular coil ABCD with coil sides AB and CD being rotated in the magnetic field. The ends of the two coil sides are connected to two slip rings (S_1 and S_2). The two rings rotate along with the conductors. Two brushes (B_1 and B_2) make contact to these two slip rings to collect the current. When the coil starts rotating in anti-clockwise direction, conductor AB is under the influence of North pole and CD is under the influence of South pole. By Fleming's right hand rule, the direction of the current through the load resistance is from M to N.

After the coil rotates through 180^0, the conductor CD comes under the influence of North pole and the conductor AB under the influence of South pole. Hence, again emf is induced in the coil sides. As a result, the current flows through load resistance from N to M (reversed). This is shown in figure.

Note that, e.m.f generated in the loop is an alternating emf hence the current also. The alternating current in the load can be converted into direct current by commutator.

Practical DC Generator:



- The construction of DC generator and motor are same.
- DC generator can be run as a dc motor and vice versa.

A dc generator consists of

i) Field system (stationary)

ii) Armature (rotating)

iii) Armature is having the following parts

a) Armature core

b) Armature winding

c) Commutator

d) Brushes

e) Shaft and bearings

(i) Field system: The main function of the field system is to produce uniform magnetic field within which the armature rotates. It consists of

(a) Yoke (or frame): Yoke forms the outermost cover for the machine. Its functions are:

(i) Giving mechanical protection to the generator and

(ii) to provide path for the flux.

For small generators, yoke is made of cast iron; for large generators, it is made of silicon steel.

(b)Pole core, pole shoes and pole coils: The main poles are made of steel of high relative permeability. The pole core is made of thin laminations to reduce eddy current loss. The poles are fixed to the yoke with bolts and nuts.

The pole shoe performs the following functions.

(i) It supports the field winding.

(ii) It spreads out the flux uniformly in the air gap and also reduces the reluctance of the magnetic path.

The field coils (or field winding) are mounted on the poles and carry the d.c. exciting current.

The field coils are made of copper.

(ii) Armature Core: It is a cylindrical drum like structure made of thin laminations of silicon steel. Each lamination is insulated to reduce the eddy current loss. Silicon steel is used for the core to reduce hysteresis loss. For large machine (length>13cm) ventilating ducts are provided in the core for cooling purpose.

(iii) Armature Winding: The outer periphery of the armature is cut into number of slots to hold insulated conductor called armature winding.

There are two types of windings:

a) **Lap winding**
b) **Wave winding**

(iv) Commutator: The function of the commutator is to convert, alternating current to direct current. The commutator is made up of hard drawn copper segments insulated from each other by mica sheets and mounted on the shaft.

(v) Brushes: The function of brushes is to collect the direct current from the commutator segments and supply it to the external circuit. The brushes are made of carbon. Carbon is having negative temperature coefficient and is very soft.

(vi) Shaft and Bearings: For small generators, ball bearings are used. For large rating generators, roller bearings are used.

E.M.F Equation of DC Generator:

Let, ϕ = Flux / pole in webers

$\Rightarrow$ Change in flux $d\phi = \phi P$ webers

Z = Total number armature conductors

= Number of slots x Number of conductors per slot

P = Number of poles

A = Number of parallel paths in the armature.

N = Rotational speed of armature in revolutions per minute (r.p.m)

$\Rightarrow$ Time taken to complete one revolution = 60/N sec.

E = e.m.f induced / parallel path in armature.

Generated e.m.fE_g = e.m.f generated /parallel path

By Faraday's Law ,

$$\text{E.M.F generated per conductor} = \frac{d\phi}{dt} = \frac{\phi PN}{60 \text{ volts}}$$

$$\text{Number of armature conductors per parallel path} = \frac{Z}{A}$$

$$E_g = \text{e.m.f generated per conductor} \times \text{Number of conductors in each parallel path}$$

$$E_g = \left(\frac{\phi PN}{60}\right) \times \frac{Z}{A} \text{ volts} \qquad \ldots\ldots\ldots(i)$$

For a Simplex Wave-Wound Generator

Number of parallel paths A = 2

$$E_g = \frac{\phi PN \,.\left(\frac{Z}{2}\right)}{60} = \frac{\phi ZPN}{120} \text{volts}$$

For Simplex Lap-Wound Generator:

Number of parallel paths, A = P

Equation (i) becomes

$$E_g = \frac{\phi PN \,.\left(\frac{Z}{P}\right)}{60} = \frac{\phi ZN}{60} \text{volts}$$

Armature Reaction

The current flowing through armature conductors also creates a magnetic flux (called armature flux) that distorts and weakens the flux coming from the poles. This distortion and field weakening takes place in both generators and motors. The action of armature flux on the main flux is known as armature reaction.The phenomenon of armature reaction in a d.c. generator is shown in Fig. Only one pole is shown for clarity. When the generator is on no-load, a smal1 current flowing in the armature does not appreciably affect the main flux □1coming from the pole [See Fig 2.1 (i)]. When the generator is loaded, the current flowing through armature conductors sets up flux 1. Fig. (2.1) (ii) shows flux due to armature current alone. By superimposing 1 and 2, we obtain the resulting flux 3 as shown in Fig. (2.1) (iii). Referring to Fig (2.1) (iii), it is clear that flux density at; the trailing pole tip (point B) is increased while at the leading pole tip (point A) it is decreased. This unequal field distribution produces the following two effects:

(i) The main flux is distorted.

(ii) Due to higher flux density at pole tip B, saturation sets in.

Consequently, the increase in flux at pole tip B is less than the decrease in flux under pole tip A. Flux 3 at full load is, therefore, less than flux 1 at no load. As we shall see, the weakening of flux due to armature reaction depends upon the position of brushes.

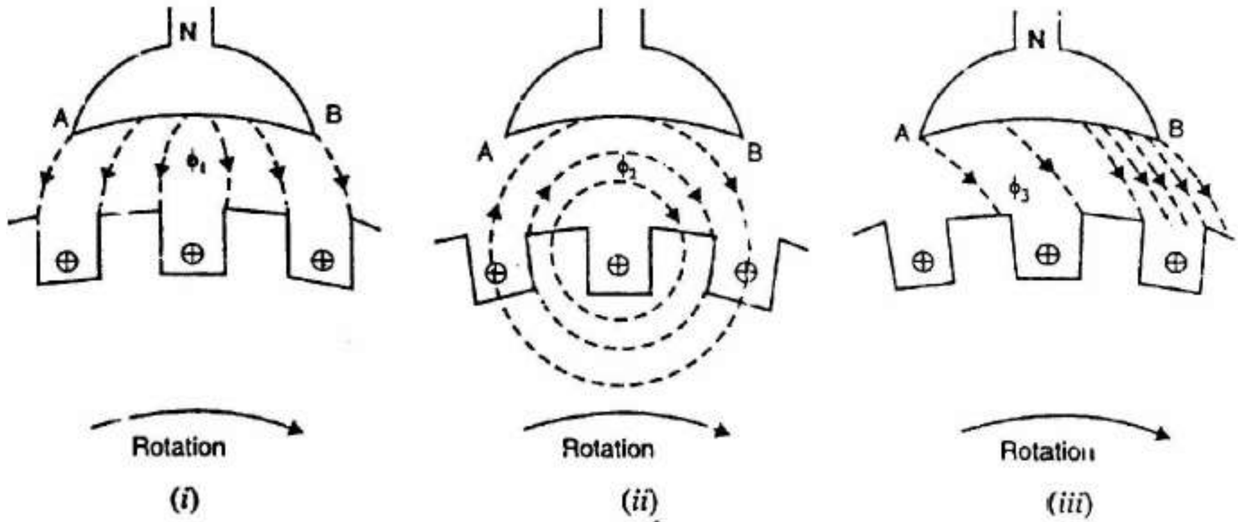


Fig:2.1

Geometrical and Magnetic Neutral Axes

(i) The geometrical neutral axis (G.N.A.) is the axis that bisects the angle between the centre line of adjacent poles [See Fig. 2.2 (i)]. Clearly, it is the axis of symmetry between two adjacent poles.

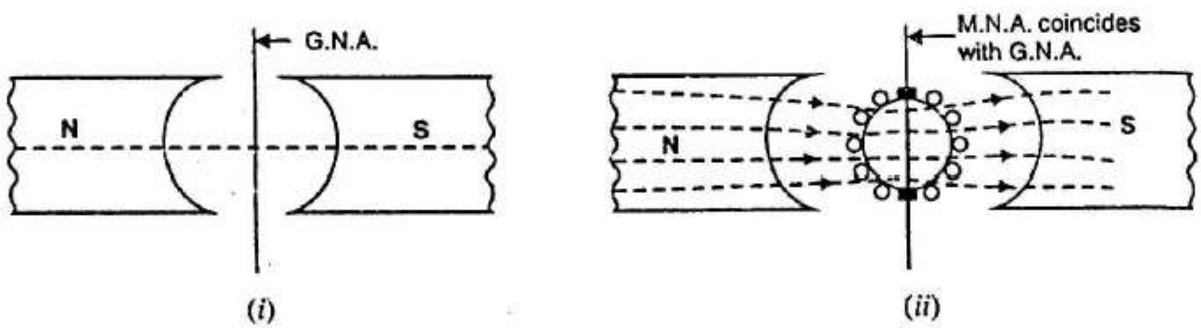


Fig:2.2

(ii) The magnetic neutral axis (M. N. A.) is the axis drawn perpendicular to the mean direction of the flux passing through the centre of the armature. Clearly, no e.m.f. is produced in the armature conductors along this axis because then they cut no flux. With no current in the armature conductors, the M.N.A. coincides with G, N. A. as shown in Fig. (2.2).

(iii). In order to achieve sparkless commutation, the brushes must lie along M.N.A.

Explanation of Armature Reaction

With no current in armature conductors, the M.N.A. coincides with G.N.A. However, when current flows in armature conductors, the combined action of main flux and armature flux shifts the M.N.A. from G.N.A. In case of a generator, the M.N.A. is shifted in the direction of rotation of the machine. In order to achieve sparkless commutation, the brushes have to be moved along the new M.N.A. Under such a condition, the armature reaction produces the following two effects:

1. It demagnetizes or weakens the main flux.

2. It cross-magnetizes or distorts the main flux.

Let us discuss these effects of armature reaction by considering a 2-pole generator (though the following remarks also hold good for a multipolar generator).

i) Fig. (2.3) (i) shows the flux due to main poles (main flux) when the armature conductors carry no current. The flux across the air gap is uniform. The m.m.f. producing the main flux is represented in magnitude and direction by the vector OFm in Fig. (2.3) (i). Note that OFm is perpendicular to G.N.A.

ii) (ii) Fig. (2.3) (ii) shows the flux due to current flowing in armature conductors alone (main poles unexcited). The armature conductors to the left of G.N.A. carry current “in” (′) and those to the right carry current “out” (•). The direction of magnetic lines of force can be found by cork screw rule. It is clear that armature flux is directed downward parallel to the brush axis. The m.m.f. producing the armature flux is represented in magnitude and direction by the vector OFA in Fig. (2.3) (ii).

(iii) Fig. (2.3) (iii) shows the flux due to the main poles and that due to current in armature conductors acting together. The resultant m.m.f. OF is the vector sum of OFm and OFA as shown in Fig. (2.3) (iii). Since M.N.A. is always perpendicular to the resultant m.m.f., the M.N.A. is shifted through an angle q. Note that M.N.A. is shifted in the direction of rotation of the generator.

(iii) In order to achieve sparkless commutation, the brushes must lie along the M.N.A. Consequently, the brushes are shifted through an angle q so as to lie along the new M.N.A. as shown in Fig. (2.3)

(iv) (iv). Due to brush shift, the m.m.f. FA of the armature is also rotated through the same angle q. It is because some of the conductors which were earlier under N-pole now come under S-pole and vice-versa. The result is that armature m.m.f. FA will no longer be vertically downward but will be rotated in the direction of rotation through an angle q as shown in Fig.

(a) The component Fd is in direct opposition to the m.m.f. OFm due to main poles. It has a demagnetizing effect on the flux due to main poles. For this reason, it is called the demagnetizing or weakening component of armature reaction.

(b) The component Fc is at right angles to the m.m.f. OFm due to main poles. It distorts the main field. For this reason, it is called the cross magnetizing or distorting component of armature reaction.

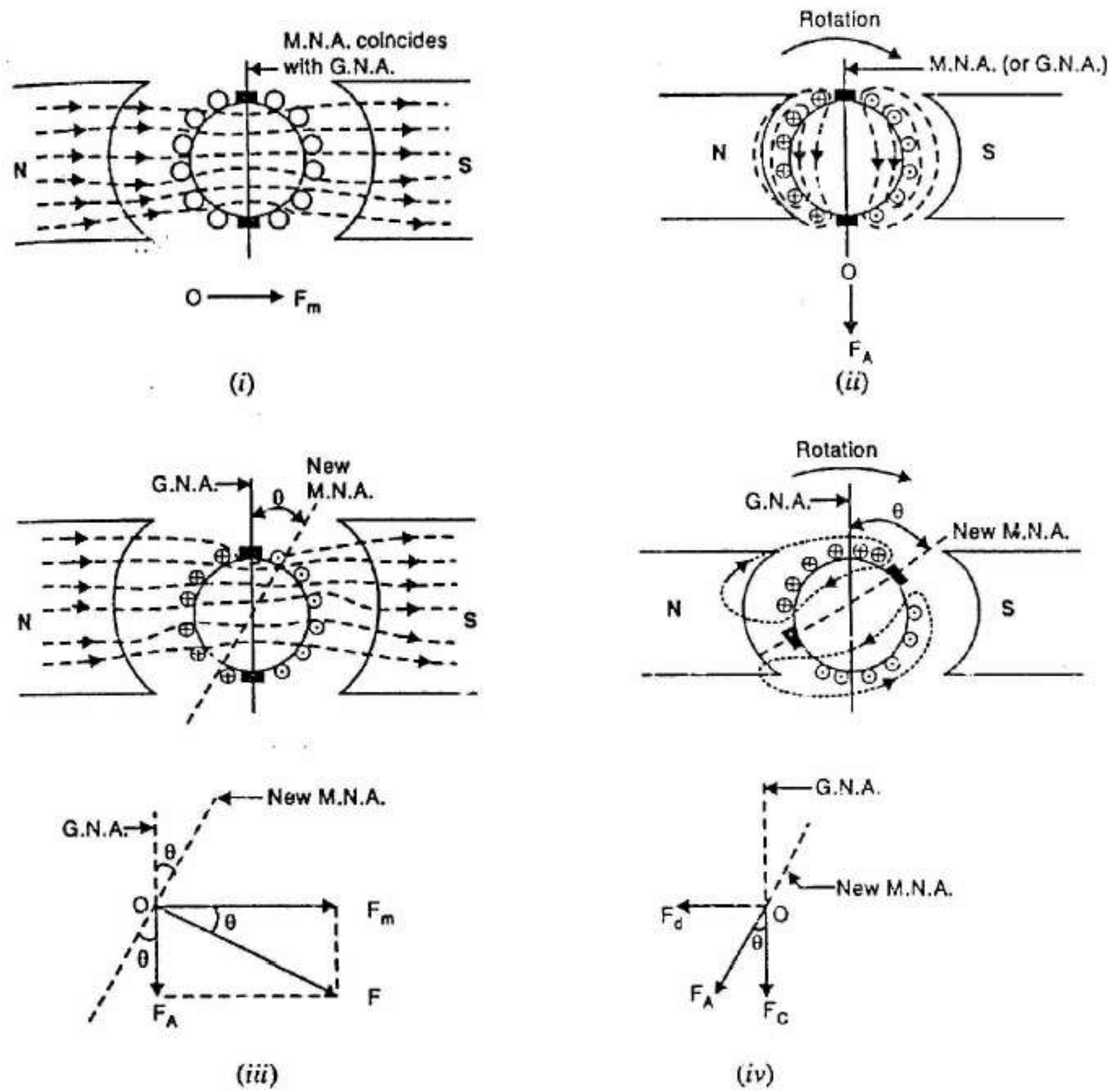


Fig:2.3

Demagnetizing and Cross-Magnetizing Conductors

With the brushes in the G.N.A. position, there is only cross-magnetizing effect of armature reaction. However, when the brushes are shifted from the G.N.A. position, the armature reaction will have both demagnetizing and crossmagnetizing effects. Consider a 2-

pole generator with brushes shifted (lead) qm mechanical degrees from G.N.A. We shall identify the armature conductors that produce demagnetizing effect and those that produce cross-magnetizing effect.

(i) The armature conductors oqm on either side of G.N.A. produce flux in direct opposition to main flux as shown in Fig. (2.4) (i). Thus theconductors lying within angles AOC = BOD = 2qm at the top and bottom ofthe armature produce demagnetizing effect. These are called demagnetizing armature conductors and constitute the demagnetizing ampere-turns of armature reaction (Remember two conductors constitute a turn).

(ii) The axis of magnetization of the remaining armature conductors lying between angles AOD and COB is at right angles to the main flux as shown in Fig. (2.4) (ii). These conductors produce the cross-magnetizing (or distorting) effect i.e., they produce uneven flux distribution on each pole. Therefore, they are called cross-magnetizing conductors and constitute the cross-magnetizing ampere-turns of armature reaction.

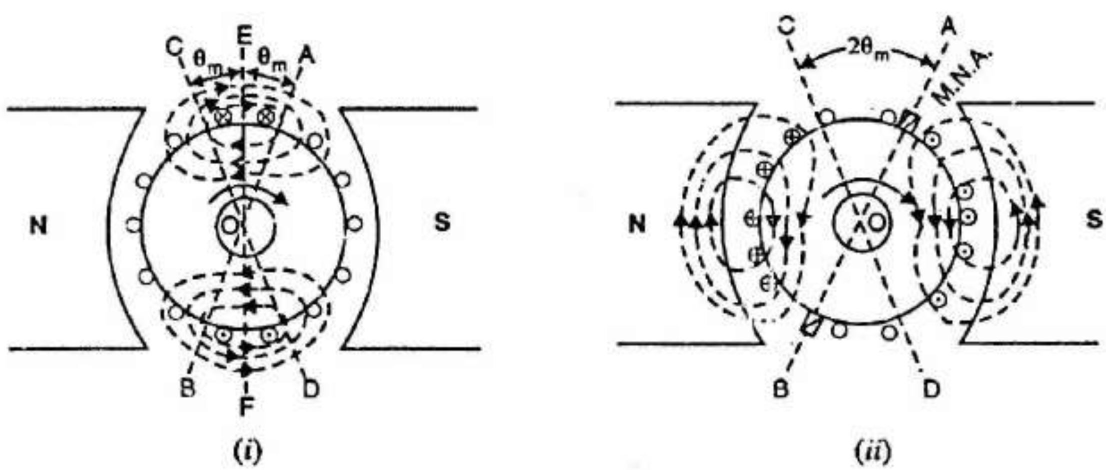


Fig:2.4

Calculation of Demagnetizing Ampere-Turns Per Pole (ATd/Pole)

It is sometimes desirable to neutralize the demagnetizing ampere-turns of armature reaction. This is achieved by adding extra ampere-turns to the main field winding. We shall now calculate the demagnetizing ampere-turns per pole (ATd/pole).

Let
Z = total number of armature conductors
I = current in each armature conductor
$= I_a/2$ ... for simplex wave winding
$= I_a/P$ ... for simplex lap winding
θ_m = forward lead in mechanical degrees

Referring to Fig. (2.4) (i) above, we have,
Total demagnetizing armature conductors

$$= \text{Conductors in angles AOC and BOD} = \frac{4\theta_m}{360} \times Z$$

Since two conductors constitute one turn,

$$\therefore \quad \text{Total demagnetizing ampere-turns} = \frac{1}{2}\left[\frac{4\theta_m}{360} \times Z\right] \times I = \frac{2\theta_m}{360} \times ZI$$

These demagnetizing ampere-turns are due to a pair of poles.

$$\therefore \quad \text{Demagnetizing ampere-turns/pole} = \frac{\theta_m}{360} \times ZI$$

i.e.,
$$AT_d / \text{pole} = \frac{\theta_m}{360} \times ZI$$

As mentioned above, the demagnetizing ampere-turns of armature reaction can be neutralized by putting extra turns on each pole of the generator.

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

$$= \frac{AT_d}{I_a} \quad \text{for a series generator}$$

Cross-Magnetizing Ampere-Turns Per Pole (ATc/Pole)

We now calculate the cross-magnetizing ampere-turns per pole (ATc/pole).

Total armature reaction ampere-turns per pole

$$= \frac{Z/2}{P} \times I = \frac{Z}{2P} \times I \qquad (\because \text{ two conductors make one turn})$$

Demagnetizing ampere-turns per pole is given by;

$$AT_d / \text{pole} = \frac{\theta_m}{360} \times ZI$$

□□Cross-magnetizing ampere-turns/pole are

$$AT_d / \text{pole} = \frac{Z}{2P} \times I - \frac{\theta_m}{360} \times ZI = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$$

$$\therefore \qquad AT_d / \text{pole} = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$$

Commutation:

Fig. (2.5) shows the schematic diagram of 2-pole lap-wound generator. There are two parallel paths between the brushes. Therefore, each coil of the winding carries one half (Ia/2 in this case) of the total current (Ia) entering or leaving the armature.

Note that the currents in the coils connected to a brush are either all towards the brush (positive brush) or all directed away from the brush (negative brush). Therefore, current in a coil will reverse as the coil passes a brush. This reversal of current as the coil passes & brush is called commutation. The reversal of current in a coil as the coil passes the brush axis is called commutation.

When commutation takes place, the coil undergoing commutation is short circuited by the brush. The brief period during which the coil remains short circuited is known as commutation period Tc. If the current reversal is completed by the end of commutation period, it is called ideal commutation. If the current reversal is not completed by that time, then sparking occurs between the brush and the commutator which results in progressive damage to both.

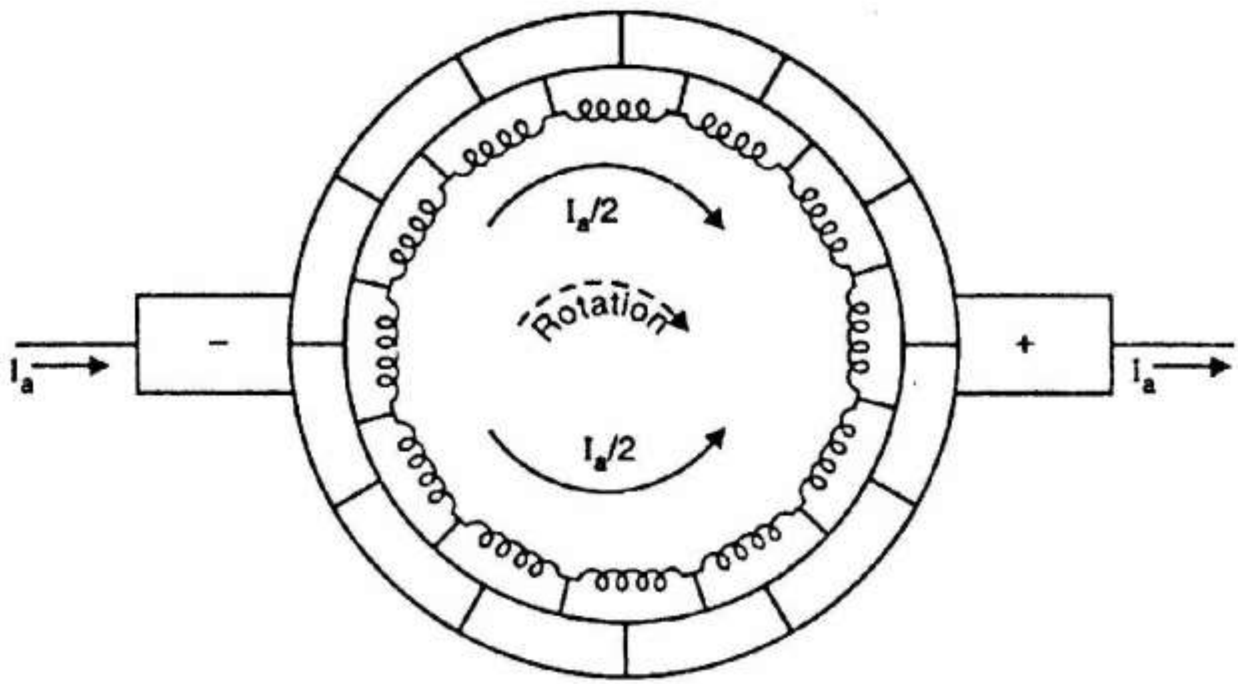


Fig:2.5

Ideal commutation

Let us discuss the phenomenon of ideal commutation (i.e., coil has no inductance) in one coil in the armature winding shown in Fig. (2.6) above. For this purpose, we consider the coil A. The brush width is equal to the width of one commutator segment and one mica insulation. Suppose the total armature current is 40 A. Since there are two parallel paths, each coil carries a current of 20 A.

(i) In Fig. (2.7) (i), the brush is in contact with segment 1 of the commutator. The commutator segment 1 conducts a current of 40 A to the brush; 20 A from coil A and 20 A from the adjacent coil as shown. The coil A has yet to undergo commutation

(ii) As the armature rotates, the brush will make contact with segment 2 and thus short-circuits the coil A as shown in Fig. (2.7) (ii). There are now two parallel paths into the brush as long as the short-circuit of coil A exists. Fig. (2.7) (ii) shows the instant when the brush is one-fourth on segment 2 and three-fourth on segment 1. For this condition, the resistance of the path through segment 2 is three times the resistance of the path through segment 1 (Q contact resistance varies inversely as the area of contact of brush with the segment). The brush again conducts a current of 40 A; 30 A through segment 1 and 10 A through segment 2. Note that current in coil A (the coil undergoing commutation) is reduced from 20 A to 10 A.

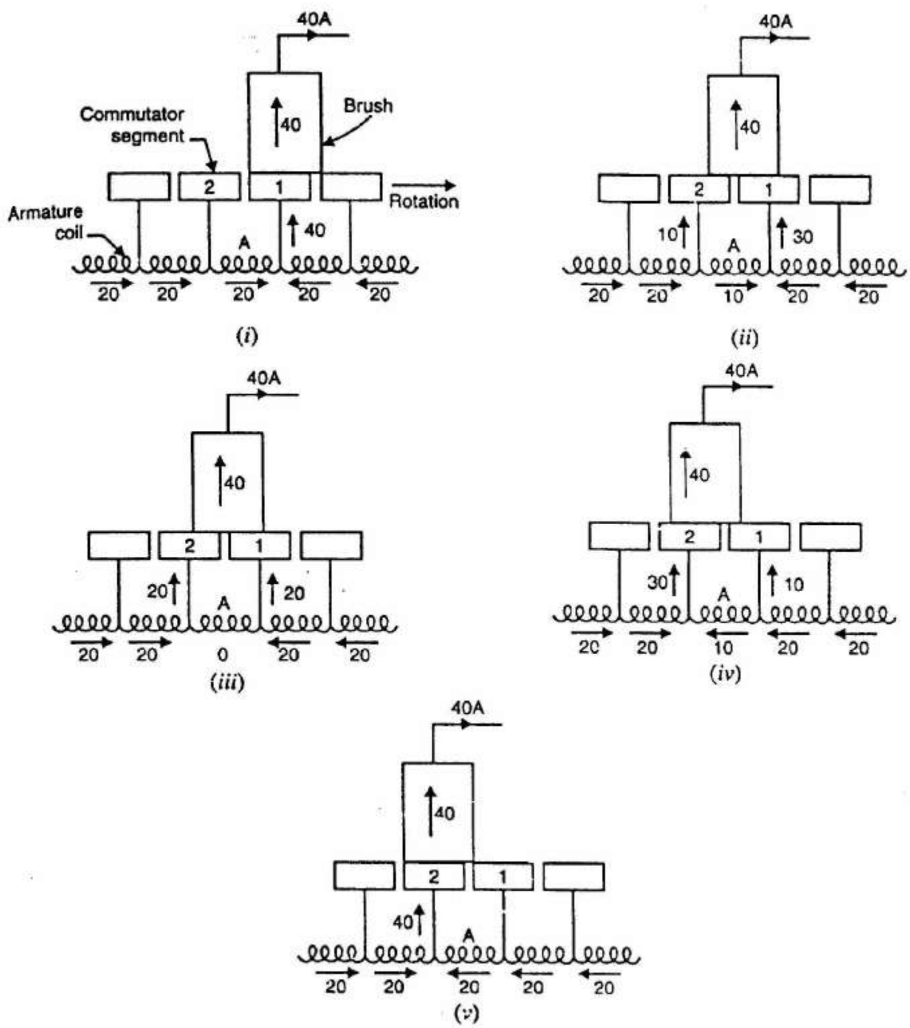


Fig :2.7

(iii) Fig. (2.7) (iii) shows the instant when the brush is one-half on segment 2 and one-half on segment 1. The brush again conducts 40 A; 20 A through segment 1 and 20 A through segment 2 (Q now the resistances of the two parallel paths are equal). Note that now. current in coil A is zero.

(iv) Fig. (2.7) (iv) shows the instant when the brush is three-fourth on segment 2 and one-fourth on segment 1. The brush conducts a current of 40 A; 30 A through segment 2 and 10 A through segment 1. Note that current in coil A is 10 A but in the reverse direction to that before the start of commutation. The reader may see the action of the commutator in reversing the current in a coil as the coil passes the brush axis.

(v) Fig. (2.7) (v) shows the instant when the brush is in contact only with segment 2. The brush again conducts 40 A; 20 A from coil A and 20 A from the adjacent coil to coil A. Note that now current in coil A is 20 A but in the reverse direction. Thus the coil A has undergone commutation. Each coil undergoes commutation in this way as it passes the brush axis. Note that during commutation, the coil under consideration remains short circuited by the brush. Fig. (2.8) shows the current-time graph for the coil A undergoing commutation. The horizontal line AB represents a constant current of 20 A upto the beginning of commutation. From the finish of commutation, it is represented by another horizontal line CD on the opposite side of the zero line and the same distance from it as AB i.e., the current has exactly reversed (- 20 A). The way in which current changes from B to C depends upon the conditions under which the coil undergoes commutation. If the current changes at a uniform rate (i.e., BC is a straight line), then it is called ideal commutation as shown in Fig. (2.8). under such conditions, no sparking will take place between the brush and the commutator

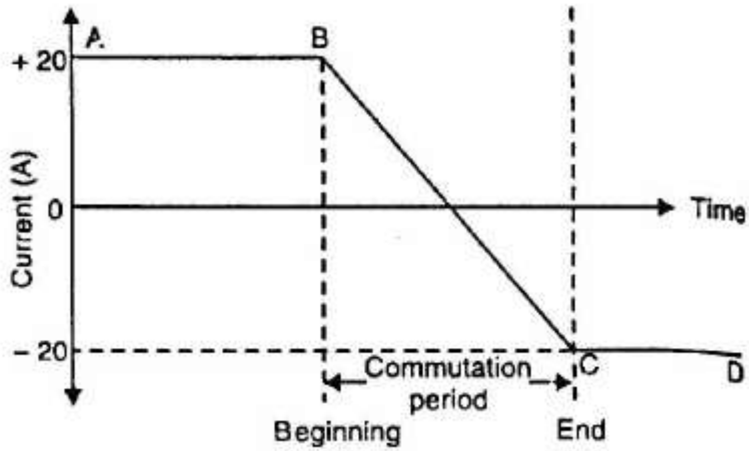


Fig:2.8

Practical difficulties

The ideal commutation (i.e., straight line change of current) cannot be attained in practice. This is mainly due to the fact that the armature coils have appreciable inductance. When the current in the coil undergoing commutation changes, self-induced e.m.f. is produced in the coil. This is generally called reactance voltage. This reactance voltage opposes the change of current in the coil undergoing commutation. The result is that the change of current in the coil undergoing commutation occurs more slowly than it would be under ideal commutation. This is illustrated in Fig. (2.9). The straight line RC represents the ideal commutation whereas the curve BE represents the change in current when self-inductance of the coil is taken into account. Note that current CE (= 8A in Fig. 2.9) is flowing from the commutator segment 1 to the brush at the instant when they part company. This results in sparking just as when any other current carrying circuit is broken. The sparking results in overheating of commutator brush contact and causing damage to both. Fig. (2.10) illustrates how sparking takes place between the commutator segment and the brush. At the end of commutation or short-circuit period, the

current in coil A is reversed to a value of 12 A (instead of 20 A) due to inductance of the coil. When the brush breaks contact with segment 1, the remaining 8 A current jumps from segment 1 to the brush through air causing sparking between segment 1 and the brush.

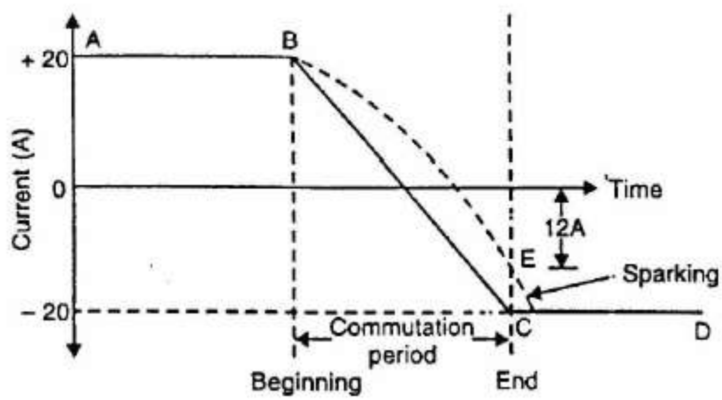


Fig. (2.9)

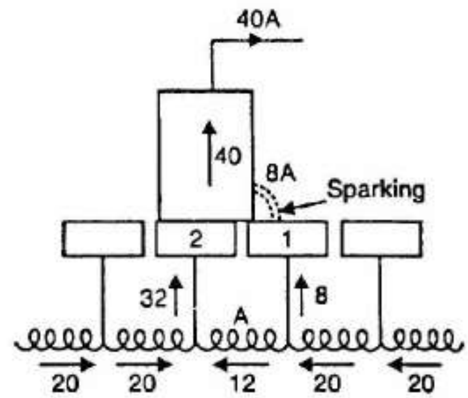


Fig. (2.10)

Methods of Improving Commutation

Improving commutation means to make current reversal in the short-circuited coil as sparkless as possible. The following are the two principal methods of improving commutation:

(i) Resistance commutation

(ii) E.M.F. commutation

Resistance Commutation

The reversal of current in a coil (i.e., commutation) takes place while the coil is short-circuited by the brush. Therefore, there are two parallel paths for the current as long as the short circuit exists. If the contact resistance between the brush and the commutator is made large, then current would divide in the inverse ratio of contact resistances (as for any two resistances in parallel). This is the key point in improving commutation. This is achieved by using carbon brushes (instead of Cu brushes) which have high contact resistance. This method of improving commutation is called resistance commutation. Figs. (2.11) and (2.12) illustrates how high contact resistance of carbon brush improves commutation (i.e., reversal of current) in coil A. In Fig. (2.11) (i), the brush is entirely on segment 1 and, therefore, the current in coil A is 20 A. The coil A is yet to undergo commutation. As the armature rotates, the brush short circuits the coil A and there are two parallel paths for the current into the brush. Fig. (2.11) (ii) shows the instant when the brush is one-fourth on segment 2 and three-fourth on segment 1. The equivalent electric circuit is shown in Fig. (2.11) (iii) where R1 and R2 represent the brush contact resistances on segments 1 and 2. A resistor is not shown for coil A since it is assumed that the coil resistance is negligible as compared to the brush contact resistance. The values of current in the parallel paths of the equivalent circuit are determined by the respective resistances of the paths. For the condition shown in Fig. (2.11) (ii), resistor R2 has three times the resistance of resistor R1. Therefore, the current distribution in the paths will be as shown. Note that current in coil A is reduced from 20 A to 10 A due to division of current in (he inverse ratio of contact resistances. If the Cu brush is used (which has low contact resistance), R1 R2 and the current in coil A would not have reduced to 10 A.

E.M.F. Commutation

In this method, an arrangement is made to neutralize the reactance voltage by producing a reversing voltage in the coil undergoing commutation. The reversing voltage acts in opposition to the reactance voltage and neutralizes it to some extent. If the reversing voltage is equal to the reactance voltage, the effect of the latter is completely wiped out and we get sparkless commutation. The reversing voltage may be produced in the following two ways:

(i) By brush shifting

(ii) By using interpoles or compoles

(i) By brush shifting

In this method, the brushes are given sufficient forward lead (for a generator) to bring the short-circuited coil (i.e., coil undergoing commutation) under the influence of the next pole of opposite polarity. Since the short-circuited coil is now in the reversing field, the reversing voltage produced cancels the reactance voltage. This method suffers from the following drawbacks:

(a) The reactance voltage depends upon armature current. Therefore, the brush shift will depend on the magnitude of armature current which keeps on changing. This necessitates frequent shifting of brushes.

(b) The greater the armature current, the greater must be the forward lead for a generator. This increases the demagnetizing effect of armature reaction and further weakens the main field.

(ii) By using interpoles or compotes

The best method of neutralizing reactance voltage is by, using interpoles or compoles.

Generator types & Characteristics

D.C generators may be classified as

(i) separately excited generator,

(ii) shunt generator,

(iii) series generator and

(iv) compound generator.

In a separately excited generator field winding is energised from a separate voltage source in order to produce flux in the machine. So long the machine operates in unsaturated condition the flux produced will be proportional to the field current. In order to implement shunt connection, the field winding is connected in parallel with the armature. It will be shown that subject to fulfillment of certain conditions, the machine may have sufficient field current developed on its own by virtue of its shunt connection.

In series d.c machine, there is one field winding wound over the main poles with fewer turns and large cross sectional area. Series winding is meant to be connected in series with the armature and naturally to be designed for rated armature current. Obviously there will be practically no voltage or very small voltage due to residual field under no load condition ($I_a = 0$). However, field gets strengthened as load will develop rated voltage across the armature with reverse polarity, is connected and terminal voltage increases. Variation in load resistance causes the terminal voltage to vary. Terminal voltage will start falling, when saturation sets in and armature reaction effect becomes pronounced at large load current. Hence, series generators are not used for delivering power at constant voltage. Series generator found application in boosting up voltage in d.c transmission system.

A compound generator has two separate field coils wound over the field poles. The coil having large number of turns and thinner cross sectional area is called the *shunt field coil* and the other coil having few numbers of turns and large cross sectional area is called the *series field coil*. Series coil is generally connected in series with the armature while the shunt field coil is connected in parallel with the armature. If series coil is left alone without any connection, then it becomes a shunt machine with the other coil connected in parallel. Placement of field coils for shunt, series and compound generators are shown in figure 38.1. Will develop rated voltage across the armature with reverse polarity.

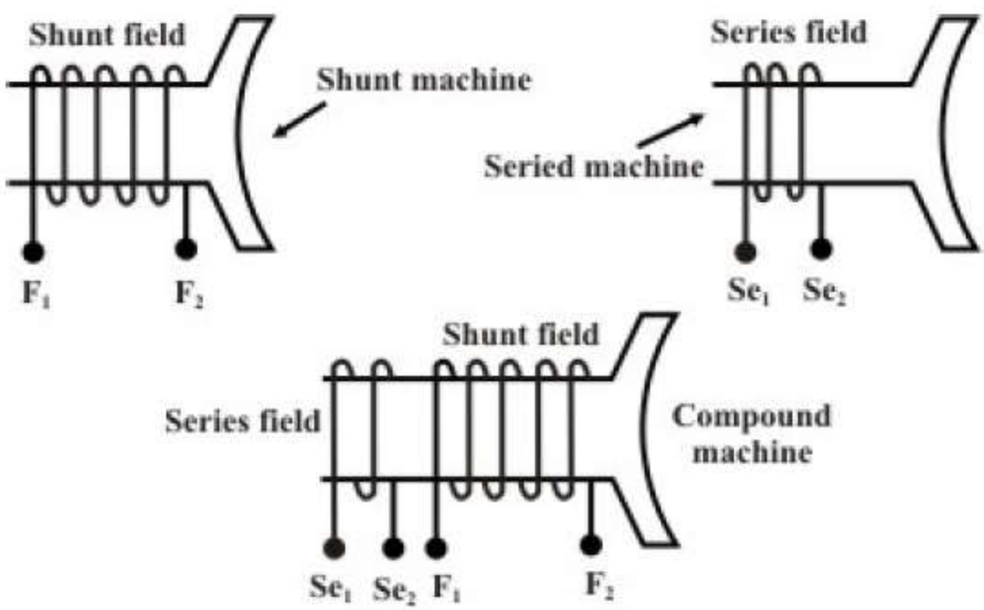


Fig2.11: Field coils for different DC machines

Characteristics of a separately excited generator

No load or Open circuit characteristic

In this type of generator field winding is excited from a separate source, hence field current is independent of armature terminal voltage as shown on figure (38.2). The generator is driven by a prime mover at rated speed, say *n* rps. With switch *S* in opened condition, field is excited via a *potential divider* connection from a separate d.c source and field current is gradually increased. The field current will establish the flux per pole φ. The voltmeter V connected across the armature terminals of the machine will record the generated emf $E_G = \frac{PZ}{A}\varphi n$ $=kn\varphi$). Remember $\frac{pz}{a}$is a constant (k) of the machine. As field current is increased, E_G will increase. E_G versus I_f plot at constant speed *n* is shown in figure.

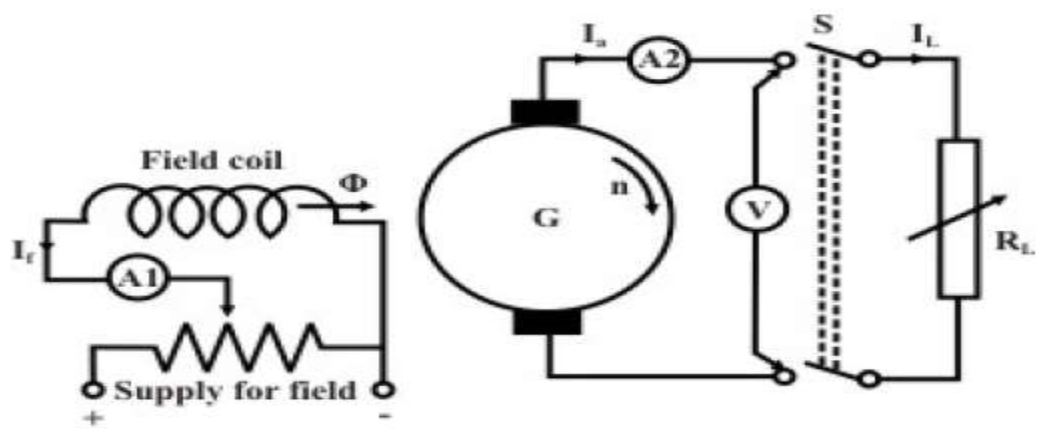


Fig2.12: Connection of separately excited generator.

It may be noted that even when there is no field current, a small voltage (OD) is generated due to residual flux. If field current is increased, φ increases linearly initially and O.C.C follows a straight line. However, when *saturation* sets in, φ practically becomes constant and hence E_g too becomes constant. In other words, O.C.C follows the *B-H* characteristic, hence this characteristic is sometimes also called the *magnetisation* characteristic of the machine.

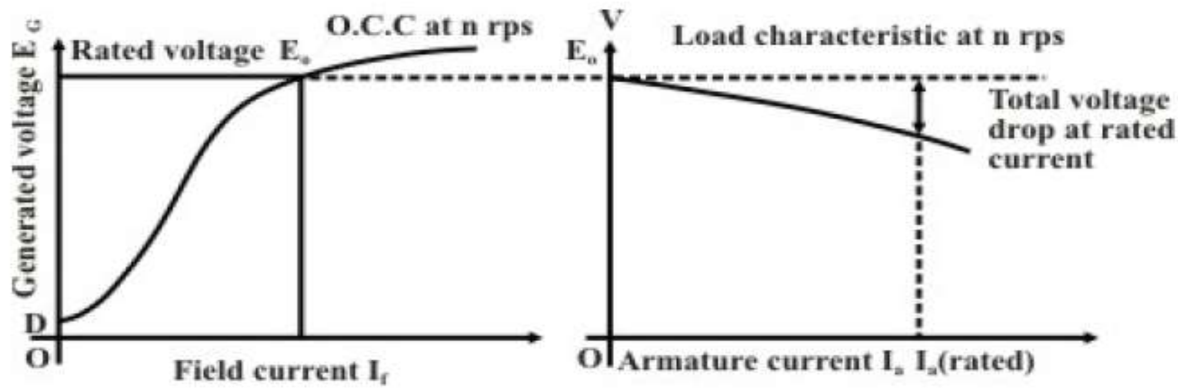


Fig: No load and Load characteristics of separately exited DC Generator

It is important to note that if O.C.C is known at a certain speed n_1, O.C.C at another speed n_2 can easily be predicted. It is because for a constant field current, ratio of the generated voltages becomes the ratio of the speeds as shown below.

$$\frac{E_{G2}}{E_{G1}} = \frac{\text{Gen. voltage at } n_2}{\text{Gen. voltage at } n_1}$$

$$= \frac{k\phi n_2}{k\phi n_1} \quad \because \text{voltage is calculated at same field current}$$

$$\therefore \frac{E_{G2}}{E_{G1}} = \frac{n_2}{n_1}\bigg| \, i_f = \text{constant}$$

$$\text{or, } E_{G2} = \frac{n_2}{n_1} E_{G1}$$

Therefore points on O.C.C at n_2 can be obtained by multiplying ordinates of O.C.C at n_1 with the ratio $\frac{n2}{n1}$ O.C.C at two different speeds are shown in the following figure

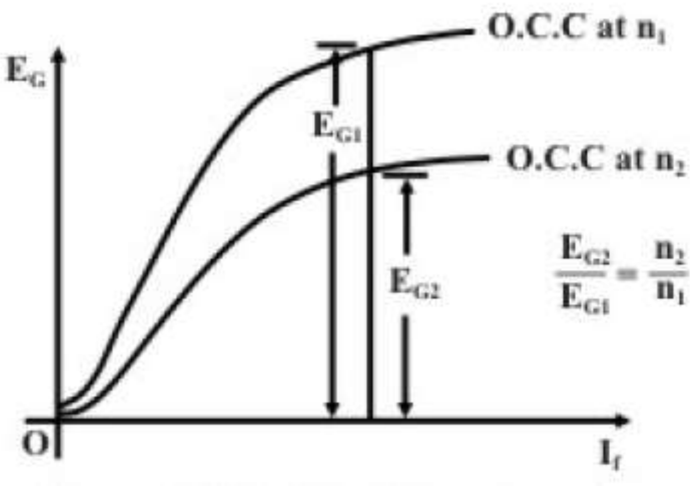


Fig: O C C at different Speeds

Load characteristic of separately excited generator

Load characteristic essentially describes how the terminal voltage of the armature of a generator changes for varying armature current I_a. First at rated speed, rated voltage is generated across the armature terminals with no load resistance connected across it (i.e., with S opened) by adjusting the field current. So for $I_a = 0$, $V = E_o$ should be the first point on the load characteristic. Now with S is closed and by decreasing R_L from infinitely large value, we can increase I_a gradually and note the voltmeter reading. Voltmeter reads the terminal voltage and is expected to decrease due to various drops such as armature resistance drop and brush voltage drop. In an uncompensated generator, armature reaction effect causes additional voltage drop. While noting down the readings of the ammeter A2 and the voltmeter V, one must see that the speed remains constant at rated value. Hence the load characteristic will be *drooping* in nature as shown in figure .

Characteristics of a shunt generator

We have seen in the previous section that one needs a separate d.c supply to generate d.c voltage. Is it possible to generate d.c voltage without using another d.c source? The answer is yes and for obvious reason such a generator is called *self excited* generator. Field coil (F1, F2) along with a series external resistance is connected in parallel with the armature terminals (A1, A2) of the machine as shown in figure. Let us first qualitatively explain how such connection can produce sufficient voltage. Suppose there exists some residual field. Therefore, if the generator is driven at rated speed, we should expect a small voltage $kn\varphi$ to be induced across the armature. But this small voltage will be directly applied across the field circuit since it is connected in parallel with the armature. Hence a small field current flows producing additional flux. If it so happens that this additional flux aids the already existing residual flux, total flux now becomes more generating more voltage. This more voltage will drive more field current generating more voltage. Both field current and armature generated voltage grow *cumulatively*.

This growth of voltage and the final value to which it will settle down can be understood by referring to where two plots have been shown. One corresponds to the O.C.C at rated speed and obtained by connecting the generator in separately excited fashion as detailed in the preceding section. The other one is the V-I characteristic of the field circuit which is a straight line passing through origin and its slope represents the total field circuit resistance.

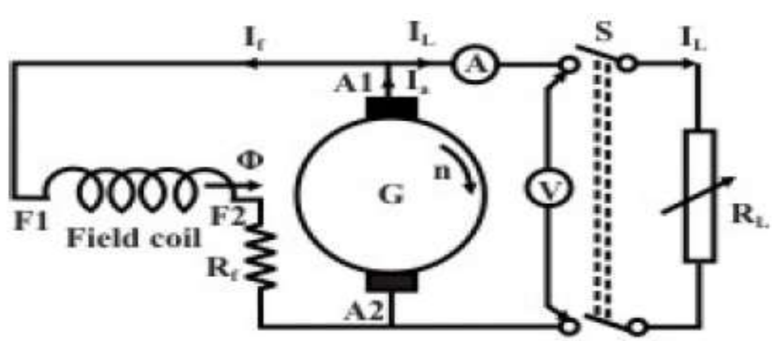


Fig2.13: DC Shunt Generator.

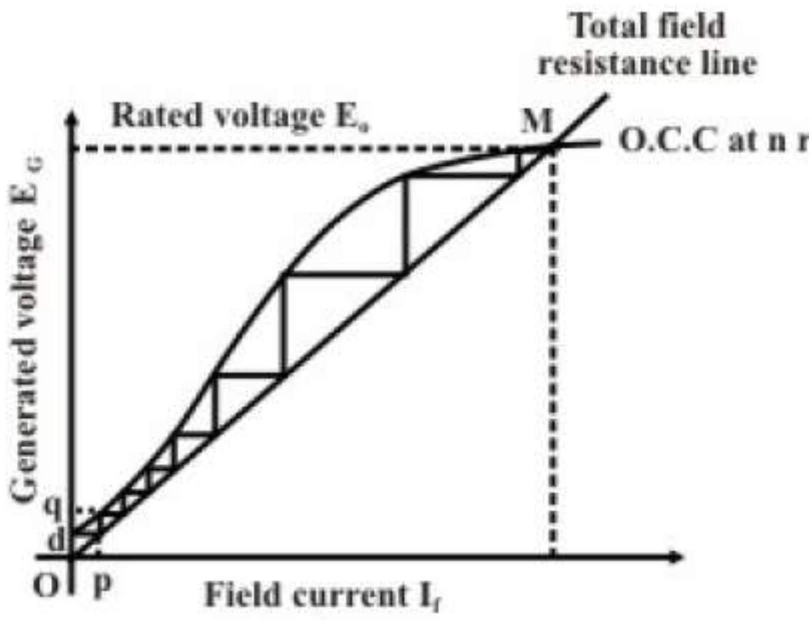
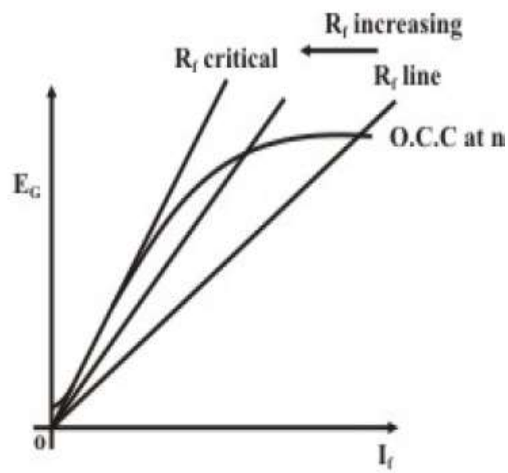


Fig 2.14: Voltage Build up in Shunt generator.

Initially voltage induced due to residual flux is obtained from O.C.C and given by Od. The field current thus produced can be obtained from field circuit resistance line and given by Op. In this way voltage build up process continues along the stair case. The final stable operating point (M) will be the point of intersection between the O.C.C and the field resistance line. If field circuit resistance is increased, final voltage decreases as point of intersection shifts toward left. The field circuit resistance line which is tangential to the O.C.C is called the *critical* field resistance. If the field circuit resistance is more than the critical value, the machine will fail to excite and no voltage will be induced. The reason being no point of intersection is possible in this case.

Suppose a shunt generator has built up voltage at a certain speed. Now if the speed of the prime mover is reduced without changing R_f, the developed voltage will be less as because the O.C.C at lower speed will come down. If speed is further reduced to a certain critical speed (n_{cr}), the present field resistance line will become tangential to the O.C.C at n_{cr}. For any speed below n_{cr}, no voltage built up is possible in a shunt generator.



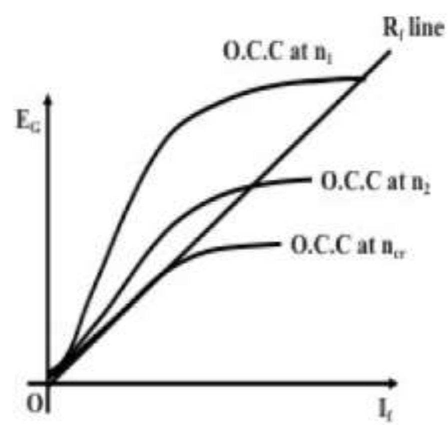


Fig 2.15a: Critical Field Resistance Fig 2.15b: Critical Speed

A shunt generator driven by a prime mover, can not built up voltage if it fails to comply any of the conditions listed below.

1. The machine must have some *residual* field. To ensure this one can at the beginning excite the field separately with some constant current. Now removal of this current will leave some amount of residual field.

2. Field winding connection should be such that the residual flux is strengthened by the field current in the coil. If due to this, no voltage is being built up, reverse the field terminal connection.

3. Total field circuit resistance must be less than the critical field resistance.

Load characteristic of shunt generator

With switch S in open condition, the generator is practically under no load condition as field current is pretty small. The voltmeter reading will be E_o as shown in figures and In other words, E_o and $I_a = 0$ is the first point in the load characteristic. To load the machine S is closed and the load resistances decreased so that it delivers load current I_L. Unlike separately as well. The drop in the terminal voltage will be caused by the usual *Ir*drop, brush voltage drop and armature reaction effect. Apart from these, in shunt generator, as terminal voltage decreases, field current hence excited motor, here $I_L \neq I_a$. In fact, for shunt generator, $I_a = I_L - I_f$. So increase of I_L will mean increase of $I_{a\,aa}$ φ also decreases causing additional drop in terminal voltage. Remember in shunt generator, field current is decided by the terminal voltage by virtue of its parallel connection with the armature. Figure (38.9) shows the plot of terminal voltage versus armature current which is called the *load characteristic*. One can of course translate the V versus I_a characteristic into V versus I_L characteristic by subtracting the correct value of the field current from the armature current. For example, suppose the machine is loaded such that terminal voltage becomes V_1 and the armature current is I_{a1}. The field current at this load can be read from the field resistance line corresponding to the existing voltage V_1 across the field as shown in figure (38.9). Suppose I_{f1} is the noted field current. Therefore, $I_{Ll} = I_{a1} - I_{f1}$.Thus the point $[I_{a1}, V_1]$ is translated into $[I_{Ll}, V_1]$ point. Repeating these step for all the points we can get the V versus I_L characteristic as well. It is interesting to note that the generated voltage at this loading is E_{G1} (obtained from OCC corresponding to I_{f1}). Therefore the length PQ must represents sum of all the voltage drops that has taken place in the armature when it delivers I_a.

$$\begin{aligned} E_{G1} - V_1 &= lengthPQ \\ &= I_{a1}r_a + \text{brush drop} + \text{drop due to armature reaction} \\ E_{G1} - V_1 &\approx I_{a1}r_a \text{ neglecting brush drop \& armature reaction drop.} \end{aligned}$$

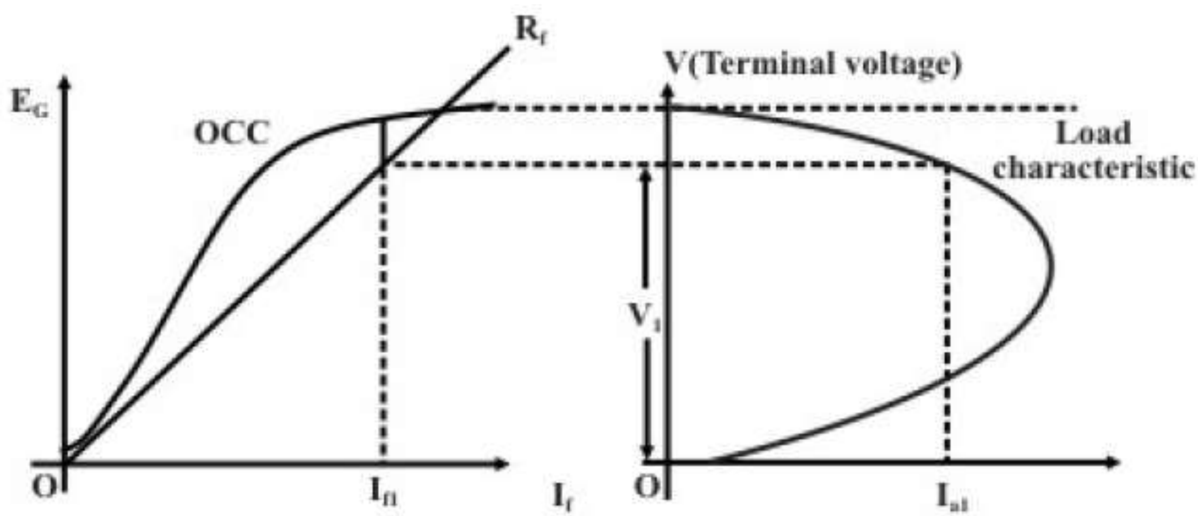


Fig 2.16: Load Characteristics of shunt generator

A compound machines have both series and shunt field coils. On each pole these two coils are placed as shown in figure 38.1. Series field coil has low resistance, fewer numbers of turns with large cross sectional area and connected either in series with the armature or in series with the line. On the other hand shunt field coil has large number of turns, higher resistance, small cross sectional area and either connected in parallel across the armature or connected in parallel across the series combination of the armature and the series field. Depending on how the field coils are connected, compound motors are classified as *short shunt* and *long shunt* types as shown in figures

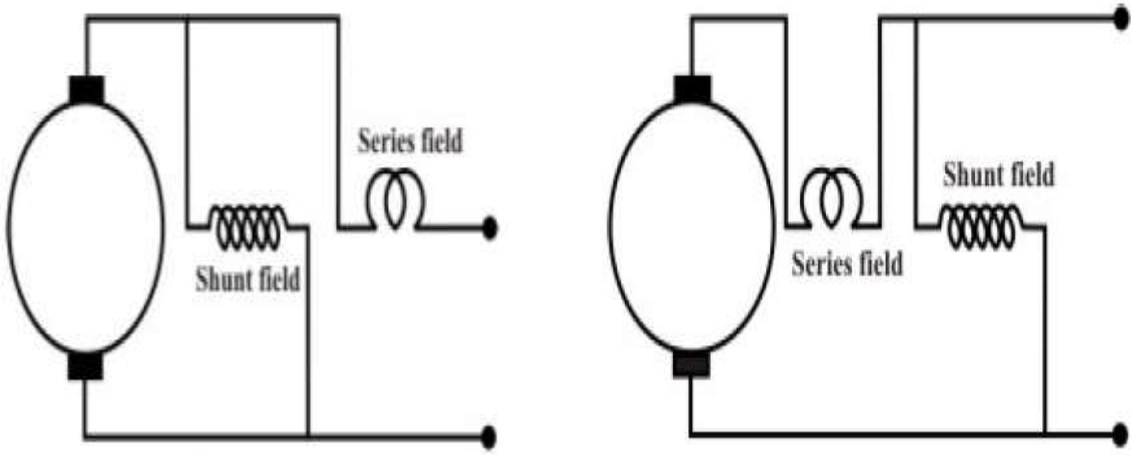


Fig2.17 a: Short Shunt connection. Fig2.17 b: Long Shunt Connection.

Series field coil may be connected in such a way that the mmf produced by it aids the shunt field mmf-then the machine is said to be cumulative compound machine, otherwise if the series field mmf acts in opposition with the shunt field mmf – then the machine is said to be differential compound machine.

In a compound generator, series field coil current is load dependent. Therefore, for a cumulatively compound generator, with the increase of load, flux per pole increases. This in turn increases the generated emf and terminal voltage. Unlike a shunt motor, depending on the strength of the series field mmf, terminal voltage at full load current may be same or more than the no load voltage. When the terminal voltage at rated current is same that at no load condition, then it is called a level compound generator. If however, terminal voltage at rated current is more than the voltage at no load, it is called a over compound generator. The load characteristic of a cumulative compound generator will naturally be above the load characteristic of a shunt generator as depicted in figure 38.14. At load current higher than the rated current, terminal voltage starts decreasing due to saturation, armature reaction effect and more drop in armature and series field resistances.

To understand the usefulness of the series coil in a compound machine let us undertake the following simple calculations. Suppose as a shunt generator (series coil not connected) 300 AT/pole is necessary to get no load terminal voltage of 220 V. Let the terminal voltage becomes 210 V at rated armature current of 20 A. To restore the terminal voltage to 220 V, shunt excitation needs to be raised such that AT/pole required is 380 at 20 A of rated current. As a level compound generator, the extra AT (380-300 = 80) will be provided by series field. Therefore, number of series turns per pole will be 80/20 = 4. Thus in a compound generator series field will automatically provide the extra AT to arrest the drop in terminal voltage which otherwise is inevitable for a shunt generator.

For the differentially compounded generator where series field mmf opposes the shunt field mmf the terminal voltage decreases fast with the increase in the load current.

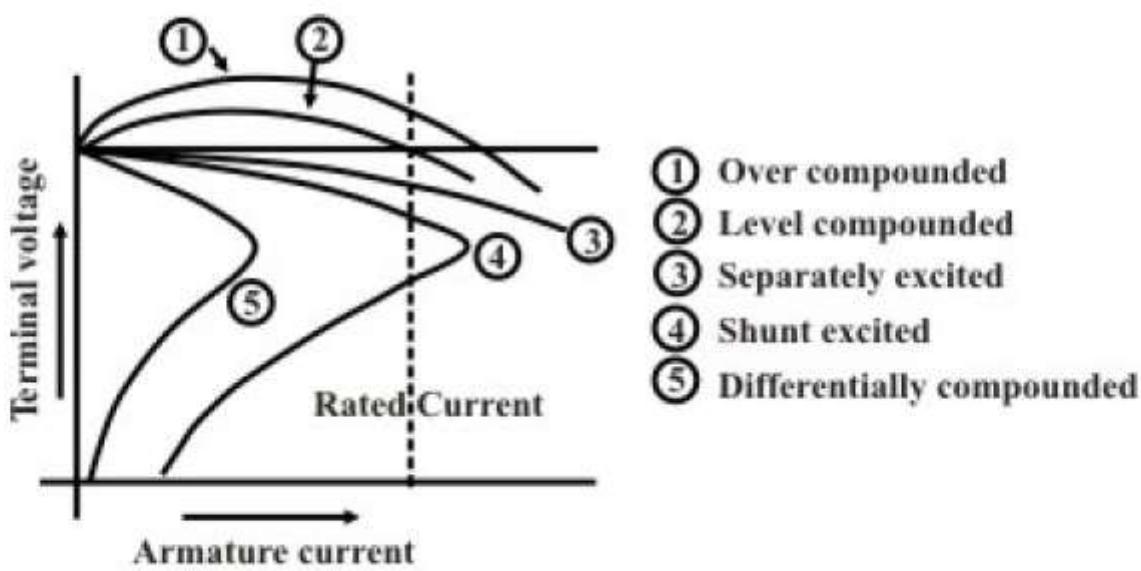


Fig 2.18: Load Characteristics of DC generator.

Synchronous Generators:

Introduction:-

An alternator is an alternating current voltage generator. It is also called a **"Synchronous generator"**. In the case of an alternator, the field system is rotating and the armature is stationary. This is because, in the case of an alternator, having a stationary armature has several advantages, which are listed below:

1. The generated voltage can be directly connected to the load, so that, the load current need not pass through brush contacts.
2. It is easy to insulate the stationary armature for high ac generated voltages, which may be as high as 11kv to 33kv.
3. The sliding contacts i.e. the slip rings are transferred to the low voltage,low power dc field circuit which can be easily insulated. The excitation voltage is only of the order 110volts to 220volts.
4. The armature windings can be easily braced to prevent any deformation produced by large mechanical stresses set up due to short circuit and large centrifugal forces that might set up.

Construction:

Basically an alternator consists of two parts.

a) Stator
b) Rotor

<u>Stator</u>

The stator of an alternator consists of a stator frame made of mild steel plates, welded together to form a cylindrical drum. Inside the cylindrical drum, cylindrical statorlaminations made of special steel alloy are fixed. The stator core laminations are insulated from one another and pressed together to form a core. On the inner periphery of stator core, uniform slots are cut to house the stator conductors. These are holes cast in the stator frame and radial ventilating spaces in the lamination which circulate free air and help in cooling of the alternator. For small alternators the laminations are in one section and for large alternators each lamination is made up of small segments

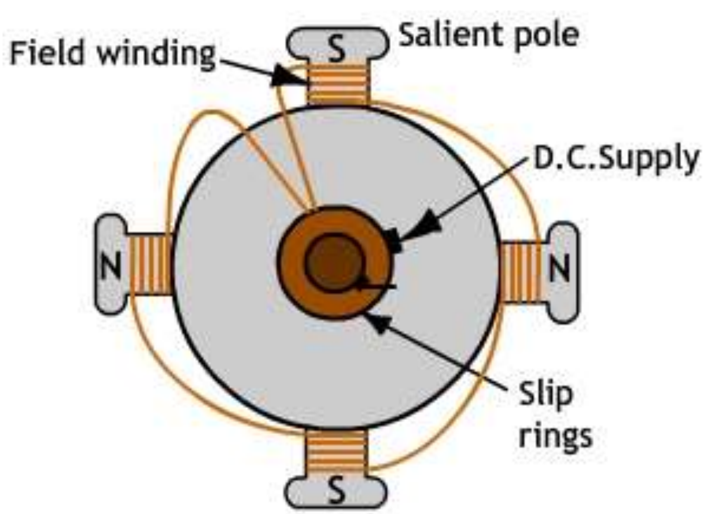
Rotor

There are two types of rotor.

1) Salient Pole Type
2) SmoothCylindrical Type

The alternator with salient pole type rotor is called salient pole alternator and the alternator with smooth cylindrical type rotor is called non-salient pole alternator or turbo alternator.

Salient Pole Type Alternator-

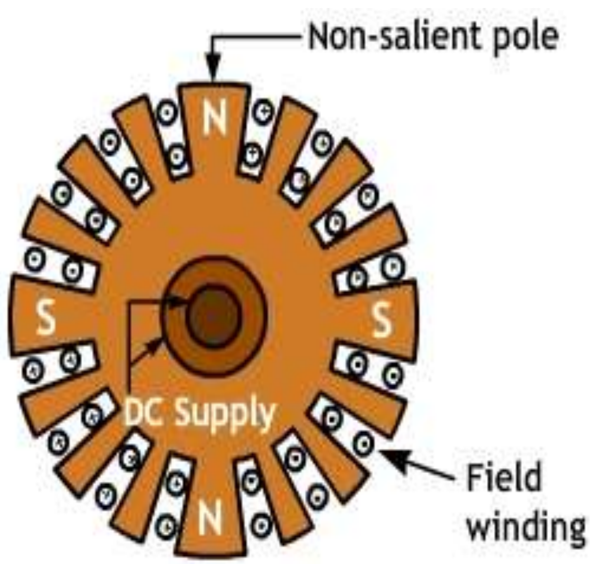


This is also called project pole type as all the poles are projected out from the surface of the rotor.

The poles are built up of thick steel laminations. The poles are bolted to the rotor as shown in figure above. The field winding is provided on the pole shoe. These rotors have large diameters and small axial lengths. The limiting factor for the size of the rotor is the centrifugal force acting on the rotating member of the machine. As mechanical strength of salient pole type is less, this is preferred for low speed alternators ranging from 125rpm to 500rpm. The prime movers used to drive such rotors are generally water turbines and IC engines.

Smooth Cylindrical Type Rotor. (Non Salientor Non Projected Pole Type)

The rotor consists of smooth solid steel cylinder having a number of slots to accommodate the field coils. These slots are covered at the top with the help of steel or manganese wedges. Theunslotted portions of the cylinder itself act as the poles.



The poles are not projecting out and the surface of the rotor is smooth which maintains uniform air gap between stator and rotor. These rotors have small diameters and large axial lengths. This is to keep peripheral speed into limits. The main advantage of this type is that these are mechanically very strong and thus preferred for high speed alternators ranging 1500rpm to 3000rpm. Such high speed alternators are called 'turbo alternators'. The prime movers used to drive such type of rotors are steam turbines, electric motors.

Working principle

The field winding of the rotor is supplied with a dc voltage of 110v or 220 volts generated by the pilot exciter through the two brushes which are set to slide on two slip rings fixed to the shafts of the alternator. The rotor is rotated by a prime mover and the flux produced by the rotor poles sweeps across the stator conductors and hence the EMF is induced in the

Relation between Poles, Speed and the Frequency:

Let P= number of poles

N= speed of rotor in rpm.

f= frequency of generated emf in Hz.

Since one cycle of emf is induced when a conductor passes through a pair of poles, the number of cycles of emf induced in one revolution of rotor is equal to the number of pair of poles.

No. of cycles/revolution = P/2

No. of revolution/sec = N/60

Frequency = no. of cycles/sec

Frequency (f) =no. of cycles/revolution x No. of revolutions/sec

$$f = \frac{P}{2} \times \frac{N}{60}$$

$$f = \frac{PN}{120}\ Hz \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

EMF Equation of an Alternator:

Let N= speed of rotor in rpm

Φ= flux per pole in wb.

P= no. of poles

f= frequency

Z=number of armature conductors in series per phase.

Z=2T, T→No. of turns per phase.

Time taken for one revolution → 60/N se

During this time a conductor crosses P poles and cuts a flux of PΦ wb.

Therefore according to faraday's law,

Average induced emf / conductor= flux cut/ time taken = PΦ/ (60/N)

= NPΦ/60 volts

But f= PN/120 Hz.

Therefore, $avg\ induced\ emf/conductor\ = 120f\Phi/60 = 2f\Phi \quad volts$.

Z conductors are connected in series per phase,

$E(avg)/phase\ = 2fZ\Phi\ volts.$

But Z=2T

$$E(avg)/phase = Zf\Phi 2T$$

$$= 4fT\Phi \qquad volts.$$

Wkt,

$Form\ factor = rms\ value/average\ value = 1.11\ for\ sine\ wave.$

Therefore $E(rms/phase) = 4.44\ fT\Phi\ volts \dots\dots\dots\dots\dots\dots\dots\dots (2)$

The above emf is derived assuming that the stator winding is full pitched and the emf's induced in the various conductors are equal in magnitude and does not have any phase difference. It is also assumed that all the conductors per pole per phase are connected in a single slot. But, in practice the coils are short pitched. The conductors are uniformly distributed in all the slots of the stator. Due to these two facts, the emf induced in the alternator gets reduced by a small quantity. The equation for induced emf is modified as,

$E_{ph} = 2.22K_p K_d\ fZ\Phi \quad volts$

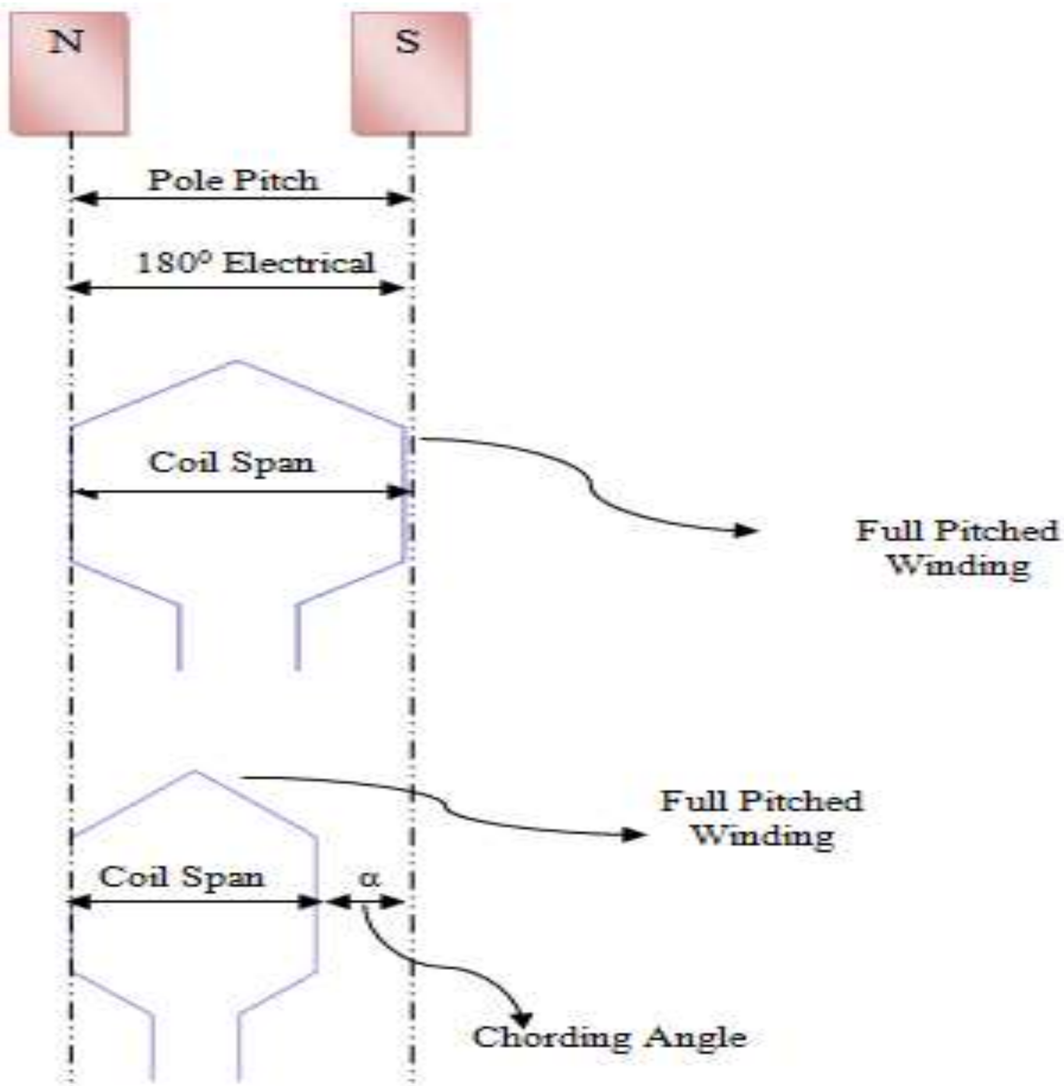
Where K_P=pitch factor

K_d= distribution factor

Pitch factor

It is **also** known as coil span factor or chording factor. Pole pitch is the distance between two similar points on adjacent poles and it is defined to be 180° electrical. Coil pitch or coil span is the distance between two adjacent sides of a coil.

If the armature winding is so wound that the coil pitch equals the pole pitch then it is called a full pitched winding. But for practical reasons, we make the coil span less than the pole pitch by angle α where α is called the chording angle(then the winding is said to be short pitched).



Due to this, the induced emf reduces by a pitch factor K_p, the pitch factor and $Kp = cos(\alpha/2)$

Distribution factor K_d

This is also known as breadth factor orwinding factor. Under the influence of each pole, Z/P conductors belong to one phase. All these conductors can be accommodated in one armature slot and we have to distribute them over two or more slots. This again reduces the induced emf by a factor K_d.

$$K_d = \frac{\sin\left({m\beta}/{2}\right)}{m\sin\left({\beta}/{2}\right)}$$

$$Where\ m = \ number\ of\ slots/pole/phase.$$

$$= total\ no.of\ armature\ slots/\ (no.of\ poles\ x\ no.of\ phases)$$

$$And\ \beta = \frac{180°}{(no.of\ slots \times\ pole)}$$

Taking these two factors into account,

$$E_{rms/ph} = \ 4.44\ K_p K_d\ fT\Phi\ volts$$

$$Or\ E_{rms/ph} \ = \ 4.44K_w fT\ \Phi\ volts\ \dots\dots\dots\dots\dots..K_w = \ K_p K_d$$

Voltage Regulation of an Alternator:

The total change in terminal voltage of the alternator from no load to full load, at constant speed and field excitation, is termed as *voltage regulation*.

[OR]

The voltage regulation of an alternator is the change in its terminal voltage when full load is removed keeping the field excitation and speed constant, divided by the rated terminal voltage.

$$Regulation = \frac{E_0 - V}{V}$$

Where E_0= no load terminal voltage.

V= full load terminal voltage.

The regulation is usually expressed as a % of the voltage drop from no load to full load w.r.t full load terminal voltage.

$$\%Regulation = \frac{E_0 - V}{V} \times 100$$