Transformers

1 Introduction

Michael Faraday propounded the principle of electro-magnetic induction in 1831. It states that a voltage appears across the terminals of an electric coil when the flux linked with the same changes. The magnitude of the induced voltage is proportional to the rate of change of the flux linkages. This finding forms the basis for many magneto electric machines. The earliest use of this phenomenon was in the development of induction coils. These coils were used to generate high voltage pulses to ignite the explosive charges in the mines. As the d.c. power system was in use at that time, very little of transformer principle was made use of. In the d.c. supply system the generating station and the load center have to be necessarily close to each other due to the requirement of economic transmission of power. Also the d.c. generators cannot be scaled up due to the limitations of the commutator. This made the world look for other efficient methods for bulk power generation and transmission. During the second half of the 19th century the alternators, transformers and induction motors were invented. These machines work on alternating power supply. The role of the transformers became obvious. The transformer which consisted of two electric circuits linked by a common magnetic circuit helped the voltage and current levels to be changed keeping the power invariant. The efficiency of such conversion was extremely high. Thus one could choose a moderate voltage for the generation of a.c. power, a high voltage for the transmission of this power over long distances and finally use a small and safe operating voltage at the user end. All these are made possible by transformers. The a.c. power systems thus got well established.

Transformers can link two or more electric circuits. In its simple form two electric circuits can be linked by a magnetic circuit, one of the electric coils is used for the creation of a time varying magnetic filed. The second coil which is made to link this field has an induced voltage in the same. The magnitude of the induced emf is decided by the number of turns used in each coil. Thus the voltage level can be increased or decreased by changing the number of turns. This excitation winding is called a primary and the output winding is called a secondary. As a magnetic medium forms the link between the primary and the secondary windings there is no conductive connection between the two electric circuits. The transformer thus provides an electric isolation between the two circuits. The frequency on the two sides will be the same. As there is no change in the nature of the power, the resulting machine is called a 'transformer' and not a 'converter'. The electric power at one voltage/current level is only 'transformed' into electric power, at the same frequency, to another voltage/current level.

Even though most of the large-power transformers can be found in the power systems, the use of the transformers is not limited to the power systems. The use of the principle of transformers is universal. Transformers can be found operating in the frequency range starting from a few hertz going up to several mega hertz. Power ratings vary from a few milliwatts to several hundreds of megawatts. The use of the transformers is so wide spread that it is virtually impossible to think of a large power system without transformers. Demand on electric power generation doubles every decade in a developing country. For every MVA of generation the installed capacity of transformers grows by about 7MVA. These figures show the indispensable nature of power transformers.

is assumed to be varying sinusoidally, and can be expressed as,

$$B = B_m \sin \omega t \tag{4}$$

where B_m is the peak amplitude of the flux density. ω is the angular rate of change with time. Then, the instantaneous value of the flux linkage is given by,

$$\psi = N\phi = NLXB_m \sin \omega t \tag{5}$$

The instantaneous value of the induced emf is given by,

$$e = \frac{d\psi}{dt} = N\phi_m.\omega \cos \omega t = N\phi_m.\omega. \sin(\omega t + \frac{\pi}{2}) \tag{6}$$

Here $\phi_m = B_m.L.X$. The peak value of the induced emf is

$$e_m = N\phi_m.\omega \tag{7}$$

and the rms value is given by

$$E = \frac{N\phi_m.\omega}{\sqrt{2}} \text{ volt.}$$

Further, this induced emf has a phase difference of $\pi/2$ radian with respect to the flux linked by the turn. This emf is termed as 'transformer' emf and this principle is used in a transformer. Polarity of the emf is obtained by the application of Lenz's law. Lenz's law states that the reaction to the change in the flux linkages would be such as to oppose the cause. The emf if permitted to drive a current would produce a counter mmf to oppose this changing flux linkage. In the present case, presented in Fig. 2 the flux linkages are assumed to be increasing. The polarity of the emf is as indicated. The loop also experiences a compressive force.

Fig. 2(b) shows the same example as above but with a small difference. The flux density is held constant at B Tesla. The flux linked by the coil at the current position is reactance can be substantially reduced.

3.3 Insulation

The insulation used in the case of electrical conductors in a transformer is varnish or enamel in dry type of transformers. In larger transformers to improve the heat transfer characteristics the conductors are insulated using un-impregnated paper or cloth and the whole core-winding assembly is immersed in a tank containing transformer oil. The transformer oil thus has dual role. It is an insulator and also a coolant. The porous insulation around the conductor helps the oil to reach the conductor surface and extract the heat. The conductor insulation may be called the minor insulation as the voltage required to be withstood is not high. The major insulation is between the windings. Annular bakelite cylinders serve this purpose. Oil ducts are also used as part of insulation between windings. The oil used in the transformer tank should be free from moisture or other contamination to be of any use as an insulator.

3.4 Cooling of transformers

Scaling advantages make the design of larger and larger unit sizes of transformers economically attractive. This can be explained as below. Consider a transformer of certain rating designed with certain flux density and current density. If now the linear dimensions are made larger by a factor of K keeping the current and flux densities the same the core and conductor areas increase by a factor of K^2. The losses in the machine, which are proportional to the volume of the materials used, increase by a factor of K^3.The rating of the machine increases by a factor of K^4.

3.4.1 Properties of the transformer coil

Even though the basic functions of the oil used in transformers are a) heat conduction and b) electrical insulation, there are many other properties which make a particular oil eminently suitable. Organic oils of vegetative or animal origin are good insulators but tend to decompose giving rise to acidic by-products which attack the paper or cloth insulation around the conductors.

Mineral oils are suitable from the point of electrical properties but tend to form sludge. The properties that are required to be looked into before selecting an oil for transformer application are as follows:

Insulting property This is a very important property. However most of the oils naturally fulfil this. Therefore deterioration in insulating property due to moisture or contamination may be more relevant.

Viscosity It is important as it determines the rate of flow of the fluid. Highly viscous fluids need much bigger clearances for adequate heat removal.

Purity The oil must not contain impurities which are corrosive. Sulphur or its compounds as impurities cause formation of sludge and also attack metal parts.

Sludge formation Thickening of oil into a semisolid form is called a sludge. Sludge formation properties have to be considered while choosing the oil as the oil slowly forms semi-solid hydrocarbons. These impede flows and due to the acidic nature, corrode metal parts. Heat in the presence of oxygen is seen to accelerate sludge formation. If the hot oil is prevented from coming into contact with atmospheric air sludge formation can be greatly reduced.

Acidity Oxidized oil normally produces CO_2 and acids. The cellulose which is in the paper insulation contains good amount of moisture. These form corrosive vapors. A good breather can reduce the problems due to the formation of acids.

Flash point And Fire point Flash point of an oil is the temperature at which the oil ignites spontaneously. This must be as high as possible (not less than $160°C$ from the point of safety). Fire point is the temperature at which the oil flashes and continuously burns. This must be very high for the chosen oil (not less than $200°C$).

Inhibited oils and synthetic oils are therefore used in the transformers. Inhibited oils contain additives which slow down the deterioration of properties under heat and moisture and hence the degradation of oil. Synthetic transformer oil like chlorinated diphenyl has excellent properties like chemical stability, non-oxidizing, good dielectric strength, moisture repellant, reduced risk due fire and explosion.

It is therefore necessary to check the quality of the oil periodically and take corrective steps to avoid major break downs in the transformer.

There are several other structural and insulating parts in a large transformer. These are considered to be outside the scope here.

a nonlinear manner to establish the flux of sinusoidal shape. This non-linear current can be resolved into fundamental and harmonic currents. This is discussed to some extent under harmonics. At present the effect of this non-linear behavior is neglected as a secondary effect. Hence the current drawn from the mains is assumed to be purely sinusoidal and directly proportional to the flux density of operation. This current can be represented by a current drawn by an inductive reactance in the circuit as the net energy associated with the same over a cycle is zero. The energy absorbed when the current increases is returned to the electric circuit when the current collapses to zero. This current is called the magnetizing current of the transformer. The magnetizing current I_m is given by $I_m = E_1/X_m$ where X_m is called the magnetizing reactance. The magnetic circuit being lossy absorbs and dissipates the power depending upon the flux density of operation. These losses arise out of hysteresis, eddy current inside the magnetic core. These are given by the following expressions:

$$P_h \propto B^{1.6} f \tag{25}$$

$$P_e \propto B^2 f^2 t^2 \tag{26}$$

P_h -Hysteresis loss, Watts

B- Flux density of operation Tesla.

f - Frequency of operation, Hz

t - Thickness of the laminations of the core, m.

For a constant voltage, constant frequency operation B is constant and so are these losses. An active power consumption by the no-load current can be represented in the input circuit as a resistance R_c connected in parallel to the magnetizing reactance X_m. Thus the no-load current I_0 may be made up of I_c(loss component) and I_m (magnetizing component

$$\begin{aligned} V_1 &= aV_2 + aI_2(r_2 + jx_{l2}) + I_1(r_1 + jx_{l1}) \\ &= V_2' + I_1(a^2 r_2 + ja^2 x_{l2}) + I_1(r_1 + jx_{l1}) \\ &= V_2' + I_1(\overline{r_1 + r_2'} + j\overline{x_{l1} + x_{l2}'}) \qquad (37) \end{aligned}$$

A similar procedure can be used to refer all parameters to secondary side. (Shown in fig. 15.)

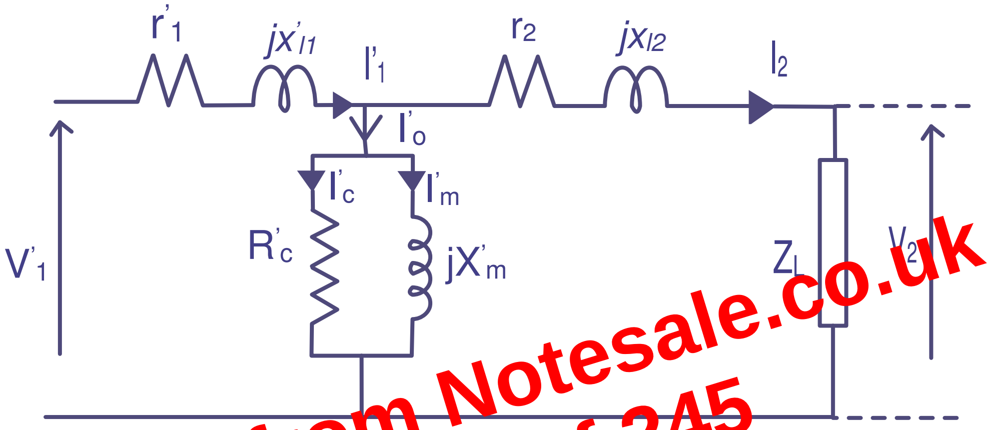
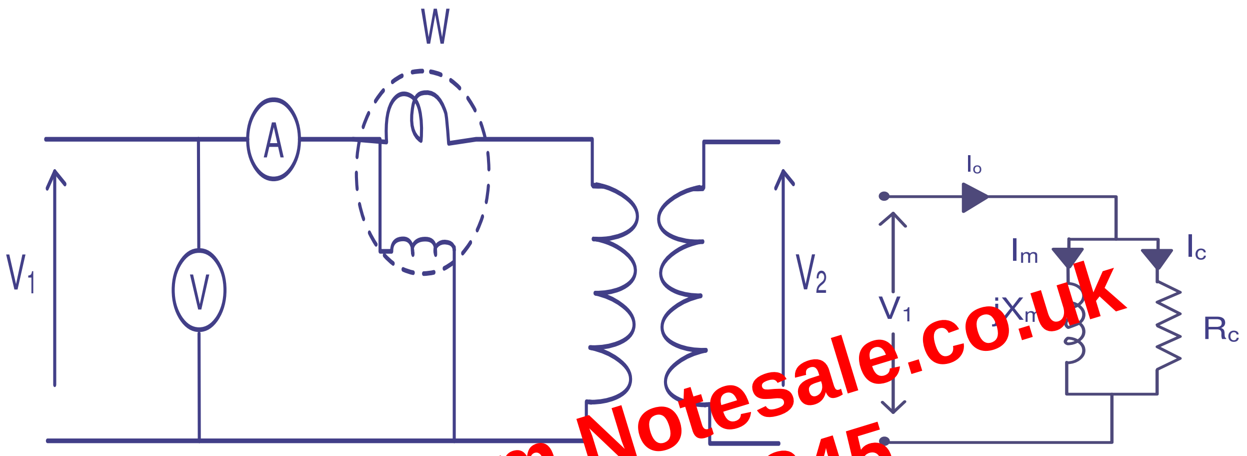


Figure 15: Equivalent Circuit Referred to the Secondary Side

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.

7.3 Open Circuit Test

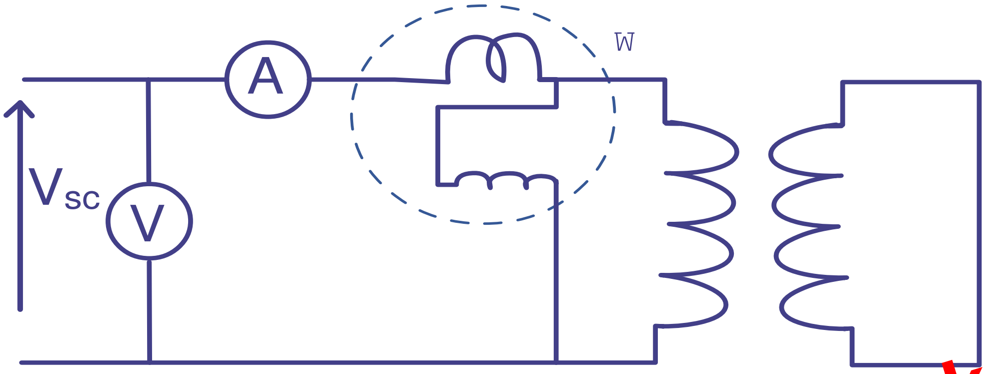


(a)Physical Arrangement

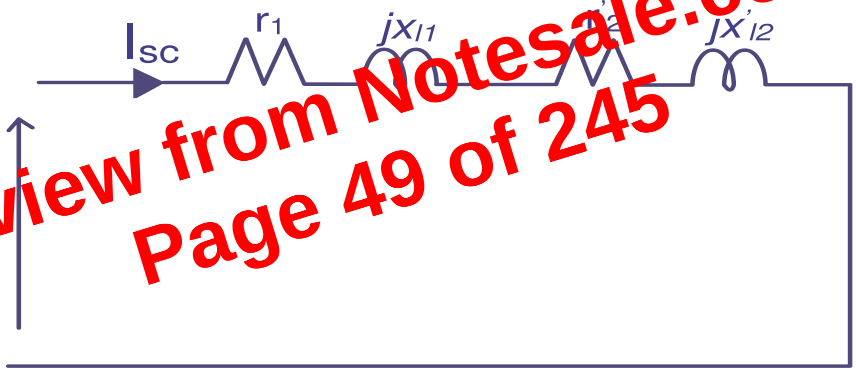
(b)Equivalent Circuit

Figure 19: No Load Test

As the name suggests, the secondary is kept open circuited and nominal value of the input voltage is applied to the primary winding and the input current and power are measured. In Fig. 19(a) V, A, W are the voltmeter, ammeter and wattmeter respectively. Let these meters read V_1, I_0 and W_0 respectively.Fig. 19(b) shows the equivalent circuit of the transformer under this test. The no load current at rated voltage is less than 1 percent of nominal current and hence the loss and drop that take place in primary impedance $r_1 + jx_{l1}$ due to the no load current I_0 is negligible. The active component I_c of the no load current I_0



(a)Physical Arrangement



(b)Equivalent Circuit

Figure 21: Short Circuit Test

If the approximate equivalent circuit is required then there is no need to separate r_1 and $r_2^{'}$ or x_{l1} and $x_{l2}^{'}$. However if the exact equivalent circuit is needed then either r_1 or $r_2^{'}$ is determined from the resistance measurement and the other separated from the total. As for the separation of x_{l1} and $x_{l2}^{'}$ is concerned, they are assumed to be equal. This is a fairly valid assumption for many types of transformer windings as the leakage flux paths are through air and are similar.

7.5 Load Test

Load Test helps to determine the total loss that takes place, when the transformer is loaded. Unlike the tests described previously, in the present case nominal voltage is applied across the primary and rated current is drown from the secondary. Load test is used mainly

1. to determine the rated load of the machine and the temperature rise
2. to determine the voltage regulation and efficiency of the transformer.

Rated load is determined by loading the transformer on a continuous basis and observing the steady state temperature rise. The losses that are generated inside the transformer on load appear as heat. This heats the transformer and the temperature of the transformer increases. The insulation of the transformer is the one to get affected by this rise in the temperature. Both paper and oil which are used for insulation in the transformer start getting degenerated and get decomposed. If the flash point of the oil is reached the transformer goes up in flames. Hence to have a reasonable life expectancy the loading of the transformer must be limited to that value which gives the maximum temperature rise tolerated by the insulation. This aspect of temperature rise cannot be guessed from the electrical equivalent circuit. Further, the losses like dielectric losses and stray load losses are not modeled in the

$$\frac{v_2^2}{2(1+v_1)} \simeq \frac{v_2^2}{2}.\frac{(1-v_1)}{(1-v_1^2)} \simeq \frac{v_2^2}{2}.(1-v_1) \simeq \frac{v_2^2}{2} \tag{63}$$

Powers higher than 2 for v_1 and v_2 are negligible as v_1 and v_2 are already small. As v_2 is small its second power may be neglected as a further approximation and the expression for the regulation of the transform boils down to

regulation $R = e_r \cos\phi \pm e_x \sin\phi$

The negative sign is applicable when the power factor is leading. It can be seen from the above expression, the full load regulation becomes zero when the power factor is leading and $e_r \cos\phi = e_x \sin\phi$ or $\tan\phi = e_r/e_x$

or the power factor angle $\phi = \tan^{-1}(e_r/e_x) = \tan^{-1}(R_e/X_e)$ leading.

Similarly, the value of the regulation is maximum at a power factor angle $\phi = \tan^{-1}(e_x/e_r) = \tan^{-1}(X_e/R_e)$ lagging.

An alternative expression for the regulation of a transformer can be derived by the method shown in Fig. 24. Here the phasor are resolved along the current axis and normal to it.

We have,

$$\begin{aligned} OD^2 &= (OA+AB)^2 + (BC+CD)^2 && (64)\\ &= (V_2' \cos\phi + I_2'R_e)^2 + (V_2' \sin\phi + I_2'X_e)^2 && (65)\\ \therefore Regulation R &= \frac{OD - V_2'}{V_2'} = \frac{OD}{V_2'} - 1 && (66)\end{aligned}$$

$$\sqrt{\frac{(V_2' \cos\phi + I_2'R_e)}{V_2'}^2 + \frac{(V_2' \sin\phi + I_2'X_e)}{V_2'}^2} - 1 \tag{67}$$

$$= \sqrt{(\cos\phi + R_{p.u})^2 + (\sin\phi + X_{p.u)}^2} - 1 \tag{68}$$

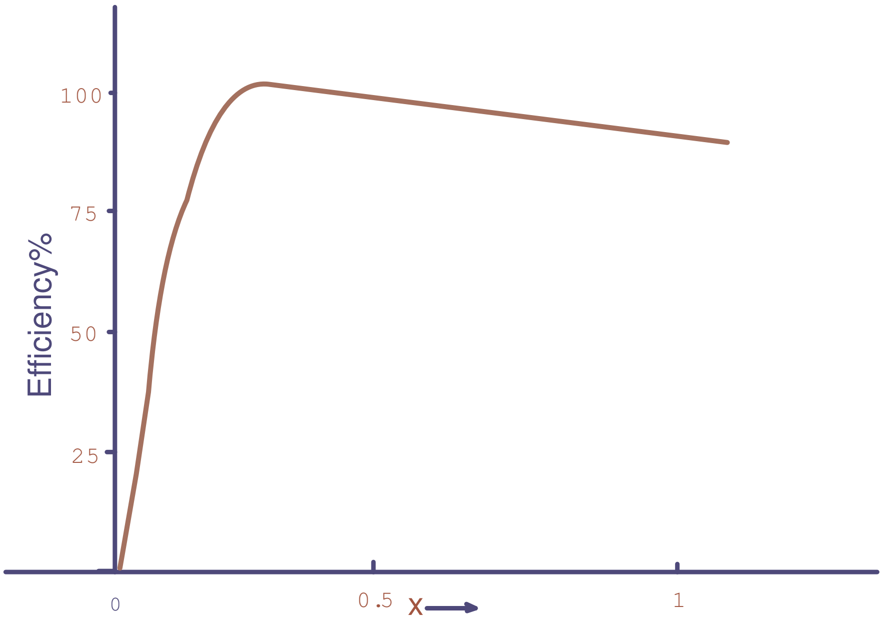


Figure 26: Efficiency

A typical curve for the variation of efficiency as a function of output is given in Fig. 26 The losses that take place inside the machine expressed as a fraction of the input is some times termed as deficiency. Except in the case of an ideal machine, a certain fraction of the input power gets lost inside the machine while handling the power. Thus the value for the efficiency is always less than one. In the case of a.c. machines the rating is expressed in terms of apparent power. It is nothing but the product of the applied voltage and the current drawn. The actual power delivered is a function of the power factor at which this current is drawn. As the reactive power shuttles between the source and the load and has a zero average value over a cycle of the supply wave it does not have any direct effect on the efficiency. The reactive power however increases the current handled by the machine and the losses resulting from it. Therefore the losses that take place inside a transformer at any given load play a vital role in determining the efficiency. The losses taking place inside a transformer can be enumerated as below:

1. Primary copper loss
2. Secondary copper loss
3. Iron loss
4. Dielectric loss
5. Stray load loss

These are explained in sequence below.

Primary and secondary copper losses take place in the respective winding resistances due to the flow of the current in them.

$$P_c = I_1^2 r_1 + I_2^2 r_2 = I_2'^2 R_e \tag{70}$$

The primary and secondary resistances differ from their d.c. values due to skin effect and the temperature rise of the windings. While the average temperature rise can be approximately used, the skin effect is harder to get analytically. The short circuit test gives the value of R_e taking into account the skin effect.

The iron losses contain two components - Hysteresis loss and Eddy current loss. The Hysteresis loss is a function of the material used for the core.

$$P_h = K_h B^{1.6} f$$

Auto transformers are used in applications where electrical isolation is not a critical requirement. When the ratio $V_2 : V_1$ is 0.3 or more they are used with advantage. The normal applications are motor starters, boosters or static balancers.

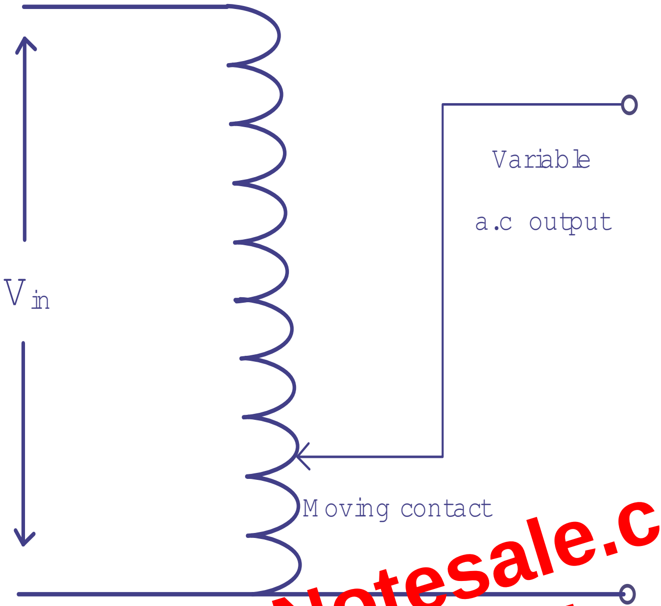


Figure 33: Variable Secondary Voltage Arrangement

Another wide spread application of auto transformer type of arrangement is in obtaining a variable a.c. voltage from a fixed a.c. voltage supply. Here only one winding is used as in the auto transformer. The secondary voltage is tapped by a brush whose position and hence the output voltage is variable. The primary conductor is bared to facilitate electrical contact Fig. 33. Such arrangement cannot exploit the savings in the copper as the output voltage is required right from zero volts upwards.

The conductor is selected based on the maximum secondary current that could be drawn as the output voltage varies in practically continuous manner. These are used in

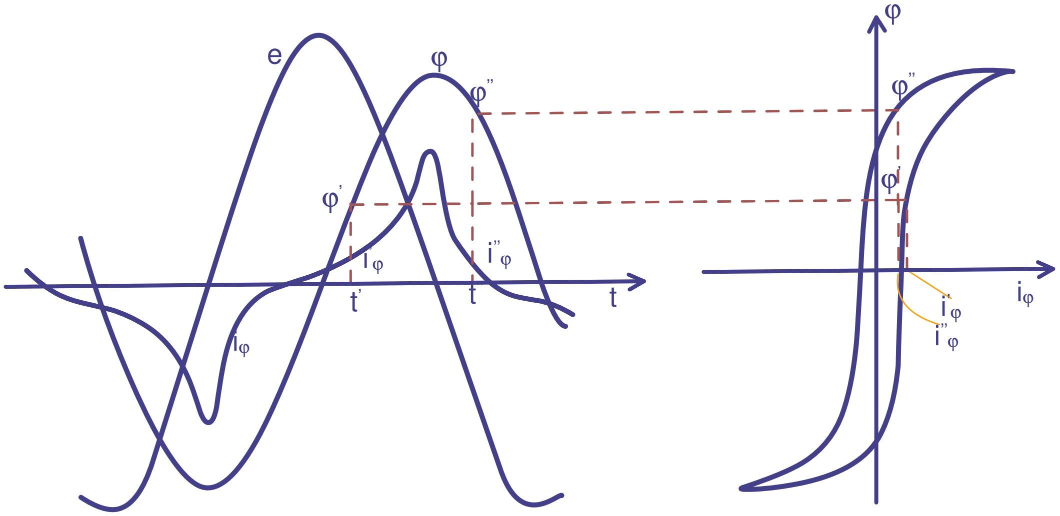


Figure 34: Harmonics Generated by Transformers

12.1 Single phase transformers

Modern transformers operate at increasing levels of saturation in order to reduce the weight and cost of the core used in the same. Because of this and due to the hysteresis, the transformer core behaves as a highly non-linear element and generates harmonic voltages and currents. This is explained below. Fig. 34 shows the manner in which the shape of the magnetizing current can be obtained and plotted. At any instant of the flux density wave the ampere turns required to establish the same is read out and plotted, traversing the hysteresis loop once per cycle. The sinusoidal flux density curve represents the sinusoidal applied voltage to some other scale. The plot of the magnetizing current which is peaky is analyzed using Fourier analysis. The harmonic current components are obtained from this analysis. These harmonic currents produce harmonic fields in the core and harmonic voltages in the windings. Relatively small value of harmonic fields generate considerable magnitude of harmonic voltages. For example a 10% magnitude of 3rd harmonic flux produces 30%

referring to 12 o'clock position. These vector groups are especially important when two or more transformers are to be connected in parallel.

Star connection is normally cheaper as there are fewer turns and lesser cost of insulation. The advantage becomes more with increase in voltage above 11kv. In a star connected winding with earthed-neutral the maximum voltage to the earth is $(\frac{1}{\sqrt{3}})$of the line voltage. Also star connection permits mixed loading due to the presence of the neutral. Mesh connections are advantageous in low voltage transformers as insulation costs are insignificant and the conductor size becomes $(\frac{1}{\sqrt{3}})$ of that of star connection and permits ease of winding. The common polyphase connections are briefly discussed now.

Star/star (Yy0, Yy6)connection This is the most economical one for small high voltage transformers. Insulation cost is highly reduced. Neutral wire can permit mixed loading. Triplen harmonics are absent in the lines. These triplen harmonic currents cannot flow, unless there is a neutral wire. This connection produces oscillating neutral. Three phase shell type units have large triplen harmonic phase voltage. However three phase core type transformers work satisfactorily. A tertiary mesh connected winding may be required to stabilize the oscillating neutral due to third harmonics in three phase banks.

Mesh/mesh (Dd0, Dd6) This is an economical configuration for large low voltage transformers. Large amount of unbalanced load can be met with ease. Mesh permits a circulating path for triplen harmonics thus attenuates the same. It is possible to operate with one transformer removed in open delta or Vee connection meeting 58 percent of the balanced load. Three phase units cannot have this facility. Mixed single phase loading is not possible due to the absence of neutral.

Star/mesh(Dy or Yd) This arrangement is very common for power supply transformers. The delta winding permits triplen harmonic currents to circulate in the closed path and attenuates them.

Zig zag/ star (ZY1 or Zy11) Zigzag connection is obtained by inter connection of phases. 4-wire system is possible on both sides. Unbalanced loading is also possible. Oscillating neutral problem is absent in this connection. This connection requires 15% more turns for the same voltage on the zigzag side and hence costs more.

Generally speaking a bank of three single phase transformers cost about 15% more than their 3-phase counter part. Also, they occupy more space. But the spare capacity cost will be less and single phase units are easier to transport.

Mesh connected three phase transformers resemble 3- single phase units but kept in a common tank. In view of this single tank, the space occupied is less. Other than that there is no big difference. The 3-phase core type transformer on the other hand has a simple core arrangement. The three limbs are equal in cross section. Primary and secondary of each phase are housed on the same limb. The flux setup in any limb will return through the other two limbs as the mmf of those limbs are in the proper directions so as to aid the same. Even though magnetically this is not a symmetrical arrangement, as the reluctance to the flux setup by side limbs is different from that of the central limb, it does not adversely affect the performance. This is due to the fact that the magnetizing current itself forms a small fraction of the total phase current drawn on load. The added advantage of 3-phase core is that it can tolerate substantially bars. Certain conditions have to be met before two or more transformers are connected in parallel and share a common load satisfactorily. They are,

1. The voltage ratio must be the same.
2. The per unit impedance of each machine on its own base must be the same.
3. The polarity must be the same, so that there is no circulating current between the transformers.
4. The phase sequence must be the same and no phase difference must exist between the voltages of the two transformers.

These conditions are examined first with reference to single phase transformers and then the three phase cases are discussed.

Same voltage ratio Generally the turns ratio and voltage ratio are taken to be the same. If the ratio is large there can be considerable error in the voltages even if the turns ratios are the same. When the primaries are connected to same bus bars, if the secondaries do not show the same voltage, paralleling them would result in a circulating current between the secondaries. Reflected circulating current will be there on the primary side also. Thus even without connecting a load considerable current can be drawn by the transformers and they produce copper losses. In two identical transformers with percentage impedance of 5 percent, a no-load voltage difference of one percent will result in a circulating current of 10 percent of full load current. This circulating current gets added to the load current when the load is connected resulting in unequal sharing of the load. In such cases the combined full load of the two transformers can never be met without one transformer getting overloaded.

The major objection to this scheme seems to be that the reactor is in the circuit always generating extra loss.

Parallel winding, transformer method In order to maintain the continuity of supply the primary winding is split into two parallel circuits each circuit having the taps as shown in Fig. 44. Two circuit breakers A and B are used in the two circuits. Initially tap 1_a and 1_b are closed and the transformer is energized with full primary voltage. To change the tap the circuit breaker A is opened momentarily and tap is moved from 1a to 2a. Then circuit breaker A is closed. When the circuit A is opened whole of the primary current of the transformer flows through the circuit B. A small difference in the number of turns between the two circuit exists. This produces a circulating current between them. Next, circuit breaker B is opened momentarily, the tap is changed from 1b to 2b and the breaker is closed. In this position the two circuits are similar and there is no circulating current. The circulating current is controlled by careful selection of the leakage reactance. Generally, parallel circuits are needed in primary and secondary to carry the large current in a big transformer. Provision of taps switches and circuit breakers are to be additionally provided to achieve tap changing in these machines.

Series booster method In this case a separate transformer is used to buck/boost the voltage of the main transformer. The main transformer need not be having a tapped arrangement. This arrangement can be added to an existing system also. Fig. 42shows the booster arrangement for a single phase supply. The reverser switch reverses the polarity of the injected voltage and hence a boost is converted into a buck and vice versa. The power rating of this transformer need be a small fraction of the main transformer as it is required to handle only the power associated with the injected voltage. One precaution to be taken with this arrangement is that the winding must

The Case(i) has no mechanical energy associated with it. This is the principle used in transformers. One coil carrying time varying current produces the time varying field and a second coil kept in the vicinity of the same has an emf induced in it. The induced emf of this variety is often termed as the transformer emf.

The Case(ii) is the one which is employed in d.c. machines and alternators. A static magnetic field is produced by a permanent magnet or by a coil carrying a d.c. current. A coil is moved under this field to produce the change in the flux linkages and induce an emf in the same. In order to produce the emf on a continuous manner a cylindrical geometry is chosen for the machines. The direction of the field, the direction of the conductor of the coil and the direction of movement are mutually perpendicular as mentioned above in the example taken.

In the example shown above, only one conductor is taken and the flux 'cut' by the same in the normal direction is used for the computation of the emf. The second conductor of the turn may be assumed to be far away or unmoving. This greatly simplifies the computation of the induced voltage as the determination of flux linkages and finding its rate of change are dispensed with. For a conductor moving at a constant velocity v the induced emf becomes just proportional to the uniform flux density of the magnetic field where the conductor is situated. If the conductor, field and motion are not normal to each other then the mutually normal components are to be taken for the computation of the voltage. The induced emf of this type is usually referred to as a rotational emf (due to the geometry).

Application of Faradays law according to Case(iii) above for electro mechani-

2 Principles of d.c. machines

D.C. machines are the electro mechanical energy converters which work from a d.c. source and generate mechanical power or convert mechanical power into a d.c. power. These machines can be broadly classified into two types, on the basis of their magnetic structure. They are,

1. Homopolar machines
2. Heteropolar machines.

These are discussed in sequence below.

2.1 Homopolar machines

Homopolar generators

Even though the magnetic poles occur in pairs, in a homopolar generator the conductors are arranged in such a manner that they always move under one polarity. Either north pole or south pole could be used for this purpose. Since the conductor encounters the magnetic flux of the same polarity every where it is called a homopolar generator. A cylindrically symmetric geometry is chosen. The conductor can be situated on the surface of the rotor with one slip-ring at each end of the conductor. A simple structure where there is only one cylindrical conductor with ring brushes situated at the ends is shown in Fig. 4. The excitation coil produces a field which enters the inner member from outside all along the periphery. The conductor thus sees only one pole polarity or the flux directed in one sense. A steady voltage now appears across the brushes at any given speed of rotation. The polarity of the induced voltage can be reversed by reversing either the excitation or the direction of sides of the laminations. Riveted through bolts hold the assembly together. The pole shoes are shaped so as to have a slightly increased air gap at the tips.

Inter-poles These are small additional poles located in between the main poles. These can be solid, or laminated just as the main poles. These are also fastened to the yoke by bolts. Sometimes the yoke may be slotted to receive these poles. The inter poles could be of tapered section or of uniform cross section. These are also called as commutating poles or compoles. The width of the tip of the compole can be about a rotor slot pitch.

Armature The armature is where the moving conductors are located. The armature is constructed by stacking laminated sheets of silicon steel. Thickness of these lamination is kept low to reduce eddy current losses. As the laminations carry alternating flux the choice of suitable material, insulation coating on the laminations, stacking it etc are to be done more carefully. The core is divided into packets to facilitate ventilation. The winding cannot be placed on the surface of the rotor due to the mechanical forces coming on the same. Open parallel sided equally spaced slots are normally punched in the rotor laminations. These slots house the armature winding. Large sized machines employ a spider on which the laminations are stacked in segments. End plates are suitably shaped so as to serve as 'Winding supporters'. Armature construction process must ensure provision of sufficient axial and radial ducts to facilitate easy removal of heat from the armature winding.

Field windings In the case of wound field machines (as against permanent magnet excited machines) the field winding takes the form of a concentric coil wound around the main poles. These carry the excitation current and produce the main field in the machine. Thus the poles are created electromagnetically. Two types of windings are generally employed. In shunt winding large number of turns of small section copper conductor is used. The resistance of such winding would be an order of magnitude larger than the armature winding resistance. In the case of series winding a few turns of heavy cross section conductor is used. The resistance of such windings is low and is comparable to armature resistance. Some machines may have both the windings on the poles. The total ampere turns required to establish the necessary flux under the poles is calculated from the magnetic circuit calculations. The total mmf required is divided equally between north and south poles as the poles are produced in pairs. The mmf required to be shared between shunt and series windings are apportioned as per the design requirements. As these work on the same magnetic system they are in the form of concentric coils. Mmf 'per pole' is normally used in these calculations.

Armature winding As mentioned earlier, if the armature coils are wound on the surface of the armature, such construction becomes mechanically weak. The conductors may fly away when the armature starts rotating. Hence the armature windings are in general pre-formed, taped and lowered into the open slots on the armature. In the case of small machines, they can be hand wound. The coils are prevented from flying out due to the centrifugal forces by means of bands of steel wire on the surface of the rotor in small groves cut into it. In the case of large machines slot wedges are additionally used to restrain the coils from flying away. The end portion of the windings are taped at the free end and bound to the winding carrier ring of the armature at the commutator end. The armature must be dynamically balanced to reduce the centrifugal forces at the operating speeds.

Compensating winding One may find a bar winding housed in the slots on the pole shoes. This is mostly found in d.c. machines of very large rating. Such winding is called compensating winding. In smaller machines, they may be absent. The function and the need of such windings will be discussed later on.

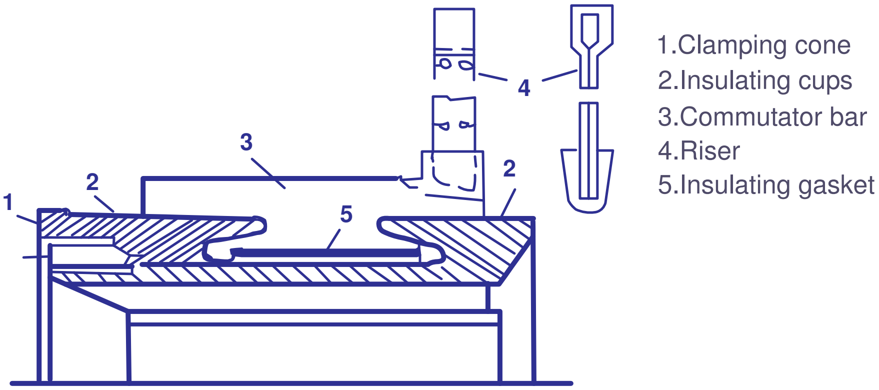


Figure 8: Cylindrical type commutator-a longitudinal section

Commutator Commutator is the key element which made the d.c. machine of the present day possible. It consists of copper segments tightly fastened together with mica/micanite insulating separators on an insulated base. The whole commutator forms a rigid and solid assembly of insulated copper strips and can rotate at high speeds. Each commutator segment is provided with a 'riser' where the ends of the armature coils get connected. The surface of the commutator is machined and surface is made concentric with the shaft and the current collecting brushes rest on the same. Under-cutting the mica insulators that are between these commutator segments has to be done periodically to avoid fouling of the surface of the commutator by mica when the commutator gets worn out. Some details of the construction of the commutator are seen in Fig. 8.

Brush and brush holders Brushes rest on the surface of the commutator. Normally electro-graphite is used as brush material. The actual composition of the brush depends on the peripheral speed of the commutator and the working voltage. The hardness of the graphite brush is selected to be lower than that of the commutator. When the

the brushes and the commutator even under high speeds of operation. Jumping of brushes must be avoided to ensure arc free current collection and to keep the brush contact drop low. Fig. 9 shows a brush holder arrangement. Radial positioning of the brushes helps in providing similar current collection conditions for both direction of rotation. For unidirectional drives trailing brush arrangement or reaction arrangement may be used in Fig. 9-(b) Reaction arrangement is preferred as it results in zero side thrust on brush box and the brush can slide down or up freely. Also staggering of the brushes along the length of the commutator is adopted to avoid formation of 'tracks' on the commutator. This is especially true if the machine is operating in a dusty environment like the one found in cement plants.

Other mechanical parts End covers, fan and shaft bearings form other important mechanical parts. End covers are completely solid or have opening for ventilation. They support the bearings which are on the shaft. Proper machining is to be ensured for easy assembly. Fans can be external or internal. In most machines the fan is on the non-commutator end sucking the air from the commutator end and throwing the same out. Adequate quantity of hot air removal has to be ensured.

Bearings Small machines employ ball bearings at both ends. For larger machines roller bearings are used especially at the driving end. The bearings are mounted press-fit on the shaft. They are housed inside the end shield in such a manner that it is not necessary to remove the bearings from the shaft for dismantling. The bearings must be kept in closed housing with suitable lubricant keeping dust and other foreign materials away. Thrust bearings, roller bearings, pedestal bearings etc are used under special cases. Care must be taken to see that there are no bearing currents or axial forces on the shaft both of which destroy the bearings.

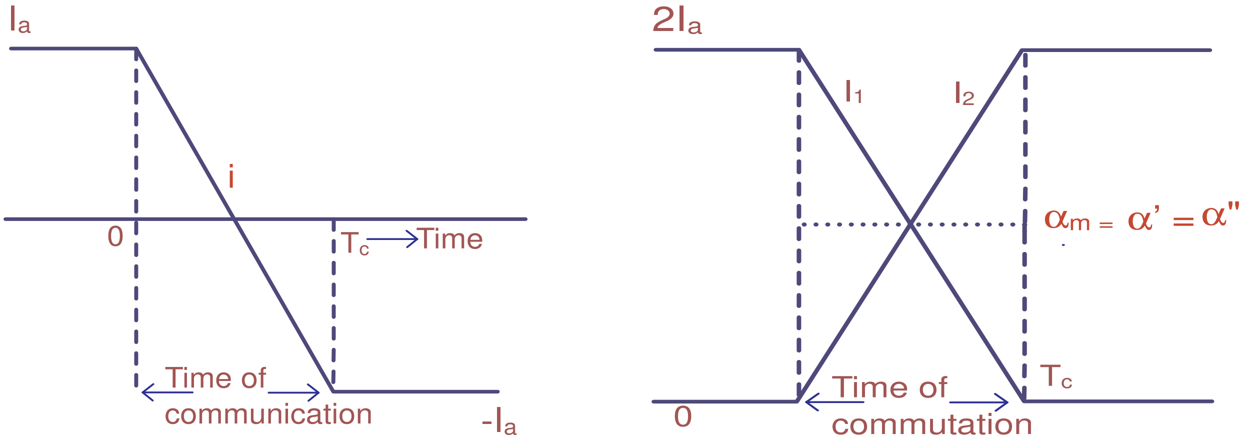
This shows the decrease in the mmf at one tip of a pole and a substantial rise at the other tip. If the machine has a pole arc to pole pitch ratio of 0.7 then 70% of the armature reaction mmf gets added at this tip leading to considerable amount of saturation under full load conditions. The flux distribution also is shown in Fig. 20. This is obtained by multiplying mmf and permeance waves point by point in space. Actual flux distribution differs from this slightly due to fringing. As seen from the figure, the flux in the inter polar region is substantially lower due to the high reluctance of the medium. The air gaps under the pole tips are also increased in practice to reduce excessive saturation of this part. The advantage of the salient pole field construction is thus obvious. It greatly mitigates the effect of the armature reaction. Also, the coils under going commutation have very little emf induced in them and hence better commutation is achieved. Even though the armature reaction produced a cross magnetizing effect, the net flux per pole gets slightly reduced, on load, due to the saturation under one tip of the pole. This is more so in modern d.c. machines where the normal excitation of the field makes the machine work under some level of saturation.

5.0.4 Effect of brush shift

In some small d.c. machines the brushes are shifted from the position of the magnetic neutral axis in order to improve the commutation. This is especially true of machines with unidirectional operation and uni-modal (either as a generator or as a motor) operation. Such a shift in the direction of rotation is termed 'lead' (or forward lead). Shift of brushes in the opposite to the direction of rotation is called 'backward lead'. This lead is expressed in terms of the number of commutator segments or in terms of the electrical angle. A pole pitch corresponds to an electrical angle of 180 degrees. Fig. 21 shows the effect of a forward source of internal resistance equal to the armature circuit resistance and a series voltage drop equal to the brush contact drop, under steady state. With this circuit model one can arrive at the external characteristics of the d.c. machine under different modes of operation.

5.1 Commutation

As seen earlier, in an armature conductor of a heteropolar machine a.c. voltages are induced as the conductor moves under north and south pole polarities alternately. The frequency of this induced emf is given by the product of the pole-pairs and the speed in revolutions per second. The induced emf in a full pitch coil changes sign as the coil crosses magnetic neutral axis. In order to get maximum d.c. voltage in the external circuit the coil should be shifted to the negative group. This process of switching is called commutation. During a short interval when the two adjacent commutator segments get bridged by the brush the coils connected in series between these two segments get short circuited. Thus in the case of ring winding and simple lap winding 2p coils get short circuited. In a simple wave winding in a 2p pole machine 2 coils get short circuited. The current in these coils become zero and get reversed as the brush moves over to the next commutator segment. Thus brush and commutator play an important role in commutation. Commutation is the key process which converts the induced a.c. voltages in the conductors into d.c. It is important to learn about the working of the same in order to ensure a smooth and trouble free operation of the machine.



(a) (b)

Figure 25: Linear commutation

5.1.3 Retarded commutation

Retarded commutation is mainly due to emf of self induction in the coil. Here the current transfer from 1 to 2 gets retarded as the name suggests. This is best explained with the help of time diagrams as shown in Fig. 26.(a). The variation of i is the change in the current of the coil undergoing commutation, while i' is that during linear commutation. Fig. 26(b) shows the variation of I_1 and current density in the brush at the leaving edge and Fig. 26.(c) shows the same phenomenon with respect to I_2 at entering edge. The value of current in the coil is given by i undergoing commutation. α_m is the mean current density in the brush given by total current divided by brush area of cross section. α_l and α_e are the current density under leaving and entering edges of the brush. As before,

$$I_1 = I_a + i \qquad \text{and} \qquad I_2 = I_a - i \tag{31}$$

employed only in extremely small machines where providing a field coil becomes infeasible. Also, permanent magnet excited fields cannot be varied for control purposes. Permanent magnets for large machines are either not available or expensive. However, an advantage of permanent magnet is that there are no losses associated with the establishment of the field.

Electromagnetic excitation is universally used. Even though certain amount of energy is lost in establishing the field it has the advantages like lesser cost, ease of control.

The required ampere turns for establishing the desired flux per pole may be computed by doing the magnetic circuit calculations. MMF required for the poles, air gap, armature teeth, armature core and stator yoke are computed and added. Fig. 2a shows two poles of a 4-pole machine with the flux paths marked on it. Considering one complete flux loop, the permeance of the different segments can be computed as

$$P = A\mu/l$$

Where P- permeance
A- Area of cross section of the part
mu- permeability of the medium
l- Length of the part

A flux loop traverses a stator yoke, armature yoke, and two numbers each of poles, air gap, armature teeth in its path. For an assumed flux density B_g in the pole region the flux crossing each of the above regions is calculated. The mmf requirement for

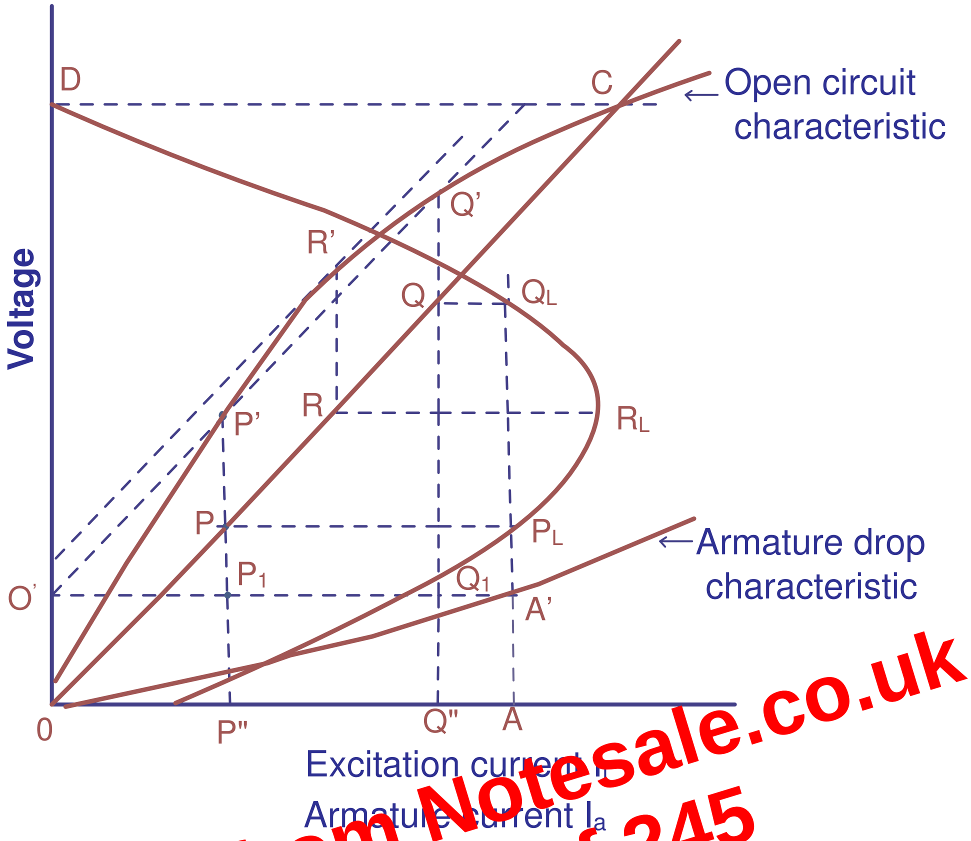


Figure 32: External characteristic of a self excited of a shunt generator

gets applied across the shunt field winding and produces a small mmf. If this mmf is such as to aid the residual field then it gets strengthened and produces larger voltage across the brushes. It is like a positive feed back. The induced emf gradually increases till the voltage induced in the armature is just enough to meet the ohmic drop inside the field circuit. Under such situation there is no further increase in the field mmf and the build up of emf also stops. If the voltage build up is 'substantial', then the machine is said to have 'self excited'.

Fig. 31(b) shows the magnetization curve of a shunt generator. The field resistance line is also shown by a straight line OC. The point of intersection of the open circuit characit is seen that these family of curves are nothing but OCC shifted downwards by armature drop. Determining their intercepts with the field resistance line gives us the requisite result. Instead of shifting the OCC downwards, the x axis and the field resistance line is shifted 'upwards' corresponding to the drops at the different currents, and their intercepts with OCC are found. These ordinates are then plotted on the original plot. This is shown clearly in Fig. 32. The same procedure can be repeated with different field circuit resistance to yield external characteristics with different values of field resistance. The points of operation up to the maximum current represent a stable region of operation. The second region is unstable. The decrease in the load resistance decreases the terminal voltage in this region.

5.4.1 External characteristics of series generators

In the case of series generators also, the procedure for the determination of the external characteristic is the same. From the occ obtained by running the machine as a separately excited one, the armature drops are deducted to yield external /load characteristics. The armature drop characteristics can be obtained by a short circuit test as before.

Fig. 33 shows the load characteristics of a series generator. The first half of the curve is unstable for constant resistance load. The second half is the region where series generator connected to a constant resistance load could work stably. The load characteristics in the first half however is useful for operating the series generator as a booster. In a booster the current through the machine is decided by the external circuit and the voltage injected into that circuit is decided by the series generator. This is shown in Fig. 35

of the machine remains more or less constant with load. With highly saturated machines the on-load speed may even slightly increase at over load conditions. This effects gets more pronounced if the machine is designed to have its normal field ampere turns much less than the armature ampere turns. This type of external characteristics introduces instability during operation Fig. 42(b)(ii) and hence must be avoided. This may be simply achieved by providing a series stability winding which aids the shunt field mmf.

5.8 Load characteristics of a series motor

Following the procedure described earlier under shunt motor, the torque speed characteristics of a series motor can also be determined. The armature current also happens to be the excitation current of the series field and hence the flux variation resembles the magnetization curve of the machine. At large value of the armature currents the useful flux would be less than the no-load magnetization curve for the machine. Similarly for small values of the load currents the torque varies as a square of the armature currents as the flux is proportional to armature current in this region. As the magnetic circuit becomes more and more saturated the torque becomes proportional to I_a as flux variation becomes small. Fig. 43(a) shows the variation of E_1, flux , torque and speed following the above procedure from which the torque-speed characteristics of the series motor for a given applied voltage V can be plotted as shown in Fig. 43.(b) The initial portion of this torque-speed curve is seen to be a rectangular hyperbola and the final portion is nearly a straight line. The speed under light load conditions is many times more than the rated speed of the motor. Such high speeds are unsafe, as the centrifugal forces acting on the armature and commutator can destroy them giving rise to a catastrophic break down. Hence series motors are not recommended for use where there is a possibility of the load becoming zero. In order to safeguard the motor and personnel, in the modern machines, a ‘weak’ shunt field is provided on series motors to ensure a definite, though small, value of flux even when the armature current is nearly zero. This way the no-load speed is limited to a safe maximum speed. It is needless to say, this field should be connected so as to aid the series field.

5.9 Load characteristics of a compound motor

Two situations arise in the case of compound motors. The mmf of the shunt field and series field may oppose each other or they may aid each other. The first configuration is called differential compounding and is rarely used. They lead to unstable operation of the machine unless the armature mmf is small and there is no magnetic saturation. This mode may sometimes result due to the motoring operation of a level-compounded generator, say by the failure of the prime mover. Also, differential compounding may result in large negative mmf under overload/starting condition and the machine may start in the reverse direction. In motors intended for constant speed operation the level of compounding is very low as not to cause any problems.

Cumulatively compounded motors are very widely used for industrial drives. High degree of compounding will make the machine approach a series machine like characteristics but with a safe no-load speed. The major benefit of the compounding is that the field is strengthened on load. Thus the torque per ampere of the armature current is made high. This feature makes a cumulatively compounded machine well suited for intermittent peak loads. Due to the large speed variation between light load and peak load conditions, a fly wheel can be used with such motors with advantage. Due to the reasons provided under shunt and series motors for the provision of an additional series/shunt winding, it can be general is assumed to be off a constant voltage d.c. supply.

The relevant expressions may be written as,

$$n = \frac{E}{K_e\phi} = \frac{V - I_aR_a - V_b}{pZ\phi/b} \tag{44}$$

$$T_M = K_t.\phi.I_a = \frac{1}{2\pi}.\frac{p.Z}{b}.\phi I_a \tag{45}$$

$$T_M - T_L = J\frac{d\omega}{dt} \tag{46}$$

As can be seen, speed is a function of E and ϕ and T is a function of ϕ and I_a. Using these equations, the methods for starting , speed control and braking can be discussed.

8.1 Starting of d.c. machines

For the machine to start, the torque developed by the motor at zero speed must exceed that demanded by the load. Then $T_M - T_L$ will be positive so also is $d\omega/dt$, and the machine accelerates. The induced emf at starting point is zero as the $\omega = 0$ The armature current with rated applied voltage is given by V/R_a where R_a is armature circuit resistance. Normally the armature resistance of a d.c. machine is such as to cause 1 to 5 percent drop at full load current. Hence the starting current tends to rise to several times the full load current. The same can be told of the torque if full flux is already established. The machine instantly picks up the speed. As the speed increases the induced emf appears across the terminals opposing the applied voltage. The current drawn from the mains thus decreases, so also the torque. This continues till the load torque and the motor torque are equal to each other. Machine tends to run continuously at this speed as the acceleration is zero at this point of operation.

The starting is now discussed with respect to specific machines.

8.2 Speed control of d.c. motors

In the case of speed control, armature voltage control and flux control methods are available. The voltage control can be from a variable voltage source like Ward-Leonard arrangement or by the use of series armature resistance. Unlike the starting conditions the series resistance has to be in the circuit throughout in the case of speed control. That means considerable energy is lost in these resistors. Further these resistors must be adequately cooled for continuous operation. The variable voltage source on the other hand gives the motor the voltage just needed by it and the losses in the control gear is a minimum. This method is commonly used when the speed ratio required is large, as also the power rating.

Field control or flux control is also used for speed control purposes. Normally field weakening is used. This causes operation at higher speeds than the nominal speed. Strengthening the field has little scope for speed control as the machines are already in a state of saturation and large field mmf is needed for small increase in the flux. Even though flux weakening gives higher speeds of operation it reduces the torque produced by the machine for a given armature current and hence the power delivered does not increase at any armature current. The machine is said to be in constant power mode under field weakening mode of control. Above the nominal speed of operation, constant flux mode with increased applied voltage can be used; but this is never done as the stress on the commutator insulation increases.

Thus operation below nominal speed is done by voltage control. Above the nominal speed field weakening is adopted. For weakening the field, series resistances are used for shunt as well as compound motors. In the case of series motors however field weakening process time requirement can be reduced if braking time is reduced. The reduction of the process time improves the throughput.

Basically the electric braking involved is fairly simple. The electric motor can be made to work as a generator by suitable terminal conditions and absorb mechanical energy. This converted mechanical power is dissipated/used on the electrical network suitably. Braking can be broadly classified into:

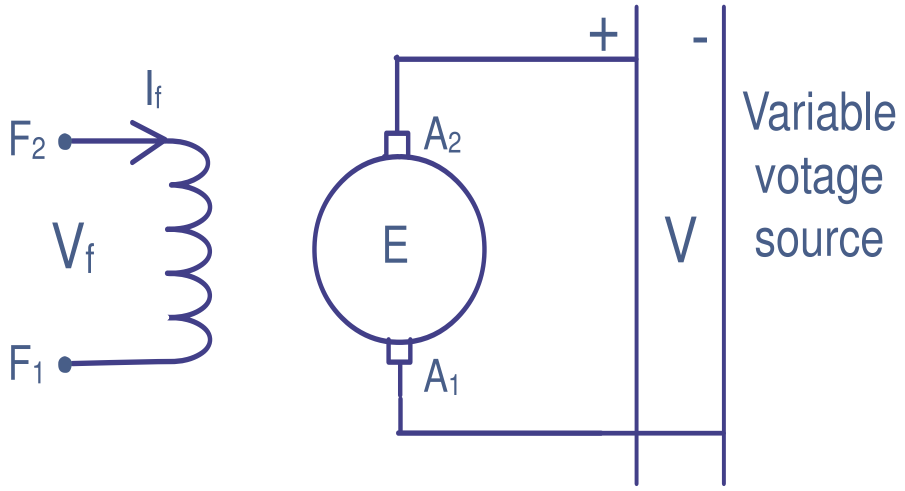
1. Dynamic
2. Regenerative
3. Reverse voltage braking or plugging

These are now explained briefly with reference to shunt ,series and compound motors.

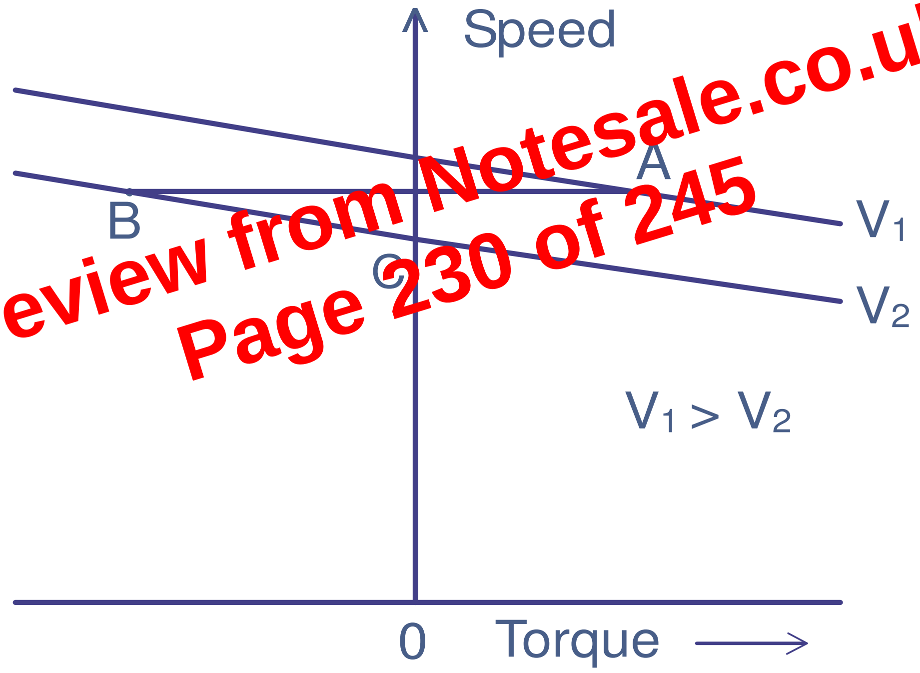
8.3.1 Dynamic braking

- Shunt machine

  In dynamic braking the motor is disconnected from the supply and connected to a dynamic braking resistance R_{DB}. In and Fig. 49 this is done by changing the switch from position 1 to 2 . The supply to the field should not be removed. Due to the rotation of the armature during motoring mode and due to the inertia, the armature continues to rotate. An emf is induced due to the presence of the field and the rotation. This voltage drives a current through the braking resistance. The direction of this current is opposite to the one which was flowing before change in the connection. Therefore, torque developed also gets reversed. The machine acts like a brake. The



(a)Physical connection



(b)Characteristics

Figure 51: Regenerative braking of a shunt machine

the series field at the time of braking by short circuiting the same. In such cases the braking proceeds just as in a shunt motor. If plugging is done to operate the motor in the negative direction of rotation as well, then the series field has to be reversed and connected for getting the proper mmf. Unlike dynamic braking and regenerative braking where the motor is made to work as a generator during braking period, plugging makes the motor work on reverse motoring mode.

8.4 Application of d.c motors and generators

It is seen from the earlier sections that the d.c.machine is capable of having variety of torque-speed characteristics depending on the circuit conditions. The need for generating these characteristics will be clear only when they are seen along with the characteristics of the loads that they operate with. Even though a detailed treatment of motor load systems is outside the scope here, it may be useful to look into the typical torque-speed characteristics of some of the common loads.
Loads are broadly divided into

(a) Passive loads

(b) Active loads

They may be unidirectional in operation or work in either direction (Reversible loads).

Passive loads absorb the mechanical energy developed by the motors while active loads are capable of working as both sinks and sources for mechanical energy. The direction of rotation may be taken to be clockwise/counter clockwise rotation. Normally the of the induced emf as a function of excitation current, when the speed is held constant, with the load current being zero. It is also called the no-load saturation curve or no load magnetization characteristic. This is experimentally determined by running the machine as a separately excited generator on no-load at a constant speed and noting the terminal voltage as a function of the excitation current. This curve can be used to find the OCC at other speeds and also the self excited voltage when the machine works as a shunt generator.

9.3 Short circuit characteristics:(SCC)

In the case of short circuit test the armature is kept short circuited through an ammeter. The machine is demagnetized and an extremely small field current is passed through the field. The variation of the short circuit current as a function of excitation current is plotted as the SCC. The speed is to be held constant during this test also. The short circuit test gives an idea of the armature drop at any load current.

9.4 Load test

To assess the rating of a machine a load test has to be conducted. When the machine is loaded, certain fraction of the input is lost inside the machine and appears as heat, increasing the temperature of the machine. If the temperature rise is excessive then it affects the insulations, ultimately leading to the breakdown of the insulation and the machine. The load test gives the information about the efficiency of a given machine at any load condition. Also, it gives the temperature rise of the machine. If the temperature rise is below the permissible value for the insulation then the machine can be safely operated at that load, else the load has to be reduced. The maximum continuous load that can be