5. Explain briefly the following :
   (*i*) U-tube manometer
   (*ii*) Micro-manometer.
6. Describe briefly the following pressure gauges :
   (*i*) Bourdon tube pressure gauge
   (*ii*) Diaphragm gauge.
7. Explain briefly the following :
   (*i*) Electrical transducers
   (*ii*) Electromagnetic transducers.
8. How is temperature defined ?
9. How are temperature measurements made ?
10. How are thermometers classified ?
11. Explain briefly the following :
    (*i*) Bimetallic thermometers
    (*ii*) Liquid filled thermometers
    (*iii*) Gas-filled thermometers.
12. Write a short note on resistance thermometers.
13. Explain with a help of a neat sketch the construction and working of a radiation pyrometer.
14. What are the advantages of pyrometers ?
15. State the principle on which an optical pyrometer works.
16. Describe with the help of a neat sketch an optical pyrometer.
17. Explain briefly the following liquid level gauges :
    (*i*) Gauge glass
    (*ii*) Electrical level gauges.
18. Write a short note on 'Flow meters'.
19. Explain the procedure for measuring CO_2 content in the gases.
20. What is humidity ? How can it be measured ?
21. Give the description of resistive hygrometer.
22. How can the dryness fraction of steam determined by the following ?
    (*i*) Tank or bucket calorimeter
    (*ii*) Separating and throttling calorimeter.

12

Major Electrical Equipment in Power Plants

12.1. Introduction. 12.2. Generating equipment—Classification—Two-wire direct current generators—Alternator-current generators. 12.3. Transformers—General aspects—Basic definitions—Working principle of a transformer—Transformer ratings—Kinds of transformers—Transformer construction—Transformer windings, terminals, tappings and bushings—Transformer Cooling—Three phase transformer—Instrument transformers—Constant-current transformers. 12.4. Switchgear—Functions of a switchgear—Switches—Fuses—Circuit breakers—Types of switchgear 12.5. Protection of electrical systems—General aspects— Different types of relays—Alternator protection—Transformer protection—Bus protection—Protection of transmission lines. 12.6. Short circuits in electrical installations and limiting methods. 12.7. Control room. 12.8. Earthing of a power system. 12.9. Electrical equipment-layout. 12.10. Voltage regulation. 12.11. Transmission of electric power—Systems of transmission—Line supports—Conductor material—Line insulators—Distribution systems—Underground cables. 12.12. Substations—Classification of substations. 12.13. Indian Electricity Act—Highlights—Theoretical Questions—Competitive Examinations Questions.

12.1. INTRODUCTION

In different types of power plants such as thermal power plant, hydro-power plant, nuclear power plant etc. the electricity is generated. A number of electrical equipments which are available in a power plant are listed below :

1. Generators
2. Excitors
3. Transformers
4. Reactors
5. Circuit breakers
6. Switchgear and protective equipment
7. Control board equipment
8. Busbars
9. Standby generators etc.

12.2. GENERATING EQUIPMENT

12.2.1. Classification

A broad classification of generating equipment may include the following types of machines :

Generating equipment

- Direct current
  - (*i*) Two wire generator
  - (*ii*) Three wire generator
  - (*iii*) Major generator set
  - (*iv*) Rotary converter
  - (*v*) Mercury arc rectifier.
- Alternating current
  - (*i*) Synchronous generator
  - (*ii*) Induction generator
  - (*iii*) Frequency-changes set
  - (*iv*) Phase converter.

12.2.2. Two-wire Direct Current Generators

By two-wire generators are meant such generators as have only two line terminals, one known as the positive terminal and the other as the negative terminal. Direct current generators may be further classified according to :

1. **Method of excitation** →
   - Self-excited
     - Shunt
     - Series
     - Compound
       - Short shunt
       - Long shunt
       - Flat compound
       - Over compound
       - Differentially compound
   - Separately excited
2. **The number of poles** →
   - Bipolar
   - Multipolar
   - Homopolar
3. **The type of armature winding** →
   - Multiple or lap
   - Series, two circuit or wave
   - Combination of multiple and series
4. **The method of prime mover drive** →
   - Engine type
   - Direct connected to a steam turbine
   - Geared to steam turbine
   - Water turbine

5. The type of service →

- General power and lighting
- Railway
- Electrolytic and furnace
- Booster
- Exciter
- Balancer

6. Special features of construction →

- Non-commutating-pole machines
- Commutating-pole machines
- Compensating wound machines
- Diverter-pole machines

12.2.2.1. Principle of a generator

An electrical generator is a machine which converts mechanical energy (or power) into electrical energy (or power). This energy conversion is based on the *principle of the production of dynamically induced e.m.f.* As seen from Fig. 12.1, *whenever a conductor cuts magnetic flux, dynamically induced e.m.f. is produced in it according to Faraday's Laws of Electromagnetic induction. This e.m.f. causes current to flow if the conductor circuit is closed.* Therefore, the basic essential parts of an electrical generator are :

(*i*) A magnetic field.

(*ii*) A conductor/conductors which can so move to cut the flux.

12.2.2.2. Elementary generator

If a single-turn coil (see Figs. 12.1 and 12.2) is rotated in a uniform magnetic field at a constant speed, as shown in Figs. 12.1 and 12.2. (*a*), the e.m.f. induced in a given coil side will vary as the coil moves through various positions from 0° to 360° as shown in Fig. 12.2.

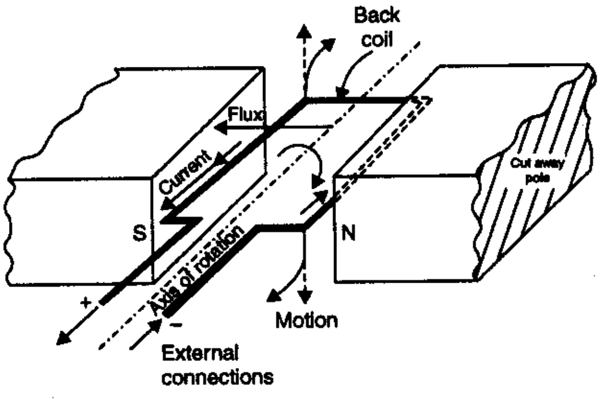
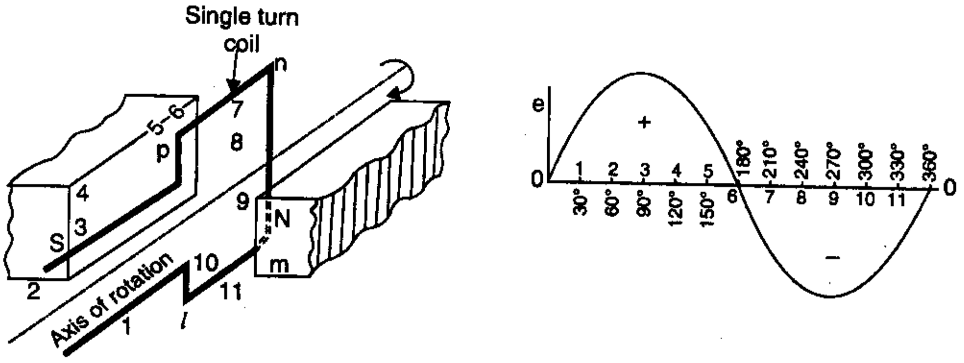


Fig. 12.1. Elementary generator.

- Using coil side *lm* as a reference, it will be noted that when this coil side is in *position 1* shown in Fig. 12.2 (*a*), the e.m.f. induced in the coil is *zero*, since-conductor *lm* (and conductor *np*, as well) is *moving parallel to the magnetic field and experiencing no change in flux linkages.*



(a) Instantaneous positions of rotation at constant speed.

(b) E.m.f. at respective positions.

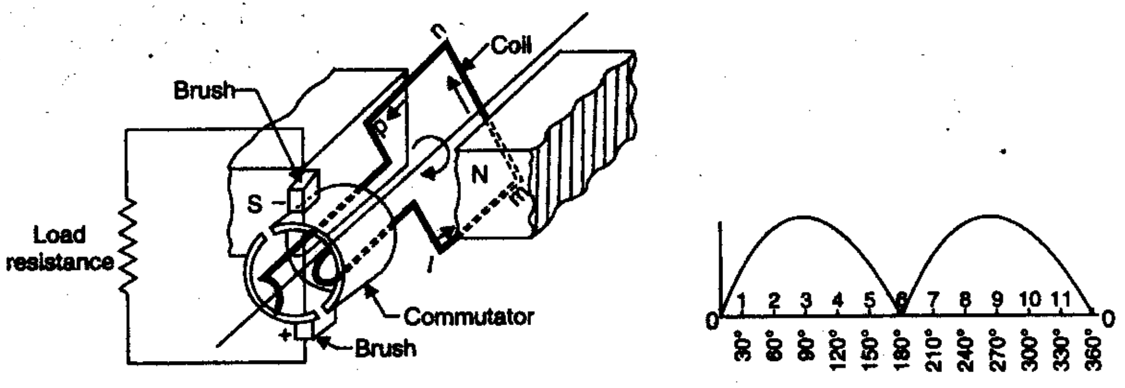
Fig. 12.2. E.m.f. generated by a coil moving in a uniform field.

- When conductor *lm* moves to position 1, rotating in clockwise direction it cuts the uniform magnetic field at an oblique angle of 30°. The e.m.f. induced in this upward-moving conductor with respect to an external load will be positive and will amount to 50 per cent (e.m.f. α sin θ) of the maximum induced voltage. The change in voltage is shown graphically in Fig. 12.2 (*b*), where the e.m.f. is positive at position 1 and has the value given.
- When the coil moves to position 2, the e.m.f. induced will be positive and will amount to approximately 86.6 per cent of the maximum induced voltage.
- When the coil reaches 90° (*see* Fig. 12.1), position 3 [*see* Figs. 12.1 and 12.2 (*a*)], the conductor *lm* has the *maximum number of flux linkages, since it is moving perpendicularly to the magnetic field, and has the maximum positive value* shown in Fig. 12.2 (*b*).
- Positions 4 and 5 corresponding to 120° and 150° of rotation respectively, yields an e.m.f. in coil side *lm* identical to those produced at positions 1 and 2 [sin 120° = sin 60°, sin 150° = sin 30°] respectively with a positive polarity since the conductor is still moving upward but the change in flux linkage occurs at a slower rate than a position 3 respectively.
- When the conductor *lm* reaches 180°, position 6, the *induced e.m.f. is again zero*, since no *change in flux linkages occurs when a conductor is moving parallel to a magnetic field.*
- In positions 7 and 8 corresponding to 210° and 240° respectively, the e.m.f. in conductor *lm* is reversed since conductor *lm* is now moving downward in the same uniform magnetic field. The e.m.f. induced increases to a negative maximum at 270°, position 9, and finally decreases through positions 10 and 11 corresponding to 300° and 330° back to zero at position 0.
- It is worth noting that the *e.m.f. in a conductor rotating in a magnetic field is both sinusoidal and alternating.* It may be observed that during this process no e.m.f. is induced in coil-sides *mn* or *pl* since these conductors experience no change in flux linkages. Even if an e.m.f. were produced in these coil sides, they would not contribute to the e.m.f. of the coil because they are moving in the same direction through the same field and hence produce equal e.m.f.'s in opposition. Coil sides *lm* and *np*, however, aid each other, and the total e.m.f. produced by the coil is twice the magnitude represented in Fig. 12.2 (*b*). It should be noted that no e.m.f. is produced in positions 0 and 6 known as the *interpolar* or neutral zones of the dynamo.
- It may be noted that a *sinusoidal wave shape is produced by a conductor rotating in a theoretically uniform field represented in Fig. 12.2, in which the air gap is not constant*

because of the straight pole sides. If the pole tips are curved so that the pole face produces a more uniform gap and flux density except in the inter-polar regions, the wave shape of the induced e.m.f. will tend to be flat-topped, approaching a square wave more nearly than a sine wave.

Conversion of Alternating Current into Direct Current by Means of a Commutator. In order to convert the alternating voltage (A.C.) to unidirectional current (D.C.), it is necessary to employ a mechanical switching device which is actuated by the mechanical rotation of the dynamo/ generator shaft, called a *'commutator'* (*see* Fig. 12.3).

- The simple split-ring commutator shown consists of two segments (A and B), secured to and insulated from the armature shaft and from each other as well. Each conducting commutator segment is connected, respectively, to a coil side. Since both coil side and commutator segment are *fastened mechanically* to the same shaft, *the action of the mechanical rotation is to reverse the armature coil and connections to the stationary external circuit at the same instant that the induced e.m.f. reverses in the armature coil side* (*i.e.*, when the coil side moves under an opposite pole). Fixed brushes are arranged to contact the commutator segments, as shown in Fig. 12.3.



(a) (b)

Fig. 12.3. Bipolar generator with two segment commutator.

- As shown in Figs. 12.2 and 12.3, the e.m.f. induced in coil-side lm causes a positive polarity for the first 180° of rotation (positions 0 through 6) and a negative polarity for the remaining 180° (positions 6 through 0). But, in Fig. 12.3, coil side lm is connected to commutator segment A and the coil side np is connected to commutator segment B. For the first 180° of rotation, therefore, the positive e.m.f. produced by the coil-side lm is connected to the stationary positive brush. For the second 180° of rotation, the negative e.m.f. produced by coil side lm is connected to the secondary negative brush. The same effect occurs in reverse order for coil-side np.

In effect, therefore, *the action of the commutator is to reverse connections to the external circuit simultaneously and at the same instant the direction of e.m.f. reverses in each of the coil sides. Each brush, positive or negative respectively, is always maintained, therefore, at the same polarity.* Fig. 12.3 (*b*) shows the e.m.f. (and current) wave form produced as a result of the above process for one full cycle (or 360°) of rotation.

- The pulsating unidirectional current which has a zero value twice each cycle as shown in Fig. 12.3 (*b*), is hardly suitable for commercial D.C. use. *The output e.m.f. may be made less pulsating by using a large number of coils and commutator segments* (*see* Fig. 12.4).

— It may be noted that a single turn armature coil generates voltage which is quite small in magnitude. Therefore, the coils employed in commercial generators consist of several turns in series thereby increasing the magnitude of generated e.m.f. in direct proportion to the number of the turns in the coil.

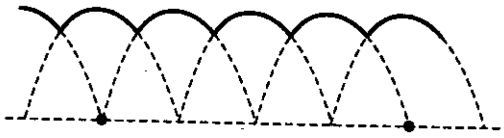


Fig. 12.4. The output e.m.f. with a large number of coils and commutator segments.

12.2.2.3. Construction of D.C. machines

A D.C. machine consists of *two* main parts :

(*i*) **Stationary Part.** It is designed mainly for *producing a magnetic flux.*

(*ii*) **Rotating Part.** It is called the *armature,* where mechanical energy is converted into electrical (electrical generator), or conversely, electrical energy into mechanical (electric motor).

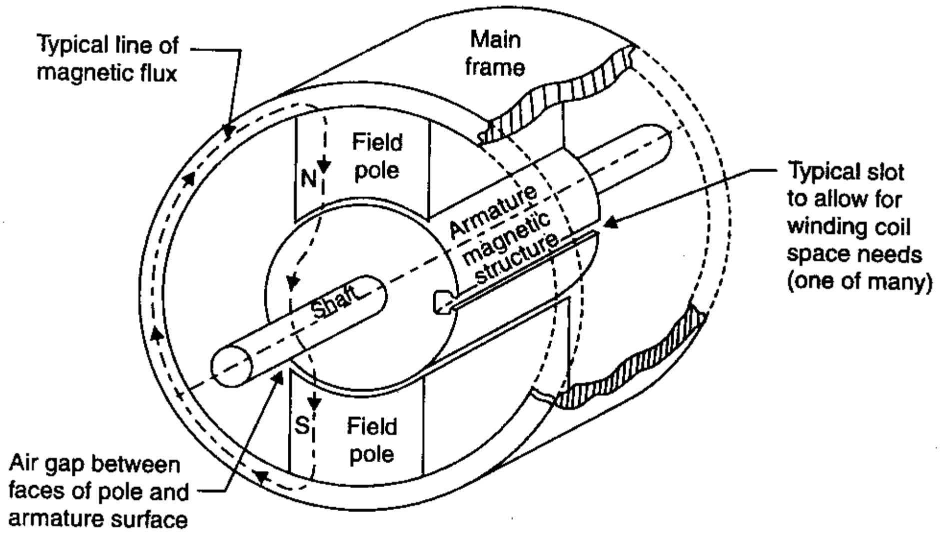


Fig. 12.5. Generator or motor magnetic structure.

The stationary and rotating parts are separated from each other by an *air-gap.*

— The *stationary part* of a D.C. machine consists of *main poles,* designed to create the magnetic flux, *commutating poles* interposed between the main poles and designed to ensure sparkless operation of the brushes at the commutator (in very small machines with a lack of space commutating poles are not used) ; and a *frame*/yoke.

— The *armature* is a cylindrical body rotating in the space between the poles and comprising a *slotted armature core,* a *winding* inserted in the armature core slots, a *commutator* and *brush gear.*

Fig. 12.5 shows generator or motor magnetic structure.

Description of Parts of D.C. Machines :

Frame :

Fig. 12.6 shows the sectional view of four pole D.C. machine.

- *The frame is the stationary part of a machine to which are fixed the main and commutating poles and by means of which the machine is bolted to its bed plate.*
- *The ring-shaped portion which serves as the path for the main and commutating pole fluxes is called the 'yoke'.*

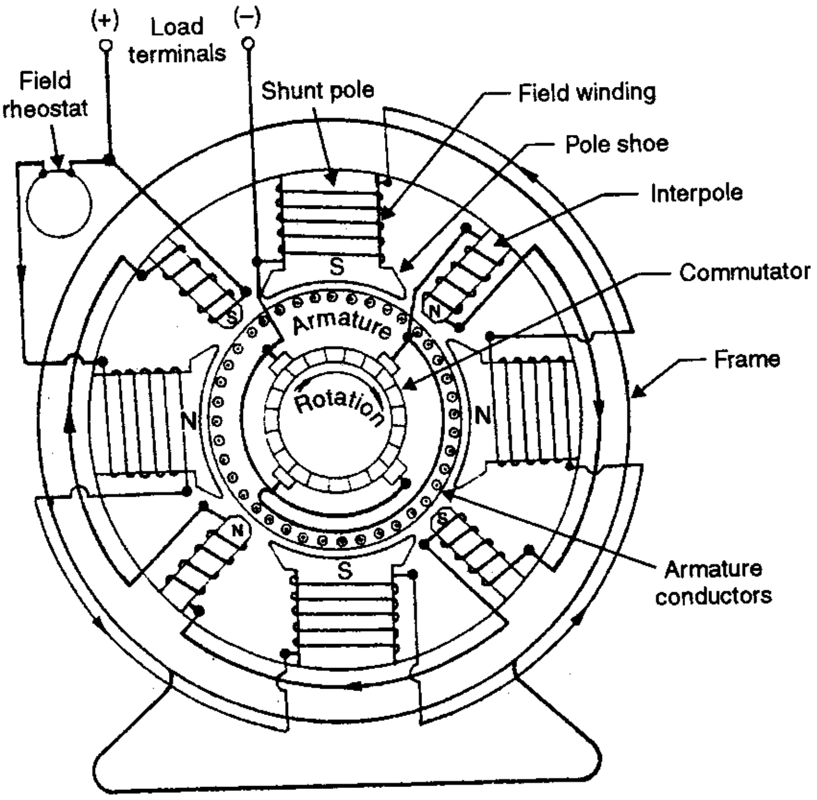


Fig. 12.6. Sectional view of a four pole D.C. machine.

- *Cast iron* used to be the material for the frame/yoke in *early machines* but now it has been *replaced by cast steel.* This is because cast iron is saturated by a flux density of about 0.8 Wb/m^2 while saturation with cast steel is at about 1.5 Wb/m^2. Thus the cross-section of a cast iron frame is about twice that of a cast steel frame for the same value of magnetic flux. Hence, if it is necessary to reduce the weight of machine, cast steel is used. Another disadvantage with the use of cast iron is that its mechanical and magnetic properties are uncertain due to the presence of blow holes in the casting. Lately, rolled steel yokes have been developed with the improvements in the welding techniques. The *advantages of fabricated yokes are that there are no pattern charges and the magnetic and mechanical properties of the form are absolutely consistent.*

It may be advantageous to use cast iron for small frames but for medium and large sizes usually rolled steel is used.

- If the armature diameter does not exceed 35 to 45 cm, then, in addition to the poles, end shields or frame-heads which carry the bearings are also attached to the frame. When the armature diameter exceeds 1 m, it is common practice to use pedestal-type bearings, mounted separately, on the machine bed plated outside the frame.
- The end shield bearings, and sometimes the pedestal bearings, are of ball or roller type. However, more frequently plain pedestal bearings are used.
- In machines with large diameter armatures a brush-holder yoke is frequently fixed to the frame.

Field poles :

- Formerly the poles were cast integral with the yoke. This practice is still being followed for small machines. But in present day machines *it is usual to use either a completely laminated pole, or solid steel poles with laminated pole shoe.*
- Laminated construction is necessary because of the pulsations of field strength that result when the notched armature rotor magnetic structure passes the pole shoe. Variations in field strength result in internal eddy currents being generated in a magnetic structure. These eddy currents cause losses ; they may be largely prevented by having laminated magnetic structures. Laminated structures allow magnetic flux to pass along the length of the laminations, but do not allow electric eddy currents to pass across the structure from one lamination to another. The assembled stack of laminations is held together as a unit by appropriately placed rivets. *The outer end of the laminated pole is curved to fit very closely into the inner surface of the main frame.*
- Fig. 12.7 shows the constructional details of a field pole. *The pole shoe acts as a support to the field coils and spreads out the flux in the air gap and also being of larger cross-section reduces the reluctance of the magnetic path.*

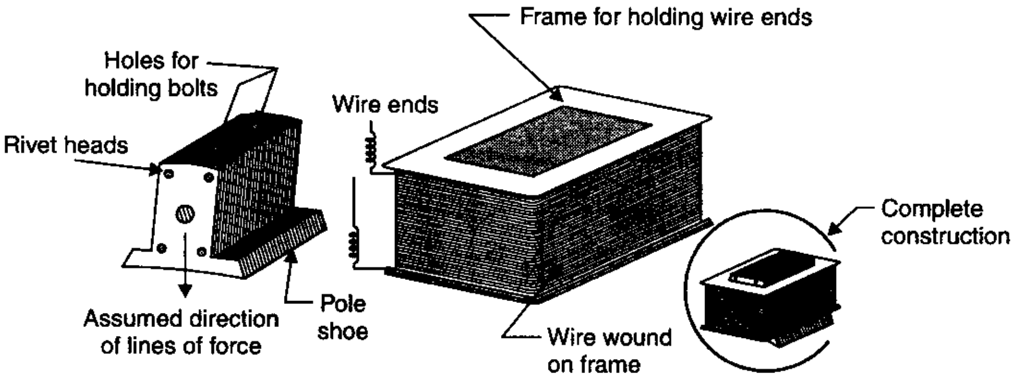


Fig. 12.7. Constructional details of a field pole.

- Different methods are used for attaching poles to the yoke. In case of *smaller sizes*, the back of the pole is drilled and tapped to receive pole bolts (*see* Fig. 12.8). In *larger sizes*, a circular or a rectangular pole bar is fitted to the pole. This pole bar is drilled and tapped and the pole bolts passing through laminations screw into the tapped bar (*see* Fig. 12.9).

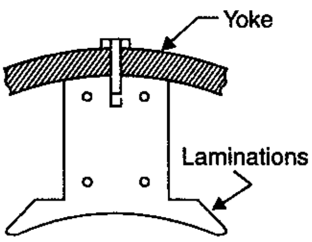


Fig. 12.8. Fixing pole to the yoke.

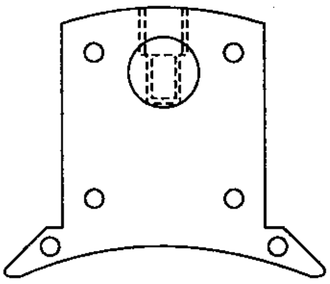


Fig. 12.9

Commutating poles :

- A commutating pole (also called *interpole*) is similar to a main pole and consists of core terminating in a pole shoe, which may have various shapes, and coil mounted on the core.
- The commutating poles *are arranged strictly midway between the main poles* and are bolted to the yoke.
- *Commutating poles are usually made of solid steel, but for machines operating on sharply varying loads they are made of sheet steel.*

Armature :

- The armature consists of core and winding. *Iron being the magnetic material is used for armature core.* However, iron is also a good conductor of electricity. The rotation of solid iron core in the magnetic field results in eddy currents. The flow of eddy currents in the core leads to wastage of energy and creates the problem of heat dissipation. *To reduce the eddy currents the core is made of thin laminations.*
- *The armature of D.C. machines (see Fig. 12.10) is built up of thin lamination of low loss silicon steel.* The laminations are usually 0.4 to 0.5 mm thick and are insulated with varnish.

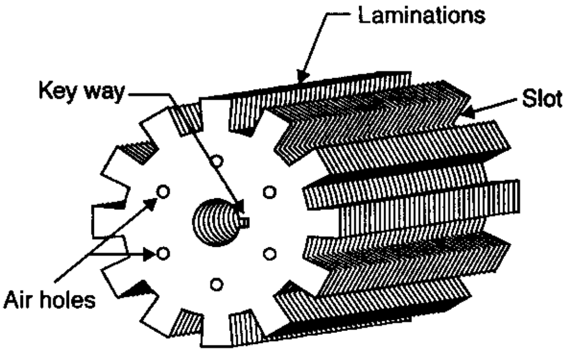


Fig. 12.10. Armature of a D.C. machine.

- The armature laminations, in *small machines*, are fitted directly on to the shaft and are clamped tightly between the flanges which also act as supports for the armature winding. One end of flange rests against a shoulder on the shaft, the laminations are fitted and other end is pressed on the shaft and retained by a key.

  The core (except in small size) is divided into number of packets by radial ventilation spacers. The spacers are usually I sections welded to thick steel laminations and arranged to pass centrally down each tooth.

— For small machines the laminations are punched in one piece (*see* Fig. 12.11). These laminations are built up directly on the shaft. With such an arrangement, it is necessary to provide *axial ventilation holes* so that air can pass into ventilating ducts.

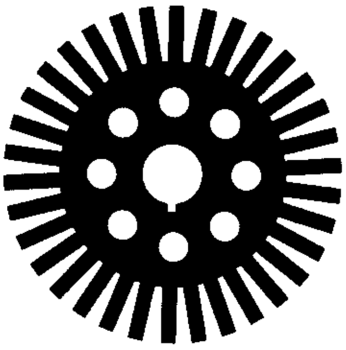


Fig. 12.11. Drum armature stamping with axial flow ventilation system.

— The armature laminations of medium size machines (having more than four poles) are built on a spider. The spider may be fabricated. Laminations up to a diameter of about 100 cm are punched in one piece and are directly keyed on the spider (*see* Fig. 12.12).

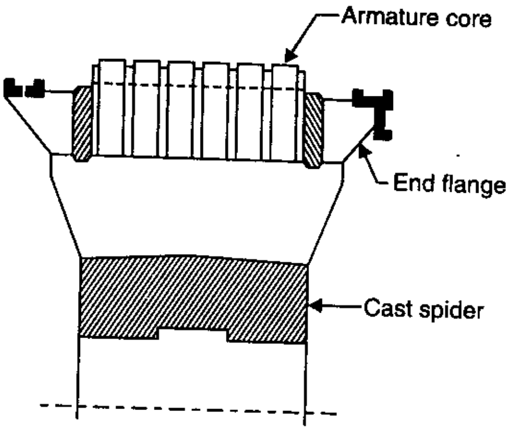


Fig. 12.12. Clamping of an armature core.

— In case of large machines, the laminations of such thin sections are difficult to handle because they tend to distort and become wavy when assembled together. Hence circular laminations instead of being cut in one piece are cut in a number of suitable sections or *segments* which form part of a complete ring (*see* Fig. 12.13). A complete circular lamination is made up of four or six or even eight segmental laminations. Usually two keyways are notched in each segment and are dove-tailed or wedge shaped to make the laminations self-locking in position.

— The armature winding is housed in slots on the surface of the armature. The conductors of each coil are so spaced that when one side of the coil is under a north pole, the opposite is under a south pole.

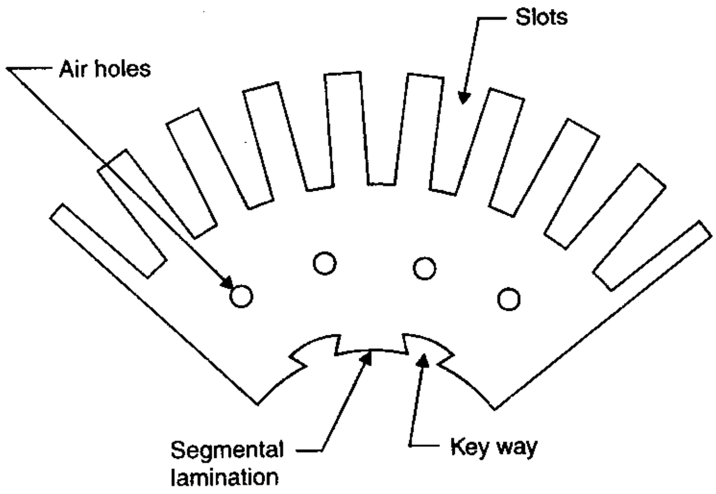


Fig. 12.13. Segmental stampings.

Fig. 12.14 shows the arrangement of conductors and insulation in a slot.

— *In D.C. machines two layer winding with diamond shaped coils is used.* The coils are usually former wound. In *small machines*, the coils are held in position by band of steel wire, wound under tension along the core length. In *large machines*, it is useful to employ wedges of fibre or wood to hold coils in place in the slots. Wire bands are employed for holding the overhang. The *equilizer connections* are located under the overhang on the side of the commutator. Fig. 12.15 shows a typical arrangement for equilizers. The equilizers can be accommodated on the other end of the armature also.

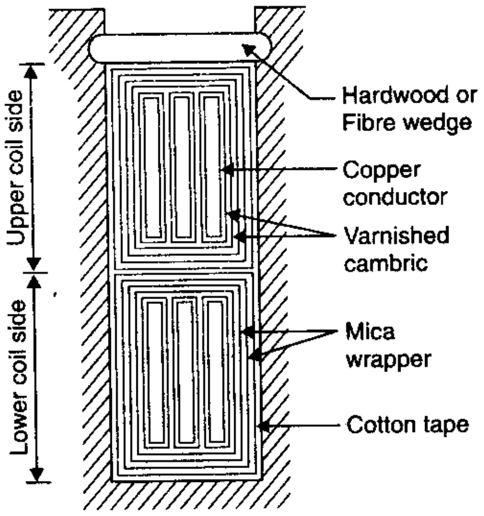


Fig. 12.14. Cross-section of an armature slot.

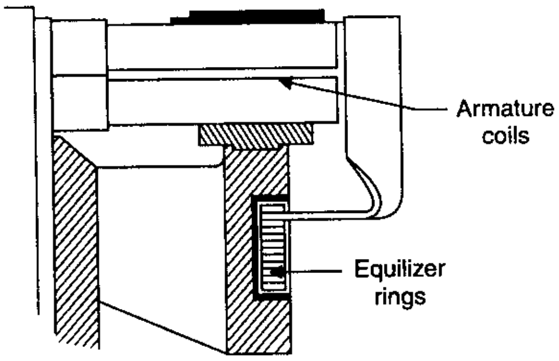


Fig. 12.15. Ring type equilizers.

Commutator :

— A commutator converts alternating voltage to a direct voltage.

— A commutator is a cylindrical structure built up of segments made of hard drawn copper. These segments are separated from one another and from the frame of the machine by *mica strips*. The segments are connected to the winding through risers. The risers have air spaces between one another so that air is drawn across the commutator thereby keeping the commutator cool.

Fig. 12.16 shows the components of a commutator. The general appearance of a commutator when completed is as shown in Fig. 12.17 (*a*). The commutator and armature assembly is shown in Fig. 12.17 (*b*).

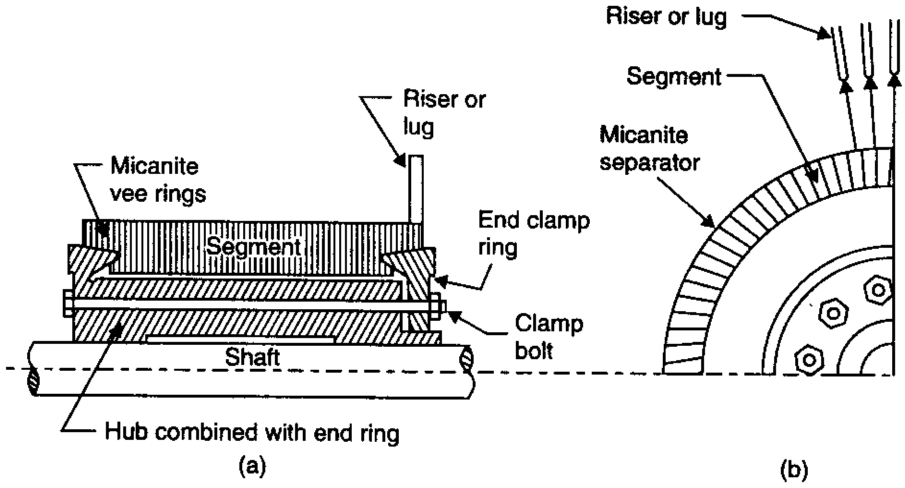


Fig. 12.16. Commutator components.

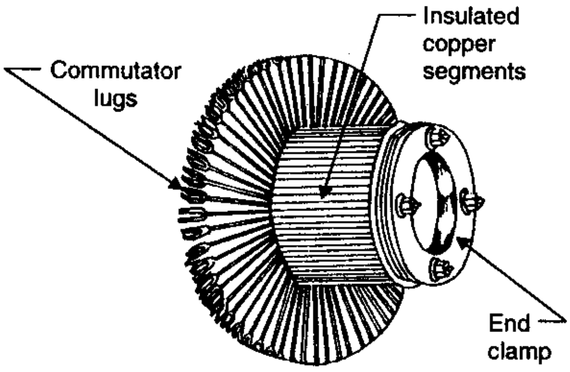


Fig. 12.17. (*a*) General appearance of a commutator after assembly.

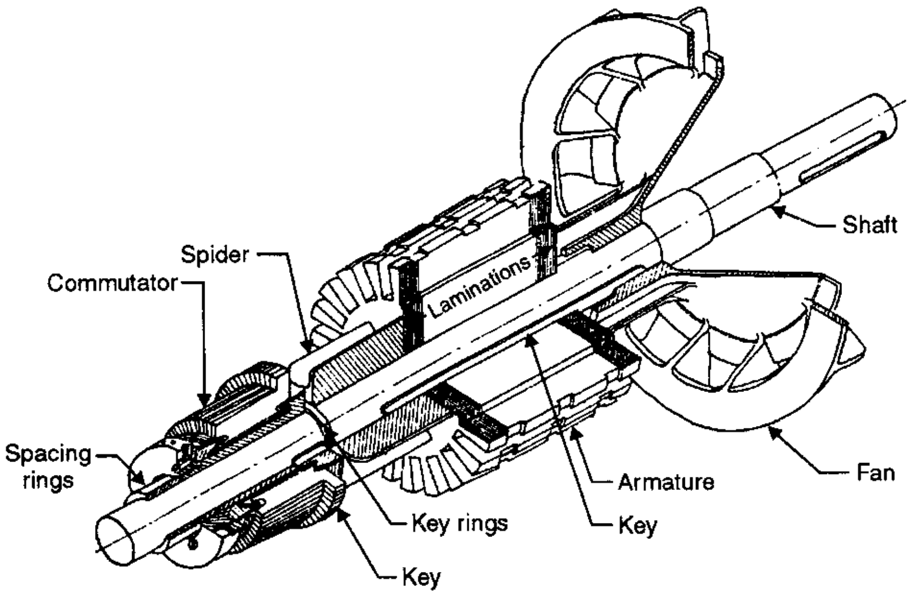


Fig. 12.17. (*b*) Commutator and armature assembly.

Brush gear. To collect current from a rotating commutator or to feed current to it use is made of *brush-gear* which consists of :

(*i*) Brushes
(*ii*) Brush holders
(*iii*) Brush studs or brush-holder arms
(*iv*) Brush rocker
(*v*) Current-collecting bus bars.

Brushes. The brushes used for D.C. machines are divided into five classes :

(*i*) Metal graphite
(*ii*) Carbon graphite
(*iii*) Graphite
(*iv*) Electro-graphite
(*v*) Copper.

— The allowable *current density* at the brush contact varies from 5 A/cm^2 in case of carbon to 23 A/cm^2 in case of copper.

— The use of *copper brushes* is made for machines designed for *large currents at low voltages.* Unless very carefully lubricated, they cut the commutator very quickly and in any case, the wear is rapid. *Graphite and carbon graphite brushes are self lubricating and, are, therefore widely used.* Even with the softest brushes, however, there is a gradual wearing away of the commutator, and if mica between the commutator segments does not wear down so rapidly as the segments do, the high mica will cause the brushes to make poor contact with segments, and sparking will result and consequent damage to commutator. So to prevent this, the mica is frequently *'undercut'* to a level below the commutator surface by means of a narrow milling cutter.

Brush holders. *Box type brush holders* are used in all ordinary D.C. machines. A box type brush holder is shown in Fig. 12.18. At the outer end of the arm, a brush box, open at top and bottom is attached. The brush is pressed on to the commutator by a *clock spring.* The *pressure can be adjusted by a lever arrangement provided with the spring.* The brush is connected to a flexible conductor called *pig tail.* The flexible conductor may be attached to the brush by a screw or may be soldered.

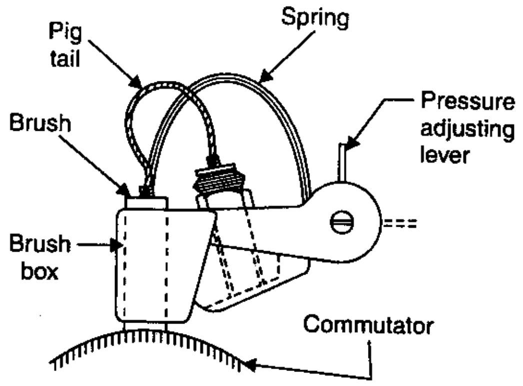


Fig. 12.18. Box type brush holder.

- The brush boxes are usually made of *bronze casting* or *sheet brass.* In low voltage D.C. machines where the commutation conditions are easy galvanised steel box may be used.
- Some manufacturers use individual brush holders while others use multiple holders, *i.e.*, a number of single boxes built up into one long assembly.

Brush rockers. Brush holders are fixed to brush rockers with bolts. The brush rocker is arranged concentrically round the commutator. *Cast iron is usually, used for brush rockers.*

Armature shaft bearings :

- *With small machines roller bearings are used at both ends.*
- For *larger machines roller bearings are used for driving end and ball bearings are used for non-driving* (commutator) *end.*
- The bearings are housed in the end shields.
- For large machines pedestal bearings are used.

Armature windings

The *armature winding* is very important element of a machine, as it directly takes part in the conversion of energy from one form into another. The requirements which a winding must meet are diverse and often of a conflicting nature. Among these requirements the following are of major importance.

- The winding must be designed with the *most advantageous utilisation of the material in respect to weight and efficiency.*
- The winding should *provide the necessary mechanical, thermal and electrical strength of the machine* to ensure the usual service life of 16-20 years.
- For D.C. machines proper current collection at the commutator (*i.e.* absence of detrimental sparking) must be ensured.

12.2.2.4. Characteristics of D.C. generators

The properties of generators are analysed with the aid of characteristics which give the relations between fundamental quantities determining the operation of a generator. These include the voltage across the generator terminals V, the field or exciting current I_f, the armature current I_a, and the speed of rotation N.

The three most important characteristics of D.C. generators are given below :

1. No load saturation characteristics $\left(\frac{E_0}{I_f}\right)$.

2. Internal or total characteristics $\left(\frac{E}{I_a}\right)$.

3. External characteristics $\left(\frac{V}{I}\right)$.

1. **No load saturation characteristic** $\left(\frac{\mathbf{E_0}}{\mathbf{I_f}}\right)$. It is also a known as magnetic or open circuit characteristic (O.C.C.). It shows the relationship between the no-load generated e.m.f. in armature, E_0 and field or exciting current I_f at a given fixed speed. The shaped of the curve is practically the same for all types of generators whether they are separately excited or self-excited. It is just the magnetisation curve for the material of the electromagnets.

2. **Internal or total characteristic** $\left(\frac{\mathbf{E}}{\mathbf{I_a}}\right)$. It gives the relationship between the *e.m.f. E actually induced* in the armature after allowing for the demagnetising effect of armature reaction and the *armature current* I_a. This characteristic is of interest mainly to the *designer.*

3. **External characteristic** $\left(\frac{\mathbf{V}}{\mathbf{I}}\right)$:

- This characteristic is also referred to as *performance characteristic* or sometimes *voltage-regulating curve.*
- It gives relation between the *terminal voltage V* and *load current I.*
- The curve lies below the internal characteristics because it takes into account the voltage drop over the armature circuit resistance. The *values of V are obtained by substracting* I_aR_a *from corresponding values of E.*
- This characteristic is of great importance in judging the *suitability of a generator for a particular purpose.*

The external characteristic can be obtained by the following two ways :

(*i*) By making simultaneous measurements with a suitable voltmeter and an ammeter on a loaded generator.

(*ii*) Graphically from the O.C.C. provided the armature and field resistances are known and also if the demagnetising effect of the armature reaction is known.

Separately excited generator :

- Fig. 12.19 shows the connections of a separately excited generator, a battery being indicated as the source of exciting current, although any other constant voltage source could be used.

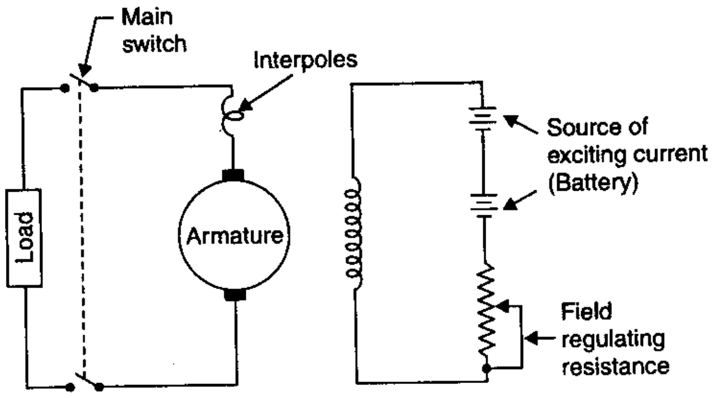


Fig. 12.19. Connection for a separately excited generator.

The field circuit is provided with a variable resistance and would normally contain a field switch and an ammeter, these being omitted from the diagram for simplicity. The armature is connected through 2-pole main switch to the bus bars, between which the load is connected.

(*a*) ***No-load saturation characteristic (or O.C.C.)***

— If the generator is run at constant speed with the main switch open, and the terminal voltage is noted at various values of exciting or field current then the O.C.C. shown in Fig. 12.20 can be plotted. This is also referred to as the '*magnetisation curve*' since the same graph shows, to a suitably chosen scale, the amount of magnetic flux, there being a constant relationship (depending upon speed of rotation) between flux and induced voltage.

— It will be noticed that a small voltage is produced when the field current is zero, this being due to a small amount of permanent magnetism in the field poles. This is called *residual magnetism* and is usually sufficient to produce 2 or 3 per cent of normal terminal voltage, although in some special cases it is purposely increased to 10 per cent or more.

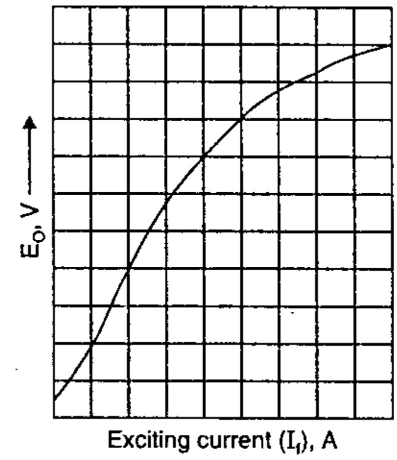


Fig. 12.20. Open-circuit characteristic of a separately excited generator.

— The *first part of the curve is approximately straight* and *shows that the flux produced is proportional to the exciting current ; but after a certain point, saturation of the iron becomes perceptible as the curve departs from straight line form.*

(*b*) **Internal and external characteristics (or load characteristics)**

— Load characteristics for a separately excited generator are shown in Fig. 12.21. The most important is the '*external characteristic*' (or total characteristic), which indicates the way in which the terminal voltage (*V*) varies as the load current is increased from zero to its full load value, the speed of rotation and exciting current being constant.

The voltage drop (drop of volts) at any particular load current, *indicated by the vertical distance between the external characteristic and the no-load voltage* is brought about by two causes :

(*i*) *Armature reaction which has a demagnetising effect upon the field.*

(*ii*) *Resistance drop,* this being the product of the armature current and the total armature-circuit resistance, consisting of the armature resistance, interpole resistance and brush contact resistance.

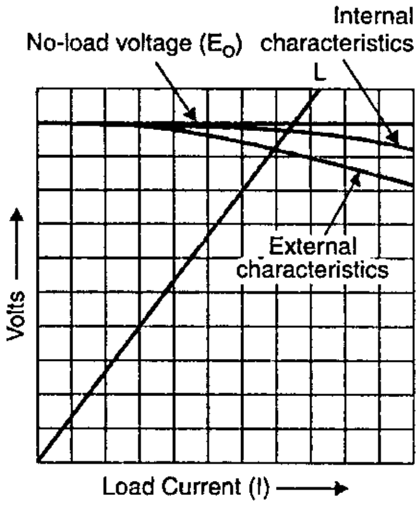


Fig. 12.21. Load characteristics of a separately excited generator.

- The '*internal characteristic*' is obtained by *calculating the resistance drop for a few values of current and adding this to the voltage shown by the external characteristics. The vertical distance between the internal characteristic and no load voltage then represents the effect of armature reaction alone.*
- When the resistance of load is R, then voltage across its terminals is $V = IR$, where I represents the current, so that if the value of V corresponding to various values of I are calculated, the values will all lie upon a straight line such as OL in Fig. 12.21. *The load current and terminal voltage corresponding to this resistance are given by the inter-section of the line OL with the external characteristics.*

Note. The great *advantage of separate excitation* over all other forms of excitation is that the *current is entirely independent of the load current in the armature.* It is, however, rather inconvenient to have to depend upon a separate source of supply and, therefore, the *method is used only in special cases, where the generator has to operate over a wide range of terminal voltage.*

Building up the voltage of self-excited shunt generator :

One of the simplest forms of 'self-excited' generator is the shunt-wound machine, the connection diagram (without load) of which is shown in Fig. 12.22. The manner in which a self-excited generator manages to excite its own field and build a D.C. voltage across its armature is described with reference to Fig. 12.23 in the following steps :

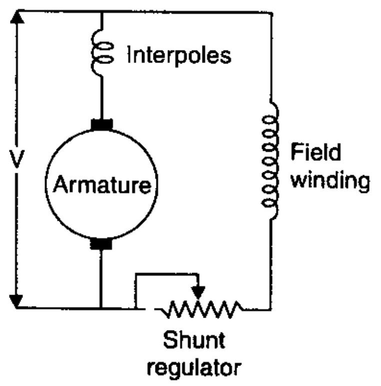


Fig. 12.22. Self-excited shunt generator.

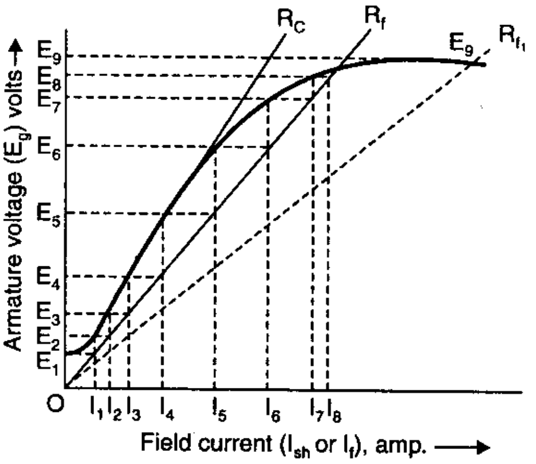


Fig. 12.23. Building up the voltage of a shunt generator.

- Assume that the generator starts from rest, *i.e.*, prime-mover speed is zero. Despite a residual magnetism, the generated e.m.f. E, is zero.
- As the prime-mover rotates the generator armature and the speed approaches rate speed, the voltage due to residual magnetism and speed increases.
- At rated speed, the voltage across the armature due to residual magnetism is small, E_1, as shown in the figure. But this voltage is also across the field circuit whose resistance is R_f. Thus, the current which flows in the field circuit I_1, is also small.
- When I_1 flows in the field circuit of the generator of Fig. 12.22, an increases in m.m.f. results (due to I_fT_f, T_f being field turns, which aids the residual magnetism in increasing the induced voltage to E_2 as shown in Fig. 12.23.
- Voltage E_2 is now impressed across the field, causing a large current I_2 to flow in the field circuit. I_2T_f is an increased m.m.f., which produces generated voltage E_3.

- E_3 yields I_3 in the field circuit, producing E_4. But E_4 causes I_4 to flow in the field producing E_5 ; and so on, up to E_8, the maximum value.
- The *process continues until that point where the field resistance line crosses the magnetisation curve* in Fig. 12.23. Here the process stops. The induced voltage produced, when impressed across the field circuit, produces a current flow that in turn produces an induced voltage of the same magnitude, E_8, as shown in the figure.

Critical resistance :

- In the above description a particular value of field resistance R_f was used for building up of self-excited shunt generator. If the field resistance were reduced by means of adjusting the field reheostat of Fig. 12.22 to a lower value say R_{f_1}, shown in Fig. 12.23, the build-up process would take place along field resistance line R_{f_1}, and build-up a somewhat higher value than E_8, *i.e.*, the point where R_{f_1} intersects the magnetisation curve, E_9. Since the curve is extremely saturated in the vicinity of E_9, reducing the field resistance (to its limiting field winding resistance) will not increase the voltage appreciably. Conversely, increasing the field rheostat resistance and the field circuit resistance (to a value having a higher slope than R_f in the figure) will cause a reduction of the maximum value to which build-up can possibly occur.
- The field resistance may be increased until the field circuit reaches a *critical field resistance. Field circuit resistance above the critical field resistance will fail to produce build-up.* The critical field circuit resistance, R_c, is shown as tangent to the saturation curve passing through the origin, O, of the axes of the curve of Fig. 3.5. Thus a field circuit resistance higher than R_c will produce an armature voltage of E_1 approximately (and no more).

Reasons for Failure of Self-Excited Shunt Generator to Build-up Voltage :

The reasons why a self-excited generator may fail to build-up voltage are given below :

1. **No residual magnetism.** The start of the build-up process requires some residual magnetism in the magnetic circuit of the generator. If there is little or no residual magnetism, because of inactivity or jarring in shipment, no voltage will be generated that can produce field current. To overcome this difficulty, a separate source of direct current is applied to the field for a short period of time and then removed. The magnetic field should now be sufficient to allow the voltage to build-up. *The application of a separate source of direct current to the field is called 'flashing the field'.*

2. **Field connection reversed.** The voltage generated due to residual magnetism is applied to the field. Current should flow in the field coils in such a direction as to produce lines of flux in the same direction as the residual flux. If the field connections are reversed, the *lines of flux produced by the current flow will oppose the residual flux* so that the generated voltage will *decrease* rather than increase when the field circuit is closed. In this instance it is necessary to *reverse the field connections with respect to the armature.*

3. **Field circuit resistance too high.** A field circuit resistance greater than critical value will prevent an appreciable build-up. At no load, resistance greater than the critical may be caused by the following :

- **Open field circuit connection.** The effects of an open circuit are apparent. The field circuit resistance is *much greater than the critical value* ; hence *generator will not build-up.*
- **Dirty commutator.** A dirty commutator does not permit good contact between the brushes and the commutator. This poor contact shows up as a high resistance to the flow of current in the field circuit and produces the same effect as a high field circuit resistance.

Shunt generator characteristics :

In a shunt generator the field circuit is connected directly across the armature. Appliances, motors, light bulbs, and other electrical devices connected in *parallel* across the generator terminals represent a *load* on the generator. As more devices are connected in parallel, the load on the generator increases; that is, the generator current increases. Because the generator current increases, the terminal voltage of the generator decreases. There are three factors that cause this decrease in voltage :

(*i*) Armature-circuit resistance (R_a) (*ii*) Armature reaction

(*iii*) Reduction in field current.

(*i*) **Armature-circuit resistance.** The armature circuit of a generator, like every electrical circuit, contains resistance. This resistance includes the resistance of : (*i*) *the copper conductors of the armature winding, (ii) the commutator, (iii) contact resistance between brushes and commutator* and *(iv) the brushes themselves.* When no current flows through the armature, there is no *IR* drop in the armature and the voltage at the terminals is the same as the generated voltage. However, when there is current in the armature circuit, a voltage drop exists due to the armature resistance, and the terminal voltage is less than the generated voltage. The terminal voltage may be calculated from the following reaction :

$$V = E_g - I_a R_a$$

where V = voltage at terminals of generator

E_g = generated or induced voltage

I_a = total armature current

R_a = armature-circuit resistance.

(*ii*) **Armature reaction.** When current flows in the armature conductors a flux surrounds these conductors. The direction of this armature flux is such that it reduces the flux from the field poles, resulting in both a reduced generated voltage and terminal voltage.

(*iii*) **Reduction in the field current.** The field circuit is connected across the terminals of the generators. When the terminal voltage of the generator becomes smaller because of the armature-resistance volt drop and armature reaction, the voltage across the field circuit also becomes smaller and therefore field current will be less. A reduction in the magnitude of field current also reduces the flux from the field poles, which in turn reduces the generated voltage and also the terminal voltage.

External characteristic :

— See Figs. 12.24 and 12.25. The effect of the preceding three factors is shown in Fig. 12.25, which shows external (load-voltage) characteristic of a shunt generator.

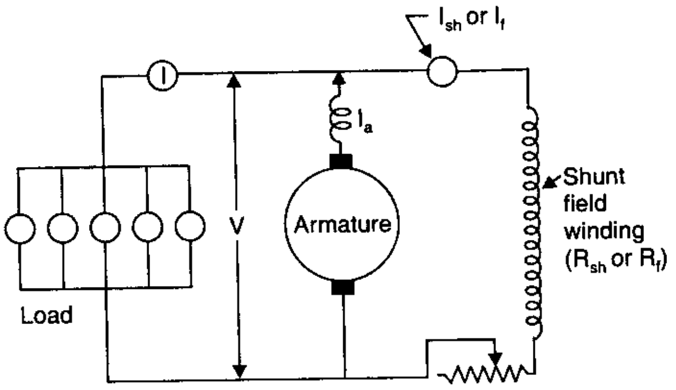


Fig. 12.24. Shunt generator under load.

— As shown in the circuit of Fig. 12.24, the readings of the voltage across the armature (and load), V are plotted as a function of load current, I. The voltage, V, is the same as E_g at no-load (neglecting the I_aR_a and armature reaction drop produced by the field current). The effects of armature reaction, armature circuit voltage drop, and decrease in field current are all shown with progressive increase in load. Note that both the armature reaction and the I_aR_a drop are shown as dashed straight lines, representing theoretically linear voltage directly proportional to the increase in load current. The drop owing to decreased field current is a curved line, since it depends on the degree of saturation existing in the field at the value of load.

— Generally, the external load-voltage characteristic decreases with application of load only to a *small extent up to its rated load* (current) *value*. Thus, the shunt generator is considered as having a fairly constant output voltage with application of load, and in practice, is *rarely operated beyond the rated load current value continuously for any appreciable time.*

— As shown in the Fig. 12.25 *further application of load causes the generator to reach a breakdown point beyond which further load causes it to 'unbuild' as it operates on the unsaturated portion of its magnetisation curve. This unbuilding process continues until the terminal voltage is zero, at which point the load current is of such magnitude that the internal armature circuit voltage drop equals the e.m.f. generated on the unsaturated or linear portion of its magnetisation curve.*

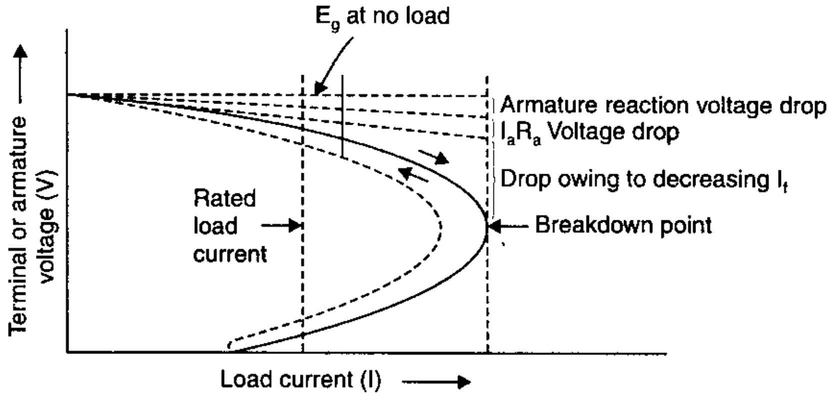


Fig. 12.25. Shunt generator load characteristics.

— It may be noted that if the *external load is decreased* (an increase of external load resistances), the*generator will tend to build up gradually along the dashed line* shown in Fig. 12.25.

Voltage regulation. The term '*voltage regulation*' is used to indicate the degree of change in armature voltage produced by application of load. If there is little change from no-load to full load, the generator or voltage-supplying device is said to possess good voltage regulation. If the *voltage changes appreciably with load, it is considered to have poor voltage regulation.*

'*Voltage regulation*' is defined as the *change in voltage from no-load to full load, expressed as a percentage of the rated terminal voltage* (armature voltage at full load).

i.e., Per cent voltage regulation $= \dfrac{V_{nl} - V_{fl}}{v_{fl}} \times 100$ ...(12.1)

where V_{nl} = No load terminal voltage

V_{fl} = Full load (rated) terminal voltage.

Internal or total characteristic. To determine internal characteristic from external characteristic the following procedure is adopted [*see* Fig. 12.26 (*a*)].

Steps. 1. From the given data, draw the external characteristic (*I*).

2. Draw the shunt field resistance line *OL* and armature resistance line *OM*.

3. On the external characteristic take any point say *F*.

4. From point *F* draw vertical and horizontal lines intersecting *X* and *Y* axes respectively. Let these lines be *FC* and *FA* respectively.

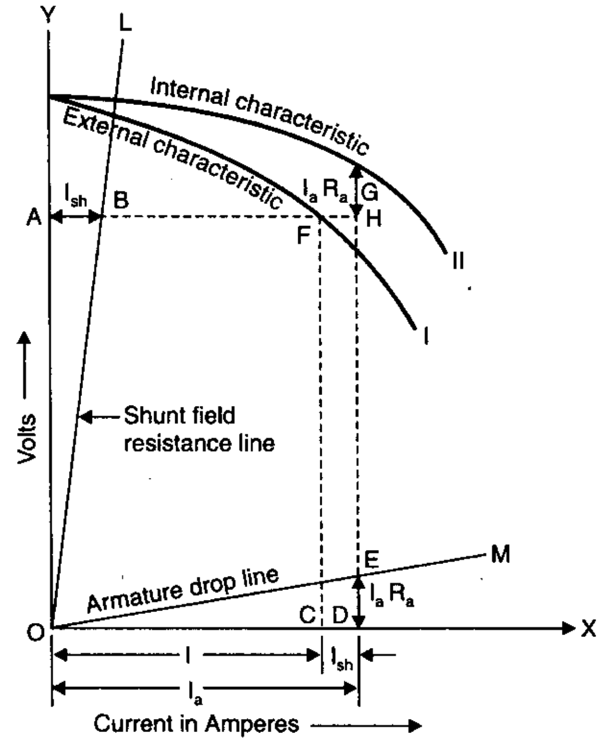


Fig. 12.26. (*a*) Determination of internal characteristic from external characteristic.

5. Take point *D* on *X*-axis so that *CD* = *AB* representing the shunt field current, I_{sh}.

6. From point *D* draw vertical *DE* and produce it intersecting line *AF* produced at *H*.

7. Take point *G* on line *DH* produced so that *HG* = *DE* (= $I_a R_a$) representing the armature drop.

8. Following the above procedure take a number of points on external characteristic and find corresponding points lying on internal characteristic.

9. Draw a curve passing through these points which is the required internal characteristic (*II*).

External characteristic and no-load saturation curve. The external characteristic of a shunt generator can be obtained directly from its no-load saturation curve as explained below. Following two cases will be considered :

(A) When armature reaction is so small as to be *negligible.* This is *more or less true for generators fitted with compoles.*

(B) When armature reaction is *not negligible.*

(A) **Armature reaction negligible :**

Steps. 1. From given data draw O.C.C. [*see* Fig. 12.26 (*b*)].

2. Draw shunt field resistance line (say *OS*) meeting O.C.C. at any point (say *A*).

3. From point *A* draw horizontal line intersecting *Y*-axis, say at point *B*.

Hence, *OB* is the maximum no-load or open circuit voltage.

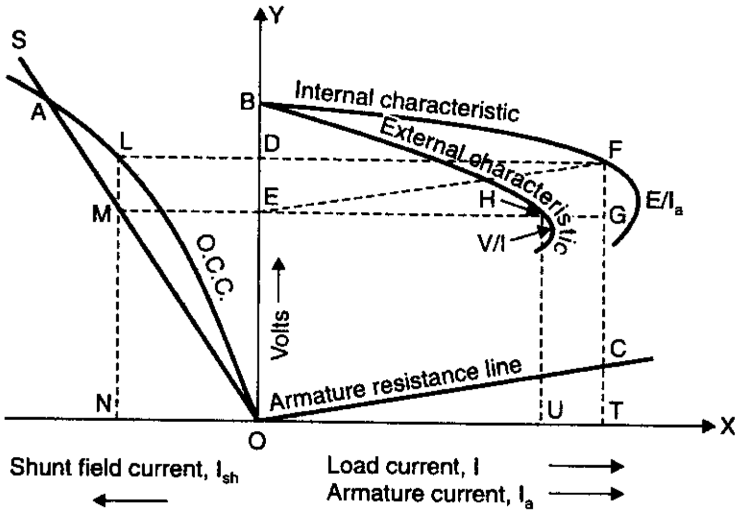


Fig. 12.26. (*b*) Determination of external and internal characteristic from O.C.C.

4. Take any point (say *L*) on the O.C.C. and draw an ordinate, say, *LMN* intersecting field resistance line at *M* and *X*-axis at *N*. Now *LN represents the generated e.m.f., MN represents the terminal voltage and LM represents voltage drop in armature.*

5. From points *L* and *M* draw horizontal lines cutting vertical axis say at point *D* and *E* respectively.

6. Draw armature resistance line *OC*.

7. From point *E*, draw line *EF* parallel to line *OC* cutting line *LD* produced at *F*. Hence, *F* is lying on the internal characteristic.

Similarly other points can be obtained and internal characteristic may be drawn through these points.

8. From point *F* draw vertical line intersecting produced line *ME* at any point *G* and *X*-axis say, at point *T*. Since *FG* = *LM* = *CT*, hence point *G* lies on the *curve representing relation between armature current and terminal voltage.*

9. Take *TU* = shunt field current (I_{sh}) *ON* (scale being different). *OU* represents the load current corresponding to armature current represented by *OT* and terminal voltage *OE*.

10. From point *U* draw a vertical line intersecting line *EG* at *H*. Point *H lies on the external characteristic.*

Similarly other points may be obtained and curve may be drawn, which is the required *external characteristic.*

(B) **Taking armature reaction into account :**

Here, in addition to considering the voltage drop in armature, voltage drop due to armature reaction is also taken into account.

Let $I_a R_a$ = Voltage drop in armature, and

I_{sh} = Increase in shunt field current to counteract the demagnetising effect.

Now if a right-angled triangle say *lmn* is drawn as that *ln* = voltage drop in armature, and *mn* = shunt field current. The triangle *lmn* is called as the *drop reaction triangle.*

In order to draw external and internal characteristic repeat the process as in *A* with following modifications in steps 4 and 9 respectively.

4. Take any point *L* on the O.C.C. and draw line *LM* parallel to the line *lm* of triangle *lmn* and complete the triangle *LMN*. Now from the points *L* and *M* draw vertical lines cutting *X*-axis at points *N'* and *M'*. Now *LN' represents the generated e.m.f. MM'* represents the terminal voltage, *LN represents the voltage drop in armature due to armature resistance ON' is the shunt field current to induce an e.m.f. represented by LN'* and *N'M'* is the *increase in shunt field current to counteract the demagnetising effect.*

5. Take *TU* = shunt field current *ON'* (scale being different). *OU* represents the load current corresponding to the armature current represented by *OT* and terminal voltage *MM'*.

Voltage control of shunt generators :

- The terminal voltage of a shunt generator may be kept constant at all loads with the use of adjustable resistance, called a *field rheostat, connected in series with the shunt-field circuit.* By adjusting the resistance of the rheostat to suit the load on the machine, changes in terminal voltage with load may be prevented. When the load changes gradually, hand control of the rheostat may be used, although *automatic control* employing a *voltage regulator* is far more satisfactory.
- The terminal voltage may also be controlled *automatically* by the addition of a series-field winding. This method has the advantage of being *automatic, cheap* and *generally satisfactory*.

Series Generator :

The field winding of a series generator is connected in series with the armature winding as shown in Fig. 12.27. It consists of a *few series of heavy wire, capable of carrying the output current of the machine without overheating.* The characteristic curves of a D.C. series generator are drawn as given below :

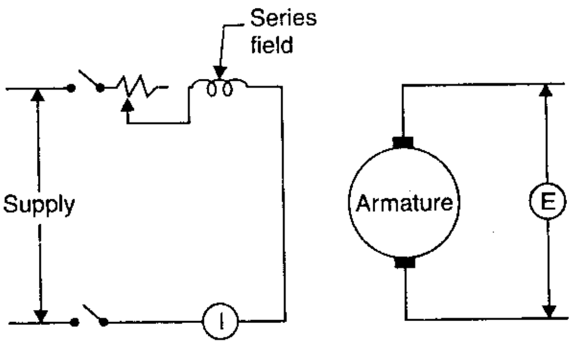


Fig. 12.27. Connection diagram for obtaining the saturation curve of a series generator.

- The *saturation* curve (1) may be obtained in a manner exactly similar to that already described for the shunt machine. The series-connected generator is illustrated in Fig. 12.27. The series connected generator illustrated in Fig. 12.28 must be capable of safely carrying the maximum current to be used, or about 125 per cent of rated load current. A plot of simultaneous readings of generated voltage and field current, taken at a rated speed, yields the magnetisation curve 1 of Fig. 12.29.

— **External characteristic (curve 2).** To obtain the data for this curve, the machine is connected to the load as shown in Fig. 12.28, ammeter and voltmeter being inserted to read the load current $I(= I_a)$ and the terminal voltage V respectively. The machine is run at constant (rated) speed, a series of simultaneous readings of voltage and current is taken while the load is varied from a minimum value to perhaps 125 per cent of rated load. When these readings are plotted, using V as co-ordinates and $I_a(= I)$ as abscissa curve 2 (*see* Fig. 12.29) is obtained.

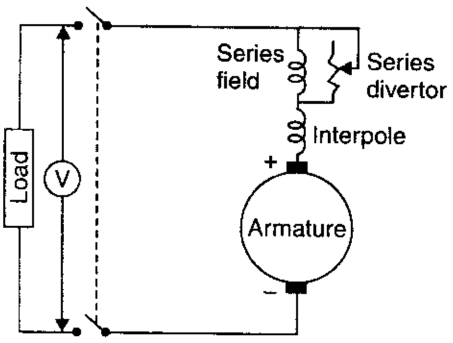


Fig. 12.28. Circuit for loading a series generator.

It may be noted that the *readings cannot begin at zero load* as with the shunt generator, for if *the resistance of the circuit including armature, series field and load is increased beyond a certain critical value, the generator unbuilds and loses its load entirely.* Thus, if OA is the resistance line for the circuit the terminal voltage is the ordinate to the curve at A. When the *resistance of the circuit* is gradually *increased,* the *load falls off* along the curve, and A approaches B. When the resistance line finally becomes tangent to the curve, however, *operation becomes unstable,* and any slight further increase in the resistance causes the machine to unbuild its voltage and lose its load. The resistance that brings about this condition is called the critical resistance. Therefore, to *begin with,* the resistance of the circuit must be reduced below the critical value before the generator delivers any load.

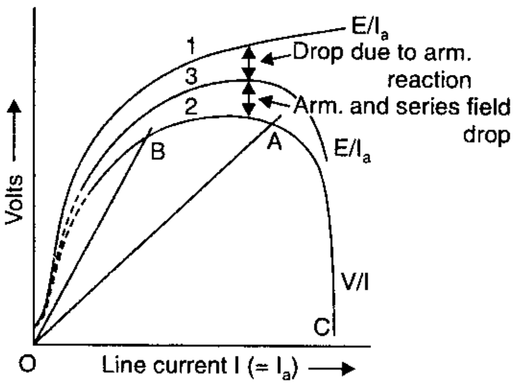


Fig. 12.29. Characteristic curves of a D.C. series generator.

— **Internal characteristic (curve 3).** This curve is obtained by adding the resistance drop $I_a(R_a + R_{se})$ to the external characteristic curve ; R_a and R_{se} being armature resistance and series field resistance respectively.

The difference between curves 1 and 3 is the *reduction in voltage caused by armature reaction.*

— It is worth noting that between A and C a considerable change in resistance brings about only a slight change in load current. Over this range the *voltage decreases rapidly,* owing to increasing armature reaction (particularly when the brushes are shifted forward), while the *current remains nearly constant.* Thus, between A and C the machine may be used to supply power to a *constant current variable-voltage circuit, such as series arc circuit.*

— Owing to initially *rising characteristic,* the series generator is often used as a *voltage booster* to give an increase of voltage practically proportional to the current.

— A series generator also finds applications in electric traction where '*dynamic braking*' is employed. The connections of the series traction motors are changed by means of a controller so that they act as generators ; the power absorbed in braking the vehicle being dissipated in resistances, which are also used for starting purposes when the machines are reconnected as motors.

Compound Wound Generator :

In case of a series generator the voltage regulation is very poor but the ability of the series field to produce additional useful magnetisation in response to increased load cannot be denied. This useful characteristic of the series field, combined with the relatively constant voltage characteristic of the shunt generator, led to the compound generator. Fig. 12.30 shows connection diagrams for a compound generator.

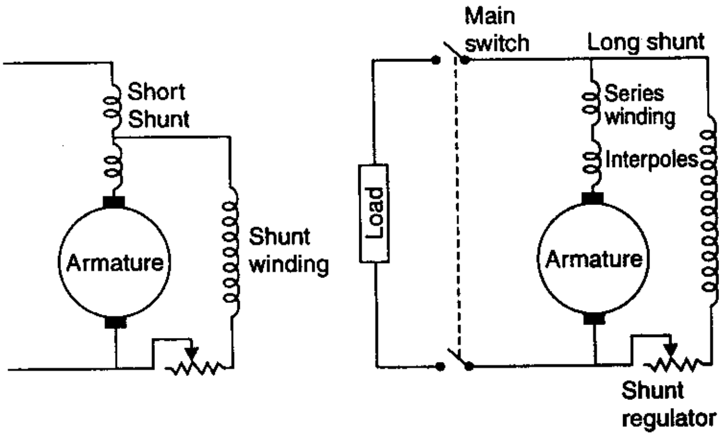
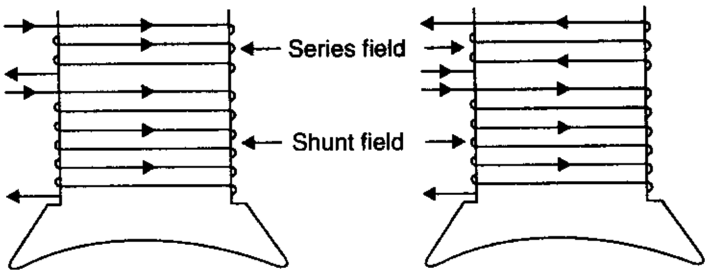


Fig. 12.30. Connection diagrams for a compound generator.

Regardless of the method of connection, the terminal voltage V of the short shunt or long shunt compound generator is same, $V = E_g - (I_{se} \cdot R_{se} + I_a R_a)$.

The generator voltage, E_g, of a compound generator is the result of the combination of m.m.f.'s produced by the series ($I_{se}T_{se}$) and shunt ($I_{sh}T_{sh}$) ampere-turns due to current which flows in their field windings. In a compound generator, the *shunt field predominates and is much the stronger of the two. When the series field m.m.f. aids the shunt field m.m.f.*, the generator is said to be '*cumulatively compounded*' (*see* Fig. 12.31). When the *series field m.m.f. opposes the shunt field m.m.f.*, the generator is said to be '*differentially compounded*' [*see* Fig. 12.31 (*b*)].



(a) Cumulative (b) Differential

Fig. 12.31. Current directions in series and shunt-field coils of cumulative and differential-compound generator.

Characteristics of Cumulative Compound Generator :

See Fig. 12.32. Depending on the relative additional aiding m.m.f., produced by the series field there are three types of load characteristics possible for the *cumulative* compound generator. These types are called

(*i*) Overcompound (*ii*) Flat-compound (*iii*) Undercompound.

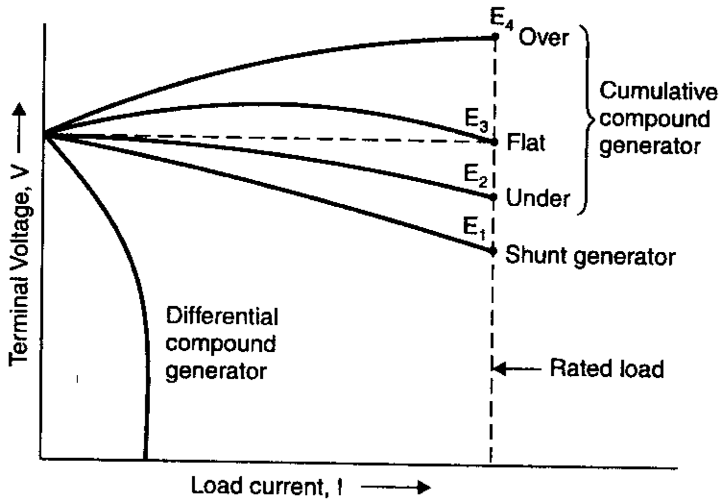


Fig. 12.32. External load voltage characteristics of cumulative and differential compound generators.

Over compound generator. An over compound generator is one whose terminal voltage *rises with the application of load* so that its full-load voltage *exceeds* its no-load voltage (*negative regulation*).

Flat compound generator. A flat compound generator has a load-voltage characteristic in which the no-load and full-load voltages are equal (*zero per cent regulation*).

Undercompound generator. An undercompound generator has a load characteristic in which the full load voltage is somewhat *less* than no-load voltage, but whose aiding series-field ampere-turns cause its characteristic to have *better regulation than an equivalent shunt generator.*

— Most commercial compound D.C. dynamos, whether used as generators or motors, are normally supplied by the manufacturer as *overcompound machines*. The *degree of compounding* (over, flat or under) may be adjusted by means of *diverter* which shunts the series field.

Characteristics of Differential Compound Generator :

— The *differential compound generator is defined as that compounding produced when the series field m.m.f. opposes the shunt field m.m.f.* The difference in current direction of the two windings is shown in Fig. 12.31 (*b*), where for the sake of clarity, the series field winding is shown above (rather than directly around) the shunt field winding.

— Fig. 12.33 shows the load characteristics of differential compound generator.

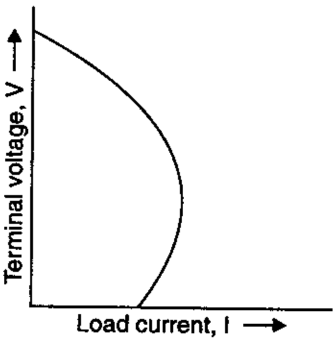


Fig. 12.33. Differential compound generator—load characteristic.

When the differential compound generator is *without load* it builds up and self-excites its shunt field in much the same manner as the shunt generator. However, *when a load is applied, the generated voltage E_g is now reduced by the* reduction in the main field flux created by the *opposing m.m.f. of the series field.* This reduction in E_g occurs *in addition to the armature and series circuit voltage drop, the armature reaction, and the reduction in field current produced* *by reduction of the armature voltage.* The result is a sharp drop in the terminal voltage with load as shown in Fig. 12.33, and as the field is below saturation and rapidly unbuilds.

— *The differential compound generator is used as a constant-current generator for the same constant-current applications as the series generator.*

Applications of D.C. Generators

Separately excited generators :

(*i*) The separately excited generators are usually *more expensive than self-excited generators* as they require *a separate source of supply.* Consequently they are generally used where self-excited are relatively unsatisfactory. These *are used in Ward Leonard systems of speed control, because self-excitation would be unsuitable at lower voltages.*

(*ii*) These generators are also used where quick and requisite response to control is important (since separate excitation gives a quicker and more precise response to the changes in the resistance of the field circuit).

Shunt generators :

(*i*) These generators are used to advantage, in conjunction with automatic regulators, *as exciters for supplying the current required to excite the fields of A.C. generators.* The regulator controls the voltage of the exciter by cutting in and out some of the resistance of the shunt-field rheostat, thereby holding the voltage at whatever value is demanded by operating conditions. This is one of the most important applications of shunt generators.

(*ii*) Shunt generators are used *to charge batteries.* In this application the voltage should drop off slightly as the load increases, because the voltage of a lead battery is lower when battery is discharged than when battery is charged. When it is discharged, however, the battery can stand a large charging current than when it is charged. *Because of its drooping characteristic the shunt generator is admirably suited to battery charging service,* for, in a general way, the voltage curve of the generator has the same shape as the voltage curve of the battery itself. In both cases, as the load falls the voltage rises.

— Shunt generators can be operated in parallel without difficulty, and the wiring of parallel-operated shunt machines is quite a bit simpler than the corresponding wiring for compound machines. When a slight drop in voltage is not objectionable, as when a motor load is fed directly from the generator terminals, shunt machines may be used to advantage.

Series generators. The field of application of series generator is limited. These are used for the following purposes :

(*i*) Series arc lighting.

(*ii*) Series incandescent lighting.

(*iii*) As a series booster for increasing the voltage across the feeder carrying current furnished by some other sources.

(*iv*) Special purposes such as supplying the field current for regenerative braking of D.C. locomotives.

Compound generators. The compound generator is used for more than any other type.

(*i*) It may be built and adjusted automatically to supply an approximately *constant voltage at the point of use,* throughout the entire range of load. This is *very great advantage.* It is possible to provide a constant supply voltage at the end of a long feeder by the simple expedient of *overcompounding* the generator, because the resistance drop in the line is compensated for by the rising characteristic of the generator.

When the point of utilisation is near the generator, a flat-compounded machine may be used.

(*ii*) *Differentially compounded generator* finds an useful application *as an arc welding generator* where the generator is practically short circuited every time the electrode touches the metal plates to be welded.

(*iii*) Compound generators are used to supply power to :

- Railway circuits,
- Motors of electrified steam rail-roads,
- Industrial motors in many fields of industry,
- Incandescent lamps, and
- Elevator motors etc.

12.2.3. Alternator-Current Generators

12.2.3.1. Introduction

- A *machine for generating alternating currents is referred to an alternator.*
- The term 'A.C. generator' is also frequently used, in place of alternator and this is often contracted to just 'generator' when it is obvious that as A.C. machine is meant. In older literature the term 'alternating current dynamo' will also be found, but the present tendency is to reserve the use of the word dynamo for D.C. generators.
- *High-speed* alternators driven by steam turbine differ considerably in their construction from the *slow speed* types and one distinguished by the use of the terms *'turbo-alternator'* whilst the slow engine-driven machines one often described as being of the *'flywheel-type'*.

12.2.3.2. Classification and operating principle

- In D.C. generators, the field poles are stationary and the armature conductors rotate. The *alternating* voltage induced in armature conductors is converted to a *direct* voltage at the brushes by means of the commutator.
- A.C. generators commonly called alternators, have *no commutators* as they are required to supply electrical energy with the *alternating* voltage. Therefore, it is not necessary that armature be the rotating member.

Alternators, according to their construction, are divided into the following two classifications :

1. Revolving armature type
2. Revolving field type.

1. **Revolving-armature type alternator**

- It has stationary *field poles* and *revolving armature.*
- It is usually of relatively small kVA *capacity* and *low voltage rating.* It resembles a D.C. generator in general appearance except that it has *slip rings instead of a commutator.* The field excitation must be direct current, and therefore, must be supplied from an external direct current source.

2. **Revolving-field type alternator**

- It has a *stationary* armature or *stator*, inside of which the *field poles rotate.*
- *Most* alternators are of the *revolving field type*, in which the *'revolving field structure'* or 'rotor' has slip rings and brushes to *supply the excitation current from an outside D.C. source.* The armature coils are placed in slots in a laminated core, called the *'stator'* which is made up of a thin steel punchings or laminations securely clamped and held in place in the steel frame of the generator. Usually the field voltage is between 100 and 250 volts and the amount of *power delivered to the field circuit is relatively small.*

The following are the *advantages* of the revolving field type alternators :

1. The armature windings are more easily braced to prevent deformation under the mechanical stresses due to short-circuit currents and centrifugal forces.

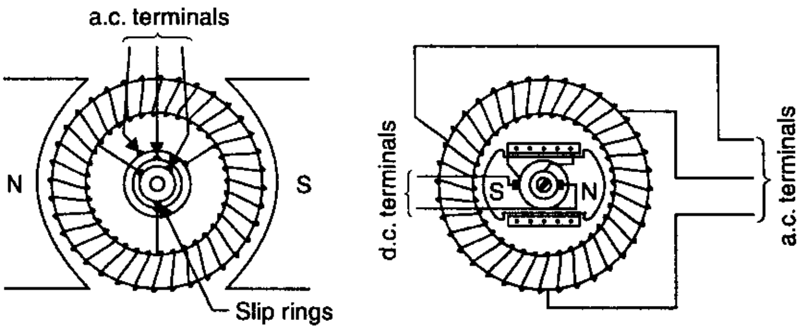
2. The armature (stator) windings must be insulated for a high voltage, while the voltage of field circuit is low (100 to 250 volts). *It is much easier to insulate the high voltage winding when it is mounted on the stationary structure.*

3. Only a small amount of power at low voltage is handled by the slip ring contacts.

4. It is easier to build and properly balance high-speed rotors when they carry the field structure.

5. The armature winding is cooled more readily because the stator core can be made large enough and with many air passages or cooling ducts for forced air circulation.

Operating principle (Revolving-field type). When the rotor rotates, the stator conductors (being stationary) are cut by the magnetic flux, hence they have induced e.m.f. produced in them. Because the magnetic poles are alternately N and S, they induce an e.m.f. and hence current in armature conductors, which first flows in one direction and then in the other. Hence, an alternating e.m.f. is produced in the stator conductors whose frequency depends on the number of N and S poles moving past a conductor in one second and whose direction is given by Fleming's right-hand rule.



(a) Revolving armature (b) Revolving field

Fig. 12.34. Operating principle of a three-phase alternator.

Fig. 12.34 shows the operating principle of a three-phase alternator.

Note. All synchronous A.C. generators and motors require direct current for excitation. Excitation is supplied by a D.C. generator called an *exciter*. The capacity of the exciter is only a *small percentage* of the rated capacity of the alternator. The exciter may be directly connected to the shaft of the alternator, or it may be driven by a separate electric motor, water wheel, or small turbine. Large power stations usually have several exciters employing different methods of drive as insurance against the failure of excitation.

12.2.3.3. Constructional details

Refer Fig. 12.35 on page 909.

Stator. The *stator* of an alternator consists essentially of a cast iron or a welded-steel frame supporting a slotted ring made of soft laminated sheet-steel punchings (Fig. 12.36) in the slots of which the armature coils are assembled.

- The *laminations* are analyzed and are insulated from each other by a thin coating of oxide and an enamel (as in D.C. machines, transformers etc.).
- *Open slots* are used, permitting easy installation of stator coils and easy removal in case of repair. Suitable spacing blocks are inserted at intervals between laminations to leave radial *air ducts,* open at both ends, through which cooling air may circulate.
- The *coils* are shaped much like the coils of a D.C. generator, the two sides of the coil being approximately a pole pitch apart. All coils are alike, and therefore, interchangeable. They are insulated before being inserted in the slots and are further protected by a horn-fibre slot lining. When in place on the stator, the coils are connected together in

groups to form a winding of the required number of phases, three-phases star-connected windings being common.

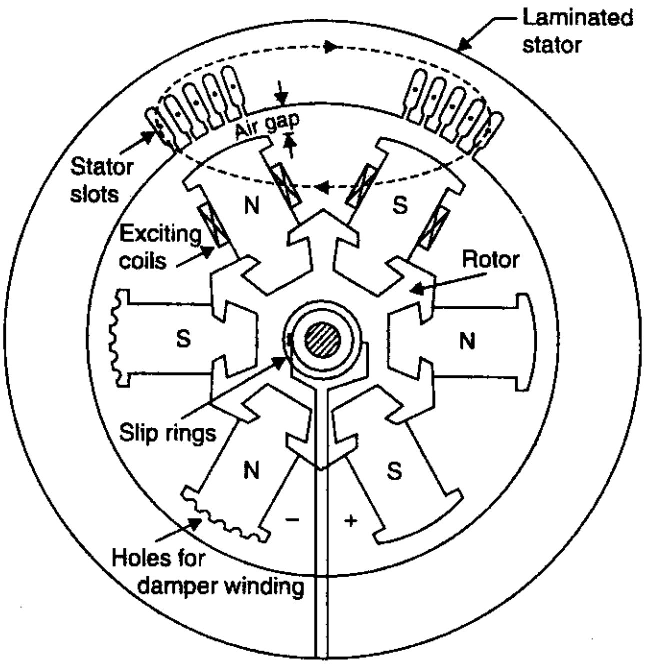


Fig. 12.35. Alternator.

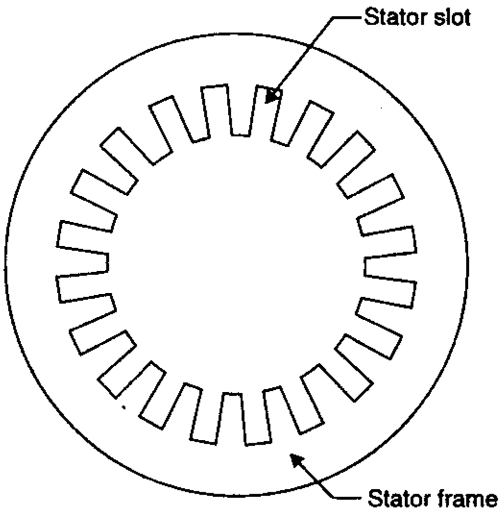


Fig. 12.36. Alternator stator.

— A fractional rather an *integral number of slots per pole is often used in order to eliminate harmonics in the waveform.*

Rotor. The revolving field structure is usually called the rotor. There are two types of rotors :

1. Salient pole type rotor.
2. Smooth cylindrical type rotor.

Salient pole type rotor. This type of rotor is used for *slow speed machines which have large diameters and small axial lengths.*

- The poles are made of thick steel laminations rivetted together and attached to a rotor by a devetail joint as shown in Fig. 12.37. The overhang of the pole gives mechanical support to the field coil.
- In most of the alternators, where the oscillation or the limiting effect is very high, the *damper winding* in the pole faces is provided. The copper bars short circuited at both ends are placed in the specially provided holes. The relative velocity of the damping winding with respect to main field will be zero when the speed is steady but as soon as it departs from the synchronous speed, there will be relative motion between the damper winding and the main field. This will induce current in them. This induced current will exert a torque in such a way as to bring the alternator to operate at synchronous speed.
- *The pole face is so shaped that the radial air gap length increases from the pole centre to pole tips. This makes the flux distribution over the armature uniform to generate sinusoidal waveform of e.m.f.* (Fig. 12.38).

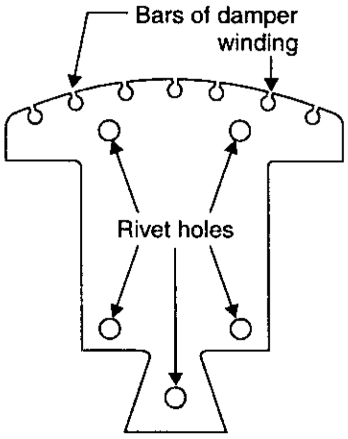


Fig. 12.37. Typical lamination of a salient pole rotor.

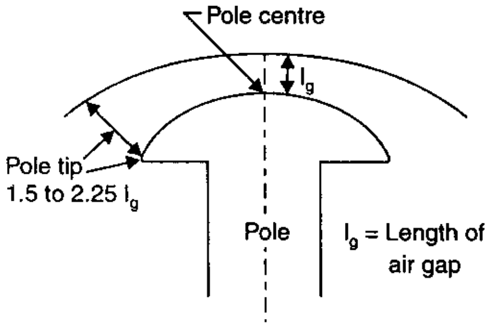


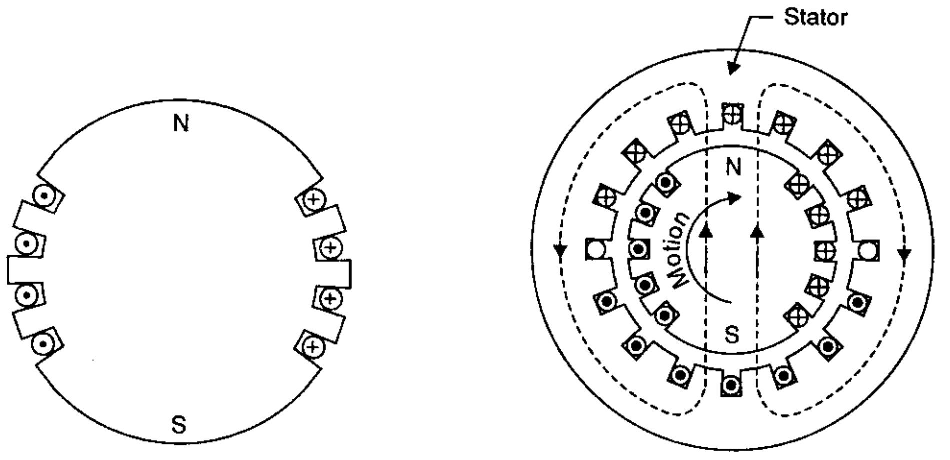
Fig. 12.38

Smooth cylindrical rotor :

- This type of rotor is used for alternators which are coupled to *steam turbines* which run at very high speeds. To reduce the peripheral speed of the alternator the *diameter of the rotor is reduced and axial length is increased.* The number of poles of the rotor are *two* or *four.*

Figs. 12.38 and 12.39 show a cylindrical rotor and cylindrical rotor alternator respectively.

- These rotors are made from solid forgings of alloy steel. The outer periphery of rotor has slots in which the field winding is placed. About 2/3rd of rotor pole pitch is slotted, leaving the 1/3rd unslotted for the pole centre. Heavy wedges of non-magnetic steel are forced into the grooves in the teeth outside the field coils to keep the field coils in position.
- *Cylindrical rotor machines have always horizontal configuration.*
- Since the rotors have large lengths of core forced ventilation is necessary for proper cooling. *Forced air cooling is used up to about 50 MVA sizes and for bigger sizes hydrogen cooling is invariably employed because the conductivity of hydrogen is about 7 times that of air.*



(a) Cylindrical rotor (two pole). (b) Cylindrical rotor alternator (two pole).

Fig. 12.39

Note. It may be worth mentioning that *cylindrical rotors* will most likely be located on alternates where *steam power* is readily available. *Salient-pole rotors* will be found where *water power* is the prime-mover source of energy. Diesel engine, gas engine, and gas turbine prime-movers are considered medium-speed machines, and their alternators will also have salient poles. Where alternators are driven by other electrical machines, either A.C. or D.C. motors, there are no such restrictions on the rotor construction. A design is developed that is compatible with the space limitations, speed considerations, and heat dissipation for both electrical machines. It may be noted here that the terms high-speed and low-speed rotors are sometimes used synonymously with cylindrical and salient-pole rotors, respectively.

Bearings

— Although antifriction bearings are occasionally used on alternators of the smaller ratings, the great majority are furnished with oil-lubricated babbitted bearings. For *horizontal shafts* these will be self-contained ring-oiled bearings whereever design conditions permit. At higher shaft peripheral speeds and higher bearing loadings ring oiling is supplemented with recirculation of externally cooled oil. The rings may be eliminated, or they may be retained to afford some degree of emergency oil supply in the event of a failure of the external system. *Lead-base babbits are commonly used for journal bearings,* although tin-base babbit may be employed for some heavy-duty application.

— Two principle types of *thrust bearings* are used on vertical alternators : the *pivoted shoe type* and the *spring type*.

Frequency

In case of a generator which has two poles, the induced e.m.f. passes through one complete revolution in one revolution of the machine. In a multipolar machine one cycle of e.m.f. would be generated when the field structure rotates through an angle subtended by a double pole pitch. Therefore, in a machine with poles, the number of cycle of e.m.f. in one revolution will be $p/2$. If a machine has a speed of N_s revolutions per minute, the frequency will be

$$\left(\frac{p}{2}\right) \times \frac{N_s}{60} \text{ per second.}$$

Thus,
$$f = \frac{p}{2} \times \frac{N_s}{60} = \frac{N_s p}{120} \text{ Hz} \qquad \text{...(12.2)}$$

In order to keep the frequency constant, the speed N_s must remain unchanged. Therefore, a synchronous generator (*i.e.*, alternator) runs at a constant speed known as synchronous speed.

12.2.3.4. Exciters

The alternator's field requires magnetism. The permanent magnets are unsuitable for the field of the alternator. Hence direct current is fed into the poles of the alternator so that one end is a north pole and the other a south pole. This direct current is supplied by a separate generator which is mounted on the same shaft as the alternator. Hence all alternators have a separate exciter which generally produce high current and low voltage. In case of large machines there are two exciters known as *main exciter* and pilot *exciter*. The *pilot exciter is a well-saturated constant voltage machine arranged to excite the main exciter.*

As the field strength depends on the d.c. exciting current in the field magnet coils, the exciting or field current is regulated accordingly to adjust the output voltage. In case of large machines the field current may be as high as 400 amperes. To regulate the exciting current is obtained by connecting the regulating resistance in the field circuit of the exciter where comparatively low current has to be handled. Fig. 12.40 shows such an arrangement.

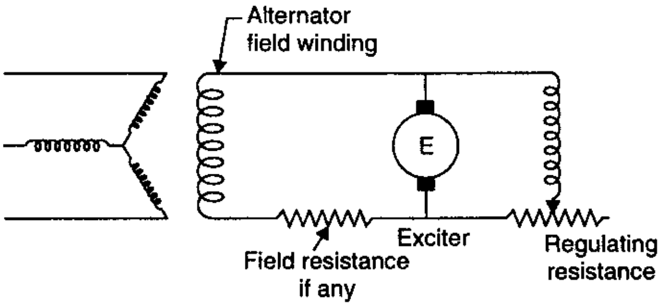


Fig. 12.40. Voltage control of an alternator.

It has been seen that the terminal voltage of the alternator depends not only the exciting current but also on the load current and the power factor of the load. If no-load terminal voltage is plotted against values of exciting current with the machine running at normal speed (field current) then the *open circuit characteristics* or *magnetisation curve* is obtained. The voltage is directly proportional to the flux per pole. The magnetisation curve is determined by the properties of the magnetic circuit. If the excitation of an alternator is adjusted to give normal voltage at no-load and then a load is applied, the terminal voltage changes, even though the speed is kept constant. The voltage usually falls, but in certain circumstances it may actually rise. These changes may be due to (*i*) resistance of each phase winding (*ii*) the reactance of each phase winding (*iii*) the armature reactors.

The *exciter is generally a shunt wound D.C. machine*. For a new machine it is often necessary to apply the first excitation with a battery. Then later on the poles of the exciter have residual magnetism and thus require no external help. However in no case of bigger machines, the pilot exciter may be started by the battery (in case of new machines only) and then with the residual magnetism in the field magnets it will generate direct current.

An exciter may be either directly coupled to the alternator shaft or it may be driven through a belt or chain drive.

Advantages of directly coupled exciters :

1. The machine as a unit is complete in itself and independent of outside sources for its operation.

2. The voltage of the system can be maintained independent of any auxiliary source of supply and is not affected by faults there on.

Disadvantages

1. Armature fitting, commutator stresses, brush chatter and ventilation, all require special attention.

2. Exciter troubles may sometimes necessitate shutting down of the main set.

3. With the high speeds in general use (1500 to 3000 r.p.m.) difficulties such as balancing, alignment of shaft and other problems crop up.

A.C. Exciters

To avoid commutation difficulties as well as commutator maintenance, A.C. exciters with silicon or germanium rectifiers have been developed for the largest turbo alternators as well as for smaller machines ; the current from the static floor mounted rectifiers is fed to the rotor of the main machine through conventional sliprings. The A.C. exciter is mounted on the main generator shaft and may be designed to operate at any economically convenient frequency, *e.g.* 100—150 Hz or more.

12.2.3.5. Alternator on load

When load on an alternator varies, its terminal voltage also varies. This variation in terminal voltage is due to the following reasons :

(*i*) Voltage drop due to armature resistance.

(*ii*) Voltage drop due to armature leakage reactance X_L.

(*iii*) Voltage drop due to armature reaction.

(*i*) **Armature resistance.** The voltage drop caused by armature resistance per phase R_a is IR_a and is in phase with current I. This drop, however, is practically negligible.

Effective resistance. The *effective resistance* of the armature winding is greater than the conductor resistance as measured by direct current. This is because additional energy over purely I^2R value is expended inside and sometimes outside of the conductor, owing to the alternating current.

The chief sources of this additional energy loss are :

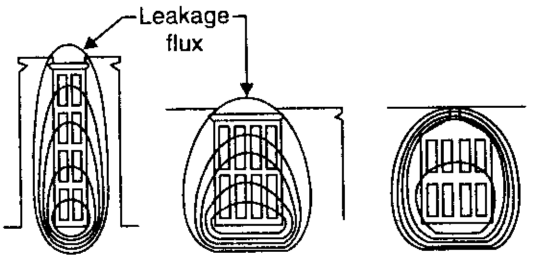
(*i*) Eddy currents in the surrounding material ;

(*ii*) Magnetic hysteresis in the surrounding material ; and

(*iii*) Eddy currents or unequal currents distribution in the conductor itself.

In many cases it is sufficiently accurate to measure the resistance of an armature by direct current and increase it to a fictitious value, called the effective resistance, which is large enough to take care of these extra losses. The exact value can vary widely from 1.25 to 1.75, or more × D.C. resistance, depending upon design. *Extreme accuracy is not necessary in this factor*, since the voltage change due to resistance is small in comparison to the changes produced by leakage reactance and armature reaction.

(*ii*) **Armature leakage reactance.** The load current, flowing through the armature winding, builds up local flux which on cutting the winding *generates a counter* (or *reactance*) *e.m.f.* This effect gives the armature a *reactance* which is numerically equal to $2\pi fL$. L, in henries, is the leakage inductance of the winding. This armature reactance is called the *leakage reactance* X_L (also known as Potier reactance X_P) since the flux *which causes it is around the armature turns only and does not effect the feld flux directly*. This *leakage flux* (Fig. 12.41) is proportional to the armature current, since the magnetic path it covers is not normally saturated. X_L varies some what with the position of the armature and field poles. It is usually assumed to be constant.



(a) Deep, narrow, open slot (b) Shallow, wide, open slot (c) Shallow, wide, partially closed slot

Fig. 12.41. Slot-leakage flux.

The voltage drop due to X_L is IX_L. A part of generated e.m.f. is used up in overcoming this voltage drop (reactance e.m.f.)

$$\therefore \qquad E = V + I(R_a + jX_L) \qquad \text{...(12.3)}$$

This fact is illustrated in Fig. 12.42.

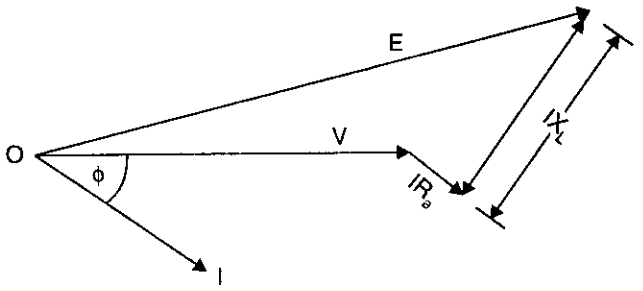


Fig. 12.42

(*iii*) **Armature reaction.** Armature reaction is the magnetomotive force produced by the armature currents in the armature conductors.

Unity power factor. At unity power factor, armature reaction consists of distortion of the main field flux.

Lagging power factor. When an alternator operates with a laging power factor a m.m.f. is set up by the current in the armature conductors which opposes the m.m.f. of the main field and causes a *decrease in the main flux*. This, in turn, results in decrease in the induced voltage. The *lower the value of lagging power factor*, the *greater will be the armature m.m.f. which will oppose and weaken the field*.

Leading power factor. In those limited applications where an alternator supplies a load with a leading power factor, the armature current sets up m.m.f. in the armature which aids the m.m.f. of the main field and *causes the main field flux to increase*. Therefore, the voltage of the alternator will increase with an increase in load current. The *lower the value of the leading power factor, the greater will be the armature m.m.f. aiding the m.m.f. of the main field to cause an increase in the main field flux*.

The following illustrations in Fig. 12.43 show how the main field flux is affected by the armature m.m.f. for different load power factors. For ease of illustration, a two-pole rotating type alternator is used. However, the same conditions take place in the revolving field type alternator.

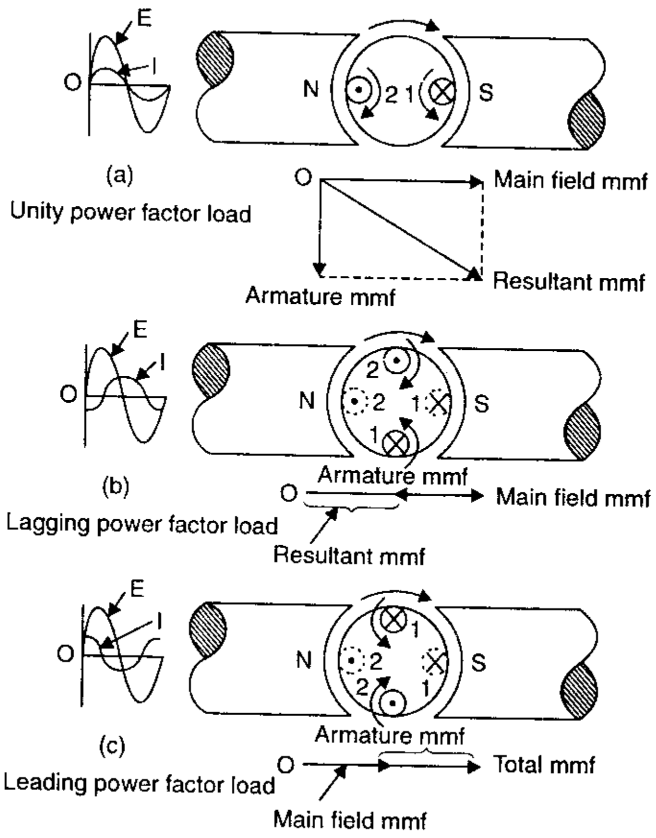


Fig. 12.43. Effects of armature reaction.

A study of illustrations in Fig. 12.43 and vector diagrams for different power factor loads, show that the *voltage drop due to inductive reactance and armature reaction are the same in their effect on the termianl voltage*. Both of these effects are proportional to the armature current.

Synchronous Reactance. The leakage reactance X_L (or X_P) and the armature reactance X_a may be combined to give '*synchronous reactance*' X_s.

Hence, $X_s = X_L + X_a$

[The ohmic value of X_a varies with the power factor of the load because armature reaction depends on load power factor].

From the above discussion, it is clear that for the same field excitation, terminal voltage is decreased from its no-load value E_0 to V (for a lagging power factor). This is because of :

(*i*) Drop due to armature resistance IR_a.

(*ii*) Drop due to synchronous reactance IX_s.

Therefore, *total voltage drop* in an alternator under load is

$$= IR_a + jIX_s = I(R_a + jX_s) = IZ_s$$

where Z_s is known as '*synchronous impedance*'. (The word synchronous simply refers to the working conditions).

Fig. 12.44 shows the vector diagram for the above fact.

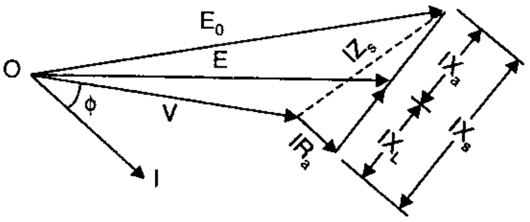


Fig. 12.44

Vector Diagrams of a Loaded Alternator. The vector diagrams for unity *power factor, for lagging power factor* and for *leading power factor* have been shown in Fig. 12.45, 12.46 and 12.47 respectively. All these diagrams apply to one phase of a 3-phase machine. Diagrams for the other phases can also be drawn in the same way.

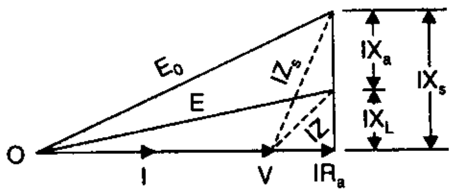


Fig. 12.45. Unity power factor.

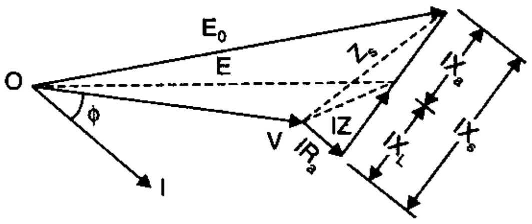


Fig. 12.46. Lagging power factor.

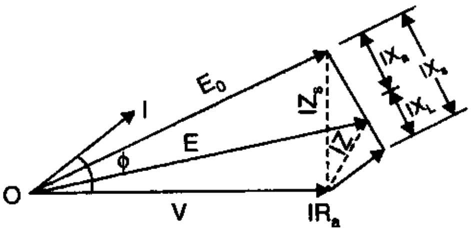


Fig. 12.47. Leading power factor.

In above diagrams :

E_0 = No-load e.m.f. This being the voltage induced in armature in the absence of IR_a, IX_L and IX_a. Hence it represents the maximum value of induced e.m.f.

E = It is the induced e.m.f. after allowing for armature reaction. E is vectorially less than E_0 by IX_a

V = Terminal voltage. It is vectorially less than E by IZ

where $Z = \sqrt{R^2 + X_L^2}$

I = Armature current/phase and

ϕ = Load power factor angle.

12.2.3.6. Voltage regulation

— When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, the amount of this variation determines the *regulation* of the machine. The numerical value of *regulation* is defined as *the percentage rise in voltage when full-load at the specified power-factor is switched off, the excitation being adjusted initially to give normal voltage.* Thus,

$$\%\ \text{Regulation 'up'} = \frac{E_0 - V}{V} \times 100 \qquad ...(12.4)$$

This gives a lower figure than the percentage drop in voltage when full-load is *switched on*, because in the latter case the excitation is only that required for normal voltage on open circuit. As actually defined, the excitation is greater, since it is that required to give normal voltage on full-load, and owing to the greater saturation of magnetic circuit in these circumstances, the rise in voltage when the load is switched off is less than the drop in voltage when the load is switched on.

— A normal alternator has a regulation of about 8 to 10 per cent at unity power factor, but the *voltage rise is considerably increased at lagging power-factors.* At 0.8 lagging power-factor the value lies between 25 and 35 per cent, or even more.

— *Close regulation is not desired, since such an alternator would deliver an excessive current if accidentally short-circuited. Coarse regulation adds to the protection of the machine*, and it is usual to design an alternator with a considerable amount of internal reactance, since this limits the short-circuit current, a most important point where alternators of high power are concerned. Indeed, large alternators are now designed to withstand a dead short-circuit with impunity. The disadvantages of coarse regulation is obviated by the usual practice of operating an alterantor in conjunction with an automatic voltage regulator, which maintains an approximately constant voltage at all loads.

Determination of Voltage Regulation. It is not usually possible or desirable to measure the regulation by direct experiment, indirect methods being adopted which do not necessitate the loading of the alternator. For this purpose, open circuit and short-circuit characteristics are required.

The following indirect methods are used to determine voltage regulation :

1. Synchronous impedance or E.M.F. method.
2. The Ampere-turn or M.M.F. method.
3. Zero power-factor or Potier method.

All these methods require :

(*i*) Armature (or stator) resistance R_a.

(*ii*) Open-circuit/no-load characteristic.

(*iii*) Short-circuit characteristic (but zero power factor lagging characteristic for Potier method).

(*i*) **Value of $\mathbf{R_a}$.** Armature resistance R_a per phase can be measured directly by voltmeter and ammeter method or by using wheatstone bridge. The effective value of R_a, however, under working conditions is increased due to skin effect. The value of R_a so obtained is increased by sixty per cent or so to allow this effect. Generally, a value 1.6 times D.C. value is taken.

(*ii*) **Open-circuit characteristic.** This type of characteristic (as in D.C. machines) is plotted by running the machine on on-load and noting the values of induced voltage and field excitation current.

(*iii*) **Short-circuit characteristic.** Short-circuit characteristic is obtained by short-circuiting the armature (*i.e.*, stator) windings through a low resistance ammeter. The excitation is so adjusted as to give 1.5 to 2 times the value of full-load current. *The speed* (not necessarily synchronous) *is kept constant during the test.*

Synchronous Impedance Method. This method involves the following *steps* :

(*i*) Plot the open-circuit characteristic (O.C.C.) from a given data as shown in Fig. 12.48.

(*ii*) Plot short-circuit characteristic (S.C.C.) from the data given by short-circuit test.

Both these curves are drawn on a common field-current base.

Consider a field current I_f. Corresponding to this field current the O.C. voltage is E_1. When winding is short-circuited, the terminal voltage is zero. Hence, it may be assumed that the whole of this voltage E_1 is being used to circulate the armature short-circuit current I_1 against the synchronous impedence Z_s.

$$\therefore \quad E_1 = I_1 Z_s$$

or

$$Z_s = \frac{E_1 \text{ (open-circuit)}}{I_1 \text{ (short-circuit)}}$$

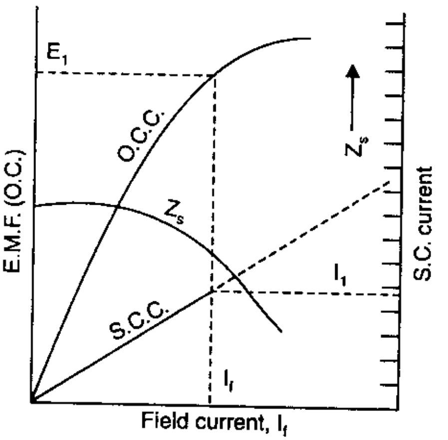


Fig. 12.48. O.C. and S.C. test curves of an alternator.

(*iii*) Find synchronous reactance, X_s as follows

$$X_s = \sqrt{Z_s^2 - R_a^2} \qquad (R_a \text{ can be found as discussed earlier})$$

(*iv*) After finding R_a and X_s vector diagrams for any load any power factor may be drawn. Three cases are considered in Fig. 12.49, (*a*) *unity power factor, (b) lagging power factor*, and (*c*) *leading power factor*.

— **Unity power factor.** Refer Fig. 12.49 (*a*)

$$OC^2 = (OA + AB)^2 + BC^2$$

$$E_0^2 = (V + IR_a)^2 + (IX_s)^2$$

$$\therefore \quad E_0 = \sqrt{(V + IR_a)^2 + (IX_s)^2} \qquad \text{...(12.5)}$$

— **Lagging power factor.** Refer Fig. 12.49 (*b*),

$$OC^2 = (OA + AB)^2 + (BD + DC)^2$$

$$= E_0^2 = (V \cos \phi + IR_a)^2 + (V \sin \phi + IX_s)^2$$

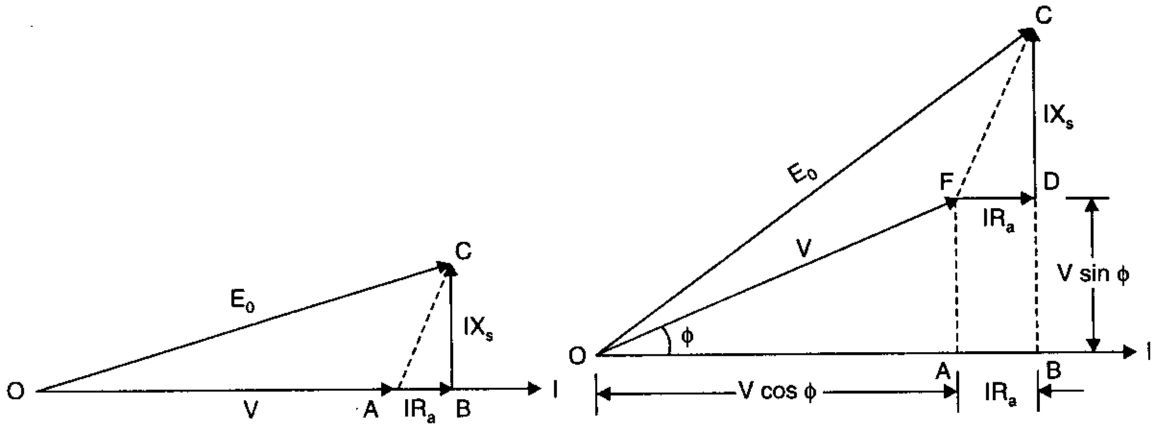
$$\therefore \quad E_0 = \sqrt{(V \cos \phi + IR_a)^2 + (V \sin \phi + IX_s)^2} \qquad \text{...(12.6)}$$

— **Leading power factor.** Refer Fig. 12.49 (*c*),

$$OC^2 = (OF + FD)^2 + (BD - BC)^2$$

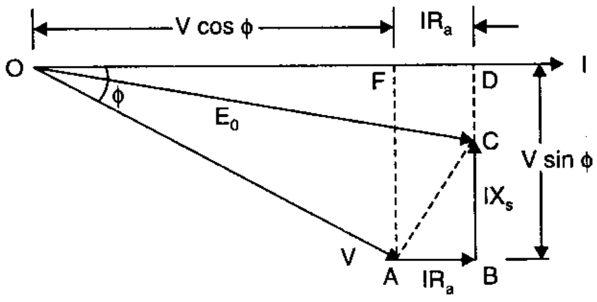
$$E_0^2 = (V \cos \phi + IR_a)^2 + (V \sin \phi - IX_s)^2$$

$$\therefore \quad E_0 = \sqrt{(V \cos \phi + IR_a)^2 + (V \sin \phi - IX_s)^2} \qquad \text{...(12.7)}$$



(a) Unity power factor

(b) Lagging power factor



(c) Leading power factor

Fig. 12.49. Regulation : (*a*) Unity p.f., (*b*) Lagging p.f., (*c*) Leading p.f.

The procedure is similar to that adopted in the case of transformers. The approximate method of calculating the total drop as was used for transformers *must not* be used for alternators where the *magnitudes involved are much greater in percentages.*

The results obtained by this method are *too high*, owing to the fact that the synchronous impedance determined at short-circuit condition is too *large due to a very low degree of saturation.* Hence this method is called the '*pessimistic*' method.

Assumptions Inherent in the Synchronous Impedance Method. The assumptions are as follows :

(*i*) *The effect of the armature-reaction flux can be replaced by a voltage drop proportional to the armature current.* The substitution of voltage for flux is the reason that the synchronous-impedance method is also called *e.m.f. method.*

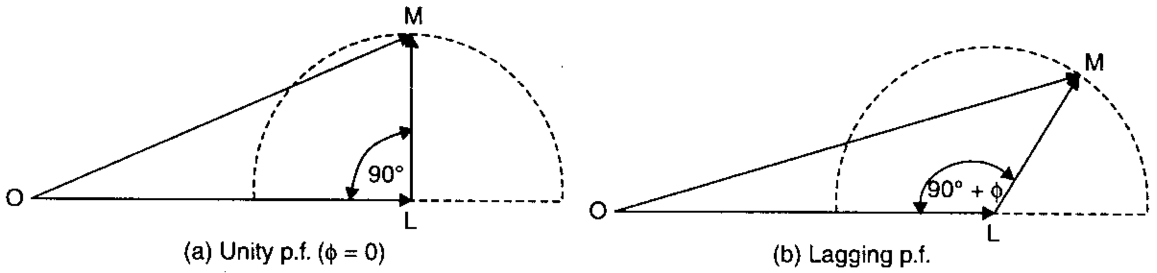
(*ii*) *Since the voltage caused by the main-field flux is added vectorially to that caused by the armature flux, it is also assumed that both fluxes have sinusoidal distribution.* Little error is introduced because of this with non-salient-pole machines, but the error is much greater in the case of the salient-pole ones which have concentrated field windings.

(*iii*) *The magnetic reluctance to the armature flux is constant regardless of the power factor.* This is substantially true for a non-salient, or round-rotor machine, whose air gap is almost constant but introduces considerable error with salient poles, since the position of the armature flux relative to the field poles is determined by the power factor.

(*iv*) There is no saturation effect.

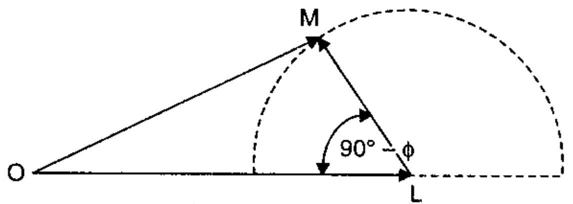
(*v*) The flux under test conditions is the same as that under load conditions.

The Ampere Turn or M.M.F. Method. The graphs of open and short circuit tests are made use of in this method. The method is converse of the 'e.m.f. method' in the sense that *armature leakage reactance is treated as an additional armature reaction.*



(a) Unity p.f. (φ = 0)

(b) Lagging p.f.



(c) Leading p.f.

Fig. 12.50

— From O.C. test field current I_f' is determined to give rated voltage V on no-load, neglecting armature resistance drop, and I_f'' is determined to cause-short-circuit current, equal to full-load current, on short-circuit.

- The field excitation I_f'', on short-circuit, *balances the impedance drop in addition to armature reaction on full-load.* But since R_a is usually very small and X_L is also small for low voltage on short circuit, so impedance drop can be neglected. Hence *power factor on short-circuit is almost zero lagging and field ampers turns are used entirely to overcome the armature reaction. Therefore, I_f'' gives demagnetising ampere-turns on full-load.*
- Now let us consider a general case when the alternator supplies full-load current at a power factor of cos ϕ.

(*i*) Draw *OL* repressing I_f' to give full-load rated voltage, *V* (or more exactly $V + IR_a \cos \phi$).

(*ii*) Draw *LM* at an angle (90° ± ϕ) representing I_f'' to give full-load current on short circuit (+ ve sign for lagging p.f. and – ve sign for leading p.f.).

(*iii*) Find field current I_f, measuring *OM*, which will give open circuit e.m.f. E_0 which can be determined from open circuit characteristic (O.C.C.).

The percentage regulation then, can be obtained from the following relation :

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

- *Regulation given by this method is much lower than that given by the synchronous impedance method, but it is nearer the correct value. This method is called the 'Optimistic' method.*

Zero Power Factor or Potier Method. This method *gives more accurate results* since it is based on the *separation of armature-leakage reactance drop and the armature reaction effects.* The following experimental data is required in this method :

(*i*) No-load or open circuit curve.

(*ii*) Full-load zero power factor curve (not S.C.C.).

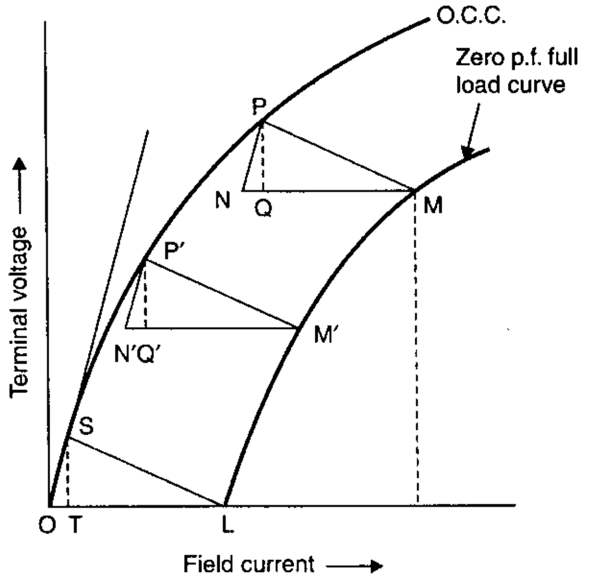


Fig. 12.51

From (*ii*) the reduction in voltage due to armature reaction is found out and voltage drop due to armature leakage reactance (also called Potier reactance) X_L is found from both (*i*) and (*ii*) both. By combining the two, E_0 can be calculated.

The above two curves are similar and displaced horizontally by the m.m.f. due to armature reaction in terms of the field current.

— Zero power factor, full-load voltage excitation characteristic can be drawn by knowing two points *L* and *M*. Point *L* is obtained from a short circuit test with full-load armature current. Hence *OL* represents field current (excitation) required to *overcome demagnetising effect of armature reaction and to balance leakage reactance drop at full-load*. Point *M* is obtained when full-load current flows through the armature and wattmeter reading is zero. *Zero power factor curve* may be drawn as follows :

(*i*) From *M* draw line *MN* equal and parallel to *OL*.

(*ii*) Through point *N* draw a line parallel to initial straight part of O.C.C. (parallel to *OS*), cutting the O.C.C. at *P*.

(*iii*) Join *PN* and drop a perpendicular *PQ* on *MN*.

(*iv*) Impose the triangle *MPQ* at various-points of O.C.C. to obtain corresponding points on the zero power factor curve.

In triangle *MPQ* :

Length *PQ* represents *leakage reactance drop* (*IX_L*).

Length *MQ* represents *armature reaction excitation*.

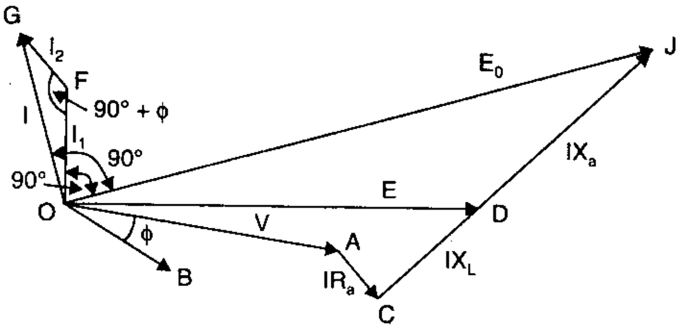


Fig. 12.52

Potier Regulation Diagram. Following is the procedure to draw Potier regulation diagram :

(*i*) Draw *OA* horizontally to represent terminal voltage *V* on full load and *OB* to represent load current (*I*) at a given power factor.

(*ii*) Draw $AC(= IR_a)$, voltage drop due to resistance R_a (if resistance is given) parallel to *OB*.

(*iii*) Draw *CD* perpendicular to *AC* and equal to reactance drop IX_L.

Now *OD* represents generated e.m.f. *E*.

(*iv*) From O.C.C., find the field current I_1 corresponding to this generated e.m.f. *E* and draw *OF* (equal to I_1) perpendicular to *OD*. Draw *FG* parallel to load current *OB* (*i.e.*, *I*) to represent excitation (field current) *equivalent to full load armature reaction*.

OG gives *total field current* required.

(*v*) If the load is thrown off, then terminal voltage will be equal to generated e.m.f. corresponding to field excitation *OG*. Hence e.m.f. E_0 may be obtained from O.C.C. corresponding to field excitation *OG*. Vector *OJ* will lag behind vector *OG* by 90°. *DJ* represents *voltage drop due to armature reaction.*

Now regulation may be obtained from the following relation :

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

12.2.3.7. Losses and efficiency

Losses. The following losses occur in an alternator :

1. **Copper losses.** These losses occur in the armature winding and in the field coils.

2. **Core loss.** The core loss consists of eddy-current and hysteresis loss in the pole faces, teeth, and stator core due to the flux resulting from the combined rotor and armature fields.

3. **Friction and windage loss.** This loss is due to the bearing and brush friction and to the power required to circulate the cooling air.

4. **Load loss.** This is due to the *armature leakage flux* which causes eddy-currents and hysteresis in the iron surrounding the armature conductors. If, however, effective resistance is used to calculate the armature copper loss, then these load losses are also included in the calculation.

Efficiency. The efficiency of an alternator is calculated as follows :

$$\text{Alternator efficiency} = \frac{\text{Output}}{\text{Output + losses}} = \frac{\text{kVA(p.f.)}}{\text{kVA(p.f.) + losses}}.$$

Maximum efficiency occurs at that load point where the constant losses (friction, windage, core loss and field copper loss) *are equal to variable losses* (armature copper and load loss). The maximum efficiency usually occurs at about 80% of full load.

Determination of losses. Losses may be determined by the following methods :

Measurement of losses method. As in most electric machines, efficiency measurement of an alternator by direct loading is rather impractical. It may also be a physical impossibility to obtain the required load, and even if it could be obtained the cost may be prohibitive. Also, the measurement of the mechanical power input is somewhat difficult, and any inaccuracy with measurement is *reflected directly in the final efficiency calculation*. Efficiency is therefore calculated by '*measurement of losses*' method which entails the following advantages :

(*i*) At any one time, only part of the losses need be provided. Therefore the source of power required for testing has a capacity of less than 5% of the rating of the alternator.

(*ii*) There is no need to put an electric load on the alternator.

(*iii*) Greater accuracy can be obtained since electrical instruments can be used for all measurements.

(*iv*) An inaccuracy that occurs in the test *is not directly reflected in the final efficiency calculation*, since the error occurs on only a small portion of the name plate rating.

Use of a calibrated d.c. motor to drive the alternator. A *quite accurate and simple method* of determining the losses is to use a calibrated D.C. motor to drive the alternator. The motor is calibrated in the sense that all its losses have been determined for varying conditions of operation, so that its output is then readily obtained.

This method involves the following procedural steps :

Step 1. Drive the alternator at synchronous speed, but *without field excitation*. The D.C. motor output is the alternator input, and hence its *friction and windage loss*.

Step 2. Repeat step 1, but this time *with field excitation*. The excitation should be that at which the alternator normally operates. If this is unknown, then the open-circuit voltage is adjusted to be equal to the rated voltage plus the internal voltage drops as determined by one of the methods used to calculate voltage regulation.

The difference between the motor output of step 2 and that of step 1 is the *core loss*.

Step 3. Short-circuit the armature and adjust the field current to obtain rated line current. The difference between this motor output and that of step 1 is the *armature copper loss plus load loss*. It is assumed that the flux density under short-circuit conditions is so low as to make the core loss negligible.

Step 4. The *field copper loss* is measured by simple D.C. measurement.

12.2.3.8. Parallel operation of alternators

Necessity. Alternators may be put in parallel because of the following reasons :

1. Local or regional power use may *exceed* the power of a *single* available generator.

2. Parallel alternators allow one or more units to be *shut down* for scheduled or emergency *maintenance* while the load is being supplied with power.

3. Generators are *inefficient at part load*, so shutting down one or more generators allows the remaining load to be carried with less machines that are efficiently loaded.

4. Load growth can be handled by *added* machines without disturbing the original installation.

5. Available machine prime movers and generators can be *matched* for economic first cost and flexible use.

Requirements for paralleling. The *requirements* for paralleling include the requirements for D.C. machines plus a few others.

1. The *voltages* must be the *same* at the *paralleling point* or junction even though not the same at the alternators.

2. The *phase sequence* for three phase (or any multiple phase) must be the *same* at the paralleling point.

3. The incoming machine must be *in phase* at the moment of paralleling. It will stay in phase under normal conditions after paralleling. It is important to recognize that *phase sequence* and *in phase* are *not the same thing*.

4. The line frequencies must be *identical* at the paralleling point. In the vast majority of cases, this means the same frequency at the generator because frequency changing is not economic. Mixed frequencies must be paralleled through some frequency conversion means for compatibility at the point of interconnection.

5. The primemovers must have relatively similar and *drooping speed-load characteristics*. This is to prevent a machine with a rising speed load characteristic from taking more and more of the load until if fails from overload.

Violation of these requirements for paralleling would result in circulating currents between the machines varying from uneconomic, to serious, to disastrous.

12.2.3.9. Alternator synchronising procedure

It may logically be assumed that one alternator is placed in parallel with one or more other alternators only when additional load requires it. Those alternators already carrying load are known as the *running machines*, while that which is to be placed in the system is known as the *incoming machine*. At the time of synchronizing, the following *conditions* must be met.

1. The effective voltage of the incoming alternator must be exactly equal to that of the others, or of the bus-bars connecting them.

2. The phase rotation, or sequence of the running and incoming alternators must be the same.

3. The individual phase voltages which are to be connected to each other must be in exact phase opposition. This is the same as saying that D.C. generators must be connected + to + and – to –.

4. The frequencies should be the same, although it is more desirable that the frequencies at the *instant* of paralleling be almost, but not quite, identical.

Synchronizing lamps :

- To satisfy the first condition of paralleling (*i.e.*, effective voltages be the same) a voltmeter can be used as shown in Fig 12.53).

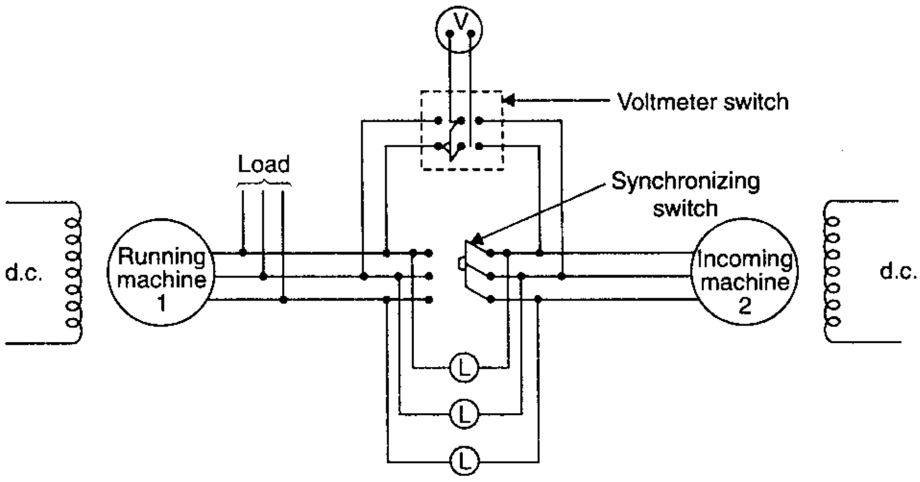


Fig. 12.53. Parallel operation of alternators : Synchronizing lamps and voltmeter.

— Satisfaction of the other conditions of *phase sequence, voltage opposition*, and *frequency* may be *determined by the use of the incandescent lamps connected between the two machines* (Fig. 12.53). The auxiliary equipment is omitted to simplify the sketch.

At any instant it is seen that the voltage across the lamp is the sum of the individual phase voltages.

The procedural steps for putting incoming alternator in parallel with the running machine are as follows :

Step 1. The primemover of the incoming machine is started, and the alternator is brought up to near its rated speed.

Step 2. By adjusting the field current, the terminal voltage of incoming machine is made the same as that running alternator.

The lamp in the circuit will now flicker at a rate equal to the difference in frequency of the two alternators. *If the phases are properly connected, all lamps will be bright and dark at the same time.* If this is not the case, then it means that the phase sequences are not correct, and it is merely necessary to interchange two of the line leads of the incoming machine.

Step 3. Further adjustment of the incoming primemover is now necessary, until the lamps flicker at a very low rate, *usually less than one dark period per second.*

Step 4. Final adjustment of the incoming voltage again made and the synchronizing switch is thrown in the middle of a dark period. The voltage across the lamps varies from zero to twice the phase voltage, and therefore, the lamps must be rated for this higher voltage. It is not convenient, however, to stock special lamps for this purpose, and two lamps of standard voltage ratings may be connected in series in each line.

The *lamp method* has the following *advantages* and *disadvantages.*

Advantages :

(*i*) Equipment is inexpensive.

(*ii*) Proper phase sequence is readily obtained.

Disadvantages :

(*i*) Lamps go dark at somewhat less than half their rated voltage, and so the synchronizing switch might be closed when there is a considerable phase difference between the machines, with a high circulating current resulting in possible damage to the machines. An experienced operator, however, can minimize this danger, since he can quickly learn to estimate the middle of the dark period.

(*ii*) The lamp filament can burn out.

(*iii*) The flicker of the lamps does not indicate which machine has the higher frequency.

There are two other lamp methods which are given below :

— If the lamps are connected across the phases, that is, P to Q', Q to R', R to P', they will again flicker in unison. This time, however, the proper synchronizing moment occurs when all three are in the middle of a bright period. This has the *advantage of avoiding synchronizing when the lamps may have burned out, but it is more difficult to estimate the middle of a bright period than the middle of a dark one.*

— In the third lamp method, known as the '*two-bright one-dark* method,' only two of the lamps are cross-connected. Thus the connections are phase P to P', Q to R' and R to Q'. This method supposedly *avoids the disadvantages of both previous lamps methods, but actually may be more confusing to the eye.*

In case of high-voltage alternators, the lamps are connected through transformers to obtain the nominal voltages for which lamps are rated.

Synchronoscope synchronization. In large central station installations, an additional device called a synchronoscope (Fig. 12.54) is used. A synchronoscope has a rotating hand and a dial labelled with slow and fast direction arrows to show the incoming machine speed relation. In addition, an index point shows the actual in-phase position. During synchronization, as the incoming machine rotational speed approaches near synchronism, the speed of the synchronoscope hand drops enough to become visible. The *hand speed is proportional to the difference in speed.* The slow indication is accompanied with an arrow showing that *counter-clockwise* hand rotation means *below* synchronous speed. Similarly *clockwise* rotation means above speed. When the speeds are matched as that the hand speed is very slow, the hand is matched until it points to the index mark, where upon the paralleling switch may be closed.

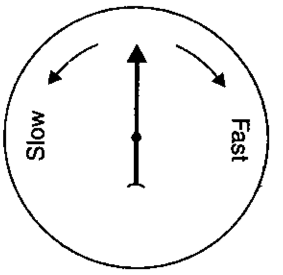


Fig. 12.54. Synchronoscope.

There are following three principal types of synchronoscopes :

(*i*) Polarized vane. (*ii*) Moving iron. (*iii*) Crossed coil.

All are used similarly. However, *none* of the types will detect an *out-of-phase sequence condition.* They are used as a convenient and accurate means of routinely achieving synchronous speed and in phase indications. The phase sequence problem is really an original test problem since, once sorted out, the phase sequence will remain correct until repair or other circuit changes are needed.

12.2.3.10. Cooling of alternators

Necessity of cooling. Due to the various losses occurring in the alternator, there is a temperature rise in various parts of the alternator and winding insulation. To prevent the temperature rise exceeding the maximum permissible value, every alternator requires continuous cooling during its operation.

Cooling methods :

1. **Open system using air.** In this system the cold air is taken in from the atmosphere with the help of the fan and passed through the machine. The outcoming hot air is either discharged to atmosphere or into the machine hall for station warming. Due to the difficulty of removal of all dust particles from the air entering the machine they are rarely used and that too on alternators having capacity upto 3 MW.

2. **Closed system using air.** In this system a given volume of air is circulated continuously through the alternator. The discharged hot air is cooled to about 40°C through heat exchangers before it is recirculated through the alternator. This system is universally used for *large machines.*

Advantages and disadvantages of closed system over open system :

Advantages :

1. Quieter operation of the station.
2. No filter is required.
3. Less possibility of dust and impurities deposition in the machine passages.
4. It is easier to combat a fire in an alternator since supply of fresh air is absent.
5. Appearance is quite good.

Disadvantages :

The only disadvantage is that this system is *costly*.

Hydrogen cooling

The gaseous hydrogen is better cooling medium than air (air-cooling is successfully used upto 100 MW generating units) and now-a-days it is universally used in almost all thermal power plants upto 200 MW capacity alternators.

The use of hydrogen gas as the cooling medium in closed circuit cooling offers the following

Advantages :

1. The thermal conductivity of hydrogen is almost seven times that of air. Its specific heat is 14.5 times that of air. The overall heat transfer with forced cooling may be as 2 to 3 times that of air.

2. *Less windage losses* since the density of hydrogen is $\frac{1}{14}$ th that of air.

3. Due to lower windage losses and better heat transfer in the cooler, *less cooling water is required.*

4. *Less space* is occupied by the hydrogen cooled machines.

5. The noise is considerably reduced due to lighter cooling medium and lower friction.

6. The fire risk is reduced in the event of electrical breakdown as oxygen is not present to maintain combustion of the insulation material.

7. The cooling surface required for H_2 cooling is considerable smaller than that needed for air coolers due to high heat transfer rates.

8. The reliability of the insulation increases and its life span is prolonged.

9. The 'corona' effects on the conductors in windings are less deleterious in hydrogen atmosphere than in air. This also increases the life of winding.

Disadvantages :

1. High cooling cost.

2. Overall capital and maintenance cost is high.

3. Gas may leak through the casing. For this reason the casing is made explosion proof against any pressure which can be developed by explosive mixture of hydrogen and air.

4. The major problem is to effectively seal the shaft glands at the alternator hourings.

5. A high degree of hydrogen purity is required to ensure high efficiency and avoid explosions, and this necessitates hydrogen purity, pressure and temperature recorders.

12.3. TRANSFORMERS

12.3.1. General Aspects

Although the transformer is not classified as an electric machine, the principles of its operation are fundamental for the induction motor and synchronous machines. Since A.C. electric machines are normally built for low frequencies only the low frequency power transformer will be considered in this text.

When energy is transformed into a higher voltage the transformer is called a *step-up transformer* but when the case is otherwise it is called a *step-down transformer*. Most power transformers operate at constant voltage, *i.e.,* if the power varies the current varies while the voltage remains fairly constant.

Applications. A transformer performs many important functions in prominent areas of electrical engineering.

- In *electrical power engineering* the transformer makes it possible to convert electric power from a generated voltage of about 11 kV (as determined by generator design limitations) to higher values of 132 kV, 220 kV, 400 kV, 500 kV and 765 kV thus permitting transmission of huge amounts of power along long distances to appropriate disribution points at tremendous savings in the cost of transmission lines as well as in power losses.
- At *distribution points* transformers are used to reduce these high voltages to a safe level of 400/230 volts for use in homes, offices etc.
- In *electric communication circuits* transformers are used for a variety of purposes *e.g.,* as an impedance transformation device to allow maximum transfer of power from the input circuit to the output device.
- In *radio and television circuits* input transformers, interstage transformers and output transformers are widely used.
- Transformers are also used in *telephone circuits, instrumentation circuits* and *control circuits.*

12.3.2. Basic Definitions

- A *transformer* is a *static electromagnetic device designed for the transformation of the (primary) alternating current system into another (secondary) one of the same frequency with other characteristics, in particulars, other voltage and current.*
- As a rule a transformer consists of a core assembled of sheet transformer steel and two or several windings coupled *electromagnetically*, and in the case of *autotransformer, also electrically.*
- A transformer with two windings is called *double-wound transformer* ; a transformer with three or more windings is termed a *triple wound* or *multi-winding* one.
- According to the kind of current, transformers are distinguished as single-phase, three-phase and poly-phase ones. A *poly-phase transformer winding is a group of all phase windings of the same voltage*, connected to each other in a definite way.
- **Primary and secondary windings.** The transformer winding to which the energy of the alternating current is delivered is called the *primary winding* ; the other winding from which energy is received is called the *secondary winding.*
- In accordance with the names of the windings, all quantities pertaining to the primary winding as for example, power, current, resistance etc., are also primary, and those pertaining to the secondary winding secondary.
- *h.v. and l.v. windings.* The winding connected to the circuit with the higher voltage is called the *high-voltage winding* (h.v.), the winding connected to the circuit with the lower

voltage is called the *low-voltage winding* (l.v.). If the secondary voltage is *less* than the primary one, the transformer is called a *step-down transformer* and if *more-a step-up transformer.*

- A *tapped transformer* is one whose windings are fitted with special taps for changing its voltage or current ratio.
- **Oil and dry transformers.** To avoid the detrimental effect of the air on the winding insulation and improve the cooling conditions of the transformer its core together with the windings assembled on it is immersed in a tank filled with transformer oil. Such transformers are called *oil transformers.* Transformers not immersed in oil are called *dry transformers.*

12.3.3. Working Principle of a Transformer

A transformer operates on the principle of *mutual inductance,* between two (and sometimes more) inductively coupled coils. It consists of two windings in close proximity as shown in Fig. 12.55. *The two windings are coupled by magnetic induction.* (There is no conductive connection between the windings). One of the windings called *primary* is energised by a sinusoidal voltage. The second winding, called *secondary* feeds the load. The alternating current in the primary winding set up an alternating flux (ϕ) in the core. The secondary winding is linked by most of this flux and e.m.fs. are induced in the two windings. The e.m.f. induced in the secondary winding drives a current through the load connected to the winding. Energy is transferred from the primary circuit to the secondary circuit through the medium of the magnetic field.

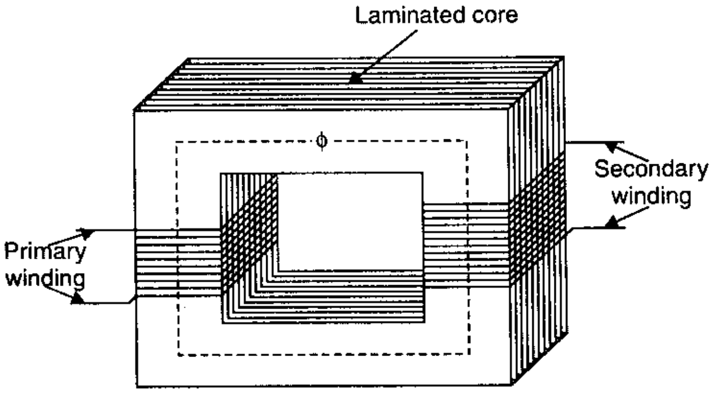


Fig. 12.55. Two winding transformer.

In brief, a transformer is a device that :

(*i*) transfers electric power from one circuit to another ;

(*ii*) it does so without change of frequency ; and

(*iii*) it accomplishes this by electromagnetic induction (or mutual inductance).

12.3.4. Transformer Ratings

The rated quantities of a transformer, its power, voltage, frequency, etc. are given in Manufacturer's name plate, which should always be arranged so as to be accessible. But the term 'rated' can also be applied to quantities not indicated on the name plate, but relating to the rated duty, as for example, the rated efficiency, rated temperature conditions of the cooling medium, etc. :

- *The rated duty* of a transformer is determined by the quantities given in the name plate.
- The *rated power* of the transformer is the power at the secondary terminals, indicated in the name plate and expressed in kVA.

- *The rated primary voltage* is the voltage indicated in the transformer name plate ; if the primary is provided with taps, the rated tapped voltage is specially noted.
- *The rated secondary voltage* is the voltage across the transformer *secondary terminals at no-load* and with the rated voltage across the primary terminals ; if the secondary winding has taps, then their rated voltage is specially indicated.
- *The rated currents of the transformer*, primary and secondary, are the currents indicated in the name plate of the transformer and calculated by using the corresponding rated values of power and voltage.

12.3.5. Kinds of Transformers

The following kinds of transformers are the most important ones :

1. **Power transformers.** For the transmission and distribution of electric power.

2. **Auto-transformers.** For converting voltages within relatively small limits to connect power systems of different voltages, to start A.C. motors etc.

3. **Transformer for feed installations with static convertors.** (Mercury are rectifiers, ignitions, semi-conductor valves, etc.). When converting A.C. into D.C. (rectifying) and converting D.C. into A.C. (inverting).

4. **Testing transformers.** For conducting tests at high and ultra-high voltages.

5. **Power transformers for special applications.** Furnace, welding etc.

6. **Radio-transformers.** It is used in radio engineering etc.

Note. *Distribution transformers* should be designed to have maximum efficiency at a load much *lower than full-load (about 50 per cent).*

Power transformers should be designed to have maximum efficiency *at or near full-load.*

12.3.6. Transformer Construction

All transformers have the following essential elements :

1. Two or more *electrical windings* insulated from each other and from the core (except in auto-transformers).

2. A *core*, which in case of a single-phase distribution transformers usually comprises *cold-rolled silicon-steel strip* instead of an assembly of punched silicon-steel laminations such as are used in the larger power-transformer cores. The *flux path in the assembled core is parallel to the directions of steel's grain or 'orientations'*. This results in a *reduction in core losses* for a given flux density and frequency, or *it permits the use of higher core densities* and *reduced size of transformers for given core losses*.

Other necessary parts are :

- A *suitable container* for the assembled core and windings.
- A *suitable medium* for insulating the core and its windings from each other and from the container.
- Suitable *bushings* for insulating and bringing the terminals of the windings out of the case.

The two basic types of transformer construction are :

1. The core type.
2. The shell type.

The above two types differ in their relative arrangements of copper conductors and the iron cores. In the *'core type'*, the *copper virtually surrounds the iron core*, while *in the 'shell type', the iron surrounds the copper winding.*

12.3.6.1. Core type transformer

The completed magnetic circuit of the core-type transformer is in the shape of a hollow rectangle, exactly as shown in Fig. 12.56 in which I_0 is the no-load current and ϕ is the flux produced by it. N_1 and N_2 are the number of turns on the primary and secondary side respectively.

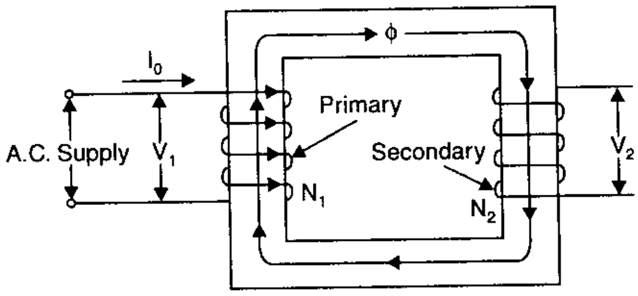


Fig. 12.56. Magnetic circuit of core-type transformer.

The core is made up of *silicon-steel laminations* which are, either rectangular or L-shaped. With the coils wound on two legs the appearance is that of Fig. 12.57. If the two coils shown were the respective high- and low-side coils as in Fig. 12.57, the leakage reactance would be much too great. In order to provide maximum *linkage* between windings, the group on each leg is made up of both high-tension and low-tension coils. This may be seen in Fig. 12.58, where a cross-sectional cut is taken across the legs of the core. By placing the high-voltage winding around the low-voltage winding, only one layer of high-voltage insulation is required, that between the two coils. If the high-voltage coils were adjacent to the core, an additional high-voltage insulation layer would be necessary between the coils and the iron core.

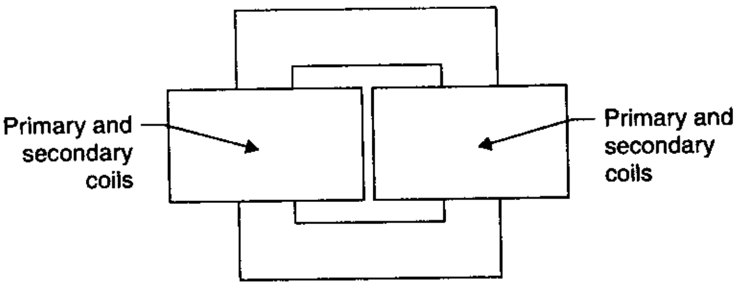


Fig. 12.57. Core-type transformer.

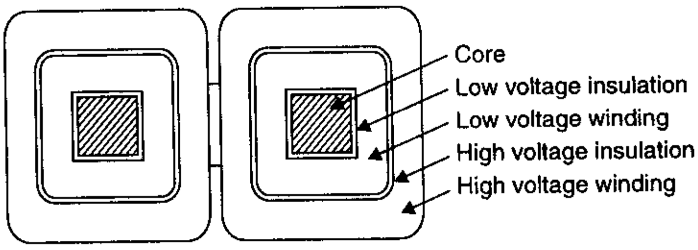


Fig. 12.58. Cross-section of core-type transformer.

Fig. 12.59 shows the coils and laminations of a core-type transformer with a cruciform core and circular coils.

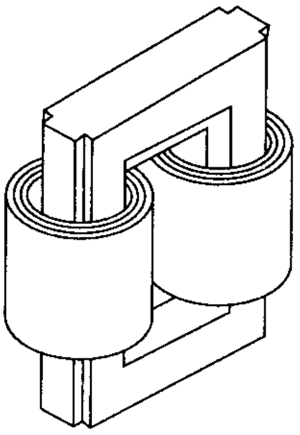


Fig. 12.59. Coils and laminations of a core-type transformer.

— Fig. 12.60 shows the different types of cores used in core transformers.

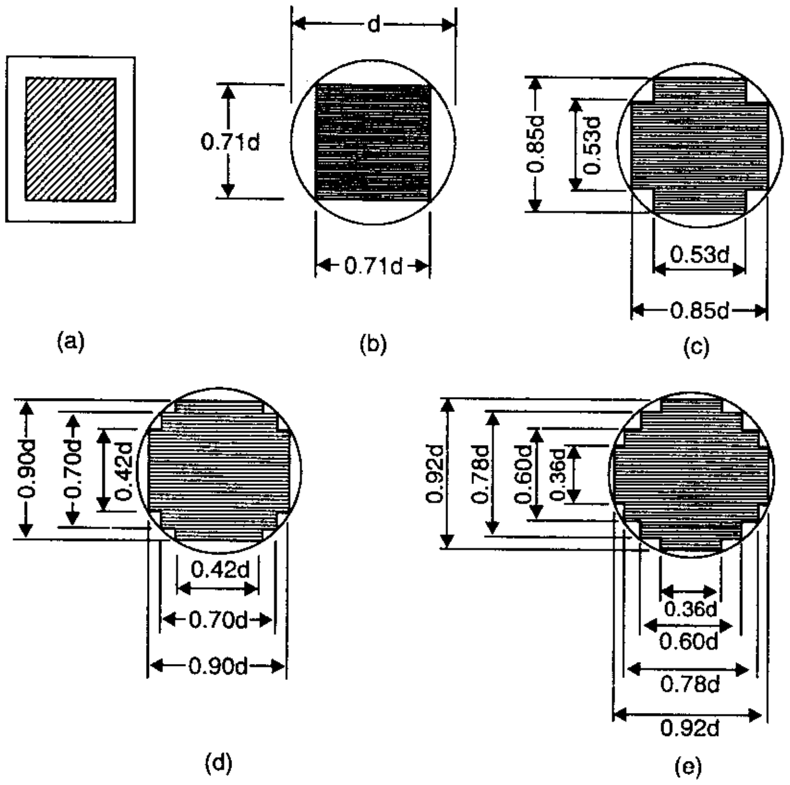


Fig. 12.60. Various types of cores.

Rectangular cores [Fig. 12.60 (*a*)] with rectangular cylindrical coils can be used for small size core-type transformers. For large size transformers it becomes wasteful to use rectangular cylindrical coils and so circular cylindrical coils are preferred. For such purpose, '*square cores*' may be used as shown in Fig. 12.60 (*b*) where circles represent the tubular former carrying the coils. Evidently, a considerable amount of useful space is still wasted. A common improvement on the square core is to employ a '*cruciform core*' [Fig. 12.60 (c)] which demands, atleast, two sizes of core strips. For *very large transformers*, further core stepping is done as in Fig. 12.60 (*d*) where atleast three sizes of core plates are necessary. *Core stepping not only gives high space factor but also results in reduced length of the mean turn and the consequent I^2R loss. Three stepped core is the most commonly* used although more steps may be used for very large transformers as shown in Fig. 12.60 (*e*).

12.3.6.2. Shell type transformer

In the shell-type construction the iron almost entirely surrounds the copper (Fig. 12.61). The core is made up of E-shaped or F-shaped laminations which are stacked to give a rectangular figure eight. All the windings are placed on the centre leg, and in order to reduce leakage, each high-side coil is adjacent to a low-side coil. The coils actually occupy the entire space of both windows, are flat or pencake in shape, and are usually constructed of strip copper. Again, to reduce the amount of high-voltage insulation required, the low-voltage coils are placed adjacent to the iron core.

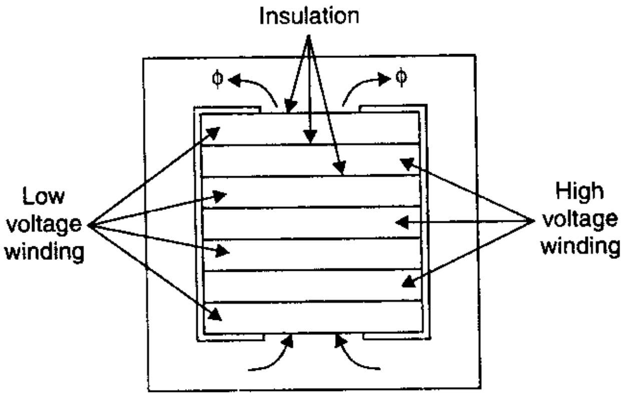


Fig. 12.61. Shell-type transformer.

Fig. 12.62 shows the coils and laminations of a typical shell-type transformer.

Choice of core or shell type construction. In general, the core-type has a longer mean length of core and a shorter mean length of coil turn. The core type also has a smaller cross-section of iron and so will need a greater number of turns of wire, since, in general, not as high a flux may be reached in the core. However, *core type is better adopted for some high-voltage service since there is more room for insulation*. The *shell type has better provision for mechanically supporting and bracing the coils*. This allows better resistance to the very high mechanical forces that develop during a high-current short circuit.

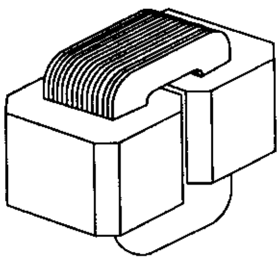


Fig. 12.62. Coils and laminations of a shell-type transformer.

The choice of core or shell type construction is usually one of *cost*, for similar characteristics can be obtained with both types.

Both core and shell forms are used, and selection is based upon many factors such as voltage rating, kVA rating, weight, insulation stress, mechanical stress, and heat distribution.

12.3.6.3. Spiral core transformer

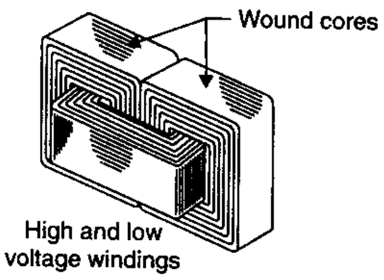


Fig. 12.63. Spiral-core transformer.

The typical spiral core is shown in Fig. 12.63. The core is assembled either of a *continuous* strip of transformer steel wound in the form of a circular or elliptical cylinder or of a group of short strips assembled to produce the same elliptical-shaped core. By using this construction the core flux always follows along the grain of the iron. Cold-rolled steel of high silicon content enables the designer to use higher operating flux densities with lower loss per kg. *The higher flux density reduces the weight per kVA.*

12.3.7. Transformer Windings, Terminals, Tappings and Bushings

12.3.7.1. Transformer windings

The most important requirements of transformer windings are :

1. The winding should be economical both as regards initial cost, with a view to the market availability of copper, and the efficiency of the transformer in service.

2. The heating conditions of the windings should meet standard requirements, since departure from these requirements towards allowing higher temperature will drastically shorten the service life of the transformer.

3. The winding should be mechanically stable in respect to the forces appearing when sudden short circuit of the transformer occurs.

4. The winding should have the necessary electrical strength in respect to over voltages.

The different types of winding are classified and briefly discussed below :

1. **Concentric Windings :**

(*i*) Cross-over (*ii*) Helical (*iii*) Disc.

2. **Sandwich Windings :**

Concentric windings. Refer Fig. 12.64. These windings are used for core type transformers. Each limb is wound with a group of coils consisting of both primary and secondary turns which may be concentric cylinders. The l.v. winding is placed next to the core and h.v. winding on the outside. But the two windings can be subdivided and interlaced with high tension and low tension section alternately to reduce leakage reactance. These windings can be further divided as follows :

(*i*) **Cross-over windings.** Cross-over windings are used for currents up to 20 A and so they are suitable for h.v. winding of small transformers. The conductors are either cotton covered round

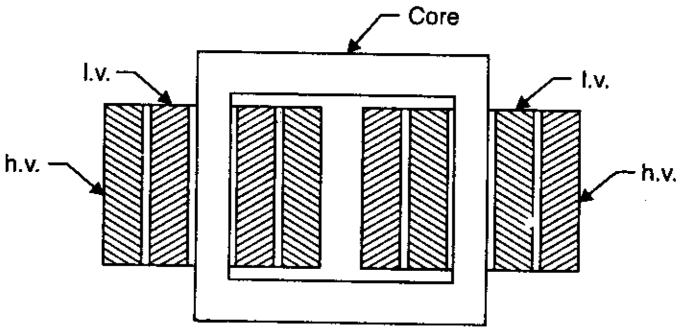


Fig. 12.64. Concentric coils.

wires or strips insulated with paper. Cross-over coils are wound over formers and each coil consists of a number of layers with a number of turns per layer. The complete winding consists of a number of coils connected in series. Two ends of each coil are brought out, one from inside and one from outside. This inside end of a coil is connected to the outside end of the adjacent coil.

(*ii*) **Helical winding.** A helical winding consists of rectangular strips wound in the form of a helix. The strips are wound in parallel radially and each turn occupies the total radial depth of winding.

Helical coils are well suited for *l.v. windings of large transformers*. They can also be used for h.v. windings by putting extra insulation between layers in addition to insulation of conductors.

(*iii*) **Continuous disc winding.** This type of winding consists of a number of flat strips wound spirally from inside (radially) outwards. The conductor is used in such lengths as are sufficient for complete winding or section of winding between tappings. The conductor can either be a single strip or a number of strips in parallel, wound on the flat. This gives a robust construction for each disc. The discs are wound on insulating cylinders spaced from it by strips along the length of cylinder. The discs are separated from each other with press board sectors attached to the vertical strips. The vertical and horizontal spacers provide ducts for free circulation of oil which is in contact with every turn.

Sandwich coils. Sandwich coils (Fig. 12.65) are employed in transformers of shell type. Both high and low voltage windings are split into a number of sections. Each high voltage section lies between the low voltage sections.

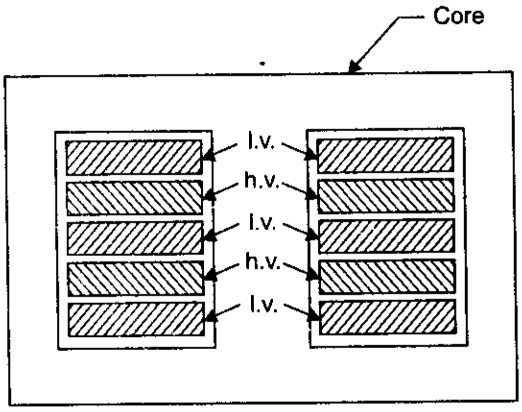


Fig. 12.65. Sandwich coils.

The *advantage of sandwich coils is that their leakage can be easily controlled and so any desired value of leakage reactance can be had by the division of windings.*

12.3.7.2. Terminals and leads

The connection to the windings are of insulated copper rods or bars. The shape and size of leads is important in high voltage transformers owing to dielectric stress and corona which are caused at bends and corners. Connections from windings are directly taken to the busbars in the case of air-cooled transformers while they are taken to insulated bushings in the case of coiled-cooled transformers.

12.3.7.3. Tappings

In a supply network the voltage can be controlled by changing the transformation ratio. This can be done by tapping the winding in order to alter the number of turns. The change in number of turns may be effected when the transformer is out of circuit (known as off load tap changing) or when on load (known as on load lap changing). The tappings are provided on the high voltage winding because a fine voltage variation is obtained owing to large number of turns. It is difficult to obtain voltage variation within close percentage limits in low voltage winding as there are few turns and voltage per turn is a large percentage of the total voltage.

In transformers, the tappings can be provided at :

(*i*) phase ends ; and

(*ii*) neutral point or in the middle of the windings.

— The advantage of providing tappings at *phase ends* is that the number of bushing insulators is reduced, this is important where the cover space is limited. Some transformers have reinforced insulation at the phase ends. It is essential that in such cases either the tapping should not be provided at end turns or the reinforcement should be carried beyond the lower tap.

— When the tappings are made at the *neutral point* the insulation between various parts is small. *This arrangement is economical especially in the case of high voltage transformers.*

12.3.7.4. Bushings

The bushings are *employed for insulating and bringing out terminals of the winding from the container to the external circuit.* For low-voltage transformers this is accomplished by employing *bushings of porcelain around the conductor at the point of entry.* For high voltages it is necessary to employ bushings of larger sizes. In modern transformers the problem is met by using *large porcelain* or *composition bushings for voltages as high as 33 kV, above that oil filled or condenser type bushings are used.*

12.3.8. Transformer Cooling

12.3.8.1. Cooling methods

The transformers get heated due to iron and copper losses occurring in them. It is necessary to dissipate this heat so that the temperature of the winding is kept below the value at which the insulation begins to deteriorate. The *cooling of transformers is more difficult than that of rotating machines because the rotating machines create a turbulent air flow which assists in removing the heat generated due to losses.* Luckily the losses in transformers are comparatively small. Nevertheless the elaborate cooling arrangements have been devised to deal with the whole range of sizes.

As far as cooling methods are concerned, the transformers are of following two types :

1. Dry type

2. Oil immersed type.

Dry Type Transformers. Small transformers upto 25 kVA size are of the dry type and have the following cooling arrangements :

(*i*) **Air natural.** In this method the natural circulation of surrounding air is utilized to carry away the heat generated by losses. A sheet metal enclosure protects the winding from mechanical injury.

(*ii*) **Air blast.** Here the transformer is cooled by a continuous blast of cool air forced through the core and windings (Fig. 12.66). The blast is produced by a fan. The air supply must be filtered to prevent accumulation of dust in ventilating ducts.

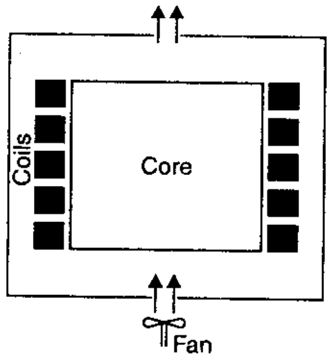


Fig. 12.66

Oil Immersed transformers. In general most transformers are of oil immersed types. The *oil provides better insulation than air and it is a better conductor of heat than air.* Mineral oil is used for this purpose.

Oil immersed transformers are classified as follows :

(*i*) **Oil immersed self-cooled transformers.** The transformer is immersed in oil and heat generated in cores and windings is passed to oil by conduction. Oil in contact with heated parts rises and its place is taken by cool oil from the bottom. The natural oil transfers its heat to the tank walls from where heat is taken away by the ambient air. The oil gets cooler and falls to the bottom from where it is dissipated into the surroundings. The tank surface is the best dissipator of heat but a plain tank will have to be excessively large, if used without any auxiliary means for high rating transformers. As both space and oil are costly, these auxiliary means should not increase the cubic capacity of the tank. The heat dissipating capacity can be increased by providing (*i*) corrugations, (*ii*) fins, (*iii*) tubes (Fig. 12.67) and (*iv*) radiator tanks.

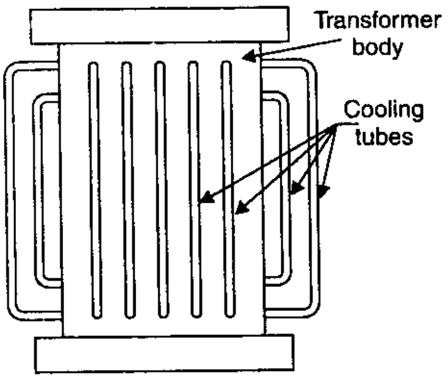


Fig. 12.67. Transformer with cooling tubes.

The *advantages of 'oil natural' cooling is that it does not clog the ducts and the windings are free from effects of moisture.*

(*ii*) **Oil immersed forced air-cooled transformers.** In this type of cooling, air is directed over the outer surfaces of the tank of the transformer immersed in oil.

(*iii*) **Oil immersed water-cooled transformers.** Heat is extracted from the oil by means of a stream of water pumped through a metallic coil immersed in the oil just below the top of the tank. The heated water is in turn cooled in a spray pond or a cooling tower.

(*iv*) **Oil immersed forced oil cooled transformers.** In such transformers heat is extracted from the oil by pumping the oil itself upward through the winding and then back by way of external radiators which may themselves be cooled by fans. The *extra cost of oil pumping equipment must of course be economically justified but it has incidentally the advantage of reducing the temperature difference between the top and bottom of enclosing tank.*

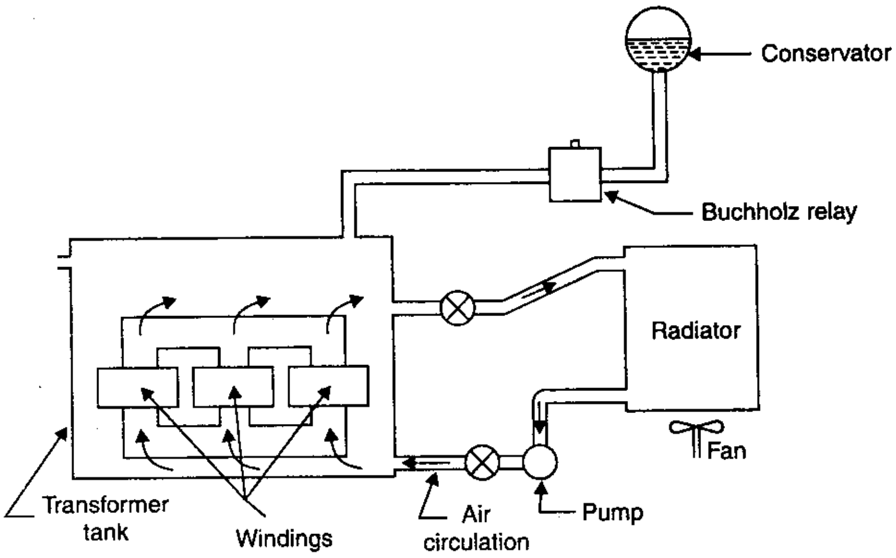


Fig. 12.68. Air blast cooling of radiator.

Fig. 12.68 shows the cooling of transformers having capacities from 10000 kVA and higher. In such cases air blast cooling of radiator is used.

12.3.8.2. Transformer oil

It is a mineral oil obtained by refining crude petroleum. It serves the following purposes :

(*i*) Provides additional insulation.

(*ii*) Carries away the heat generated in the core and coils.

(*iii*) Protects the paper from dirt and moisture.

The transformer oil should possess the following properties :

1. High dielectric strength.
2. Low viscosity to provide good heat transfer.
3. Good resistance to emulsion.
4. Free from inorganic acid, alkali and corrosive sulphur.
5. Free from sludging under normal operating conditions.
6. High flash/fire point.

12.3.8.3. Conservator and breather

Conservator. The oil should not be allowed to come in contact with atmospheric air as it may take up moisture which may spoil its insulating properties. Also air may cause acidity and sludging of oil. To prevent this, many transformers are provided with conservators. The *function of a conservator (Fig. 12.68) is to take up contraction and expansion of oil without allowing it to come in contact with outside air.* The conservator consists of an air tight metal-drum fixed above the level of the top of the tank and connected with it by a pipe. The main tank in completely filled with oil when cold. The *conservator is partially filled with oil.* So the oil surface in contact with air is greatly reduced. The sludge thus formed remains in the conservator itself and does not go to the main tank.

Breather. When the temperature changes, the oil expands or contracts and there is a displacement of air. When the transformer cools, the oil level goes down, and air is drawn in. This is known as *breathing*. The air, coming in, is passed through an apparatus called breather for the purpose of extracting moisture. The *breather consists of a small vessel which contains a drying agent like silica gel crystal impregnated with cobalt crystal.*

Note. *Sludging* means the slow formation of solid hydrocarbons due to heating and oxidation. The sludge deposit itself on the windings and cooling ducts producing overheating. This makes transformer still hotter producing more sludge. This process may continue till the transformer becomes unusable due to overheating. So the contact of oil with air should be avoided as the air contains oxygen.

12.3.9. Three Phase Transformer

12.3.9.1. Three-phase transformer connections

Virtually all power distribution is by poly-phase system of voltages. Three-phase transformations may be made with the use of properly connected single-phase transformers. These connections are in extensive commercial use. The most frequently used connections are the following :

(*i*) Primary Y—secondary Y.

(*ii*) Primary Δ—secondary Δ.

(*iii*) Primary Δ—secondary Y, or *vice versa*.

(*iv*) Primary and secondary open Δ.

(*v*) Primary T—secondary T (Scott connection)

Thus the most common connections are Y-Y, Δ-Δ, Y-Δ, Δ-Y, open delta or V-V and Scott connection or T-T connection.

The Y-Y connection. Fig. 12.69 shows a bank of three transformers connected in Y on both the primary and secondary sides. If the ratio of transformation of each transformer is K, the same ratio will exist between the *line* voltages on the primary and secondary sides. This *connection will give satisfactory service only if the three-phase load is balanced* ; when the load is unbalanced, the electrical neutral will shift from its exact centre to a point that will make the line-to-neutral voltages unequal.

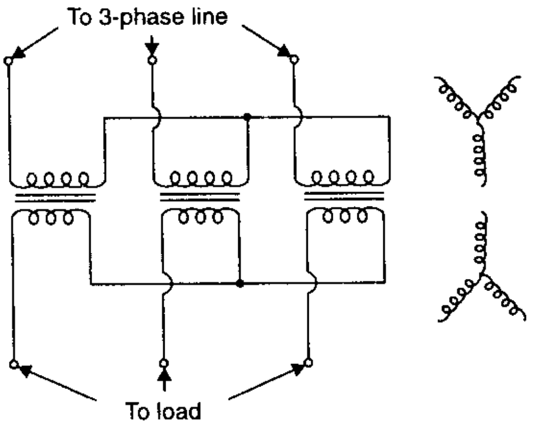


Fig. 12.69. The Y-Y connection of transformers.

Advantages :

1. This type of connection requires fewer turns per winding since the voltage across each is $\frac{1}{\sqrt{3}}$ times the line voltage ; hence it is *cheaper*.

2. The phase or winding current being equal to the line current, the cross-section of the winding wire is large, therefore, the winding is stronger to bear stresses imposed upon it during heavy load or short circuit.

3. There is less dielectric stress on the insulating materials owing to lesser voltage *i.e.*, $\frac{1}{\sqrt{3}}$ of line voltage.

The above advantages are enumerated with the understanding that, other things being equal, its rival is the delta-delta connection.

Disadvantages :

1. In case the load on the secondary side is unbalanced, as in the case of distributing network, the potential of the star-point will assume any value if the star-point is not earthed. This may impose full-line voltage on secondary windings. The shifting of the neutral point must be prevented by connecting the primary star-point to the star-point of the alternator winding.

2. In spite of grounding the star-point, if there is a third harmonic in the form of the alternator voltage, the third harmonic will appear in the voltage of the secondary side. This will cause triple frequency currents in the three-phase circuits. These currents when they flow in the neutral wire are additive and do not cancel out. Hence they will *cause interference to telephone lines located along the same route.*

3. The magnetising current in a transformer has third harmonic components. These currents will find a return path via the connection between the primary star-point of transformer and the neutral point of the alternator. However, if this connection is missing, these components will distort the flux wave which will produce a voltage having a third harmonic in each of the transformer, both

on the primary and secondary sides. And, as before, if the star-point on the secondary is earthed, or grounded, triple harmonic currents will appear in the secondary circuit, and they will flow through the neutral wire causing interference to telephone lines in the vicinity.

4. If the star-points of both the primary and the secondary sides are not earthed, the regulation of the phases will be very poor if the load happen to be unbalanced as in the case of distribution network.

The Δ-Δ connection. Fig. 12.70 shows a bank of transformers connected in Δ on both the primary and secondary sides. *This arrangement is generally used in systems in which the voltages are not very high and especially when continuity of service must be maintained even though one of the transformers should fail.*

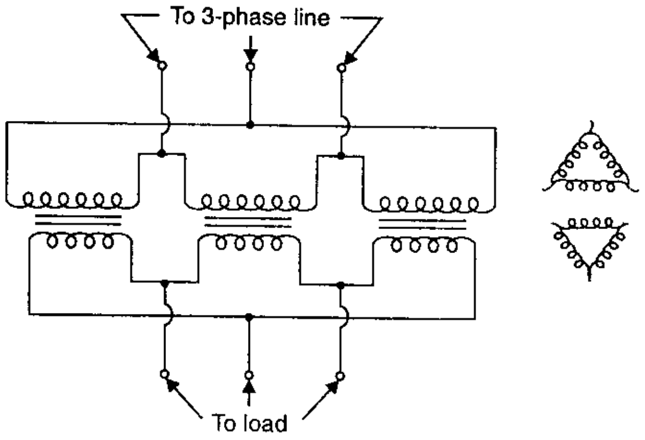


Fig. 12.70. The Δ-Δ connection of transformers.

***Advantages* :**

1. The system voltages are more stable in relation to an unbalanced load.

2. If one transformer fails it may be switched out of the line and operation continued at a reduced power level. This is known as open-delta or *V-V* operation.

3. There is no distortion of flux, because the third harmonic component of magnetising current can flow in the delta connected primary windings without flowing in the line wires.

4. No difficulty is experienced due to unbalancing of loads on secondary side.

***Disadvantages* :**

1. In comparison to *Y-Y* connections it requires more insulation.

2. The absence of star-point may be disadvantageous. If one line gets earthed due to fault, maximum voltage between windings and core will be full line voltage.

The Y-Δ connection. The *Y*-Δ connection is shown in Fig. 12.71.

It is principally used where the voltage is to be stepped down, as for example, at the end of a transmission line. It is also employed in *moderately low-voltage distribution circuits for stepping down* from transmission voltages of 4000 or 8000 V to 230 (and 115 V).

- The *Y* connection takes advantage of the fact one leg of a *Y*, or the line-to-neutral voltage, is less than the line-to-line voltage by a $\sqrt{3}$ factor. This is especially important when the primary voltage is a few hundred thousand volts.
- The *Y*-Δ does have a phase shift between the primary and secondary voltages. This 30° phase shift means that a *Y*-Δ transformer bank *cannot* be paralleled with either a *Y-Y* or

a Δ-Δ. The phasor voltage differences between the two systems would be around sin 30° = 0.5 times the secondary voltages. This would cause an excessive circulating current between transformer banks.

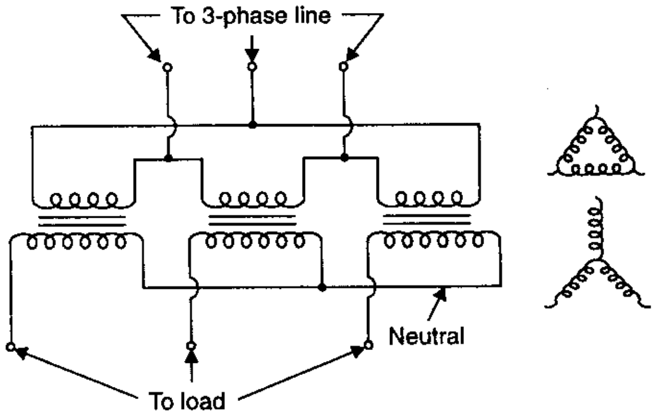


Fig. 12.71. The *Y*-Δ connection.

The Δ-Y Connection

— The three-phase Δ-*Y* connections are shown in Fig. 12.72.

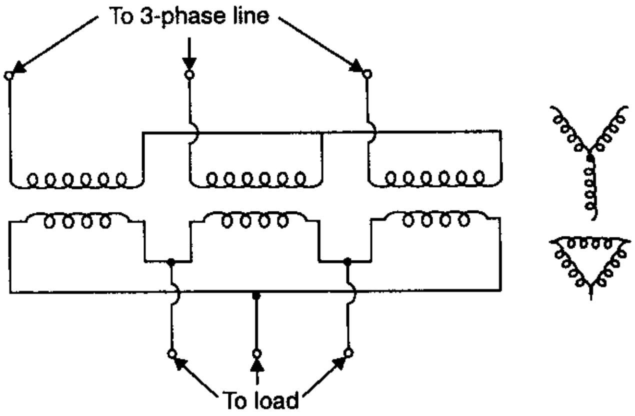


Fig. 12.72. The Δ-*Y* connection of transformers.

- This type of connection is employed where it is necessary to ***step up the voltage***, as for example, at the beginning of a high-tension transmission system.
- The ratio of secondary to primary voltage is $\sqrt{3}$ times the transformation ratio of each transformer.
- The neutral of the secondary is grounded for providing 3-phase 4-wire service. This connection is popular since it can be used to serve both the 3-phase power equipment and single-phase lighting circuit.
- This connection is not open to the objection of a floating neutral and voltage distortion because the existence of a Δ-connection allows a path for the third-harmonic currents. It would be observed that the primary and secondary line voltages and line currents are out of phase with each other by 30°. Because of this 30° shift, it is impossible to parallel such a bank with a Δ-Δ or *Y*-*Y* bank of transformers even though the voltage ratios are correctly adjusted.

The V-V (open-Δ) Connections. Fig. 12.73 shows the *V-V* connection.

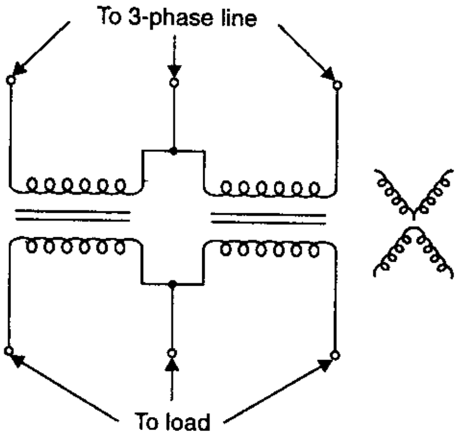


Fig. 12.73. The *V-V* (open Δ) connection of transformers.

If one of the transformers of a Δ-Δ bank is removed and a three-phase source is connected to the primaries (as shown in Fig. 12.73), three equal three-phase voltages will be measured at the secondary terminals at no-load. This method of transforming three-phase power, using two transformers, is called the open-delta, or *V-V* connection.

This type of connection is used in the following cases :

(*i*) When the three-phase load is comparatively small so that the installation does not warrant a three transformer bank.

(*ii*) When one of the transformers in a Δ-Δ bank fails, so that the service may be continued until the faulty transformer is repaired or a good one is substituted.

(*iii*) When it is anticipated that the future load will increase to warrant the chosing of the open Δ at some time later.

V-V connection has a number of *features* that are advantageous.

- Upon failure of the primary or secondary of one transformer of a complete Δ-Δ transformer circuit, the system reverts to a *V-V* circuit, so this is an ***automatic stand by***. The power-handling capacity of a *V-V* circuit is $\frac{1}{\sqrt{3}}$ times the capacity of a full Δ-Δ of the same transformers. This feature works both ways, so a circuit is sometimes installed as *V-V* with the understanding that its power handling may be multiplied by $\sqrt{3}$ by adding one more transformer.
- Open delta or *V-V* circuits do introduce some voltage unbalance due to the non-symmetry of the voltage regulation effects under load. However, the small degree of unbalance is not normally noticed by a motor load or other types of commercial load.

Disadvantages of V-V connection

1. The secondary terminal voltages tend to become unbalanced to a great extent when the load is increased, this happens even when the load is perfectly balanced.

2. The average factor at which the *V*-bank operates is less than that of the load. This power factor is actually *86.6 per cent of the balanced load factor*. Another important point to note is that, except, for a balanced unity power factor load, the two transformers in the *V-V* bank operate at different power factors.

Uses of V-V connection

(*i*) The *V-V* circuit is frequently used for two *auto-transformers.* Here advantage is taken of power handling of auto-transformers and their superior voltage regulation and efficiency.

(*ii*) Another major use of *V-V* transformer banks is in *A.C. motor starting.*

Scott or T-T connection. The connection of one polyphase system into another polyphase system is possible by suitably connecting the windings of transformers. One of the early types that was used is Scott or *T-T* connection, by which a 2-phase system is available from a 3-phase system or *vice-versa.*

Fig. 12.74 shows two single-phase transformers *M* and *T*, the primaries of which are connected to a 3-phase supply. The secondary of *M* forms one phase and the secondary of *T* the other phase of a true 2-phase system. *M* is called the *main transformer* and *T* is called the *teaser.* One end of the teaser primary is connected to the mid-point of the main primary. The two ends of the main primary are connected to two lines wires of a 3-phase, 3-wire system, and the third line wire is connected to a tapping *X* on the teaser primary.

If the supply voltages are assumed symmetrical, the triangle of voltages is equilateral as shown in Fig. 12.75. The vertical line $LS = \frac{\sqrt{3}}{2} NM$, so that it gives the relationship between the number of turns of two primaries, as

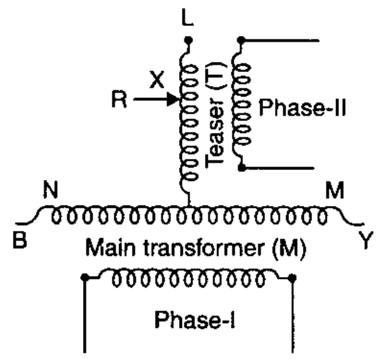


Fig. 12.74. Scott or *T-T* connection.

$$\frac{\text{Number of turns for the main transformer M}}{\text{Number of turns for the teaser T}} = \frac{100}{86.6}$$

Hence, if two identical single-phase transformers are to be used for Scott-connection, the primary one must have a tapping point brought out from its *mid-point of the primary,* and the second transformer must have a tapping *X* brought out from *86.6%* of *its primary turns.*

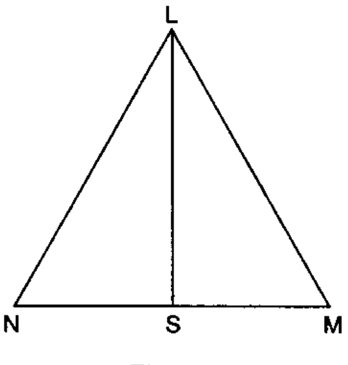


Fig. 12.75

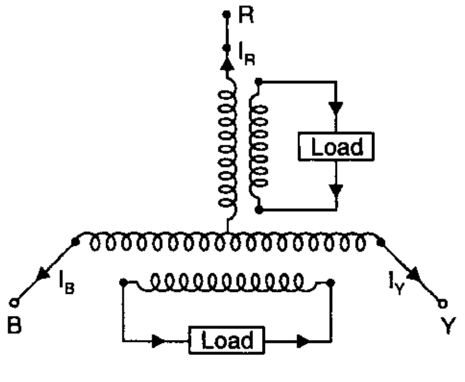


Fig. 12.76

As the two-phase side is asymmetrical, there cannot be perfect balanced conditions on the three-phase side. However, neglecting the impedance of the windings, it can be shown that if load on the 2-phase side is balanced the 3-phase side is also balanced (Figs. 12.76, 12.77 and 12.78).

- Fig. 12.76 shows the connection diagram. The 2-phase side has equal load impedances.
- In Fig. 12.77, the vector diagram is drawn for *unity power factor load.* The secondary currents are not shown. *On* is the *teaser* primary current, and since it flows at the mid-point of the *main transformer*, it divides itself equally in two halves. The resultant current

in the lines *B* and *Y* is the vector sum of the balancing amperes of the main primary and $\frac{1}{2}$ the current of the teaser primary. Hence *op* and *oq* are the line currents. Below is the proof that *ol* = *om* = *on*, and that each one of these currents is at 120° from the other two.

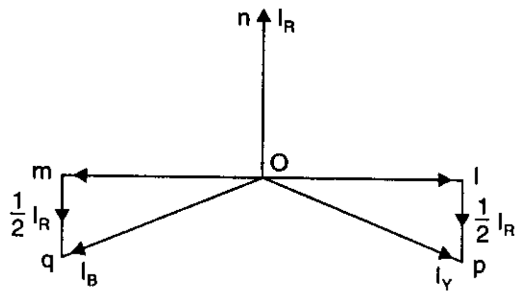


Fig. 12.77

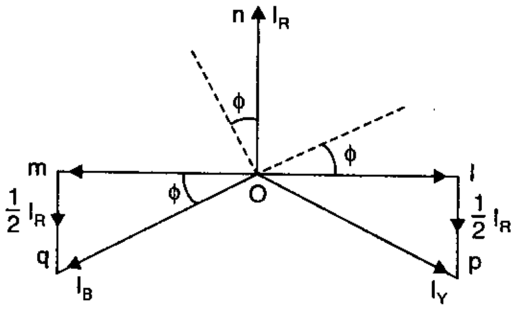


Fig. 12.78

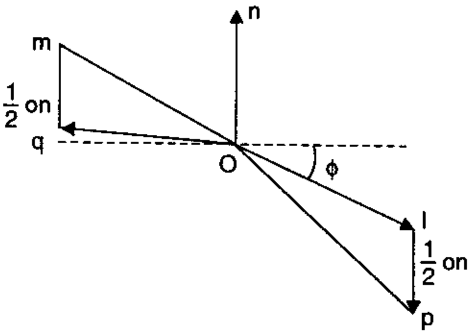


Fig. 12.79

Proof. Let us assume that the ratio of turns of the *main* transformer be 100 : 100 (primary to secondary) and that of teaser 86.6 : 100. If the secondary load-currents are 100 A at unity power factor, the primary balancing amperes of the main transformer will be 100 and lie along *ml*. The *teaser* balancing amperes will be $\frac{100}{86.6} \times 100 = 115.4$ and will lie along *on*. The *teaser* primary current splits into half at 0 and flows in the two halves of the main primary. Hence the line current in *Y* and *B* is given by $\left[(100)^2 + \left(\frac{115.4}{2}\right)^2\right]$ since these two components are at right angles to each other. Now $\left[(100)^2 + \left(\frac{115.4}{2}\right)^2\right]^{1/2} = 115.4$ A and the angle between *ol* and *op* is ϕ such that $\phi = \tan^{-1} \frac{57.7}{100} = 30°$ (Fig. 12.77). Hence *op* lags *on* by 90° + 30° = 120°. Q.E.D.

— In Fig. 12.78, the vector diagram is drawn for a condition when the *load power factor is* cos φ. The same proof can be applied to this case as was done for the case of unity power factor. If the loads are unbalanced and have different power factors, such as cos ϕ_1, and cos ϕ_2, primary side becomes unbalanced. The vector diagram of Fig. 12.79 shows the extent of unbalanced when the *teaser* load is of unity power factor and the *main* transformer load has a power factor of cos φ (lag).

12.3.9.2. Three-phase transformer construction

— The windings of three single-phase transformers can be wound on a common core. The *advantages* and *disadvantages* are given below :

***Advantages* :**

1. One 3-phase transformer is *cheaper* than three single-phase transformers.
2. It has *slightly better efficiency and regulation.*
3. A 3-phase transformer takes *less floor space.*

On the other hand, from the point of view of stand by, or same capacity, it is economical to have 3 single-phase transformers *plus* one spare rather than two 3-phase transformers one of which is a spare. However, in large central stations 3-phase transformers are often advantageous.

***Disadvantages* :**

1. Three-phase transformers are much more difficult and costly to repair than are single-phase units.

2. When failure does occur and it becomes necessary to substitute a replacement unit to maintain service, the cost of spare is much greater than it would be were a single-phase transformer to be used as a replacement in a three-transformer bank.

3. There is a difficulty in transporting a heavier three-phase transformer compared with the moving of each of the three single-phase transformers.

— Two general kinds of three-phase transformers are recognized, similar to single-phase transformers, depending upon the relative arrangements of windings and cores. These are the *core type* and the *shell type*.

Three-phase core type transformer. Fig. 12.80 shows three core-type transformers placed together so that they have a common path for the return magnetic circuit. Although the windows should be entirely filled by primary and secondary coils on each of the legs, only primary coils are shown on the outside legs. This simplifies the diagram, while it in no way changes the actual theory that follows, since the primary coils set up the flux. If the three transformers are identical in all respects, a balanced three-phase system of voltages will produce three fluxes in the cores which have the same maximum value, but differ in time phase by 120°. In the common leg of the three cores of Fig. 12.81, the three fluxes add, and the net flux is therefore always zero. The common leg may then be eliminated, with a subsequent saving in core material and size of transformer. A single polyphase transformer would be of impractical construction if it were the same as Fig. 12.80 with the centre leg omitted. Instead, the core-type polyphase transformer is manufactured so that it looks

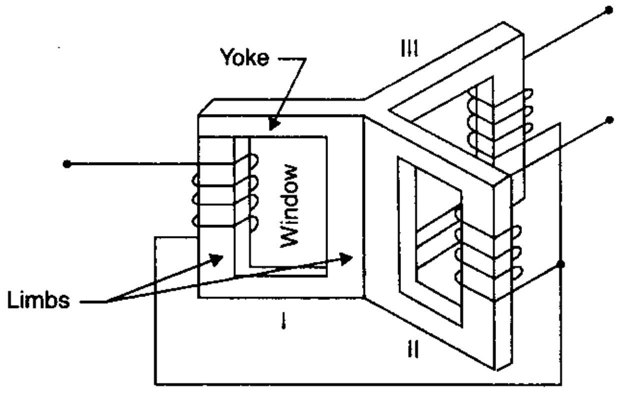


Fig. 12.80. Core-type transformers for polyphase transformation.

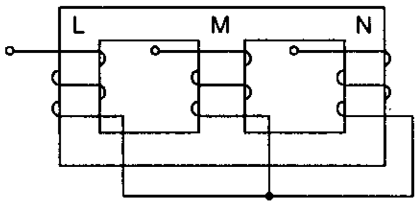
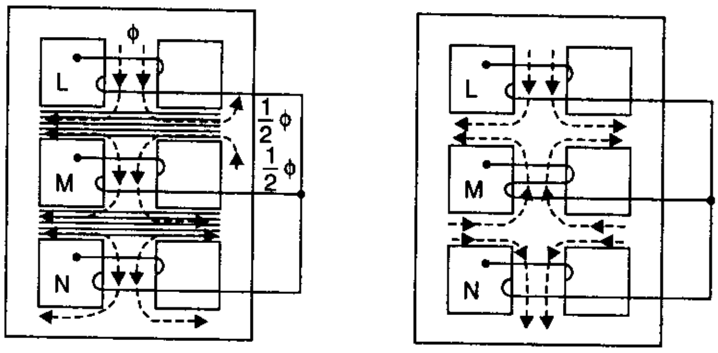


Fig. 12.81. Core-type three-phase transformer.

like that shown in Fig. 12.81. Actually, what we have done is, that axes of three coils have been moved into one plane. This causes the magnetic reluctance of coil M to differ somewhat from that of L and N. This produces a slight unbalance in the three magnetizing currents, but the effect is not serious, especially under load.

Three-phase shell type transformer

- In Fig. 12.82 are shown three shell-type transformers stacked one above the other, with only the primary coils shown.
- In Fig. 12.82 (*a*) the three coils are wound in the same direction. The flux in the common core area between adjacent phases such as the shaded portions is thus equal to the *difference* of two of the phase fluxes. Since the fluxes are 120° apart in time, this mutual flux is equal to $\sqrt{3} \times (\frac{1}{2}\ \phi)$, or 0.866 of the flux in the centre leg. If the same flux density is maintained throughout, less iron is required in the common leg. Now, however if the centre coil, phase M is reversed, the flux in the common core is equal to the *sum* of the fluxes of two adjacent phases. This is shown in Fig. 12.82 (*b*). As in any three-phase system, the sum of two fluxes is equal to either flux alone, which in this case is 0.5 ϕ. This represents a further saving in iron, and for this reason shell-type three-phase transformers are *usually wound with centre coil opposing the two outside ones.*



(a) (b)

Fig. 12.82. Shell-type three-phase transformer (*a*) coil M wound in the same direction, (*b*) coil M wound in opposite direction.

12.3.9.3. Parallel operation of 3-phase transformers

The conditions for paralleling 3-phase transformers are same as that required for parallel operation of single-phase transformer with the following additions :

(*i*) *The voltage ratio must refer to the terminal voltage of primary and secondary.*

(*ii*) *The phase displacement between primary and secondary voltages must be the same for all transformers which are to be paralleled.*

(*iii*) *The phase sequence must be the same.*

Following points are worth noting while dealing with 3-phase transformers :

- The calculations are made for one phase only. The value of equivalent impedance used is the equivalent impedance per phase referred to secondary.
- When the impedances of primary and secondary windings are given separately, then primary impedance must be transferred to secondary by multiplying it with (transformation ratio)^2.

— In case of Y/Δ or Δ/Y transformers the voltage ratios as given in the questions, refer to terminal voltages and are quite different from turn ratio.

12.3.10. Instrument transformers

It is not practicable to connect instruments and meters directly to the lines in high voltage circuits. Instead instrument transformers are used. The following are the *two basic advantages* inherent in this method :

(*i*) Standard rated instruments may be used.

(*ii*) Operating personnel coming in contact with the instruments are not subject to high voltage and current of the lines, and so there is less danger to them. Even with a low-voltage system, instrument transformers are used for measuring large currents, so that heavy leads to the instrument panel and to the ammeter and other current terminals are avoided.

The principle of the instrument transformer is fundamentally the same as that of the power transformer. The instrument transformers are classified as follows :

1. Potential transformers.
2. Current transformers.

12.3.10.1. Potential transformers (P.T.)

— A potential transformer is a *step down transformer* used along with a low range voltmeter for measuring a high voltage. The primary is connected across the high voltage supply and the secondary to the voltmeter or potential coil of the wattmeter. Since the voltmeter (or potential coil) impedance is very high, the secondary current is very small and the potential transformer behaves as an ordinary two winding transformer operating on no-load. Fig. 12.83 shows a potential transformer used to measure the voltage of a circuit. It may be noted that the secondary is grounded. This is done so that if the insulation breaks down, the high voltage does not endanger personnel who may be reading the meters.

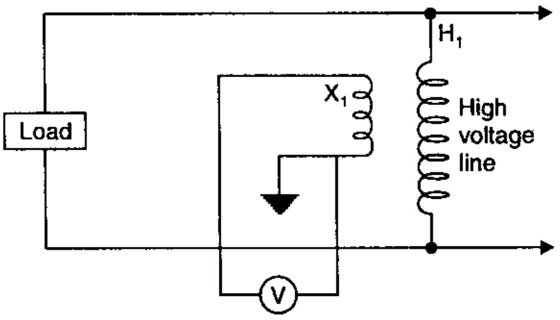


Fig. 12.83. Potential transformer connections.

— These transformers are *made with high quantity iron core operating at very low flux densities so that the magnetising current may be very small.* Careful design ensures minimum variation of voltage ratio with load and minimum phase shift between input and output voltages. Potential transformer secondaries are commonly designed for an output of 110 V.

12.3.10.2. Current transformers (C.T.)

— Just as a shunt extends the range of a D.C. ammeter, so does the current transformer perform the same function in A.C. circuits. Thus a *high magnitude alternating current can be easily measured by a combination of a current transformer and a low range ammeter.*

— The primary of a current transformer (C.T.) consists of a few turns of thick cross-section connected in *series* with the high current line. Very often the primary is just one turn formed by taking the line conductor through the secondary winding (Fig. 12.84). The secondary winding consists of a large number of turns of fine wire designed for either 5 A or 1 A rating. Thus a current transformer is *step-up* transformer. The current transformer has the secondary effectively short-circuited through the low impedance of the ammeter. Fig. 12.85 shows the current transformer connections.

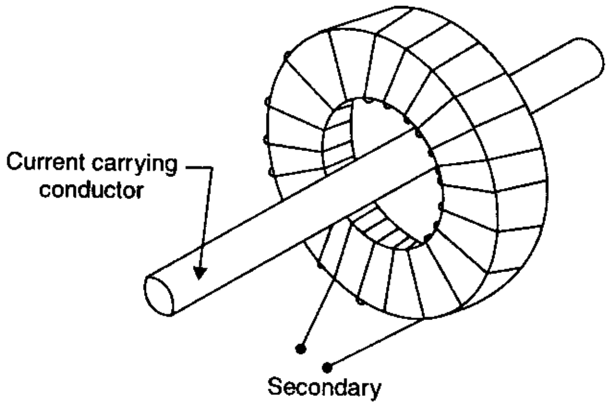


Fig. 12.84. Line conductor acting as primary.

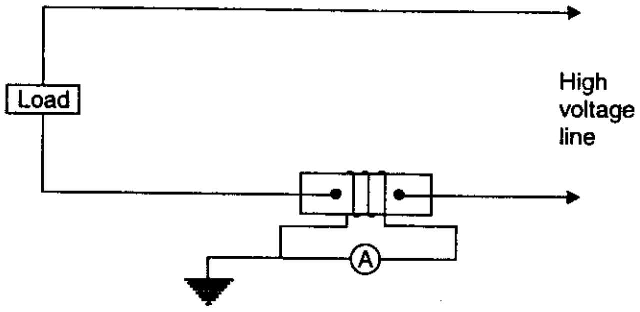


Fig. 12.85. Current transformer connections.

— The *current transformer ratio is not equal to the ratio of secondary to primary turns, mainly because of the effect of the magnetising current.* The primary current can be thought of as the sum of two currents, the first to balance secondary current so that primary and secondary m.m.fs. may balance and the second being the no-load current I_0. The component I_0 besides being responsible for a slight error in the current ratio, is also responsible for a phase angle error. The transformer *must be carefully designed to minimise the ratio and phase angle error.*

— It may be noted that current transformer must never be operated on open-circuit for the following two reasons :

(*i*) There will be no secondary m.m.f. and since the primary current (and m.m.f.) is fixed, the core flux will increase enormously. This will cause large eddy current and hysteresis losses and the *resulting high temperature may damage the insulation or even the core.*

(*ii*) A very high voltage will be induced in the multi-turn secondary and this high voltage may be dangerous both to life and to the insulation.

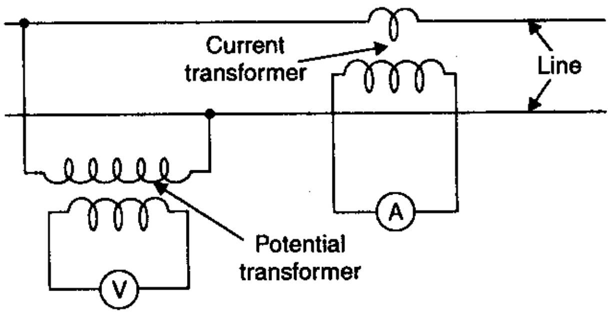


Fig. 12.86. Wiring diagrams for potential and current instrument transformers.

Fig. 12.86 shows the wiring diagrams for potential and current instrument transformers.

12.3.11. Constant-Current Transformers

A constant-current transformer is used for *supplying power to street lights which are connected in series*. The *primary of this transformer receives power at constant voltage and varying current and the secondary supplies power at constant current and varying voltage*, which depends upon the number of lamps in series.

Principle of operation. The principle of operation of a constant-current transformer is illustrated in Fig. 12.87.

- One coil is stationary while the other one is movable, and its weight is partly balanced by a counter-weight *W*. Either coil may be the movable coil.
- The openings through the coils are much longer than the core. This permits a large leakage flux to be set up through the coils when the currents are maintained in them.
- It is clear from Fig. 12.87 that a mechanical force of repulsion exists between the coils. This force tends to drive the movable coil upward on the core, and owing to the counter

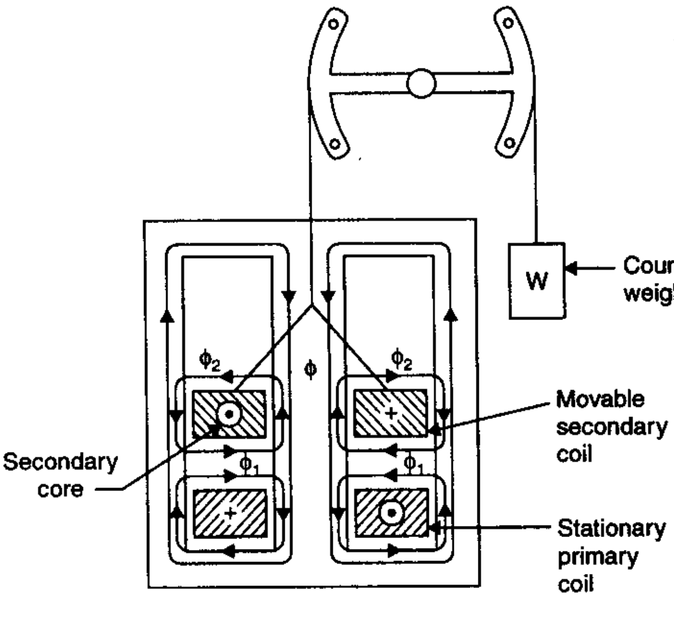


Fig. 12.87. Constant-current transformer.

weight, a relatively small force produces motion. *At maximum load the movable coil is close to the stationary one and the voltage induced in the former is a maximum.* When the secondary load is *reduced* by cutting out some of the lamps in the series circuit, the current in the remaining units increases momentarily. This cause the force of repulsion to increase. The *floating coil then moves upward and thereby increases the equivalent leakage reactance of the transformer, reduces the secondary voltage*, and *brings the current back to normal. The coil comes to rest when the terminal voltage is properly reduced to suit the lesser number of lamps and the current attains its correct constant value.*

— The *rating* is usually given in kW, and the secondary current. The standard values of current are 6.6, 7.5 and 20 A. The load power factor is almost 100%. The *regulation* is expressed as *the percentage of the current (secondary) from its rated value. The regulation should not exceed 1%.*

12.4. SWITCHGEAR

The switchgear constitutes all parts or equipments of the power plant whose function is to receive and distribute electric power. It comprises of the following :

(*i*) Assemblies of switching apparatus

(*ii*) Protective and indicating metering devices

(*iii*) Interconnecting bus bar systems and relevant accessories.

12.4.1. Functions of a switchgear

The functions performed by a switchgear are listed below :

1. To localise the effects of faults by operation of protective equipment and so automatically disconnect faulty plant from the system.
2. To break efficiently short circuits without giving rise to dangerous conditions.
3. To facilitate redistribution of loads, inspection and maintenance on the system.

12.4.2. Switches

The most important types of switches fall in one of the following classes :

(*i*) Knife switches

(*ii*) Disconnecting switches

(*iii*) Air-break switches

(*iv*) Control switches

(*v*) Auxiliary switches

(*vi*) Oil switches

(*vii*) Magnet impulse switches.

(*i*) **Knife switches.** These switches are used to open and close circuit of *low voltage and current capacity*. They are extensively used in lighting and small power circuits. In order to protect such low capacity circuits against overloads and short circuits, it is necessary that proper fuses be connected in series with the switch blades.

(*ii*) **Disconnecting switches.** For power circuits it is necessary to use some type of circuit breaker to open or close the circuit. In order to isolate the circuit breakers it is generally considered good practice to connect knife switches in series with the circuit breakers. Such knife switches are known as *disconnecting switches*. They *should never be opened until the circuit breaker in the same circuit has been opened, and should always be closed before the circuit breaker is closed.* They are *not designed to break currents* and should therefore, *never, be opened while current is flowing in the line.*

(*iii*) **Air-break switches.** By "*air-break*" switches are meant switches designed to *open circuits under load.* They are generally used outdoors for circuits of medium capacity, such as lines supplying an industrial load from a main transmission line or feeder. In order to take of the arc that occurs on opening such a switch, special arcing horns are provided, so that the arc may rise and be ruptured. Air-break switches are built for about 135,000 volts maximum but their use is in general confined to lower voltages. *These switches are not designed to operate under abnormal conditions, such as short circuits.*

(*iv*) **Control switches.** Under this class are included all the switches that are used to *control the operation of other equipment.* As a general rule, they are designed for operating voltages less than 250 volts and very small current capacities.

(*v*) **Auxiliary switches.** Under this class are included all switches or contractors that are *actuated by some other control switch or device.* In the control of power equipment, such as circuit breakers, it is impracticable to handle the operating current through the control switches on the switch-board, hence an auxiliary operating switch is placed near the circuit breaker, this switch being electrically operated by a control switch that may be located at any desired distance from the circuit breaker. Thus, the control circuits may be designed for very small currents, while the operating circuits as a general rule must handle much large currents and very often at higher voltages.

(*vi*) **Oil switches.** For certain applications at high voltages and large current capacities it is desirable to immerse the switch contacts under oil. The effect of the oil is to cool and quench the arc that tends to form when the circuit is broken.

(*vii*) **Magnet impulse switches.** In this type of switch the arc is extinguished by blowing it magnetically into arc chutes where it is lengthened, cooled, and interrupted. The magnetic effect is produced by the circuit current which is passed through suitable coils, setting up a strong magnetic field across the space between the switch contacts as they are opened. The basic principle involved in lengthening the arc is that of a simple motor, in which force is directly proportional to the product of magnetic flux and current.

12.4.3. Fuses

Fuses are used to protect circuits of small capacity against abnormal currents such as overloads or short circuits.

There is a large variety of fuses on the market, but the most important types that are used for power purposes are :

1. Cartridge fuses
2. Transformer fuse blocks
3. Expulsion fuses.

1. **Cartridge fuses.** These fuses are composed of a strong fibre casing inside of which is enclosed a fuse wire, generally an alloy of lead. The fuse voice is fastened to copper caps which are fastened to each end of the casing. Fuses of general type are available for circuits upto about 25000 volts. There are on the market a large number of fuses of the general type, the particular details of construction being very varied. They are used as a protective device in low-capacity circuits, such as small lighting and power lines, and on the secondary of instrument-potential transformers, when used for metering or relay protection.

Fig. 12.88 shows a HRC—cartridge type fuse. HRC stands for high-rupturing-capacity. In its simplest form it consists of a heat resisting ceramic body having metal (brass) end caps to which are welded fusible silver (or bimetallic) current carrying elements. The complete space within the body surrounding the elements is filled with a powder, usually quartz, which acts as an arc extinguishing agent.

When the fuse is carrying normal rated current, the temperature of the fuse element does not reach melting point. On occurrence of a fault short circuit current flows through the fuse element and the fuse element melts before the fault current reaches its first peak. As the heat is produced, the melted fuse element will vapourize. The chemical reaction between silver vapour and filling powder tends to establish the high resistance. The high resistance acts as an insulator because the fault current decreases along with the high pressure created within the fuse by the fault (excessive) current. Thereafter a transient voltage is created at the instant of fault current interruption on account of sudden release of energy.

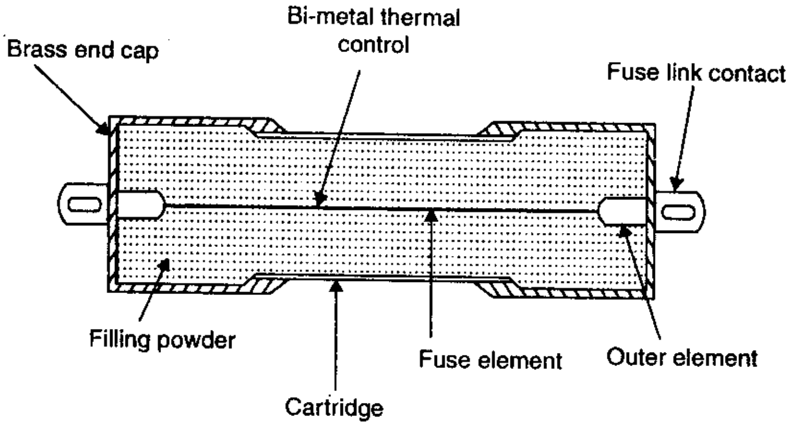


Fig. 12.88. High rupturing capacity catridge fuse.

2. **Transformer fuse block and cutout.** The proper protection of distribution circuits has for years been recognized as best fulfilled by means of fuses. Distribution transformers are as a general rule placed on poles, towers, or in manholes and any automatic protection would be entirely too complicated and expensive. Fuses offer a simple and cheap method of protection. It is common practice to place these fuses in the *secondary of such transformers*, thereby protecting the transformers against short circuits or overloads. There are two types of fuses that are generally used for the purpose. Both types include a *porcelain housing*, enclosing the fuse and contact points. In *one type* the fuse is carried on a plug that is provided with an insulating porcelain knob in order that it may be removed for re-using. A *second type* consists of a rectangular porcelain receptacle with a removable front door that carries the fuse.

3. **Expulsion fuse.** For higher voltages such as found in power circuits or main feeders, there is often a demand for a fuse, on account of its simplicity. The expulsion-type fuse has been developed for such service.

This device consists of a hollow tube, made of some heat resisting substance such as fiber with a lining of asbestos or some other material, through which is passed a fuse wire. One end of the tube is closed and connected to the line, the other end is opened and allows the fuse wire to project out and connect to the other terminal. When a short circuit or overload occurs, the fuse is blown and a certain amount of gases form inside the tube. These gases in escaping to the air cause the arc, which is generally produced, to be blown out. Since there is always a tendency for an arc to occur, these fuses are adaptable only to outdoor use. They may be obtained for practically any modern transmission line voltage.

12.4.4. Circuit Breakers

There is probably no other part of a power system that is more important than the *equipment that controls the system*. All the control devices discussed above are suitable for only relatively small capacities, but for large capacities it is necessary to employ more dependable means of control, such as is obtained by the use of circuit breakers.

12.4.4.1. Function of a circuit breaker

The *function of a circuit breaker is to break a circuit when various abnormal conditions arise and create a danger for the electrical equipment in an installation*. The heaviest duty a circuit-breaker has to perform is to interrupt a short-circuit current which may reach a value of several tens of thousands and even more (> 10^5 amperes) in a large capacity power system. At the same time, in order to quickly eliminate the source of the fault, the circuit-breaker must open the circuit with least possible delay.

12.4.4.2. Principle of circuit breaker

The breaking of circuit means *rapid conversion of predetermined section of circuit from a conductor to insulator*. When the current carrying contacts are separated, an arc (which contains an ionized gas) is produced between them. This arc provides for the gradual change-over from current carrying to voltage isolating states of the contacts. Therefore, it plays an important part in circuit interruption process. The arc has to be carefully controlled because a good deal of energy in the form of heat is generated in it. The produced arc may be extinguished by high resistance or low resistance methods.

12.4.4.3. Classification of circuit breakers

Circuit breakers may be classified as follows :

1. Low voltage circuit breakers
2. High voltage circuit breakers
   (*a*) Oil circuit breakers
      (*i*) Bulk oil circuit breakers
      (*ii*) Low oil contact circuit breakers
   (*b*) Oil-less circuit breakers
      (*i*) Air blast circuit breakers
      (*ii*) Water circuit breakers
      (*iii*) Hard gas circuit breakers.

Characteristics of High Voltage Rating Circuit Breakers

The high voltage rating circuit breakers should possess the following characteristics :

1. They should have high reliability-electrically and mechanically.

2. They should be capable of interrupting inductive and capacitive circuits and fault currents of all values within their rating.

3. The opening *i.e.*, the time interval between receipt of tripping impulse and contact separation should be the minimum mechanically possible.

Oil circuit breakers (O.C.B.)

These are the most common type of circuit breakers used in power stations. The rating range of these circuit breakers lies between 25 MVA at 2.5 kV and 5000 MVA at 250 kV. The ***advantages*** of using oil as a quenching medium are :

1. It has high dielectric strength.
2. It absorbs arc energy while decomposing.
3. Good cooling property of gas formed (as a result of decomposition of oil).
4. Surrounding oil in close proximity to the arc presents a large cooling surface.
5. It acts as an insulator between live part and earth.
6. The ability of cool oil of high dielectric strength to flow into the arc space after the current is zero.

Disadvantages :

1. It is easily inflammable.
2. It can cause explosion by mixing with air.
3. It requires maintenance and periodic replacement.

Plain break oil circuit breaker :

Fig. 12.89 shows the arrangement of this breaker. There is a strong weather tight earthed metal tank, containing oil upto a predetermined level, and an air cushion above the oil. The oil pressure is this breaker tank is solely due to the head of oil above the contacts which are enclosed in the tank.

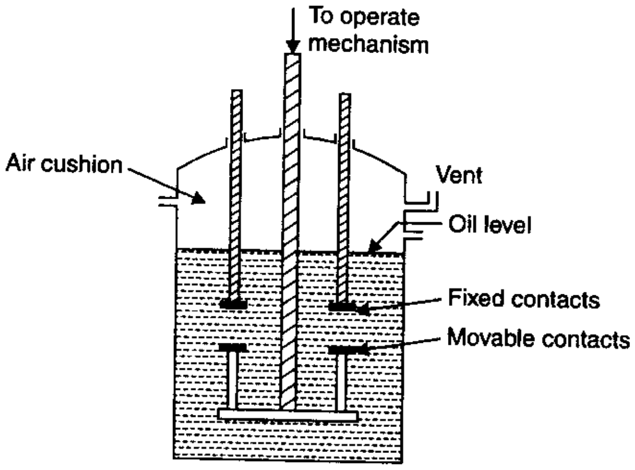


Fig. 12.89. Plain oil circuit breaker.

When the contacts separate an arc is struck. This vaporizes oil into gas. The sudden formation of the gas by arc may dissipate heat generated as a result of arc.

The major drawback of this breaker that it suffers from the defect of *permitting rather long and inconsistent arcing times*. In view of this limitation, such circuit breakers are suitable only for low current and low voltage operations not exceeding 150 MVA at 11 kV.

Air circuit breakers :

In air circuit breakers the compressed air at pressure around 15 kgf/cm^2 is used for extinction of arc. Fig. 12.90 shows a typical air-blast circuit breaker. The extinction of arc is caused by flow of air around the moving circuit. The breaker is closed by applying pressure at the lower opening, and opened by applying pressure at the upper opening. When the contacts separate, the cold air rushes round the movable contact and blows out the arc.

Advantages :

An air circuit breaker claims the following advantages over oil-circuit breaker :

1. Fire hazards due to oil are eliminated.
2. Operation takes place quickly.
3. There is less burning of contacts since arc duration is short and consistent.
4. Facility of high speed re-closure.
5. Suitable for frequent operation (since the cooling medium is replaced constantly).

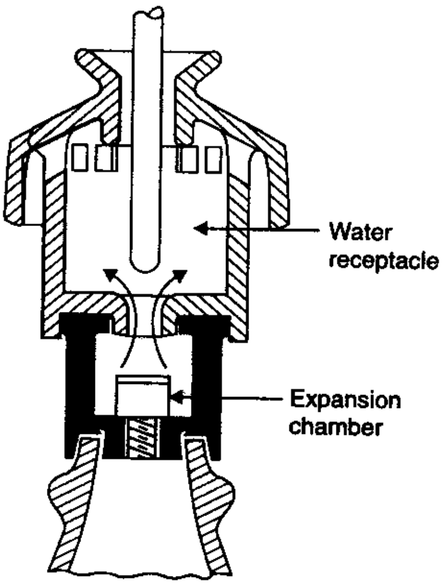


Fig. 12.90. Air blast circuit breaker.

Limitations

1. Sensitivity to restriking voltage.
2. Current chopping.
3. A compressor is constantly required to remain in operation.
4. The leakage of air at the pipe line fittings creates problems.

Water circuit breaker

The principle of the water circuit breaker is shown in Fig. 12.91. The contacts are in water, which is turned into steam by the arc and rushes past the opening to blow out the arc.

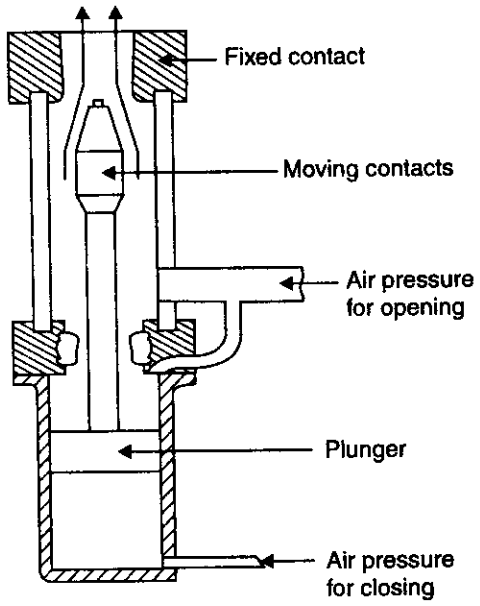


Fig. 12.91. Water circuit breaker.

12.4.4.4. Principles of layout of switchgear

The following principles should be followed while carrying out layout of switch gear :

1. The layout should be such that any section may be isolated without unduly affecting the service.
2. There should be an easy and safe access for general routine inspection and for maintenance.
3. The individual units should be so designed that the risks of failure are reduced to minimum.
4. Fire protection arrangement must be made adequately.
5. To keep the breaking duty within the capacity of the circuit breakers reactors should be used where necessary.

12.4.5. Types of Switchgear

The various types of switchgear are enumerated and discussed below :

(*i*) Cellular
(*ii*) Cubicle
(*iii*) Truck
(*iv*) Metal clad
(*v*) Outdoor switchgear.

1. **Cellular.** The components of this type of switchgear are enclosed in *cells* made of brick, concrete or moulded stone. These components can be easily inspected and modifications can be made without any difficulty. The cellular type gear has the following *disadvantages* :

(*i*) The erection of a cellular type gear is a lengthy process.

(*ii*) It occupies large space.

(*iii*) The interlocking systems may be complicated.

2. **Cubicle.** The whole of the equipment, in this case, is enclosed in steel plate cubicles with complete or partial sub-dividing barriers. It entails the following *advantages* :

(*i*) It requires relatively small floor area.

(*ii*) It presents a neat and simple layout.

3. **Truck.** In this type of switchgear a movable truck carries the circuit breaker moving isolator contacts, and the potential and current transformers. The front panel of the truck fits into the stationary steel cubicle which houses the busbars, cable box, and fixed isolator contacts. When inspection is to be carried out, the truck is withdrawn from the cubicle.

4. **Metal clad.** Here all conductors and insulators are *enclosed by an earthed metal case*. A metal clad switchgear is of two types :

(*i*) Horizontal draw out (*ii*) Vertical drop down.

A metal clad switch gear has the following *advantages* :

(*i*) As all the live parts are enclosed in metal it ensures safety to operators and reduces maintenance charges.

(*ii*) Maintenance work can be easily carried out (since working parts are easily and safely accessible).

(*iii*) To prevent operating mistakes simple and efficient interlocks can be installed.

(*iv*) Erection on the site can be easily carried out.

(*v*) Since it occupies less space, therefore, building cost in reduced.

5. **Outdoor switchgear.** The following points are worthnoting :

(*i*) Although it requires large ground space but there is a saving in building cost.

(*ii*) Maintenance work is at the mercy of the weather.

(*iii*) The damage from lightning is likely to be more since the equipment is exposed.

(*iv*) Frequent insulation cleaning.

(*v*) As compared to an indoor switchgear its maintenance cost is more.

12.5. PROTECTION OF ELECTRICAL SYSTEMS

12.5.1. General Aspects

Fig. 12.92 shows a typical power system. In such a power system the function of relays and circuit breakers is to prevent or limit damage to the system due to faults or overloads and to isolate the faulty section from the remainder of the system.

The function of the relay system is to recognize the fault and to initiate the operation of devices or circuit breakers to isolate the defective element with the minimum disturbance to the service.

Typical system protective zones are shown in Fig. 12.92. These zones might be classified as :

(*i*) Generators (*ii*) Low-tension busses

(*iii*) Transformers (*iv*) High-tension busses

(*v*) High-tension transmission lines (*vi*) Feeders.

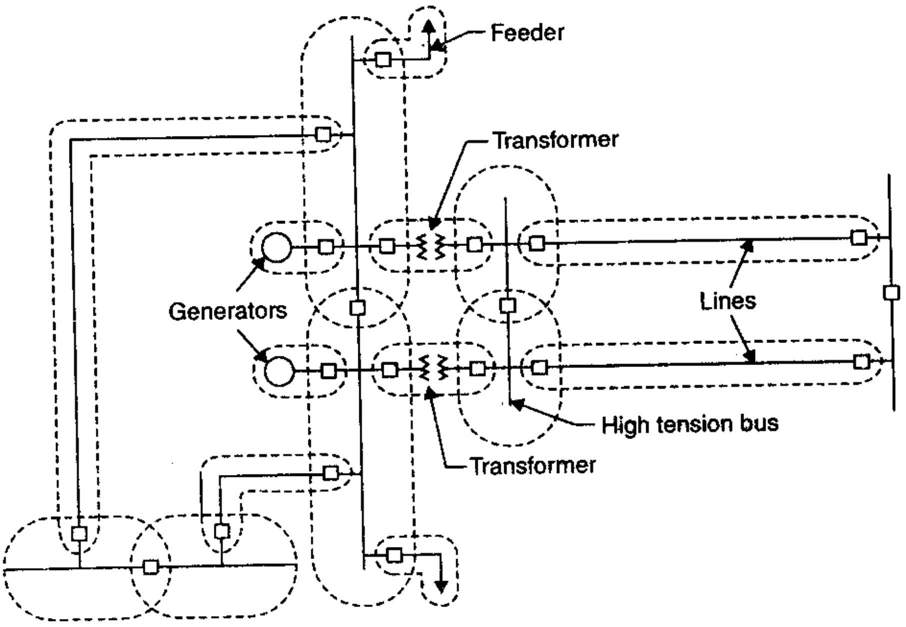


Fig. 12.92. Typical system showing zones of protection.

The speed with which relays and circuit breakers operate has a direct bearing on :

(*i*) The quality of service to consumers

(*ii*) The stability of the system

(*iii*) The amount of power that may be transmitted without exceeding the stability limit

(*iv*) The damage done by a short circuit and consequently the cost and delay in making repairs

(*v*) Safety to life and property.

The successful operation of the modern power system is to a great extent due to the modern high-speed circuit breakers.

Relays have been developed for practically all types of system disorders, which may be listed as follows :

1. **Rotating machines**

(*i*) Short circuits in machine (*ii*) Open circuits in machine

(*iii*) Over current (*iv*) Overheating

(*v*) Motoring of generator (*vi*) Loss of field

(*vii*) Over speed (*viii*) Bearing over heating

(*ix*) Single-phase and unbalanced current operation.

2. **Transformers**

(*i*) Short circuits (*ii*) Open circuits

(*iii*) Overloads.

3. **Busses.** Bus failures are somewhat remote compared with failures in other parts of a system. An insulator support may fail, producing a line-to-ground fault, or in remote cases a bus-to-bus short circuit may occur.

4. **Transmission lines.** Transmission and distribution lines, because of their length and exposed nature, are the source of most trouble. Several causes may imitate trouble, such as : (*i*) overloads and (*ii*) any type of short circuit, caused by the breaking of the conductors or falling trees etc.

12.5.2. Different Types of Relays

All relays are essentially composed of three elements :

(*i*) An actuating element (*ii*) A movable element

(*iii*) A set of contacts.

Relays may be classified as follows :

1. **According to their time action**

(*i*) Instantaneous (*ii*) Definite time limit

(*iii*) Inverse time.

2. **According to their mechanical details or principle of action**

(*i*) Plunger type (*ii*) Induction type.

3. **According to their application**

(*i*) Current relays (*ii*) Directional relays

(*iii*) Voltage relays (*iv*) Auxiliary relays

(*v*) Differential relays (*vi*) Distance or impedance relays.

Requirements of relay

1. Definite operation with accuracy
2. Selective operation
3. Flexibility
4. Sensitivity.

Description of Commonly used Relays

1. **Plunger type relay.** Refer Fig. 12.93. It consists of a core or plunger which is movable within a solenoid. When sufficient amount of current is passed through the winding, the core is pulled up, thus causing the cone-shaped disc at the top to bridge the gap between stationary contacts. The position of the plunger with respect to coil is adjustable ; the lower its position, the more current is required to pull it into the closing position, and by adjusting its position it may be set to take any predetermined value of current within the range of the coil.

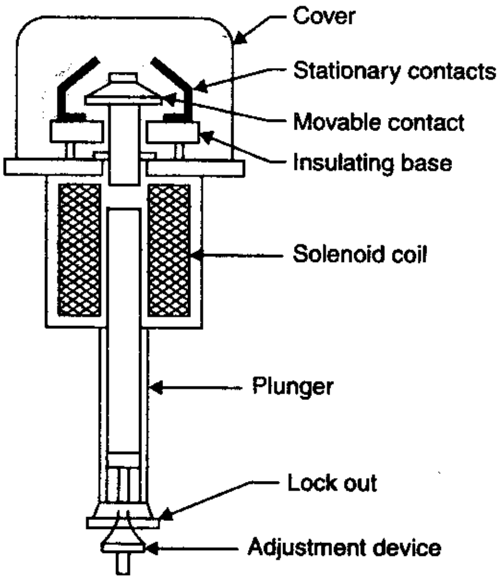


Fig. 12.93. Plunger type relay.

2. **The Over-current (Induction type) relay.** This type of relay is shown in Fig. 12.94. The output of the current transformer is supplied to the winding on the central part of E shaped core. The second winding from this place is connected to two windings on poles of the U-shaped core. The disc is mounted in between the cores. It carries contacts and is free to rotate against a mechanical restraining torque. Currents are induced in the disc due to the magnetic flux across the air gaps. Flux is also produced by the lower magnet. The combined effect produces a rotational torque. The speed of the disc is controlled by using brake magnet. The *operation line varies inversely with the current supplied to the relay by the current transformer.*

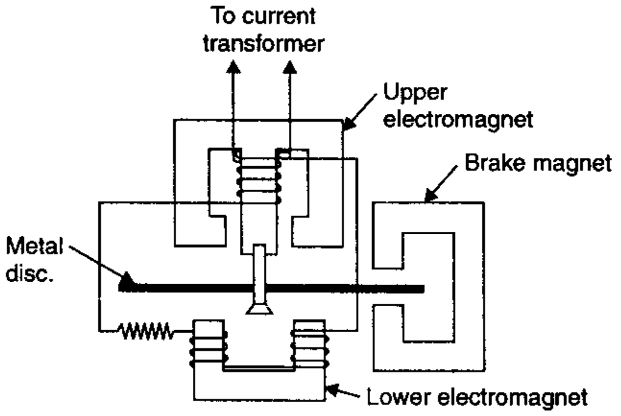


Fig. 12.94. Induction type over-current relay.

3. **Current balance relays.** This type of relay is commonly used. It operates on the principle of *current balance in which two currents are compared on a proportionate basis.* The principle of this type of relay is shown in Fig. 12.95.

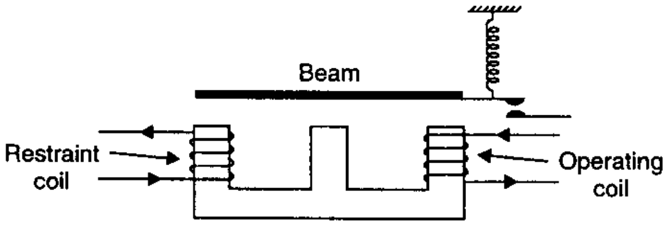


Fig. 12.95. Current balance relay.

4. **Differential relays.** As the name implies, these relays *depend for their operation on the difference in currents that might flow in two parts of a system.* In the Fig. 12.96 is shown an elementary circuit diagram of a standard differential relay. It is composed of *three* windings, the two outside ones being known as the *restraining coils* and the inner one as the *operating coil.* They are so made and connected that the *two restraining coils exert a downward pull, while the operating coil exerts an upward pull on the armature.* In Fig. 12.96 is shown how the three windings, are connected.

Coils '*a*' and '*b*' are connected to their respective current transformers in the power circuit so that under normal conditions the sum of the current through them in *zero*, and hence the operating coil '*c*' will not exert any force upon the moving mechanism. When the difference in the current in the two lines protected becomes great enough to overcome the weaker of the two retaining windings, the moving contact mechanism will rise and throw to one side, thereby completing the circuit of the trip coil of the oil circuit breaker.

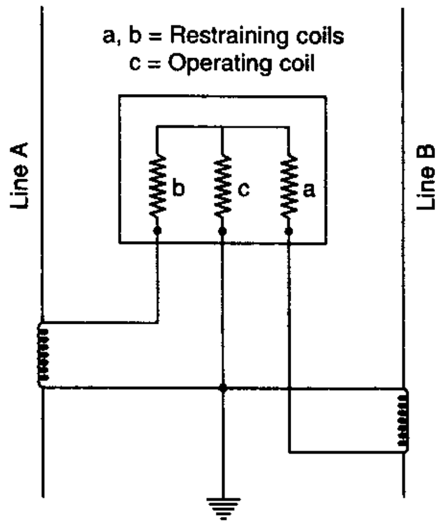


Fig. 12.96. Differential relay.

12.5.3. Alternator Protection

There are two possible ways of protecting alternators against damage due to excess current due to a short circuit. These are :

1. Overload protection
2. Differential protection.

1. **Overload protection.** In Fig. 12.97 is illustrated the method of obtaining overload protection for alternators. The disadvantage of using overload relays for alternators is due to the fact that when synchronizing several machines to the same bus, there might be a large momentary circulating current present, which will open the alternator circuit breakers and thereby cause a delay in synchronizing.

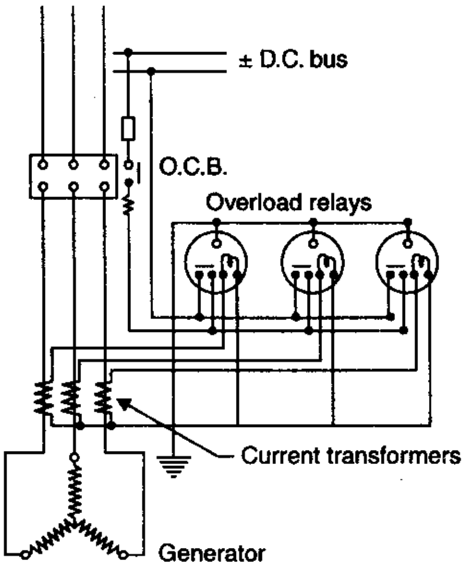
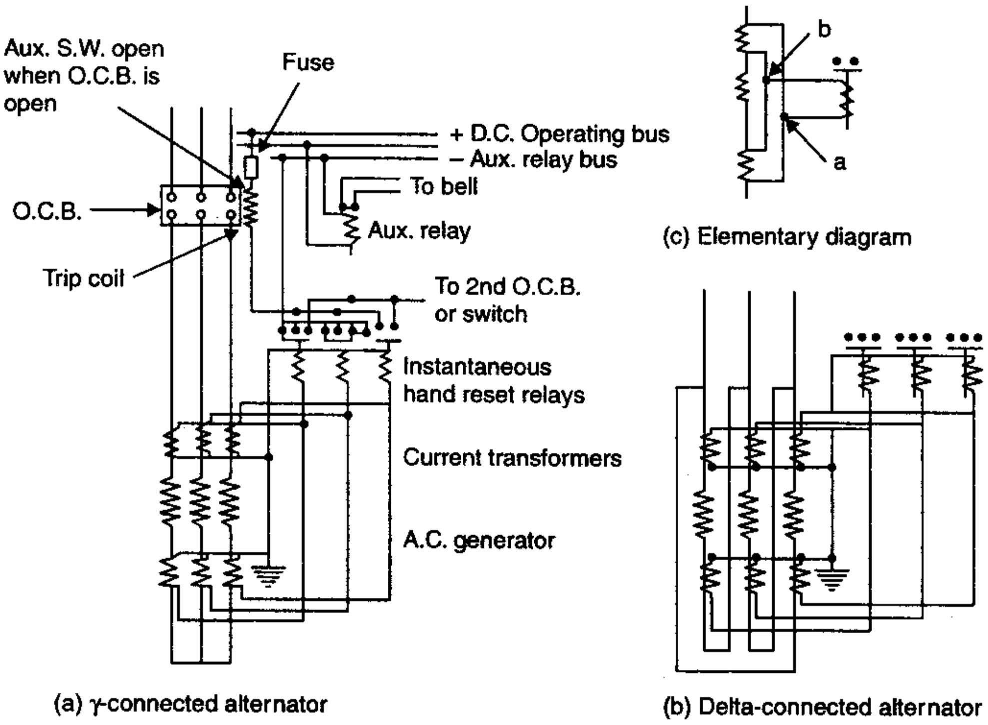


Fig. 12.97. Overload protection for alternators.

In the design of power equipment modern tendency is to build alternators with very high values of internal impedance, so that they will stand a complete short circuit at their terminals without causing any damage to themselves. Such alternators need not have any overload protection ; as a matter of fact, the operating engineer, as a general rule, does not want any overload protection, as such protection might disconnect the alternators from the power-plant bus on account of some momentary trouble outside the plant and therefore interfere with the continuity of the electric service. For such alternators the sole protection required must be one that will only recognize an internal fault in the machine.

2. **Differential protection.** Differential protection is illustrated in Fig. 12.98 where the complete diagram of connections is shown for the case of a *Y*-connected alternator, and only part of the system for a delta-connected alternator. At each end of each phase of the armature windings identical current transformers are placed. In Fig. 12.98 (*c*) is shown the elementary diagram. If the transformers are connected as shown, there cannot be any potential between the points *a* and *b* unless there is a difference of current in the secondaries of the two current transformers. Under normal conditions ; the current entering the winding is equal to current leaving the winding, hence there will be no difference of potential across '*a*' and '*b*' and hence there can be no current flow through the relay coil. As soon as an internal short circuit or ground occurs on the winding, the currents flowing in the two current transformers are unequal, and a potential will be established across '*a*' and '*b*' and therefore current will flow through the relay coil causing its contacts to close.



(c) Elementary diagram

(a) Y-connected alternator

(b) Delta-connected alternator

Fig. 12.98. Differential protection of alternators.

12.5.4. Transformer Protection

The protection that is most common for transformer banks is similar to the differential protection of alternators (see Fig. 12.99). There is one important modification. Since the primary and secondary voltages are not alike, it is necessary to use relays having two separate coils or current transformers of different turn ratio for the primary and secondary sides of the power transformers. These coils must be so designed that when connected to their respective current transformers their pulls on the plunger of each relay is neutralized. In case of a short or ground in either the high or low tension side of the transformers, the pulls exerted upon the plunger will no longer be neutralized and the relay contacts will be closed, opening the oil circuit breakers on both sides of the transformer. In case the relay coils are identical, such a system requires current transformers of different primary to secondary ratios in order that the currents acting in the two coils of one relay be equal. These two *currents must be inphase*, hence this type of protection can be used only in case the *power transformers are similarly connected on both sides.*

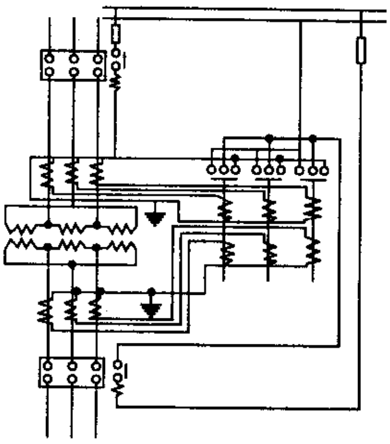


Fig. 12.99. Differential protection for transformers. High and low tension sides connected alike.

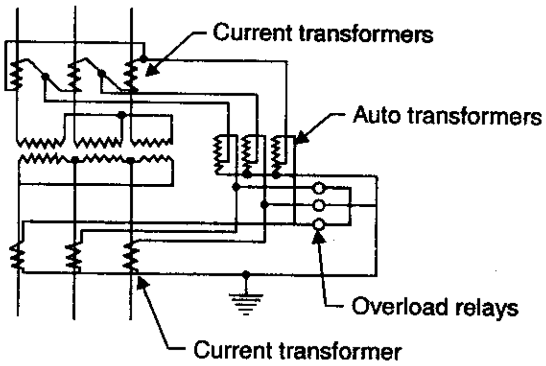


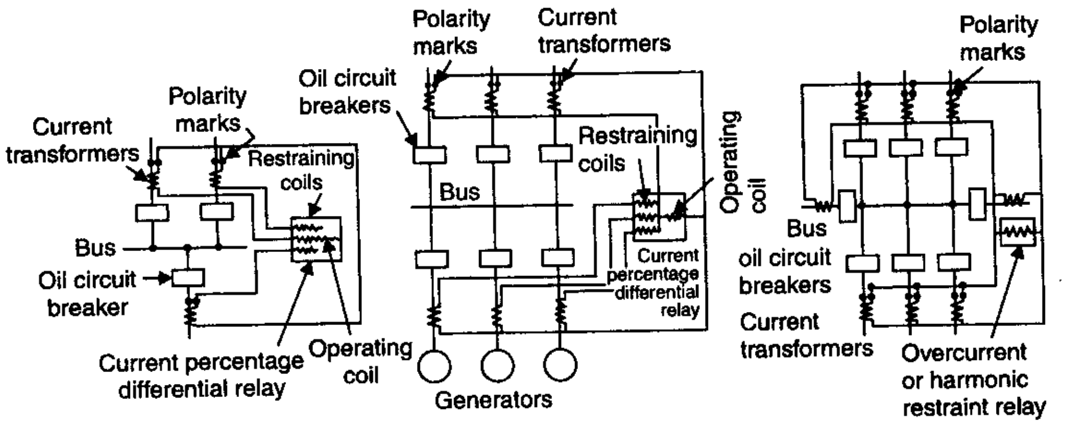
Fig. 12.100. Differential protection for transformers. High and low tension sides connected differently.

A typical method of protecting a star-delta transformer bank is shown schematically in Fig. 12.100.

12.5.5. Bus Protection

Fig. 12.101 shows three examples of bus protection. In all three cases the protection is based on the fundamental proposition that for an external fault the vector summation of all currents flowing to a bus is equal to zero, and therefore, the relay will remain in its balanced position. On the other hand, when an internal fault occurs on the bus, the summation of the currents will no longer be zero and the current will flow through the relay, causing it to operate and thereby open all circuit breakers connected to the bus. An auxiliary multicontact relay is often used to trip the several circuit breakers.

In case of a few connecting lines, it is possible to use percentage differential relays (see Fig. 12.101 *a* and *b*) ; for the case of many lines it becomes more desirable to use standard over current relays (see Fig. 12.101 *c*).



(a)
Schematic one-line diagram of current-differential protection of buses using percentage differential relay.

(b)
Schematic one-line diagram of current-differential protection of buses using percentage differential relay.

(c)
Schematic one-line diagram of current-differential protection of buses using over current relay.

Fig. 12.101

12.5.6. Protection of Transmission Lines

The requirements of line protection can be summarised as follows :

1. In the event of a short circuit the circuit breakers nearest the fault should open, all other circuit breakers remaining in a closed position.
2. In case the nearest breaker to the fault should not open fast enough, back up protection should be secured from adjacent circuit breakers.
3. Line circuit breakers should not trip due to loss of synchronism or hunting of generators.
4. The relay time should be just as short as possible in order to preserve system stability, without unnecessary tripping of circuits.

Common Methods of Line Protection Against Short Circuits

1. Overcurrent protection.
2. Distance or impedance protection.
3. Pilot protection and carrier current protection.
4. Balanced current or balanced power protection.

Some of the above methods are discussed below :

Overcurrent protection. This type of protection is the most elementary type of line protection available. It generally employs the induction-type inverse-time relay. Fig. 12.102 illustrates such an application to a radial system involving one generating station and four substations. The relay-time settings are adjusted so that the first circuit breaker to trip in the event of a fault, is the one nearest the fault. The selectivity between substations is obtained by the time interval 'S'.

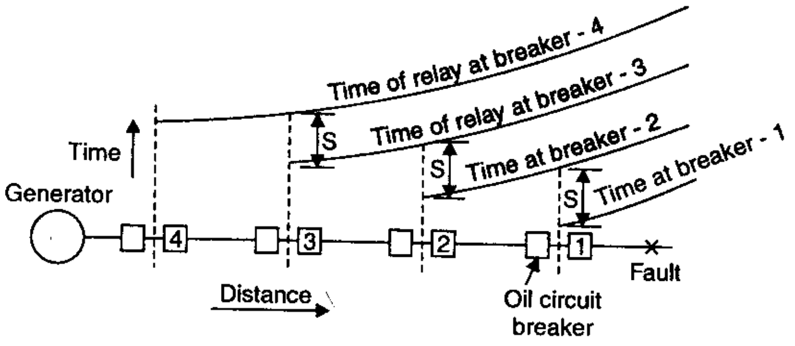


Fig. 12.102

Distance protection. For line to ground faults, the simple overcurrent protection is probably more satisfactory than distance protection. However, for *phase to phase faults, the distance protection is applicable, since the circuit impedance is quite constant and not subjected to seasonal changes, as is the case with earth impedances.*

Fig. 12.103 illustrates the application of this method of protection to a radial system.

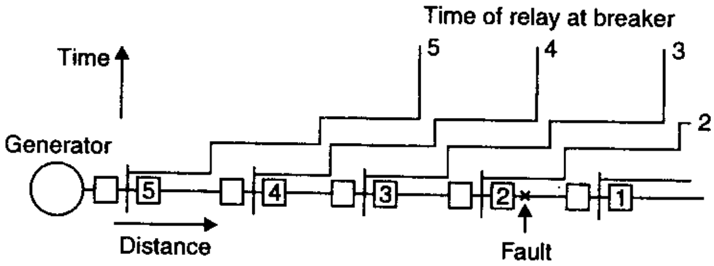


Fig. 12.103

Pilot wire protection. In the case of a short line it is possible to obtain very positive protection by the so-called "pilot wire" method. The method is essentially differential protection applied to the transmission lines. Current transformers are placed in each phase at both ends of the line and connected by means of pilot wires, as shown in Fig. 12.104. Only one phase is shown in order not to obscure the fundamental principle involved. It is evident from the above diagram that this is identical in its principle of operation with the differential protection applied to alternators. A short circuit at any point between the current transformers will cause the oil circuit breakers at both ends of the line to open. The relays used may be of either the induction or plunger type but probably the induction inverse-time relay is the most common for this type of installation. The natural objection to pilot wires is in the fact that they are likely to be broken or damaged. The expense of placing pilot wires on the transmission towers should also be considered. In *the case of long lines in which the capacity effect is appreciable, this method of protection cannot be used.*

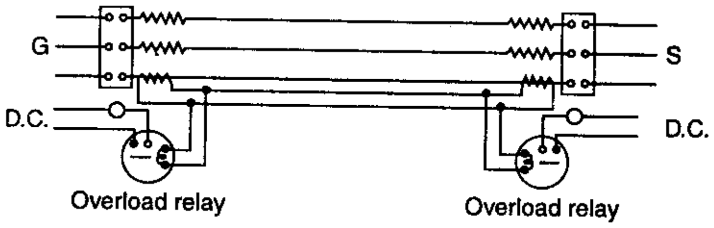


Fig. 12.104. Pilot-wire method of protection.

12.6. SHORT CIRCUITS IN ELECTRICAL INSTALLATIONS AND LIMITING METHODS

A '*short circuit*' is any *solid contact established between the different phases of an electrical installation or any bridging of them by a very low resistance.* When a *short circuit* takes place a short circuit current starts flowing which is usually many times excess of normal rated current in the currents carrying parts, circuit apparatus and even the alternators.

Cause of short circuits :

Primarily a short circuit is *caused due to failure or breakdown of the insulation between phases which allow the conductors to come into electrical contact with each other.* In electrical equipment and installations the insulation failures take place due to the following :

(*i*) Defects in material (*ii*) Poor workmanship

(*iii*) Natural ageing (*iv*) Mechanical injury and various causes.

Effects of short circuits :

1. During a short circuit a large amount of current (exceeding the normal load current) flows causing *overheating* which can prove very harmful to the electrical equipments. To avoid overheating of the current conducting parts it is generally *necessary to considerably increase their cross-section areas.*

2. Supply to the consumers is interrupted.

3. The generator e.m.f. and the voltage in the stator winding drop due to considerable large short circuit current flow through the circuit. As a consequence of the drop in the generator e.m.f., and also as a result of considerable voltage drop in the stator winding due to the flow of large short-circuit current, *every short circuit is found to cause a serious drop in voltage at the busses of the generating stations and in power circuit.*

4. Due to short circuit when there is significant decrease in voltage the motors may stall ; to prevent the stalling of motors it is necessary to switch off the faulty section of the circuit as quickly as possible.

Limiting of short circuit currents :

In installations of large capacity, short circuit currents can attain such high values that unless these are limited by some means, the selection of electrical equipment capacity of withstanding them is very difficult. This can be achieved by *interposing auxiliary inductive reactances called reactors* in each phase of the given installation.

Functions of a reactor :

1. Troubles may be localized or isolated at the point where they originate without communicating their disturbing effects to the other parts of the network.

2. They limit the flow of current into a short circuit with the view of protecting the equipment from overheating as well as from failure due to destructive mechanical forces, and also protecting the system as a whole against shutdown by maintaining the voltage on most of the system while the short circuit is being cleared.

3. They permit the installation of lower capacity circuit breakers.

Location of reactors :

Reactors may be placed in the generator leads, between bus sections, in the low-tension transformer leads, between bus sections, in the low-tension transformer leads, or in outgoing low-tension feeders. No definite statement can be given as to which one of the above locations is preferable, each installation has its own particular demands which must be carefully considered before a choice of reactor location can be made. A brief description of the most important applications is given below :

1. **Generator reactors.** In Fig. 12.105 is shown the application of reactors in the generator leads. In this case the reactor may be considered as a part of the transient reactance of the generator, hence its effects is to protect the generator in case of any short circuit beyond the reactors. In the case of slow speed alternators, as for example in some of the hydroelectric units, it is possible to incorporate as much reactance as necessary in the generator itself, hence no reactors are needed. For this reason reactors are *rarely used in the generator leads of hydraulic plants. In the case of high-speed alternators it may often be desirable to use reactors in the generator circuit.*

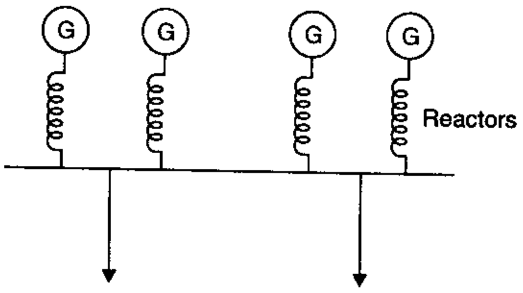


Fig. 12.105. Generator reactors.

2. **Transformer reactors.** In a few cases reactors have been installed in the low-tension side of power transformers as shown in Fig. 12.106, but as a general rule transformers can be designed with enough inherent reactance so that reactors are seldom necessary in the transformer circuits.

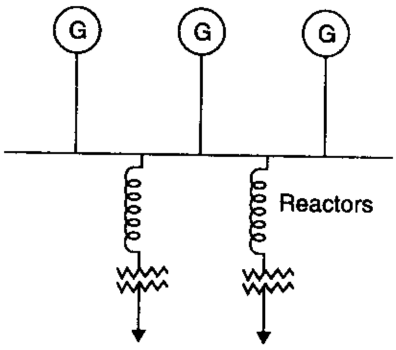


Fig. 12.106. Transformer reactors.

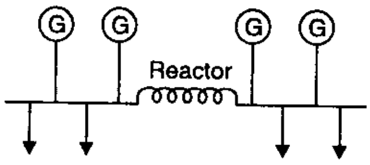


Fig. 12.107. Bus reactors.

3. **Bus reactors.** In power plant containing a large number of units it is often desirable to break up the low-tension bus into sections so that troubles can be confined to the section in which they started. These sections can be permanently connected through reactors, thereby obtaining a high degree of flexibility and also obtaining the protection under short circuit conditions due to localizing effect of the reactor (Fig. 12.107).

4. **Feeder reactors.** Most of the disturbances and short circuits occur in the low-tension distribution feeders either feeding from a power plant or distributing substation, hence it is not surprising that a large number of reactors are used for such circuits. In the case of a short circuit in a particular feeder, the *reactor prevents the communication of the trouble to the remainder of the system* (Fig. 12.108).

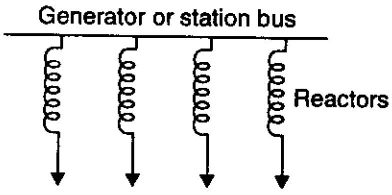


Fig. 12.108. Feeder reactors.

12.7. CONTROL ROOM

In a power station the control room (or the operating room) acts as the nerve centre. The following controls are located in a control room.

(*i*) Circuit breakers

(*ii*) Load and voltage adjustment

(*iii*) Transformer tap changing

(*iv*) Emergency tripping of the turbines etc.

(*v*) The instruments for indicating the load, voltage, frequency, power factor, winding temperatures and water levels in the case of hydrostations and so on.

(*vi*) Synchronising equipment

(*vii*) Voltage regulators

(*viii*) Relays

(*ix*) Integrating meters and other appliances

(*x*) A mimic diagram and suitable indicating equipment to show the open or closed position of circuit breakers, isolators etc.

The control room location in relation to other sections of the station, important and suitable position should be obtained. It should be located in the following manner :

(*i*) Should be located *near the switch house* so that lengths of the multicore cables are shortened.

(*ii*) Should be located *away from noise sources.*

(*iii*) From the control room there should be an access to the turbine house.

(*iv*) The location of the control room should be such that is should not be affected if any fire errupts in the switch house.

Fig. 12.109 shows the location of control room.

The control room should be well arranged as follows :

(*i*) Control room should be clean and comfortable.

(*ii*) Should be ventilated and well lighted.

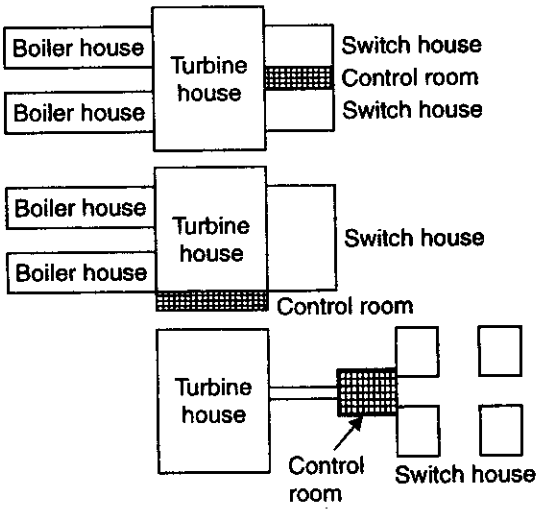


Fig. 12.109. Location of control room.

(*iii*) Should be free from draughts.

(*iv*) There should be no glare.

(*v*) The colour schemes should be soothing to eyes.

(*vi*) The instruments should have clear scales properly calibrated.

(*vii*) All the apparatus and circuits should be labelled so that they are clearly visible.

Control boards. These are of the following three forms :

(*i*) *Linear* (*ii*) *Horse shoe shaped*

(*iii*) *Semi-circular.*

The house shoe shaped and semicircular control boards occupy more floor space but they enable all the instruments to be seen from one point.

In some cases, the control boards are of *desk type* in which the control and indicating equipment are located on the front, and the relays and integrating instruments are placed behind.

Fig. 12.110 shows the layout of a control room.

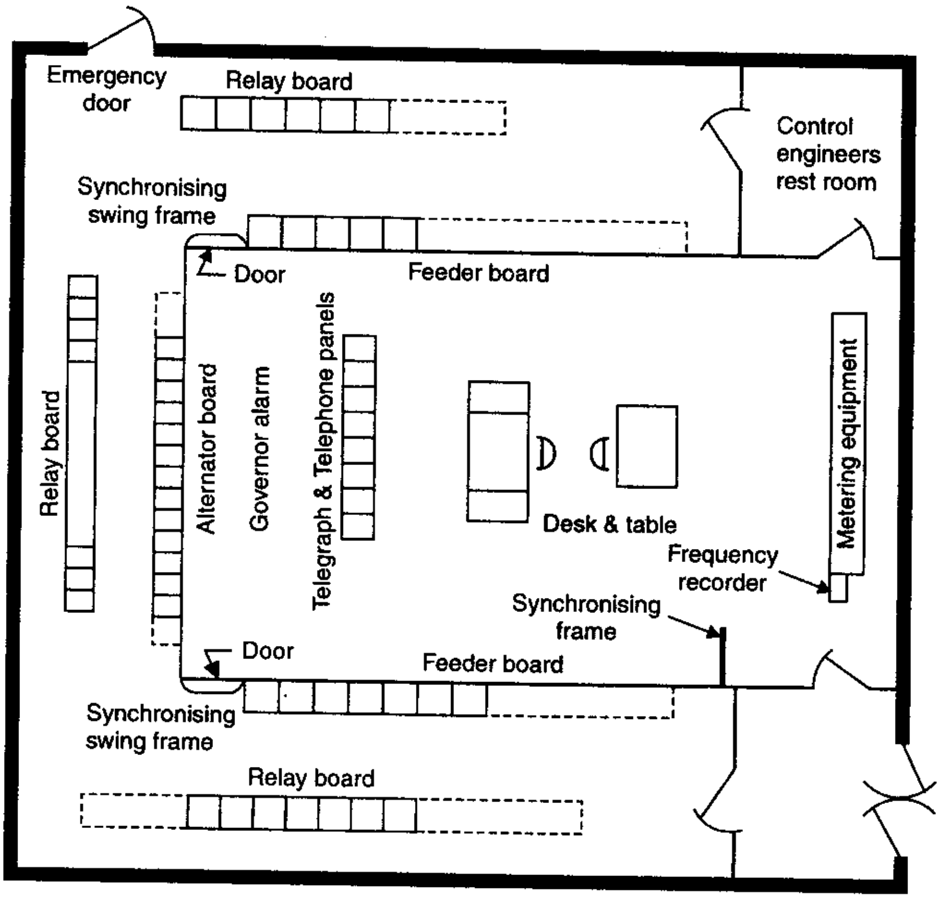


Fig. 12.110. Layout of a control room.

12.8. EARTHING OF A POWER SYSTEM

Earthing of neutrals of all industrial power systems is always preferable. Earthing is necessary as it offers many *advantages* given below :

1. Persistent arcing grounds is eliminated.
2. Over-voltage due to restriking is minimized.
3. The ground faults can be located and isolated fastly.
4. Steady state voltage stress to earth is reduced.
5. Sensitive protective apparatus can be used.
6. The maintenance expenditure is reduced.
7. Better safety is ensured.
8. Service reliability is improved.
9. Earthing provides improved lighting protection.

The earthing of systems should be done at the neutral of the supply transformers and generators. If the supply transformers and generators are delta connected, separate earthing transformers may be used.

In case the sources of power are two or more in number then the neutrals of these sources should be earthed to ensure having a neutral earthed in the event one of the sources is out of service.

The earthing of high voltage neutral is mainly done to protect the system while the low voltage neutral is earthed chiefly in order to reduce the possible danger to human life.

Where energy is transformed suitable provision should be made to protect the lower voltage system from becoming charged above its normal voltage by leakage or electrostatic induction from the higher voltage.

Methods of Earthing System Neutral

1. Solid earthing
2. Resistance earthing
3. Reactance earthing
4. Resonant earthing.

Solid earthing :

When the neutral of a generator or power transformer or earthing transformer is connected direct to the earth, as shown in Fig. 12.111 (*a*, *b*) the system is solidly earthed. Solid earthing is generally used on low voltage circuits, 600 volts or less, and on most circuits above 15 kV. In the range of 2.2 to 15 kV any of the remaining three types may be used.

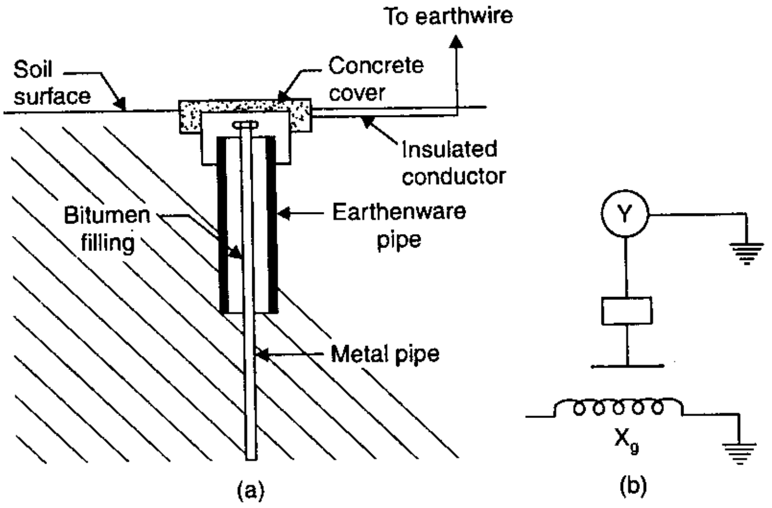


Fig. 12.111. Solid earthing.

In solid earthing, a direct metallic connection is made from the system neutral to one or more earth electrodes consisting of plates, rods or pipes buried in or driven into the ground, generally in a bed of coke below the permanent water level. Where permanently moist ground cannot be ensured a supply of water should be made available so that the periodic watering cannot be done. The value of contact resistance or resistance of the earthing system should be as small as possible and this should be checked from time to time. Now-a-days the term 'solidly earthed' has been replaced by the term '*Effectively earthed*'.

A transformer neutral may be 'solidly earthed' in that there may be no impedance between the neutral and earth. However, the transformer capacity thus solidly earthed may be too small in comparison with the sizes of the system to be effective in stabilizing the voltage from phases to ground when the fault takes place.

Resistance earthing :

The neutral of the generator is connected to the earth through a resistor as shown in Fig. 12.112. The resistance introduced in this case acts as a current limiting device. The resistors used in this case may be metallic carbon powder or liquid type. The magnitude of the resistance to be used should be such that it should limit the earth fault current to a value which will reduce minimum damage at the point of faults.

The *advantages* of resistance earthing are listed below :

1. The ground faults are readily relayed.
2. The hazards of arcing grounds are minimized.
3. The mechanical stresses in the circuit carrying fault currents are reduced.
4. Least inductive influence on neighbouring communication.
5. Electric shock hazards to the persons, caused by stay-earth fault currents in the earth return path, are reduced.
6. Line voltage drop, caused by the occurrence of earth fault, is reduced.

The main *disadvantage* of resistance earthing is that is *costlier* than the solidly earthed system.

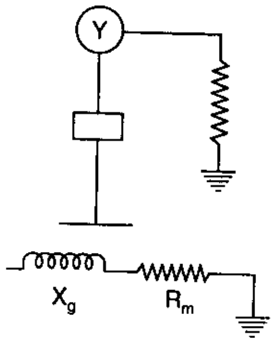


Fig. 12.112. Resistance earthing.

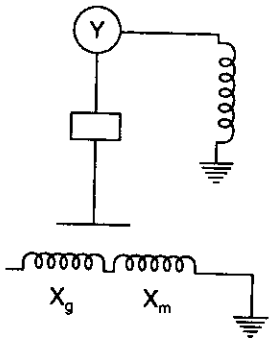


Fig. 12.113. Reactance earthing.

Reactance earthing :

In this case a reactor is connected between the neutral of the machine and earth as shown in the Fig. 12.113. Sometimes a low reactance is connected in series with the neutral of the machine to limit the earth fault current through the generator. This current should not be greater than the 3-phase fault current of the generator. The earth-fault-current of this system should not be less than 25% of the 3-phase fault current in order to minimize the transient voltages.

12.9. ELECTRICAL EQUIPMENT-LAYOUT

In a power station the layout of electrical equipment consists of the following :

(*i*) Busbars' arrangement (at generator voltage)

(*ii*) Circuit breakers and switches' arrangement

(*iii*) Transformers' location

(*iv*) Controlling switch board arrangement.

The following systems are used for layout of electrical equipment :

1. Single busbar system
2. Double busbar system
3. Ring busbar system.

1. **Single busbar system :**

Refer Fig. 12.114. In case of a power plant which has a number of generators and a single busbar arrangement, the busbar is sectionalised by circuit breakers. The main *advantage* of this system is *that fault on one part of the busbar or system does not completely shutdown the whole station*. However, the use of such a large number of circuit breakers is out of date and presently there is a tendency to use fewer.

G = generator, CB = circuit breaker, S = Isolator or switch, LVB = Low voltage bus bar, HVB = high voltage bus bar, T = step up transformer.

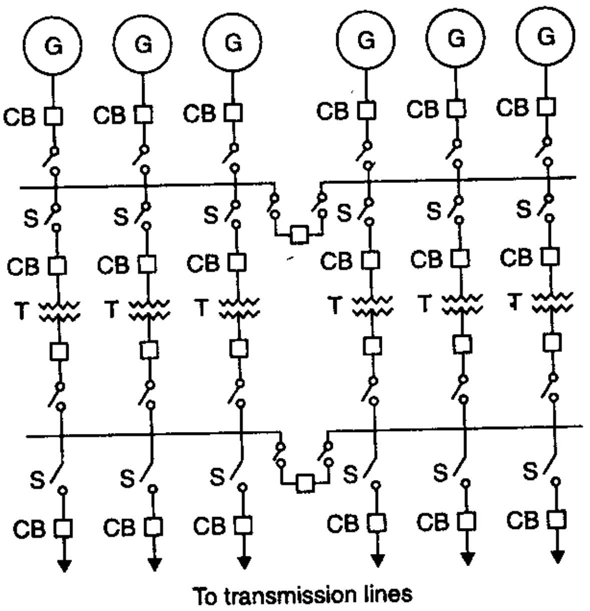
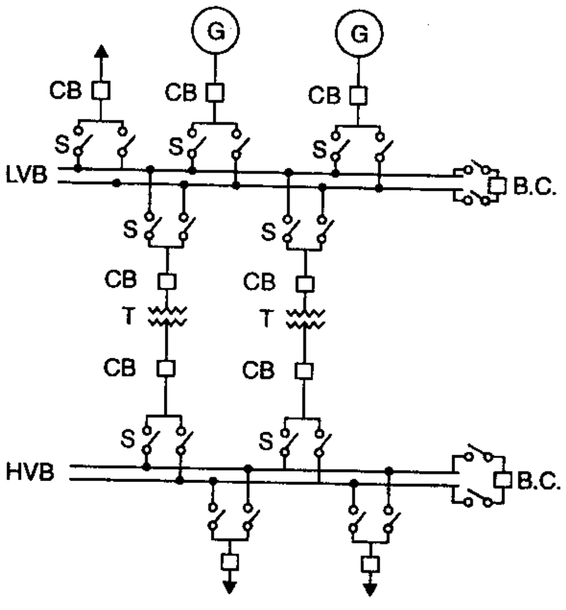


Fig. 12.114. Single busbar system.

2. **Double busbar system :**

In the Fig. 12.115 illustrated a double busbar system. In this system both low voltage and high busbars are duplicated, any one of the busbar sections can be used as desired. There is a provision of a *busbar coupling switch* for transferring operation from one busbar to another.

The *advantage* of this system is that it is possible to have one bus bar *"live"* and to carry out *repairs* on the other when required.



To Transmission Lines

Fig. 12.115. Double busbar system.

3. **Ring Busbar System :**

Refer Fig. 12.116. In this arrangement two circuit breakers serve one line. This system has the *advantage* that there are always two parallel paths to the circuit and failure of one section does not interrupt the service completely.

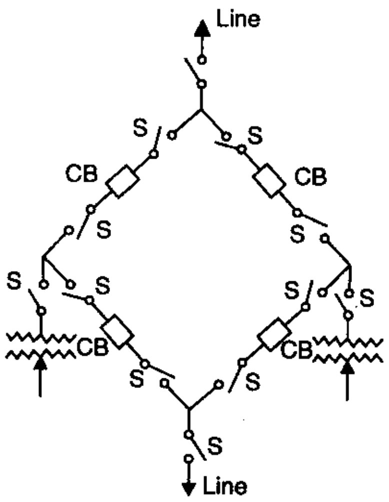


Fig. 12.116. Ring busbar system.

12.10. VOLTAGE REGULATION

For the satisfactory operation of a power system it is essential to *maintain the supply voltage within narrow limits*. In this connection there are some legal requirements. To achieve this purpose following methods are adopted :

1. Voltage control by generator excitation 2. Tap changing transformers
3. Booster transformer.

1. **Voltage control by generator excitation.** In several cases, especially in short lines, the voltage at the receiving end is kept within very narrow limits *by automatic or hand operated voltage regulators,* which act in the field circuit of the alternator excited. This method is, however, unsuitable for long lines.

The effect of *varying the excitation* depends upon the system into which the generator is feeding but in all cases the power output in unaffected as this depends on the fuel supply to the prime mover. In an interconnected system, in which there are two or more alternators, the distribution of load is unchanged by varying the voltage by excitation ; but the reactive kVA can be changed. The sharing of the load, off course, is determined by the regulation of the governor of the prime movers.

2. **Tap changing transformers.** In this case the variation of voltage is achieved by having a number of tappings on the secondary winding so that *turn-ratio can be changed as per requirement.* It can be done either manually or automatically depending upon the specific application and requirements.

3. **Booster transformer.** Booster transformers are installed immediately before the load where regulation is required. This booster system has the following *advantages* :

(*i*) It is independent of the main transformer so that a failure in the former will not throw the later out of service for any length of time.

(*ii*) It is much cheaper method when there is no main transformer at the point where regulation is desired.

Some other methods of regulation are :

(*i*) Phase angle control

(*ii*) Use of induction regulator, and

(*iii*) Voltage control by power factor.

12.11. TRANSMISSION OF ELECTRIC POWER

12.11.1. Systems of Transmission

For transmission of electrical power three-phase circuits are generally used because of economical reasons. Transmission lines may be classified as follows :

1. Single line
2. Parallel lines
3. Radial lines
4. Ring system
5. Network.

1. **Single line.** The simplest form is the single line, such as obtained from a power plant supplying its entire output to one load centre over a single-circuit line. Such a system has the *disadvantage* that in case of damage to the line the service is *interrupted.* Its use is more or less confined to small power systems and is therefore becoming more and more uncommon.

2. **Parallel lines.** Where continuity of service is necessary, it is best to use at least two circuits in parallel, placed either on the same supports or on separate supports. *Separate supports afford greater safety* against both lines being damaged at the same time, but the cost is much higher than when two circuits are placed on one support. In some cases, where very large quantities of power must be handled, more than two circuits may be run in parallel.

3. **Radial lines.** Invariably a power plant or substation supplies power to the neighbouring territory by means of radial lines. These radial lines may be either single circuit for the less important loads or double circuit for the more important loads.

4. **Ring system.** For *systems covering a large territory* the ring system of transmission is very important. With this system the main high-voltage power line makes a closed ring, taps being taken off at any advantageous point of the ring, thus supplying a large territory. In case of damage to any section of the ring, that section may be disconnected for repairs, and power will be supplied from both ends of the rings, thereby maintaining continuity of service.

5. **Network.** A network often constitutes several ring systems with sections of single, parallel, or radial lines.

12.11.2. Line Supports

Electrical power may be transmitted by overhead or underground conductors. Underground transmission, with the exception of a few notable cases, is limited to voltage less than 45,000 volts.

The supports for the overhead transmission lines may be of any one of the following classes :

1. Poles
2. Towers

1. **Poles.** Poles may be made of materials like *wood*, steel, cement concrete etc. Usually R.C.C. poles are used. Fig. 12.117 and 12.118 show the wooden poles and R.C.C. poles respectively.

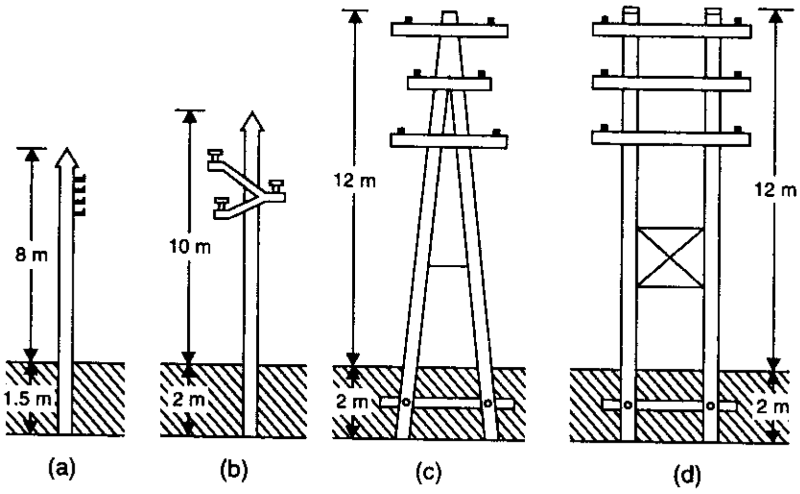


Fig. 12.117. Wooden poles : (*a*) 400 V, 4-phase, 4-wire distributor, (*b*) 11 kV, 3-phase feeder, (*c*) 'A' pole, double circuit, 33 kV feeder, (*d*) 'H' pole double circuit 33 kV feeder.

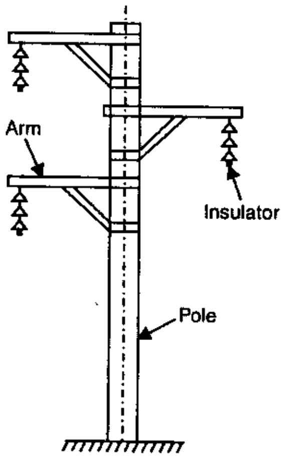


Fig. 12.118. R.C.C. pole.

2. **Towers.** Towers made of steel are mechanically sturdy and durable and are commonly used. These towers (steel) have been shown in Fig. 12.119 and Fig. 12.120. These towers are generally four legged, each leg anchored properly.

The line supports discussed above should have the following *characteristics* :

(*i*) High mechanical strength (*ii*) Cheap in cost
(*iii*) Light in weight (*iv*) Longer life
(*v*) Good looking
(*vi*) Easy accessible for painting and erection of line conductors
(*vii*) Low maintenance cost.

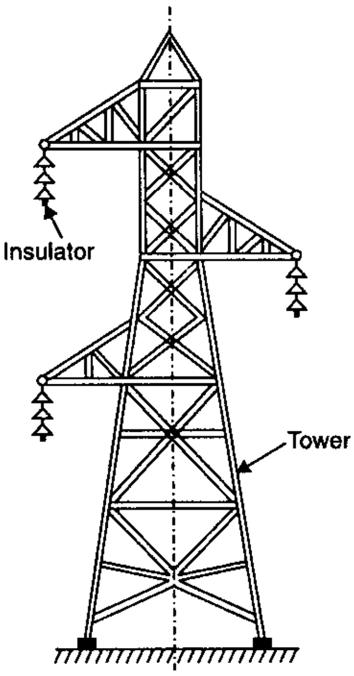


Fig. 12.119

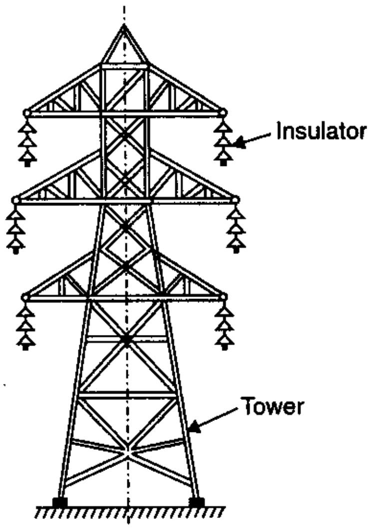


Fig. 12.120

12.11.3. Conductor Material

Electric power conductors are generally of the following materials : copper, aluminium and steel or some combination of these three metals. In some cases special alloys have been used. From a conductivity point of view, copper is the best conductor material, aluminium being second, and steel last. *Commercial conductors* are made in several forms, namely :

(*i*) Solid hard-drawn copper (*ii*) Stranded copper
(*iii*) Hollow copper conductor, stranded (*iv*) Hollow copper conductor, segmental
(*v*) Copperweld copper (*vi*) Aluminium stranded, steel cored.

12.11.4. Line Insulators

The insulators of a transmission line are its most important item, since the operation of a line cannot be any better than the insulators that support the conductors. Transmission line insulators must possess *good mechanical strength and good insulating qualities under all conditions of weather and temperature and must not deteriorate fast.* Insulators are made of *glass, porcelain,* and *patented* *compounds*. Glass is the cheapest material and when properly made will produce satisfactory insulators for low-voltage work, such as telephone and telegraph, and under favourable conditions may be used upto 25,000 volts. Though there are a number of patented compounds on the market, these do not seem to offer much competition with porcelain, since *porcelain has very good electrical characteristics as well as high mechanical strength.*

Transmission line insulators may be classified as follows :

1. Pin type
2. Suspension type
3. Strain type.

- For *low voltages, pin-type insulators* made of glass are generally used. Pin-type insulators made of porcelain are designed for voltages upto about 90,000 volts but are seldom used on lines above 66,000 volts.
- For voltages above 66,000 volts it is generally desirable to use *suspension insulators.*
- *Strain insulators* may be of pin or suspension type. Upto about 30,000 volts pin-type insulators are satisfactory, but for higher voltages the suspension type is generally used. *Strain insulators are used on dead-end towers at bends or corners of transmission lines, or when making very long spans.* Extra heavy suspension units are made for such service, but often standard units may be used. On ordinary straight line dead-end towers a single strings is often sufficient but for severe service two more strings may be connected in parallel.

12.11.5. Distribution Systems

Oftenly it is impossible to draw a line between the distribution and transmission systems of a large power network. In general, *distribution systems comprise that part of the network of a power system which distributes power for local use.*

Distribution systems may be classified as follows :

1. **Nature of current**
   - (*i*) Direct current
     - (*a*) Two wire
     - (*b*) Three wire
   - (*ii*) Alternating current.
2. **Method of connections**
   - (*i*) Series
     - (*a*) Open loop
     - (*b*) Parallel loop
     - (*c*) Combination of open and parallel loops
   - (*ii*) Multiple
     - (*a*) Three system
     - (*b*) Feeder and main
     - (*c*) Network
     - (*d*) Loop system
     - (*e*) Ring system.
3. **Number of phases**
   - (*i*) Single
     - (*a*) Two wire
     - (*b*) Three wire
   - (*ii*) Two
     - (*a*) Three wire
     - (*b*) Four wire
     - (*c*) Five wire
   - (*iii*) Three
     - (*a*) Three wire
     - (*b*) Four wire

4. **Mounting**

(*i*) Overhead (*ii*) Underground

5. **Voltage** : 115/230, 550, 1100, 2200, 6600, 11000, 12000, 13200, 32000 V.

12.11.6. Underground Cables

Underground cables consist of one or more conductors properly insulated, all surrounded by a lead sheath, which excludes air and moisture and also acts as a protecting cover.

Cables for underground service may be classified as follows :

1. **Number of conductors**

(*i*) Single conductor (*ii*) Multiconductor

2. **Arrangement of conductors**

(*i*) Single (*ii*) Sector

(*iii*) Concentric

3. **Number of phases**

(*i*) Single phase (*ii*) Polyphase

4. **Type of insulation**

(*i*) Rubber (*ii*) Varnished cambric

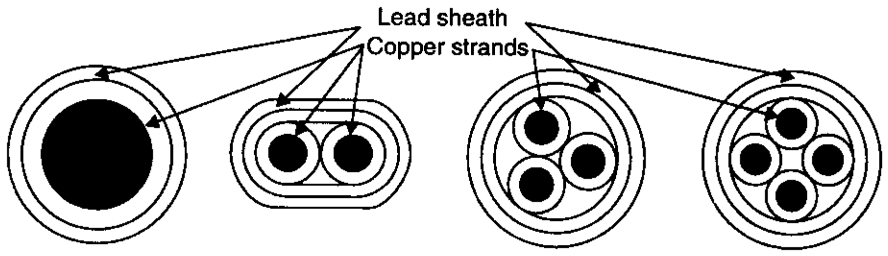
(*iii*) Oiled paper (*iv*) Graded

(*v*) Oil filled

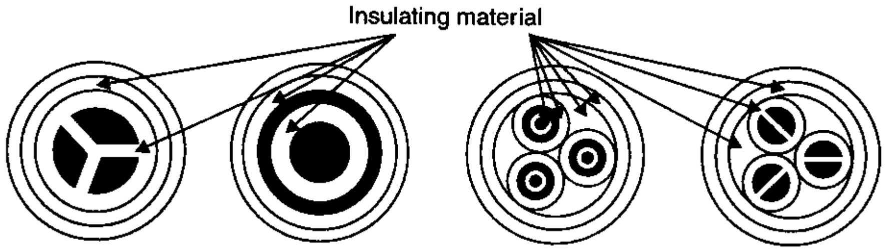
5. **Special features, split conductor**

(*i*) Concentric (*ii*) D-shaped

Fig. 12.121 shows the different types of underground cables.



(a) Single conductor (b) Two conductor (c) Three conductor (d) Four conductor



(e) Sector-type three conductor (f) Two conductor concentric (g) Three concentric split conductor (h) Three D-shaped split conductor

Fig. 12.121. Diagram illustrating different types of underground cables.

Advantages of underground power transmission systems :

1. Low maintenance cost.
2. Susceptible to less number of faults.
3. It is easier to transmit power in densely populated areas.

Advantages of Over-head power transmission systems :

1. Over-head lines can be easily repaired.
2. It is cheaper to transmit power by over-head lines than underground cables.
3. Insulation of over-head lines is easier.

12.12. SUBSTATIONS

The substations *serve as sources of energy supply* for local areas of distribution in which these are located. Their main *functions* are :

(*i*) To *receive energy transmitted at high voltage* from the generating stations,
(*ii*) To *reduce the voltage* to a value appropriate for local distribution, and
(*iii*) To provide facilities for *switching.*

Substations have some *additional functions. They provide points where safety devices may be installed to disconnect equipment or circuit in the event of fault.* A substation is convenient place for installing synchronous condensers at the end of transmission line for the purpose of improving power factor and make measurements to check the operations of various parts of the power system. Street lighting equipment as well as switch control for street lights can be installed in a substation.

Some substations are simply *switching stations* where different connections between various transmission lines are made, others are *converting substations* which convert either A.C. to D.C. or *vice versa* or convert frequency from higher to lower or *vice versa.*

12.12.1. Classification of Substations

The substations may be classified as follows :

A. According to service

1. Transformer substations
   (*i*) Transmission and primary substations
   (*ii*) Sub-transmission or secondary substations
   (*iii*) Distribution substations.
2. Industrial substations
3. Switching substations
4. Power factor correction or synchronous substations
5. Frequency charger substation
6. Converting substations

B. According to design

1. Indoor type substations
2. Outdoor substations
   (*i*) Pole mounted substations (*ii*) Foundation mounted substations.

12.12.1.1. Indoor substations

According to construction indoor distribution transformer substations and high voltage switch boards are further subdivided as follows :

1. **Substations of the integrally built type**

In such substations the apparatus is installed on site. The all structures are constructed of concrete or brick.

2. **Substations of the composite built up type**

Here the assemblies and parts are factory or workshop fabricated, but are assembled on site within a substation switchgear room. The components of such substations take form of metal cabinets or enclosures, each of which contains the equipment of one main connection cell. Within such cabinets or enclosures an oil circuit breaker, a load interrupter switch, one or more voltage transformers may be mounted.

3. **Unit type factory fabricated sub-stations and metal clay switch boards**

These are built in electrical engineering workshops and are shipped to the rite of installation fully pre-assembled. After installation of sub-stations switch board only connection to the incoming and outgoing power circuits are required to be made.

12.12.1.2. Outdoor substations

These are of the following two types :

1. **Pole-mounted substations**

These substations are erected for mounting distribution transformers of capacity upto 300 kVA. Such substations are *cheapest, simple* and *smallest of substations*. All the equipment is of outdoor type and mounted on the supporting structure of high tension distribution line. Triple Pole Mechanically Operated (T.P.M.O.) switch is used for switching "*on*" and "*off*" of high tension transmission line. Lightning arrestors are installed over the high tension line to protect the high tension line to protect the transformer from the surges.

Substation is earthed at two or more places. Generally transformers upto 125 kVA are mounted on double pole structure and for transformers of capacity above 125 kVA but not exceeding 300 kVA, 4-pole structure with suitable plateform is used.

The pole-mounted substation is erected in very thickly populated location. The *maintenance cost* of such substations is *low* and by using a large number of substations in a town it is possible to lay the distributors, at a lower cost.

2. **Foundation mounted substations**

Such substations are built entirely in the open and all the equipment is assembled into one unit usually enclosed by a fence from the point of view of safety.

Substations for primary and secondary transmission and for secondary distribution (above 300 kVA) are foundation mounted outdoor type. Since equipment required for such substations is heavy, therefore, site selected for these substations must have a good access for heavy transport.

The switch gear consists of circuit breakers of suitable type on both the sides but with the increased reliability of the modern transformers, the practice is to dispense with the circuit breaker on the incoming side from the economic consideration. The isolating switches thus serve the purpose.

While selecting the sites for such substations the following factors should be given due considerations :

1. Nearness to the load centres of distribution areas.
2. Availability of land.
3. Cost of land.
4. Local zoning laws.
5. Future load growth.