IMPROVEMENT TEST SOLUTION

1.

19.15 Sulphur Hexaflouride (SF_6) Circuit Breakers

In such circuit breakers, sulphur hexaflouride (SF_6) gas is used as the arc quenching medium. The SF_6 is an electro-negative gas and has a strong tendency to absorb free electrons. The contacts of the breaker are opened in a high pressure flow of SF_6 gas and an arc is struck between them. The conducting free electrons in the arc are rapidly captured by the gas to form relatively immobile negative ions. This loss of conducting electrons in the arc quickly builds up enough insulation strength to extinguish the arc. The SF_6 circuit breakers have been found to be very effective for high power and high voltage service.

Construction. Fig. 19.11 shows the parts of a typical SF_6 circuit breaker. It consists of fixed and moving contacts enclosed in a chamber (called arc interruption chamber) containing SF_6 gas. This chamber is connected to SF_6 gas reservior. When the contacts of breaker are opened, the valve mechanism permits a high pressure SF_6 gas from the reservoir to flow towards the arc interruption chamber. The fixed contact is a hollow cylindrical current carrying contact fitted with an arc horn. The moving contact is also a hollow cylinder with rectangular holes in the sides to permit the SF_6 gas to let out through these holes after flowing along and across the arc. The tips of fixed contact, moving contact and arcing horn are coated with copper-tungsten arc resistant material. Since SF_6 gas is costly, it is reconditioned and reclaimed by suitable auxiliary sytem after each operation of the breaker.

Working. In the closed position of the breaker, the contacts remain surrounded by SF_6 gas at a pressure of about 2·8 kg/cm^2. When the breaker operates, the moving contact is pulled apart and an arc is struck between the contacts. The movement of the moving contact is synchronised with the opening of a valve which permits SF_6 gas at 14 kg/cm^2 pressure from the reservoir to the arc interruption chamber. The high pressure flow of SF_6 rapidly absorbs the free electrons in the arc path to form immobile negative ions which are ineffective as charge carriers. The result is that the medium between the contacts quickly builds up high dielectric strength and causes the extinction of the arc. After the breaker operation (*i.e.,* after arc extinction), the valve is closed by the action of a set of springs.

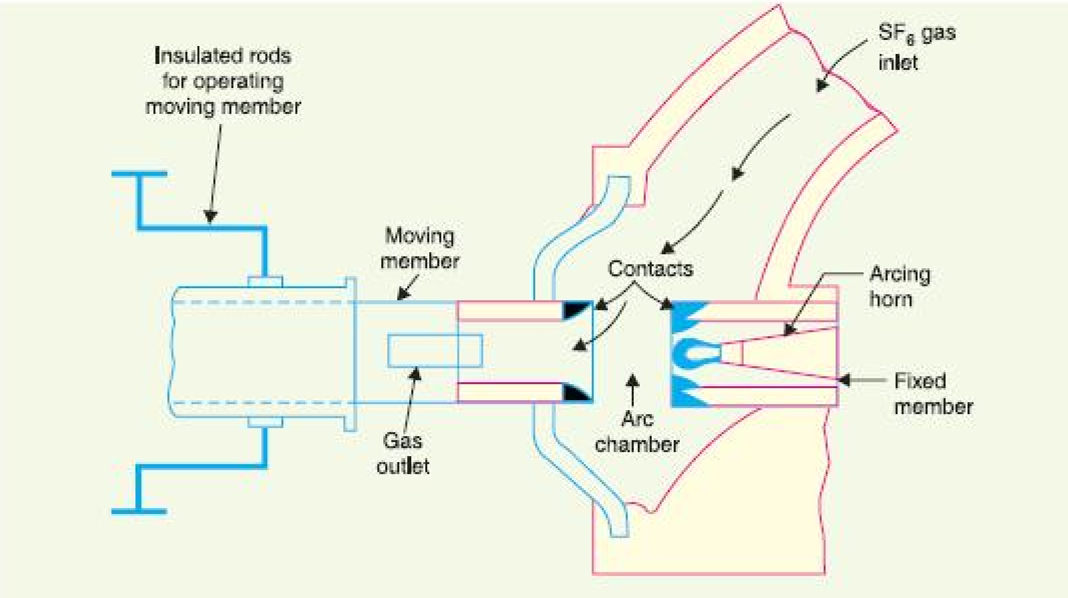


Fig. 19.11

Advantages. Due to the superior arc quenching properties of SF_6 gas, the SF_6 circuit breakers have many advantages over oil or air circuit breakers. Some of them are listed below :

(*i*) Due to the superior arc quenching property of SF_6, such circuit breakers have very short arcing time.

(*ii*) Since the dielectric strength of SF_6 gas is 2 to 3 times that of air, such breakers can interrupt much larger currents.

(*iii*) The SF_6 circuit breaker gives noiselss operation due to its closed gas circuit and no exhaust to atmosphere unlike the air blast circuit breaker.

(*iv*) The closed gas enclosure keeps the interior dry so that there is no moisture problem.

(*v*) There is no risk of fire in such breakers because SF_6 gas is non-inflammable.

(*vi*) There are no carbon deposits so that tracking and insulation problems are eliminated.

(*vii*) The SF_6 breakers have low maintenance cost, light foundation requirements and minimum auxiliary equipment.

(*viii*) Since SF_6 breakers are totally enclosed and sealed from atmosphere, they are particularly suitable where explosion hazard exists *e.g.,* coal mines.

Disadvantages

(*i*) SF_6 breakers are costly due to the high cost of SF_6.

(*ii*) Since SF_6 gas has to be reconditioned after every operation of the breaker, additional equipment is requried for this purpose.

Applications. A typical SF_6 circuit breaker consists of interrupter units each capable of dealing with currents upto 60 kA and voltages in the range of 50—80 kV. A number of units are connected in series according to the system voltage. SF_6 circuit breakers have been developed for voltages 115 kV to 230 kV, power ratings 10 MVA to 20 MVA and interrupting time less than 3 cycles.

2.

18.6 DIRECT TESTING

The direct testing of circuit breakers in a plant enables us to test under conditions largely representing those in actual network as well as tests of greater severity. The circuit breaker to be tested is subjected to the value of transient restriking voltage to which it is expected to be put in practice rather than testing it under most severe conditions. Value of the transient restriking voltage is adjusted by means of R, L and C, the constants of the circuit.

The circuit for direct testing is shown in Fig. (18.3). After making the preliminary adjustments of the constants, etc., the contacts on the sequence switch are adjusted to get desired timings. The oscillographs are also adjusted and calibrated. The operations of test follow automatically by means of sequence switch as already mentioned.

The various tests carried out for circuit breakers are described below:

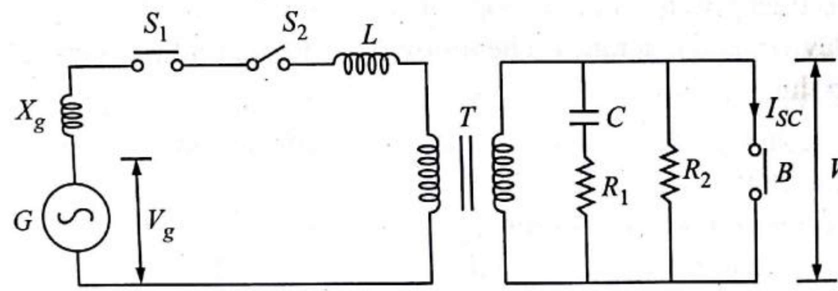


Figure 18.3: Circuit for direct testing: V_g—generator voltage; V_B—voltage across test breaker; I_{SC}—short-circuit current; X_g—generator reactance; S_1—master breaker; S_2—make switch; L—current control reactor; T—transformer; B—breaker under test; C, R_1, R_2—capacitance, resistance for adjusting the transient restriking voltage; G—short-circuit generator

18.6.1 Making Capacity

The master circuit breaker and the make switch are closed first, then the breaker under test is closed on a three-phase short-circuit. The making current is determined as explained in Chapter 14. This is a peak value of the first major loop of the current wave after the instant of contact make when current starts to flow. The measurement is made from the current zero line to the peak of the wave.

18.6.2 Breaking Capacity

The master circuit breaker and the breaker under test are closed first, short-circuit is applied by closing the make switch. The breaker under test is opened at desired moment and the following values are measured from the oscillogram as explained in Chapter 14.

(*a*) Recovery voltage obtained during the test.
(*b*) Symmetrical breaking current.
(*c*) Asymmetrical breaking current.
(*d*) Amplitude factor, natural frequency and RRRV.

18.6.3 Duty Cycle Tests

Unless the rated operating duty as marked on the name plate differs from that specified, it shall consist of the following test duties:

Test duty (1) B–3′–B–3′–B at 10% of rated symmetrical breaking capacity.

Test duty (2) B–3′–B–3′–B at 30% of rated symmetrical breaking capacity.

Test duty (3) B–3′–B–3′–B at 60% of rated symmetrical breaking capacity.

Test duty (4) B–3′–MB–3′–MB at not less than 100% of rated symmetrical breaking capacity and not less than 100% of rated making capacity. Test duty (4) may be performed as two separate duties as follows.

Test duty (4*a*) M–3′–M (Make test)

Test duty (4*b*) B–3′–B–3′–B (Break test)

Test duty (5) B–3′–B–3′–B at not less than 100% rated asymmetrical breaking capacity.

B and M in the above duty cycle denote break and make operations respectively. MB denotes a making operation followed by a breaking operation without any intentional time lag. 3′ denotes the time in minutes between successive operations of an operating duty.

18.6.4 Short-time Current Tests

Good contact should be maintained in spite of forces produced by the short-circuit current so as to avoid welding. The heat generated by the short-circuit current over the period of the test (1 sec or 3 sec) should not cause damage to any insulation in contact with the current carrying parts. When the breaker has cooled down to the ambient temperature, it should be capable of carrying full-load current continuously without excessive temperature rise.

The breaker is tested for this by means of a separate high current and low voltage transformer. The current is measured by electromagnetic oscillograph. The equivalent steady rms value of current during a short-circuit is evaluated as follows. Referring to Fig. (18.4) which illustrates a short-time current carrying test short-circuit duration is divided into ten equal parts. The asymmetrical rms value of the current at each of these eleven instants of time is calculated by the same method as that of breaking current. If these currents are $I_0, I_1, \ldots, I_{10}$. The equivalent steady rms value of current during the time or is given by Simpson formula.

$$I = \sqrt{\tfrac{1}{3}\left\{I_0^2 + 4\left(I_1^2 + I_3^2 + I_5^2 + I_7^2 + I_9^2\right) + 2\left(I_2^2 + I_4^2 + I_6^2 + I_8^2 + I_{10}^2\right)\right\}}$$

3.

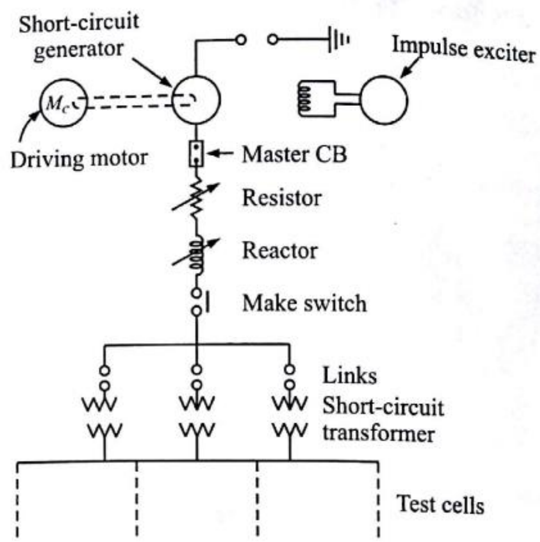


Figure 18.1: Basic circuit of short-circuit test plant

for closing on very heavy currents, but never called on to break currents. Synchronized closing is controlled by means of a small pilot generator coupled to the generator shaft and can be very accurately set to occur at any instant within the voltage wave. In this way the phase position at the commencement of short-circuit can be selected and a short-circuit current either fully symmetrical or with any degree of symmetry can be produced. In order to avoid unnecessary destruction in the event of failure of circuit breaker under test, the master circuit breaker is provided as a backup protection and opens. The testing stations are of very compact design with short connection for short-circuit so that the generator output may be utilized to full extent. They have very high natural frequency and by adding capacitors any desired frequency can be obtained. The breaker to be tested is enclosed in a test cell made of reinforced concrete having a provision of observation while test is in progress.

The recording equipment is located in a control room which is suitably remote from the test cell but situated so as to allow the test breaker to be observed. The control operations are carried out from the control room.

18.4 EQUIPMENTS USED IN THE STATION

18.4.1 Short-Circuit Generator

This is of a special design having very low reactance in order to give the maximum short-circuit output. The leakage reactance is reduced by reducing the depth of slots and the length of coil ends. The terminals are brought to a board where different connections can be made. Each winding in a phase is divided in two halves which can be connected either in series or parallel. The three windings in turn can be connected in star or delta to give different terminal voltages.

Due to heavy electrodynamic forces involved the generator foundation is specially designed and is isolated by means of materials like cork, neoprene and thermocole in order to prevent the vibrations being transmitted to the other parts of the building. The windings are also specially braced and made rugged. The short-circuit generator is provided with closed circuit aircooling. The cooling equipment consists of axial flow fans and air/water coolers. The generator is driven by a three-phase induction motor connected through a resilient shaft. The generator is equipped with a built-in flywheel which provides the kinetic energy during short-circuit and speed regulation of the set.

18.4.2 Impulse Excitation

Normal excitation is supplied by the main exciter coupled to the test set, although the main generator is equipped with a damper winding, impulse excitation or super excitation is provided to counteract the demagnetizing effect of armature reaction. The short-circuit currents which are at lagging power factor have demagnetizing effect. This results in a reduction of total field, hence in reduced induced emf. As a result recovery voltage is less than the voltage before short-circuit. It is overcome by shorting out a resistor in the generator field circuit, a moment before the short-circuit, resulting in a surge of field current 8 to 10 times its normal value. This takes care of the demagnetizing effect of short-circuit current and gives desired recovery voltage.

18.4.3 Pilot Generator

This is a small three-phase synchronous generator directly coupled to the main shaft of the short-circuit generator and synchronized in phase with the latter. Any present voltage is maintained constant by an automatic voltage regulator during short-circuit tests. This dependable voltage is necessary to supply control power to the sequence timer, electromagnetic oscillograph and various other actuating circuits for conducting the test.

18.4.4 Short-Circuit Transformers

These transformers are designed to withstand repeated short-circuits and their windings are often arranged in sections for voltage adjustment in series and parallel combinations. The leakage reactance of the short-circuit transformer is kept low. For stepping down the voltage to lower values a three-phase transformer is normally used. For voltages higher than the generated voltage the normal practice is to use banks of single-phase transformers. Depending on the type of test to be carried out in the test cells, different types and ratings of transformers are connected in different cells, *e.g.*, a high voltage testing transformer in one and a low voltage high current transformer in the other.

18.4.5 Resistors and Reactors

For regulation of the short-circuit test current, three-phase banks of resistor and reactor are used. The reactor being used to adjust the magnitude and the resistor to control the rate of decay of the d.c. component of current. The short-circuit power factor is also controlled by this means. There are a number of coils per phase and by connecting them in series parallel combinations many variations can be obtained.

18.4.6 Master Circuit Breaker

It has been provided mainly as a backup circuit breaker. If the object under test fails the current will be interrupted by the master breaker. This is normally an air-blast type, of capacity more than the breakers under test. This is set to open at a predetermined time after the initiation of the short-circuit and must be capable of clearing faults up to the highest level of each generator or other power source and have a substantial margin of safety.

18.4.7 Make Switch

The short-circuit is applied by this switch, which makes an exceptionally high short-circuit current surge from the generator at a predetermined point of the voltage wave. At the moment of making, the backup circuit breaker and the test circuit breaker are already closed. As such on closure if there is even a slight contact rebound the contacts might get burnt or even welded together. In order to ensure, that the contact separation is minimum on closure, a high air pressure is maintained in the chamber. The closing speed is also so high that the contacts are fully closed before the short-circuit current reaches its peak value.

18.4.8 Capacitors

These are used for two purposes:

(*a*) *Capacitive breaking*, which normally occurs in case of line charging duty.
(*b*) *Controlling* the rate of rise of restriking voltage given by

$$f_n = \frac{1}{2\sqrt{LC}}$$

In synthetic testing and other indirect tests, capacitors are an important element of the test circuit. These are single-phase banks and can be connected in series or parallel as desired, both individually and in any combination of the three.

18.4.9 Test Cells

Covered bays are provided for testing circuit breakers. These bays are box shaped structures of reinforced concrete with an open front facing the control and observation rooms. Separate test bays are provided for testing LV; HV and EHV circuit breakers. The test cells are supplied with compressed air and oil purification system to facilitate testing of air-blast circuit breakers and oil circuit breakers. Each test cell has got an end box where control and measuring cables are terminated.

18.4.10 Test Control Room

It is situated nearly at a distance of 20 m from test cells. It is provided with a control desk for remote control operation of the excitation of the short-circuit generators, etc. there are also an oscillograph, distribution panel, an electromagnetic oscillograph; a CRO, an electric sequence switch and an electronic sequence switch.

4.

19.11 Low Oil Circuit Breakers

In the bulk oil circuit breakers discussed so far, the oil has to perform two functions. Firstly, it acts as an arc quenching medium and secondly, it insulates the live parts from earth. It has been found that only a small percentage of oil is actually used for arc extinction while the major part is utilised for insulation purposes. For this reason, the quantity of oil in bulk oil circuit breakers reaches a very high figure as the system voltage increases. This not only increases the expenses, tank size and weight of the breaker but it also increases the fire risk and maintenance problems.

The fact that only a small percentage of oil (about 10% of total) in the bulk oil circuit breaker is actually used for arc extinction leads to the question as to why the remainder of the oil, that is not immediately surrounding the device, should not be omitted with consequent saving in bulk, weight and fire risk. This led to the development of low-oil circuit breaker. A low oil circuit breaker employs solid materials for insulation purposes and uses a small quantity of oil which is just sufficient for arc extinction. As regards quenching the arc, the oil behaves identically in bulk as well as low oil circuit breaker. By using suitable arc control devices, the arc extinction can be further facilitated in a low oil circuit breaker.

Construction. Fig 19.7 shows the cross section of a single phase low oil circuit breaker. There are two compartments separated from each other but both filled with oil. The upper chamber is the circuit breaking chamber while the lower one is the supporting chamber. The two chambers are separated by a partition and oil from one chamber is prevented from mixing with the other chamber. This arrangement permits two advantages. Firstly, the circuit breaking chamber requires a small volume of oil which is just enough for arc extinction. Secondly, the amount of oil to be replaced is reduced as the oil in the supporting chamber does not get contaminated by the arc.

(*i*) *Supporting chamber.* It is a porcelain chamber mounted on a metal chamber. It is filled with oil which is physically separated from the oil in the circuit breaking compartment. The oil inside the supporting chamber and the annular space formed between the porcelain insulation and bakelised paper is employed for insulation purposes only.

(*ii*) *Circuit-breaking chamber.* It is a porcelain enclosure mounted on the top of the supporting compartment. It is filled with oil and has the following parts :

(*a*) upper and lower fixed contacts
(*b*) moving contact
(*c*) turbulator

The moving contact is hollow and includes a cylinder which moves down over a fixed piston. The turbulator is an arc control device and has both axial and radial vents. The axial venting ensures the interruption of low currents whereas radial venting helps in the interruption of heavy currents.

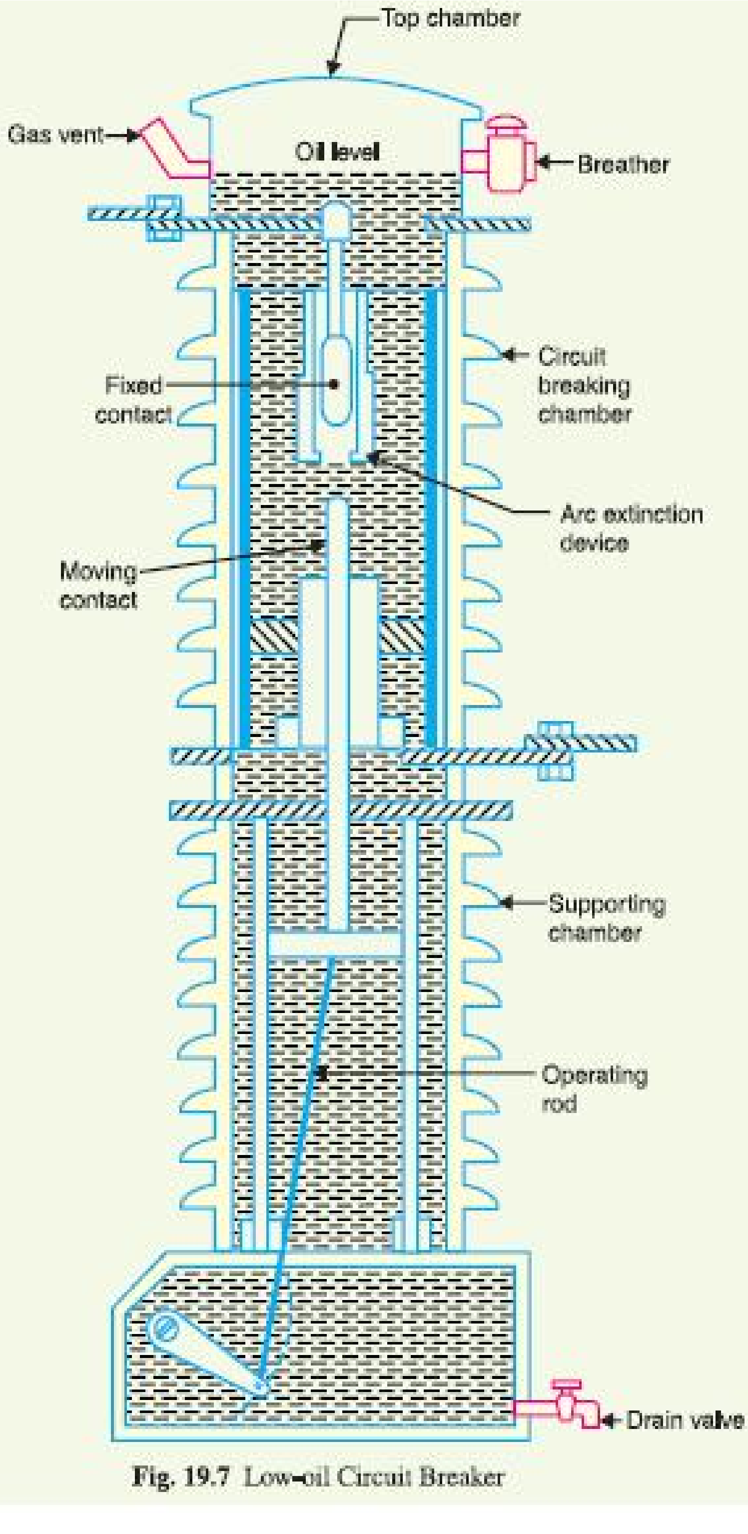


Fig. 19.7 Low-oil Circuit Breaker

(*iii*) *Top chamber.* It is a metal chamber and is mouted on the circuit-breaking chamber. It provides expansion space for the oil in the circuit breaking compartment. The top chamber is also provided with a separator which prevents any loss of oil by centrifugal action caused by circuit breaker operation during fault conditions.

Operation. Under normal operating conditions, the moving contact remains engaged with the upper fixed contact. When a fault occurs, the moving contact is pulled down by the tripping springs and an arc is struck. The arc energy vaporises the oil and produces gases under high pressure. This action constrains the oil to pass through a central hole in the moving contact and results in forcing series of oil through the respective passages of the turbulator. The process of turbulation is orderly one, in which the sections of the arc are successively quenched by the effect of separate streams of oil moving across each section in turn and bearing away its gases.

Advantages. A low oil circuit breaker has the following advantages over a bulk oil circuit breaker:

(*i*) It requires lesser quantity of oil.
(*ii*) It requires smaller space.
(*iii*) There is reduced risk of fire.
(*iv*) Maintenance problems are reduced.

Disadvantages. A low oil circuit breaker has the following disadvantages as compared to a bulk oil circuit breaker :

(*i*) Due to smaller quantity of oil, the degree of carbonisation is increased.
(*ii*) There is a difficulty of removing the gases from the contact space in time.
(*iii*) The dielectric strength of the oil deteriorates rapidly due to high degree of carbonisation.

5.

21.13 Induction Type Directional Overcurrent Relay

The directional power relay discussed above is unsuitable for use as a directional protective relay under short-circuit conditions. When a short-circuit occurs, the system voltage falls to a low value and there may be *insufficient torque developed in the relay to cause its operation. This difficulty is overcome in the directional overcurrent relay which is designed to be almost independent of system voltage and power factor.

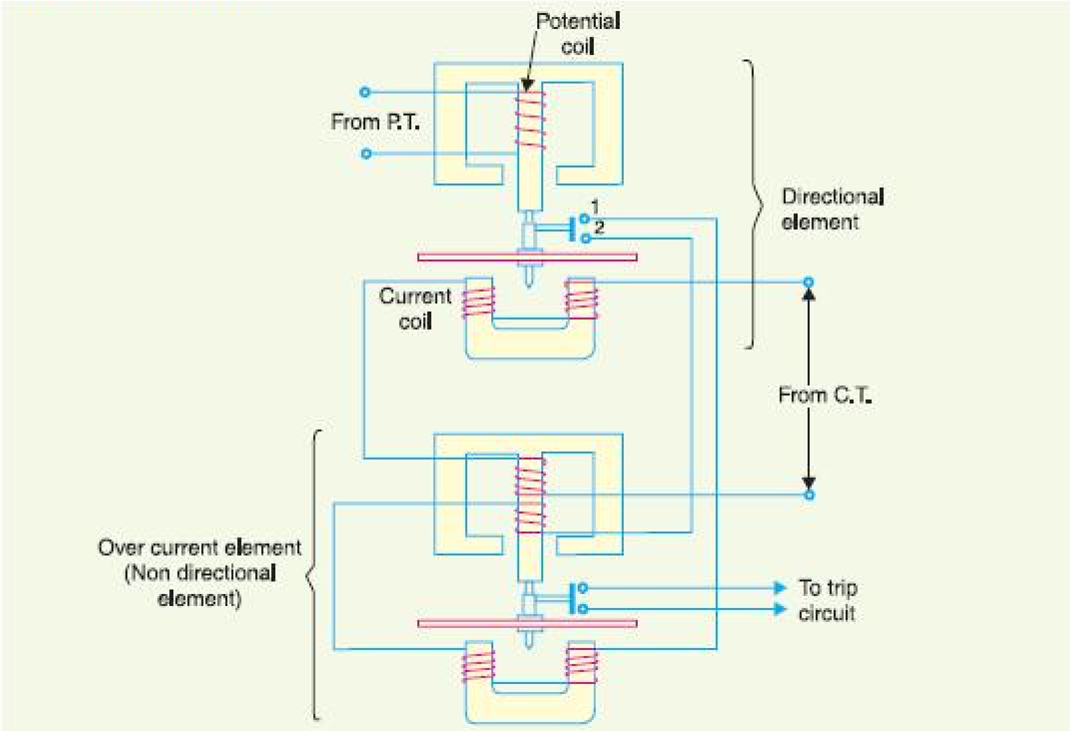


Fig. 21.19

* Directional power relay being of wattmeter type, the driving torque on the disc also depends upon the system voltage.

Constructional details. Fig. 21.19 shows the constructional details of a typical induction type directional ovecurrent relay. It consists of two relay elements mounted on a common case *viz.* (*i*) directional element and (*ii*) non-directional element.

(*i*) *Directional element.* It is essentially a directional power relay which operates when power flows in a specific direction. The potential coil of this element is connected through a potential transformer (P.T.) to the system voltage. The current coil of the element is energised through a C.T. by the circuit current. This winding is carried over the upper magnet of the non-directional element. The trip contacts (1 and 2) of the directional element are connected in series with the secondary circuit of the overcurrent element. Therefore, the latter element cannot start to operate until its secondary circuit is completed. In other words, the directional element must operate first (*i.e.* contacts 1 and 2 should close) in order to operate the overcurrent element.

(*ii*) *Non-directional element.* It is an overcurrent element similar in all respects to a non-directional overcurrent relay described in Art. 21.11. The spindle of the disc of this element carries a moving contact which closes the fixed contacts (trip circuit contacts) after the operation of directional element.

It may be noted that plug-setting bridge is also provided in the relay for current setting but has been omitted in the figure for clarity and simplicity. The tappings are provided on the upper magnet of overcurrent element and are connected to the bridge.

Operation. Under normal operating conditions, power flows in the normal direction in the circuit protected by the relay. Therefore, directional power relay (upper element) does not operate, thereby keeping the overcurrent element (lower element) unenergised. However, when a short-circuit occurs, there is a tendency for the current or power to flow in the reverse direction. Should this happen, the disc of the *upper element rotates to bridge the fixed contacts 1 and 2. This completes the circuit for overcurrent element. The disc of this element rotates and the moving contact attached to it closes the trip circuit. This operates the circuit breaker which isolates the faulty section. The two relay elements are so arranged that final tripping of the current controlled by them is not made till the following conditions are satisfied :

(*i*) current flows in a direction such as to operate the directional element.

(*ii*) current in the reverse direction exceeds the pre-set value.

(*iii*) excessive current persists for a period corresponding to the time setting of overcurrent element.

7.

21.5 Induction Relays

Electromagnetic induction relays operate on the principle of induction motor and are widely used for protective relaying purposes involving a.c. quantities. They are not used with d.c. quantities owing to the principle of operation. An induction relay essentially consists of a pivoted aluminium disc placed in two alternating magnetic fields of the same frequency but displaced in time and space. The torque is produced in the disc by the interaction of one of the magnetic fields with the currents induced in the disc by the other.

To understand the production of torque in an induction relay, refer to the elementary arrangement shown in Fig. 21.6 (*i*). The two a.c. fluxes ϕ_2 and ϕ_1 differing in phase by an angle α induce e.m.f.s' in the disc and cause the circulation of eddy currents i_2 and i_1 respectively. These currents lag behind their respective fluxes by 90°.

Referring to Fig. 21.6 (*ii*) where the two a.c. fluxes and induced currents are shown separately for clarity, let

$$\phi_1 = \phi_{1max} \sin \omega t$$

$$\phi_2 = \phi_{2max} \sin (\omega t + \alpha)$$

where ϕ_1 and ϕ_2 are the instantaneous values of fluxes and ϕ_2 leads ϕ_1 by an angle α.

Assuming that the paths in which the rotor currents flow have negligible self-inductance, the rotor currents will be in phase with their voltages.

$$\therefore \quad i_1 \propto \frac{d\phi_1}{dt} \propto \frac{d}{dt}(\phi_{1max} \sin \omega t)$$

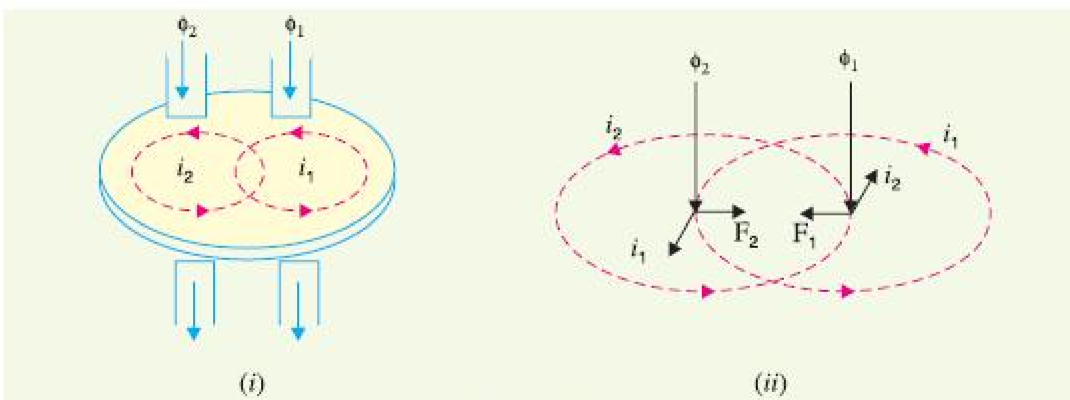


Fig. 21.6

$$\propto \phi_{1max} \cos \omega t$$

and $$i_2 \propto \frac{d\phi_2}{dt} \propto \phi_{2max} \cos (\omega t + \alpha)$$

Now, $$F_1 \propto \phi_1 i_2 \quad \text{and} \quad F_2 \propto \phi_2 i_1$$

Fig. 21.6 (*ii*) shows that the two forces are in opposition.

$\therefore$ Net force F at the instant considered is

$$F \propto F_2 - F_1$$

$$\propto \phi_2 i_1 - \phi_1 i_2$$

$$\propto \phi_{2max} \sin (\omega t + \alpha)\, \phi_{1max} \cos \omega t - \phi_{1max} \sin \omega t\, \phi_{2max} \cos (\omega t + \alpha)$$

$$\propto \phi_{1max}\, \phi_{2max} [\sin (\omega t + \alpha) \cos \omega t - \sin \omega t \cos (\omega t + \alpha)]$$

$$\propto \phi_{1max}\, \phi_{2max} \sin \alpha$$

$$\propto \phi_1\, \phi_2 \sin \alpha \qquad ...(i)$$

8.

(*iii*) *Top chamber.* It is a metal chamber and is mouted on the circuit-breaking chamber. It provides expansion space for the oil in the circuit breaking compartment. The top chamber is also provided with a separator which prevents any loss of oil by centrifugal action caused by circuit breaker operation during fault conditions.

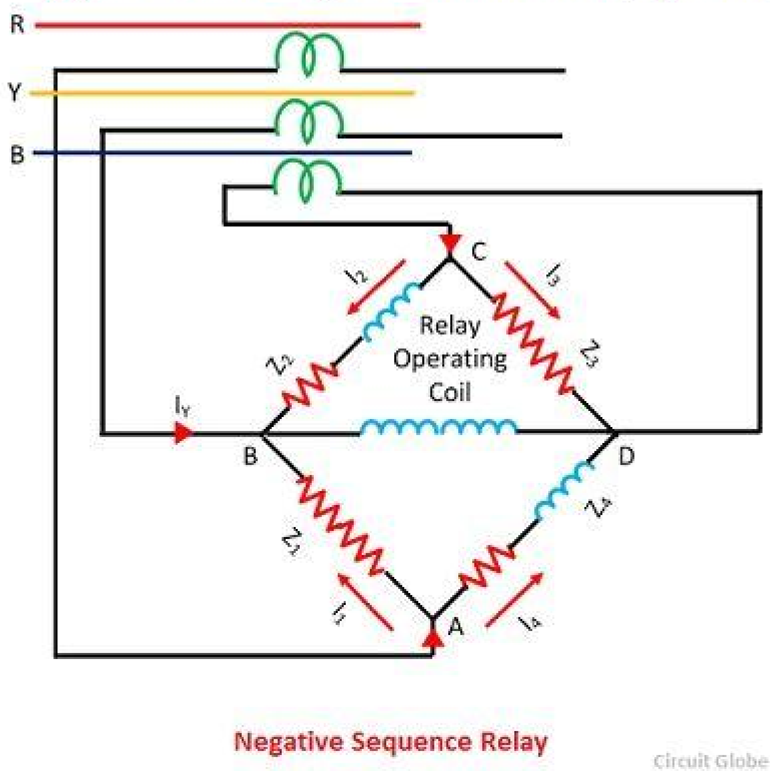
Operation. Under normal operating conditions, the moving contact remains engaged with the upper fixed contact. When a fault occurs, the moving contact is pulled down by the tripping springs and an arc is struck. The arc energy vaporises the oil and produces gases under high pressure. This action constrains the oil to pass through a central hole in the moving contact and results in forcing series of oil through the respective passages of the turbulator. The process of turbulation is orderly one, in which the sections of the arc are successively quenched by the effect of separate streams of oil moving across each section in turn and bearing away its gases.

Advantages. A low oil circuit breaker has the following advantages over a bulk oil circuit breaker:

(*i*) It requires lesser quantity of oil.
(*ii*) It requires smaller space.
(*iii*) There is reduced risk of fire.
(*iv*) Maintenance problems are reduced.

Disadvantages. A low oil circuit breaker has the following disadvantages as compared to a bulk oil circuit breaker :

(*i*) Due to smaller quantity of oil, the degree of carbonisation is increased.
(*ii*) There is a difficulty of removing the gases from the contact space in time.
(*iii*) The dielectric strength of the oil deteriorates rapidly due to high degree of carbonisation.

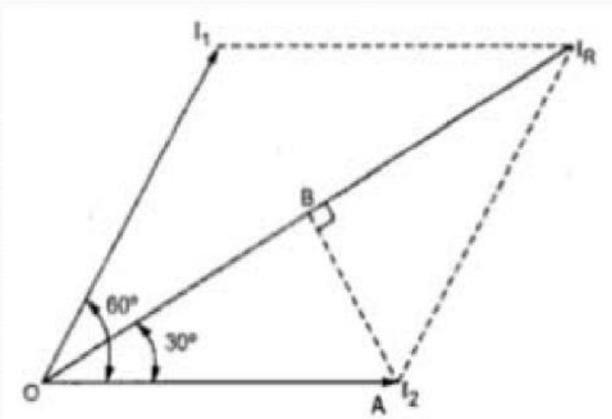


Negative Sequence Relay

CONSTRUCTION:

- It consists of a resistance bridge network.
- The magnitudes of the impedances of all the branches of the network are equal.
- The impedances Z_1 and Z_3 are purely resistive while the impedances Z_2 and Z_4 are the combinations of resistance and reactance.
- The currents in the branches Z_2 and Z_4 lag by 60° from the currents in the branches Z_1 and Z_3.
- The vertical branch B-D consists of inverse time characteristics relay. The relay has negligible impedance.

PHASOR DIAGRAM:



The current I_R gets divided into two equal parts I_1 and I_2. And I_2 lags I_1 by 60°.

$$\bar{I}_1 + \bar{I}_2 = \bar{I}_{rs}$$

Let $$I_1 = I_2 = I$$

The perpendicular is drawn from point A on the diagonal meeting it at point B. This bisects the diagonal.

$\therefore$ $$OB = I_R / 2$$

Now in triangle OAB,

$$\cos 30 = OB/OA$$

$\therefore$ $$\sqrt{3}/2 = (I_R/2)/I$$

$\therefore$ $$I = I_R/\sqrt{3} = I_1 = I_2 \quad ....(1)$$

Now I_1 leads I_R by 30° while I_2 lags I_R by 30°.

Similarly the current I_B gets divided into two equal parts I_3 and I_4. The current I_3 lags I_4 by 60°. From equation (1) we can write,

$$I_B / \sqrt{3} = I_3 = I_4 \quad ....(2)$$

The current I_4 leads by I_B while current I_3 lags I_B by 30°.

The current entering the relay at the junction point B in the Fig. 1 is the vector sum of , and .

$$I_{relay} = \bar{I}_1 + \bar{I}_3 + \bar{I}_Y$$

$$= I_Y + (I_R/\sqrt{3}) \text{ (leads } I_R \text{ by } 30°) + I_B/\sqrt{3} \text{(lags } I_B \text{ by} 30°)$$

- **when the load is balanced and no negative sequence currents exist.**