In low voltage circuits the neutral point of supply should be earthed. In ungrounded systems a single line to ground fault on one line causes increase in voltage of healthy lines with respect of neutral by $\sqrt{3}$ times. This can damage motor insulation.

To avoid this, the neutral point of supply, should be earthed at every voltage level. Cascade failure of motors can occur if supply neutral is not earthed (Ref. Sec. 18.6.2.)

Summary (Refer Table 31.1)

The protection of motor is normally provided along with stator or switchgear.

Contactor starters or circuit-breakers are used for motor switching.

Thermal relays provided overload protection, single phasing protection. This circuit protection is provided by fuses or instantaneous relays. Protection against unbalanced supply voltage is provided by negative phase sequence relays.

H.R.C. fuses are used for short circuit protection of motor. They should be co-ordinated with overload relays.

Abnormal condition is motors include : faults, under voltage, single phasing, unbalanced voltages, overloads etc.

QUESTIONS

1. Describe contactors starter of a three phase induction motor. State what protective measures are provided along with the starter ?
2. Describe the principle of operation of thermal relay used for motor protection.
3. State the various abnormal conditions in a 1200 h.p. Induction motor and protection provided against each.
4. Distinguish between overload protection, short circuit protection and earth fault protection of motor.
5. Explain how to select a fuse for motor. How to co-ordinate it with circuit breaker or contactor?
6. Explain the various methods of short circuit and earth fault protection of motors.
7. Which protections are provided for essential service motors?
8. Discuss the causes of motor failure of both electrical and mechanical origin.
9. In a factory, a 15 kW motor is to be provided with a starter. However a starter for 35 kW motor is readily available in the store. Can this starter be used ? Give technical considerations.
10. It was found that the thermal relays tripped while starting the motor was started without load the thermal relay did not trip. What can be the various causes of tripping during starting?
11. Explain the term "Single Phasing ". In what form the protection is provided in case of
    (*a*) Fractional horse power motor (*b*) Large motor above 150 h.p.
12. State whether correction or wrong. Write corrected statements if necessary.
    — Squirrel-cage motors can fail by rotor insulation failure.
    — In motor protection, thermal relay provide short circuit protection.
    — Phase sequence of supply determines the direction of rotation of motor.
    — Differential protection if provided for 100 h.p. motor.
    — Differential protection does not sense overloading of motors.
    — Undervoltage of supply reduce starting current of motor.

Ref. Sec. 43.7 and 43.8 for static protection scheme for motors.

1. Ref. Sec. 18.12. Protection against switching overvoltages. Vacuum circuit-breakers tend to chop the current giving switching voltage surges. RC surge suppressors are connected with such switchgear to protect motor insulation.

2. Thyristor-control of induction motors gives harmonic contents in the supply wave form. Harmonics cause addition heating in the magnetic circuit. The harmonic content in supply would be within certain limits. The voltage waveform should be sinusoidal with permissible deviation less than 3 per cent suitable harmonic filters should be provided on supply side.

32

Protection of Transformers

General — Protection Chart — Buchholz Relay — Sudden Pressure Relay — Biased Differential or Merz Price Protection — Problems arising in Merz Price System — Harmonic Restraint — Overcurrent Relays — Interlock protection — Restricted earth fault protection — Overfluxing protection — Protection of Arc-furnace transformers — Safety devices.

32.1. PROTECTION REQUIREMENTS

Protective equipment for transformer protection includes gas relays which give an alarm on incipient faults, differential system of protection which gives protection on phase to phase faults plus phase to ground faults, other protective relays, and surge arresters which give protection to the insulation from high voltage surges (Ref. Table 32.1)

A *Through Fault* in one which is beyond the protected zone of the transformer, but fed through the transformer. The unit protection of the transformer (usually differential current protection) should not operate for through faults. The overload relaying may be provided to operate with a time lag to provide back-up protection. Internal faults are those in the protected zone of the transformer. These faults can be between phase-to-phase and phase-to-ground. Generally they result from failure of insulation due to temperature rise or deterioration of transformer oil. Incipient faults are initially minor faults causing gradual damage. These faults grow into serious faults. Incipient fault include loose connections in conducting path, sparking, small arcing, etc.

The faults occurring in power transformers are earth-faults phase-to-phase faults, inter-turns faults and overheating from overloading or from some internal cause such as core-heating. Of these the most common are earth-faults ; inter-turns faults ; but the latter develop rapidly into earth-faults and, therefore, only earth-fault protection is generally provided.

The choice of protection for any given power-transformer depends upon a number of factors, such as its size, importance, and whether it has no-load or off-load tap changer.

The following information is necessary while selecting the protection scheme for a power transformer.

1. Particulars of transformer
   (*a*) kVA (*b*) Voltage ratio
   (*c*) Connections of windings (*d*) Percentage reactance
   (*e*) Neutral point earthing, value of resistance
   (*f*) Value of system earthing resistance
   (*g*) Whether indoor or outdoor, dry or oil filled
   (*h*) With or without conservator.
2. Length and cross-section of connecting leads between CT's and relay panel.
3. Fault level at power transformer terminals.
4. Network diagram showing position of transformer, load characteristics.

The general practice of protection of power transformer is given in Table 32.1.

The faults in transformer can be caused by failure of insulating materials due to dust, moisture, voids weakening of winding due to external short-circuits.

The surge arresters provided at the bus-bars or at transformer terminals spark-over at about 80% of impulse insulation-level of the transformer and protect the transformer against surges. (Ref. Ch. 18).

Table 32.1. Power Transformer Protection

Abnormal condition	*Protection*	*Remarks*
Incipient faults below oil level resulting in decomposition of oil, faults between phases and between phase and ground.	Buchholz relay sounds alarm (Gas actuated relay). Sudden pressure relay Pressure relief valve	Buchholz relay used for transformers of rating 500 kVA and above.
Large internal faults phase-to-phase, phase to-ground, below oil level.	1. Buchholz relay trips the circuit-breaker.	Buchholz relay too slow and less sensitive. Buchholz relay for tapchanger also.
Faults in tap-changer.	2. Percentage differential protection. 3. High speed high set over-current relay.	Percentage differential protection used for transformers of and above 5 MVA.
Saturation of magnetic circuit	1. Over fluxing protection 2. Overvoltage protection	For important generator transformer and feeder transformers.
Earth faults	1. Differential protection.	For transformers of and above 5 MVA.
	2. Earth fault relay.	(*a*) Instantaneous Restricted E.F. Relay. (*b*) Time lag E.F. Relay.
Through faults	1. Graded time lag overcurrent relay	Protection of distribution transformers.
	2. HRC Fuses (Ref. Ch. 14)	Small distribution transformers upto 500 kVA
Overloads	1. Thermal overload relays. 2. Temperature relays sound alarm.	Generally temperature indicators are provided on the transformers. Temp. increase is indicated on control board also. Fans started at certain temp.
High voltage surges due lightning, switching (Ref. Ch. 18)	1. Horn gaps.	Not favoured
	2. Surge arresters. 3. R-C Surge suppressors	In addition to arresters for incoming lines.
Small distribution transformers		Only H.V. fuses for earth faults protection and phase fault protection. Overload protection generally not provided. (Fig. 14.12, 14.15.).
		For more important transformers of about 500 kVA Overcurrent relays Instantaneous earth fault relays
Transformer in important locations, ratings 500 kVA above		Restricted earth-fault protection Overcurrent and E.F. protection Buchholz relay
Transformer of about 5 MVA and above		Differential protection, Restricted earth fault protection, Overcurrent protection, Overfluxing protection, Buchholz Relays, Sudden pressure relays.

Undervoltage and overvoltage relays : wherever necessary.

Reverse power relay : for parallel transformers. (Sec. 32.12).

32.2. SAFETY DEVICES WITH POWER TRANSFORMERS

The electrical portion systems can sense the abnormal conditions by measuring current/voltage. Besides electrical relays, a power transformer can be provided with the following safety and monitoring devices.

(*a*) Fluid level gauge
(*b*) Vacuum gauge
(*c*) Pressure/vacuum switch
(*d*) Sudden Pressure Relay
(*e*) Pressure Relief Valve
(*f*) Fluid temperature Indicator
(*g*) Hot spot temperature indicator
(*h*) Gas temperature indicator

32.3. LOW OIL LEVEL—FLUID LEVEL GAUGE

Low oil level is a harmful condition because internal insulation clearance, creepages etc. between leads, bushings and tanks are exposed to air when the oil drops below the specified level. Low oil level could result from (1) initial mistake to fill sufficient oil upto the mark (2) Leakage of oil through the tank.

If the cooling tubes are partially cool or nearly at ambient temperature, it is an indication that the oil is not circulating in the cooling tubes or oil level has dropped below the desired level. The cooling tubes are warm and level indicator gives an alarm, it may be a false alarm and level indicator needs checking. Its position may be improper.

The level indicator has a float and an arm. The float is suspended in the oil. When the oil level drops down, the float tilts the arm thereby closing the alarm contacts. Both low and high level alarm contacts are provided.

32.4. GAS ACTUATED DEVICES

During internal faults below oil level, the heat of arc causes decomposition of oil. The gases formed by decomposition are gathered in the air cushion and the conservator of the transformer. The rate of gas generation depends upon fault current and arc voltage.

The arc voltage is of the order of 50 to 200 volts and the rate of gas generation is of the order of 50 to 200 cubic centimetres per kilowatt sec. The fault may be inter-turn fault, earth fault or phase to phase fault.

The gases generated by the arc can be used for detecting these faults. The following devices are used.

(*a*) pressure relief devices
(*b*) rate of rise pressure relay
(*c*) gas accumulator relay (Buchholz Relay).

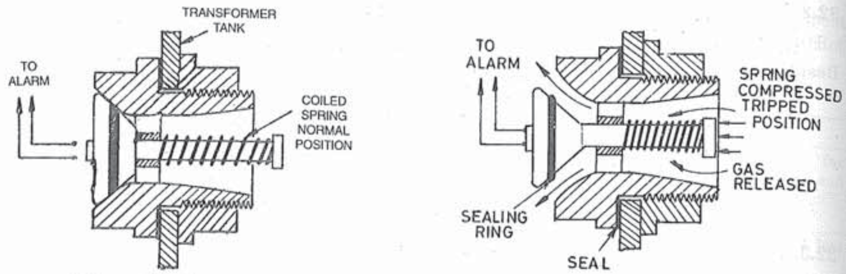
32.4.1. Pressure Relief and Pressure Relay

This is different from rate of rise pressure relay.

Pressure relay and pressure relief device is mounted on transformer tank. It releases gas pressure to the atmosphere during.

— high overload peaks
— prolonged overloads
— arcing faults within oil.

The pressure relief value is spring loaded and has a seal-seat. (Fig. 32.1 *a*). When the pressure inside the tank increases above a certain value, the force on movable sub-assembly exceeds the spring force and the valve operates (Fig 32.1 *b*). The alarm contacts are closed. After release of pressure the valve may be manually reset (not shown in figure).



(*a*) Normal Position. (*b*) During internal pressure.

Fig. 32.1. Pressure relief device and sudden pressure relay for transformer protection.

32.4.2. Rate-of-Rise Pressure Relay

Rate of rise pressure relay does not respond to static pressure. It responds only to rate of rise pressure resulting from internal arcing. The main pressure sensing element is a pressure actuated micro-switch mounted inside a metallic bellows. Static pressures do not squeeze the bellow. Dynamic pressure squeeze the bellow and operate the micro-switch. (Fig 32.2)

In some designs, oil pressure itself squeezes the bellow filled with special oil.

Rate of rise pressure relay is generally arranged to trip the transformer. It can be mounted on the tank.

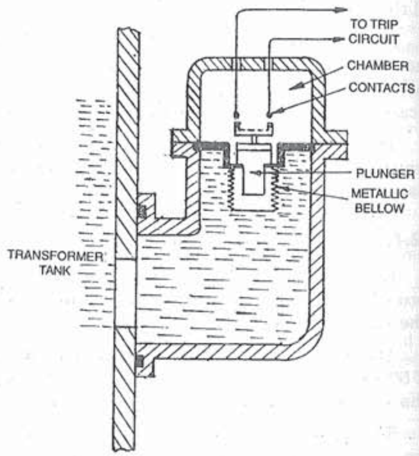


Fig. 32.2. Rate of rise pressure relay.

32.4.3. Buchholz Relay (Gas Actuated Relay)

1. **Principle.** The incipient faults in transformer tank below oil level actuate Buchholz relay so as to give an alarm. The arc due to fault causes decomposition of transformer oil. The product of decomposition contain more than 70% of hydrogen gas, which being light, rises upwards and tries to go into the conservator. The Buchholz relay is fitted in the pipe leading to the conservator. The gas gets collected in the upper portion of the Buchholz relay, thereby the oil level in the Buchholz relay drops down. The float, floating in the oil in the Buchholz relay tilts down with the lowering oil level. While doing so the mercury switch attached to the float is closed and the mercury switch closes the alarm circuit. Thereby the operators know that there is some incipient fault in the transformer. The transformer is disconnected as early as possible and the gas sample is tested. The testing of gas gives clue regarding the type of insulation failure. Buchholz relay gives an alarm so that the transformer can be disconnected before the incipient fault grows into a serious one.

When a serious short circuit occur in the transformer, the pressure in the tank increases. The oil rushes towards the conservator. While doing so it passes through the Buchholz Relay. The baffles (plates) in the Buchholz relay get pressed by the rushing oil. Thereby they close another switch with in turn closes the trip circuit of circuit-breaker. Thereafter the transformer is removed from the service.

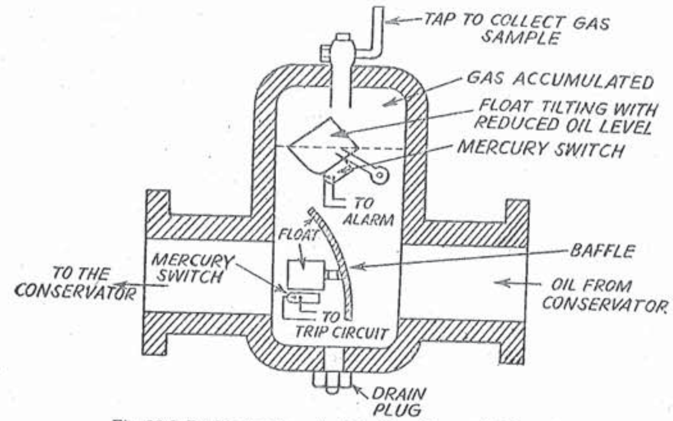


Fig. 32.3. Buchholz relay principle. (Gas Operated Relay)

The decomposition of transformer oil starts at about 350°C. The gas accumulated in the upper portion of the relay can be tapped. The gas is tested for colour, combustibility, chemical test etc. IS 3638-1966 'Application Guide for Gas operated Relay' gives details about analysis and mounting. From its analysis the kind of failure can be predicted. The insulation can be repaired before a major breakdown occurs.

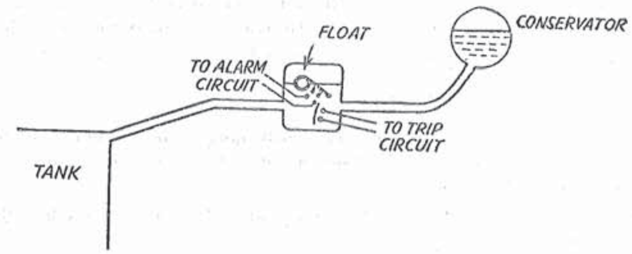


Fig. 32.4. Arrangement of Buchholz relay.

This type of relay can be used only for transformers with conservator. For faults above the oil level, this relay is ignorant. Buchholz relay gives an alarm when the oil level reduces below a certain level due to leakage of oil transformer.

A Buchholz relay is installed in the pipe connecting the transformer tank and the oil conservator (Figs. 32.3, 32.4, 32.5). The following are the guide lines for the installation.

— The angle of inclination of the axis of the pipe with horizontal plane should be between 10 to 11°

— The length of the straight run of the section of the pipe between the relay and the transformer tank should be more than 5 *D* (*D* is the internal diameter of the connecting pipe)

— The length of the straight run of pipe after the Buchholz relay upto the conservator should be more than 3*D*.

*The nominal pipe bore diameter is recommended by Standards as 25 mm for transformers upto 1000 kVA, 50 mm for between 1000 to 10,000 kVA and 80 mm for above 10,000 kVA.

Limitations of Buchholz Relay

Only faults below oil levels are detected.

Setting the mercury switch cannot be too sensitive otherwise there can be a false operation by vibrations, earthquakes, mechanical shocks to the pipe, sitting of birds etc.

The relay is slow, minimum operating time is 0.1 second, average time 0.2 second. Such a slow relay is unsatisfactory.

However, it is an excellent relay to bring to notice incipient fault.

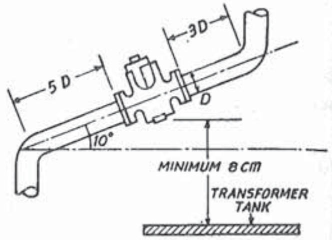


Fig. 32.5. Installation of Buchholz Relay.

Buchholz relays are not provided for transformers below 500 kVA. (This is for economic considerations). A separate Buchholz relay is provided with the tap changer to detect the incipient faults in the tap-changer. This does not respond to a small arcing.

32.5. BIASED DIFFERENTIAL PROTECTION, PERCENTAGE DIFFERENTIAL PROTECTION OF POWER TRANSFORMER (Ref. Ch. 28)

(*a*) **Description.** The differential protection responds to the vector difference between two similar quantities. In protection of transformer, CT's are connected at each end of the transformer. The CT secondaries are connected in star or delta and pilot wires are connected between the CT's of each end. The CT connections and CT ratios are such that currents fed into the pilot wires from both the ends are equal during normal conditions and for through faults. During the internal faults such as phase to phase or phase to ground, the balance is disturbed. The out of balance current $I_1 - I_2$ flows through the relay operating coils. To avoid unwanted operation on through faults resignrotraini bias coil are provided in series with pilot wires. The ampere turns provided by bias coils or restraining coil are proportional to $\frac{I_2 + I_2}{2}$.

As a result the restraining torque increases with though current and relay does not operate due to the difference in CT ratios for high values of short circuit currents. High speed relay element is provided in the Merz Price System.

(*b*) **CT connections.** Fig. 32.6 gives the connections of CT's for a star side and Fig 32.7 shows connections of a delta side.

— In both cases three currents transformers are required at each side of the protected transformer. The connections of CT secondaries are such that during normal conditions and for external faults, no current should flow through the relay operating coils.

There is an inherent phase displacement between vectors representing the voltage induced in high voltage winding and low voltage windings having same marking letter and corresponding neutral points, in case of star-delta transformers. Hence the load currents on H.V. side are displaced in phase with respect to load currents of corresponding phase on L.V. side. The power transformers are grouped according to the phase displacement *e.g.*,

Group 1 : Star-star, Phase displacement = 0°

Group 2 : Star-star, Phase displacement = 180°

Group 3 : Delta-star, Phase displacement = Minus 30°

Group 4 : Delta-star, Phase displacement = Plus 30°

(Refer. IS : 2026-1962)

In the circulating current differential protection, the phase displacement in line currents on two sides, introduces phase difference in secondary currents of CT's on two sides.

The CT connections should be such that the resultant currents fed into the pilot wires from either sides are displaced in phase by an angle equal to the phase shift between the primary and secondary currents. To get this arrangement, the following rules are followed :

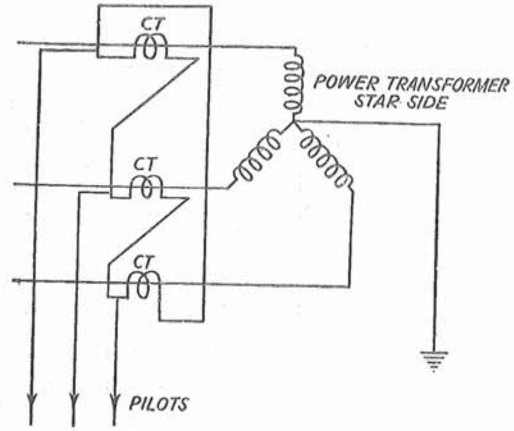


Fig. 32.6. Connection of CT secondaries on star side. (Contd.)

— Secondaries of CT's on star connected side of power transformer are connected in delta (Fig. 32.6).

— Secondaries of CT's connected on delta side of power transformer are connected in star (Fig. 32.7). With such arrangement, the phase displacement between currents gets cancelled with the phase displacement due to star/delta connections of CT secondaries, and the current fed to pilot wires from both sides are in phase during normal conditions.

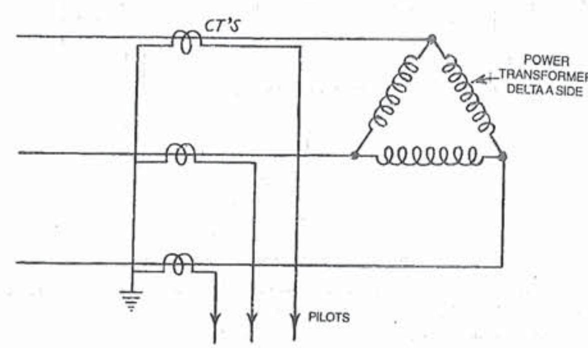


Fig. 32.7. Connections of CT secondaries on delta side.

— The neutrals of CT star and Power Transformer star connections are grounded.

— **CT ratios.** Current ratios of CT's on each side will be different depending upon line currents of power transformer and connections of CT's. The currents fed into pilots from each end should be the same for normal condition. Suppose this current is 5 Amp. then secondary current of delta connected CT will be $5/\sqrt{3}$ Amp. and star connected CT will be 5 Amp.

The star-star transformer comes under group 1 or group 2, having phase displacement of 0° or 180° respectively. The CT secondaries on both sides are connected in delta (Fig. 32.9).

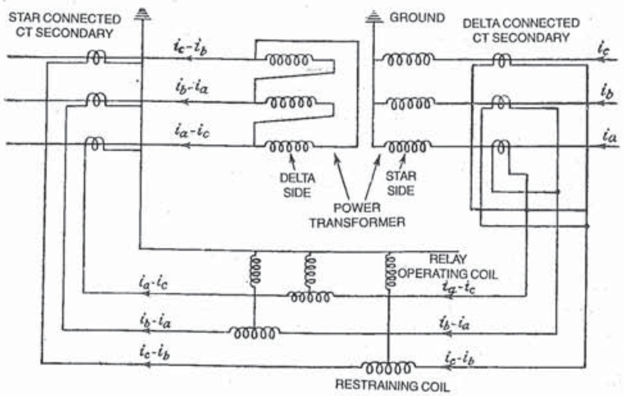


Fig. 32.8. Differential protection of delta Star transformer.

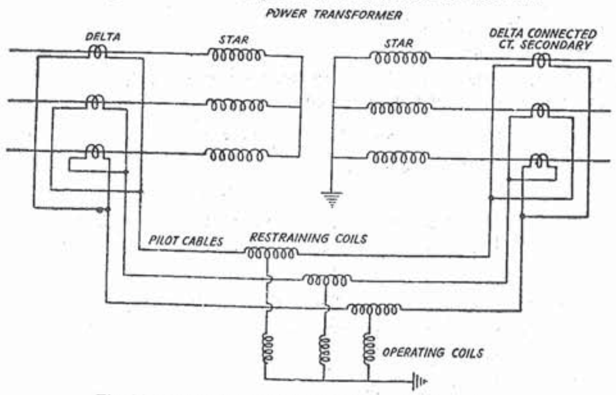


Fig. 32.9. Differential protection of star-star transformer.

Example 32.1. *Describe with the help of a neat diagram the connections of differential protection of a transformer. A 3-phase 33/6.6 kV star/delta connected transformer is protected by Differential system. The CT's on LT side have a ratio of 300/5. Show that the CT's on HT side will have a ratio* $60 : 5\sqrt{3}$.

Solution. CT's on delta side are star connected. Hence the secondary phase currents are equal to currents in pilot wires. CT's on star connected side are delta connected hence current in secondary is equal to current in pilot wires divided by $\sqrt{3}$.

Assume 300 A is flowing in the lines on LT side

$$\sqrt{3} \times 6.6 \times 300 = \sqrt{3} \times 33 \times I$$

$$I = \text{Current in HT lines}$$

$$= \frac{6.6 \times 300}{33} = 60\text{A}.$$

which is primary current of CT on HT side.

Currents in pilot wires. On the delta side of transformers the CT secondaries are star connected. Their secondary current is 5 Amp. Hence current fed in pilot wires from LT side is 5 Amperes. Same current is fed from CT connections on HT side which are delta connected.

Hence secondary current of CT's on HT side is

$$\frac{5}{\sqrt{3}} \textbf{ Amp.}$$

Hence CT ratio on HT side is

$$60 : \frac{5}{\sqrt{3}}.$$

Example 32.2. *A 30 MVA, 11.5 kV/69 kV, star-delta power-transformer is to be protected by differential protection. The high voltage side phase lags behind low voltage side phase by 30°. Formulate the complete differential protection for the transformer by selecting CT ratios, CT connections. The continuous current carrying capacity of restraining coils of the differential relay should not exceed 5 Amp. CT ratio is 3000/5 on 11.5 kV side. Determine CT ratio on 69 kV side.*

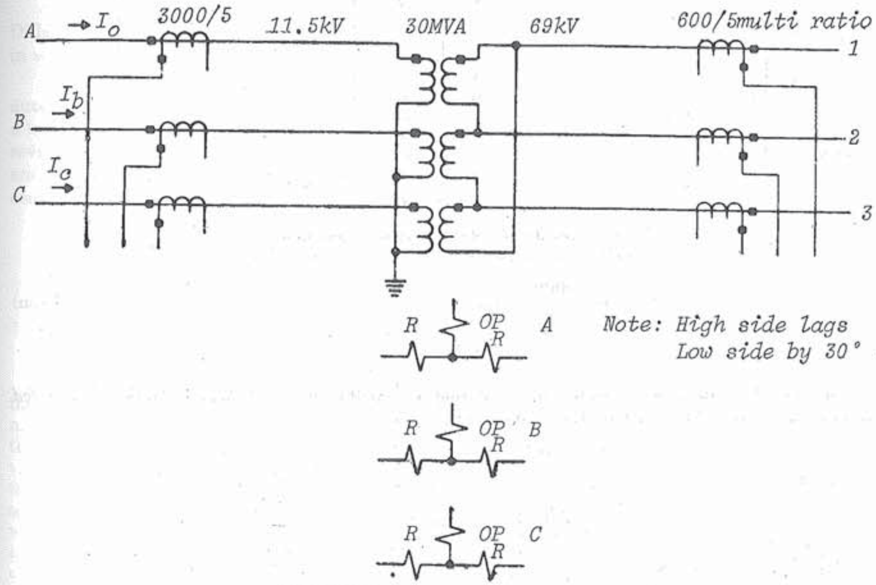


Fig. 32.10. (a) Connecting differential relays.
*Courtesy : Westinghouse Electric Corporation, U.S.A.

***Procedure.** *Draw work sheet for connection of differential relays showing the main transformer CT's, operating and restraining coils of CT's (Fig. 33.10). Connect the pilot wires with operating coils and restraining coils as described in the earlier section.*

Calculate the full load current of transformer on HV side and LV side. Select CT ratio.

Solution. Calculate full load current for a 30 MVA, 11.5 star/69 delta power transformer.

On 11.5 kV side

$$I_p = \frac{30{,}000}{\sqrt{3} \times 11.5} = 1505 \text{ A.}$$

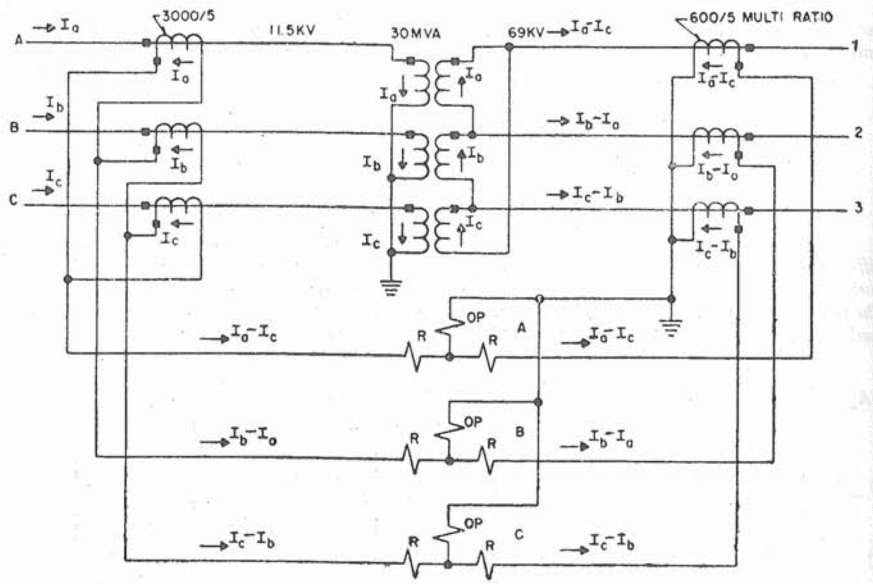


Fig. 32.10. (*b*) Complete diagram of protection.
Courtesy : Westinghouse Electric Corporation, U.S.A.

$$\text{CT ratio} = \frac{3000}{5} = 600 \qquad \text{...(Given)}$$

$$I_s = \frac{1505}{600} = 2.51 \text{ A.}$$

Since 11.5 kV side is star connected, CT secondaries will be delta connected. Hence *current fed into pilot wires* from 11.5 kV side CT secondaries is

$$\sqrt{3} \times 2.51 = 4.35 \text{ A.}$$

On 69 kV Side

$$I_p = \frac{30{,}000}{\sqrt{3} \times 69} = 251 \text{ A.}$$

CT ratio to be selected.

Current in secondary of CT's =Current in pilot wires. Since 69 kV side CT secondaries are connected in star = 4.35 A.

$$\text{Hence CT ratio} \quad = \frac{251}{4.35} = 57.7$$

Select CT ratio 60

Secondary current = 5 A.

Primary current, $60 \times 5 = 300$

CT ratio on 69 kV side = 300/5

Fig. 29.8 (*a*) and (*b*) illustrate CT connections.

32.6. PROBLEMS ARISING IN DIFFERENTIAL PROTECTION APPLIED TO TRANSFORMERS

Simple differential protection system is inadequate because the following difficulties arise.

(1) Difference in lengths of pilot wires on either sides of relays. The difficulty is overcome by connecting adjustable resistors to pilot wires. These are adjusted on site to get equipotential points on pilot wires. Taps can be provided on operating coil and restraining coil of relay for adjusting the balance.

(2) Difference in C.T. ratios due to ratio error difference at high values of short circuit currents. Because of this difference the relay operates for through faults. This difficulty is overcome by using biased differential relay for percentage differential relay. In such a relay a restraining coil is connected to pilot wires. The current flowing through restraining coil can be taken as $(I_1 + I_2)/2$.

With increase in through current the restraining torque increases too, and the current due to CT inaccuracy is not enough to cause relay operation. The characteristic of such a relay is given earlier.

(3) Tap changing alters the ratio of voltage (and currents) between H.V. side and L.V. side. Differential protection should be provided with bias (Restrain) which exceeds the effect of variation in secondary current due to tap changing.

(4) **Magnetizing current inrush.** When the transformer is energized, initially there is no induced e.m.f., the condition is similar to switching of an inductive circuit. The resistance being low a large inrush of magnetizing currents takes place. The magnitude of this current inrush can be several times that of load current. The magnitude of inrush currents depends on circuit conditions and voltage at the instant of switching. Maximum peak values equal to 6 to 8 times the rated current can occur.

The factors which influence the magnitude and duration of magnetizing current inrush include :

— size of transformer
— size of power system
— type of magnetic material in the core
— residual flux in the transformer before switching in
— how the transformer is energized.

Maximum inrush current occurs if the transformer is energized when the voltage wave is passing through zero. At this instant, the current and flux should be maximum in highly inductive circuit and in half a wave the flux should change in direction to attain maximum value in the other half-cycles. If there is residual flux in the transformer, the required flux may be in the same or opposite direction. Accordingly the magnetizing current will be less or more. If the magnetizing current is more, it will saturate the core and increase the magnetizing current component further.

The inrush currents decays rapidly for the first few cycles and then very slowly. Sometimes they take 4 to 6 seconds to subside. In high resistance path, the inrush currents decay more rapidly.

The time constant of the circuit (L/R) is not constant because L is variable due to change in permeability of the core material. The losses damp the inrush currents. The time constants of inrush currents vary from 0.2 seconds to 1 minute, depending upon whether the transformer is small or large.

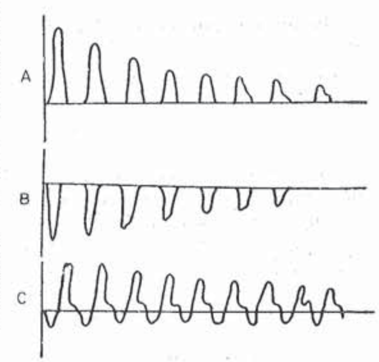


Fig. 32.11. Typical magnetizing current inrush waveforms in three phases.

The wave shapes of inrush current in three phases are different as shown in Fig. 32.11.

Inrush currents are seen only by the primary side CTs. They do not reflect on secondary side.

The inrush of magnetizing current will, therefore, cause the operation of differential protection system unless some special modification is done.

Formerly, the relay was provided with time lag of 0.2 second. By this time the inrush will vanish and relay does not trip unnecessary. But what about the protection of the transformer during this period?

While commissioning, one does not know whether there is a fault or not. Providing a time lag is therefore risky. There are several reported incidents that the relay was tripped due to internal fault during switching on for the first time. The engineers thought that the relay has tripped due to magnetizing current inrush. They made the relay in-operative and switched on the transformer. Since there was a fault and relay was inoperative the transformer was damaged.

Next development was desensitizing the relay for short period of 0.1 second during switching. After this time the shunt across the relay coil is removed. This method also leads to the same danger mentioned above. The latest method adopted in transformer protection is *Harmonic current restraint*.

32.7. HARMONIC RESTRAINT AND HARMONIC BLOCKING

The initial inrush of magnetizing currents have a high component of even and odd harmonics. Table 32.3 gives a typical analysis.

Harmonic component of short circuit currents is negligible. This principle is used for restraining the relay from operation during initial current inrush. The harmonic restrain differential relay remains sensitive to fault currents but does not operate due to magnetizing currents.

Table 32.3

Harmonic components in magnetizing current	*Amplitude as a % of Fundamental*
2nd	63.0
3rd	26.8
4th	5.1
5th	4.1
6th	3.7
7th	2.4

The operating coil of the relay receives fundamental component of current only. The restraining coil receives rectified sum of fundamental and harmonic component.

Thereby, inrush currents having more harmonic content give more restraining torque and the relay does not operate.

Harmonic blocking. The harmonic component of inrush current is used for blocking a separate blocking relay whose contacts are in series with the contacts of the differential relay. The blocking relay contains a 100 Hz blocking filter in operating coil and 50 Hz blocking filter in restraining coil. During inrush currents, the 2nd harmonic component is predominant and the blocking relay is blocked. The blocking relay contacts remain open.

During short circuits, 50 Hz component is predominant. Hence blocking relay operates and relay contact circuit is closed.

32.8. DIFFERENTIAL PROTECTION OF THREE-WINDING TRANSFORMER

The principle of differential protection can be adopted for three winding transformer. (Ref. Fig. 32.12).

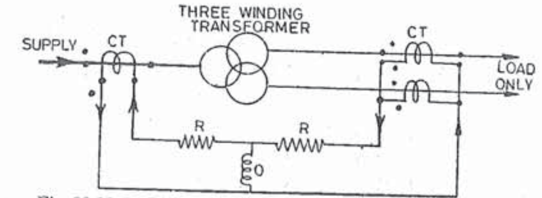


Fig. 32.12. (*a*) Differential protection of three-winding transformer, feeding loads only. (Single line diagram).

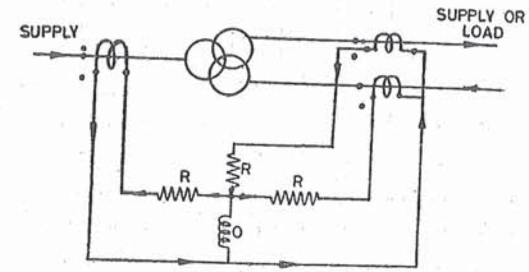


Fig. 32.12. (*b*) Differential protection of three winding transformer with supply on three side (Single line diagram).

To achieve current balance in pilot wires, ratio adjusting (current balancing) transformers are, used in some schemes. The relay unit used in such protection have three restraining coils and one operating coil.

32.9. DIFFERENTIAL PROTECTION OF AUTO-TRANSFORMERS

The principle of differential protection can be applied to three phase auto-transformers. The connections of CT secondaries differs for earth-fault protection alone and combined phase fault and earth fault protection. (Ref. Fig. 32.13).

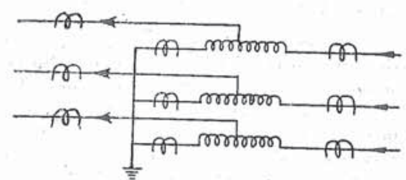
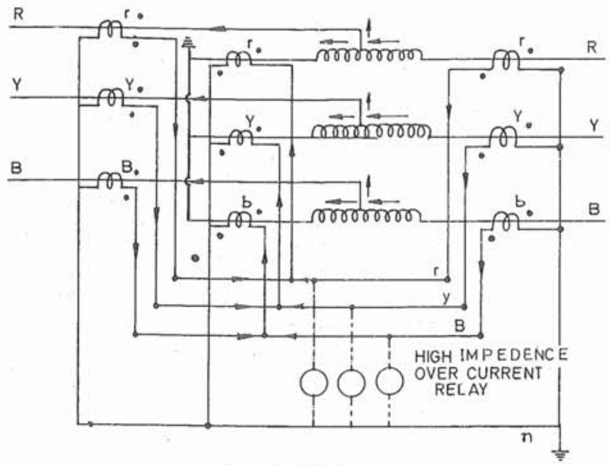


Fig. 32.13. (*a*) Location of CT's.

The Kirchhoff's current law states that the vector sum of component currents entering (or leaving) a point in electric circuit is zero. Thus the CT secondaries can be so connected that during normal condition and external faults, the vector sum of currents in relay operating coil is zero. During internal faults, this balance is disturbed and relay operates.

Procedure of connections is as follows :

— Draw the diagram of auto transformer. Indicate three sets of CT's [Fig. 32.12 (*a*)].
— Connect the one end of each set of CT in star.
— Connect other end of each CT of a phase to pilot wire for same phase (say *r*, *y*, *b*).
— Connect star points of CT secondaries to common pilot wire '*n*'. Provide one earthing.
— Connect relays between *r*—*n*, *y*—*n*, *b*—*n* of pilot wires.



(b) CT connection

Fig. 32.13. Protection of Auto-transformer from phase faults and earth faults.

32.10. EARTH-FAULT PROTECTION (Refer Sec. 27.6)

Earth fault protection of transformer can be in one or more forms such as

— restricted earth-fault protection by differential protection (Ref. Sec. 28.3, 33.4).
— additional/separate restricted earth-fault protection.
— leakage to frame protection (Ref. Sec. 27.10).
— neutral current relays (Ref. Sec. 27.7).

Leakage-to-Frame Protection for Small Transformers

Principle explained in Sec. 27.10 can be used for small transformers.

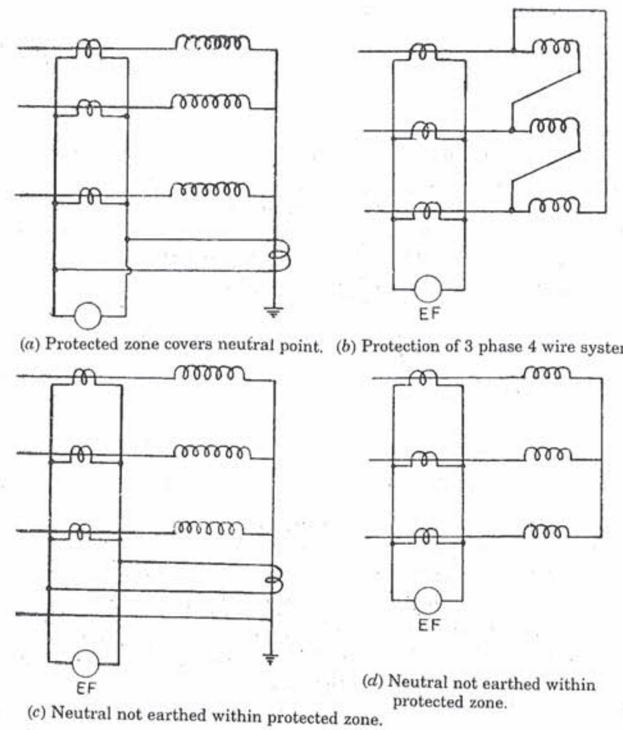
32.11. RESTRICTED EARTH FAULT PROTECTION

Earth fault relays connected in residual circuit of line CT's [Fig. 32.15] give protection against earth faults on the delta or unearthed star connected windings of transformers. Earth faults on secondary side are not reflected on primary side, when the primary winding is delta connected or has unearthed star point. In such cases, an earth fault relay connected in residual circuit of 3 CT's on primary side operates on internal earth faults in primary windings only. Because earth faults on secondary side do not produce zero sequence currents on primary side. Restricted earth fault protection may then be used for high speed tripping for faults on star connected earthed secondary winding of power transformer.

In Fig. 32.16 the star connected side is protected by **Restricted Earth Fault Protection.** An earth fault (F_1) beyond the transformer causes the currents I_2 and I_1 in CT secondaries as shown in Fig. 32.16. Therefore, the resultant current in earth fault relay is negligible.

For earth fault within the transformer star connected winding (F_2), only I_2 flows and I_1 is negligible. Hence I_2 flows through the earth fault relay. Thus restricted earth fault-relay does not operate for earth fault beyond the protected zone of the transformer.

When fault occurs very near the neutral point of the transformer, the voltage available for driving earth fault current is small. Hence fault current would be low. If the relay is to sense such faults, it has to be too sensitive and would therefore operate for spurious signals, external faults



(a) Protected zone covers neutral point. (b) Protection of 3 phase 4 wire system.

(c) Neutral not earthed within protected zone. (d) Neutral not earthed within protected zone.

Fig. 32.15. Restricted earth fault protection (Earth faults with the boundary of CT's are detected).

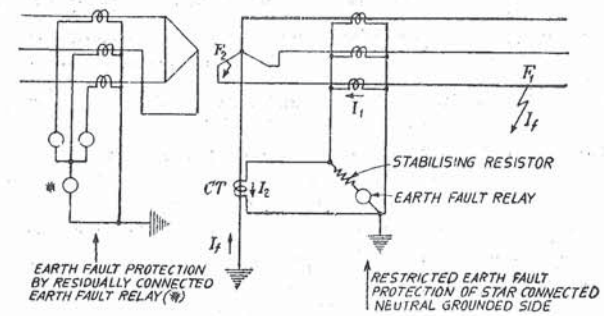


Fig. 32.16. Earth fault protection of transformers.

and switching surges. Hence the practice is to set the relay such that it operates for earth fault current of the order of 15% of rated winding current. Such setting protects restricted portion of the winding. Hence the name restricted earth fault protection (Ref. Sec. 33.4).

32.12. PROTECTION OF TRANSFORMERS IN PARALLEL

The following protections are necessary in case of transformers operating in parallel :

— Overcurrent protection

— Earth-fault protection

— Directional overcurrent and Directional earth fault relays on secondary side to prevent the healthy section feeding into faulty section.

Fig. 32.17 illustrates the scheme. The feedback is prevented by operation of directional overcurrent relay of faster setting. By operation of this directional overcurrent relay, the corresponding CB is quickly tripped and the feedback from healthy section is prevented. The current coils of d.o.c. relay and o.c. relay on secondary side may be connected in series.

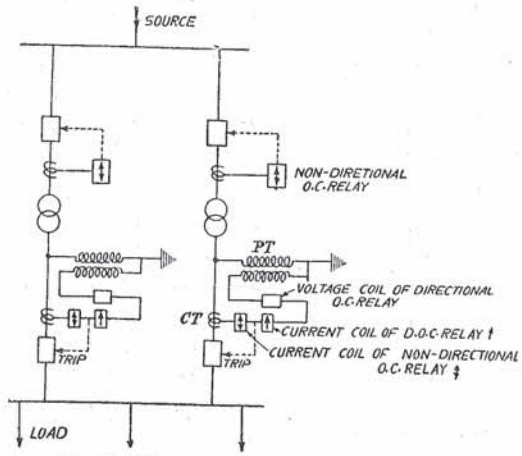


Fig. 32.17. Protection of parallel transformers.

32.13. OVERCURRENT PROTECTION OF POWER TRANSFORMERS

Differential protection is generally uneconomical for power transformers below about 5 MVA. In such cases, overcurrent protection is employed as main protection against phase faults. For transformers above about 5 MVA, if differential protection is used as a main protection, overcurrent protection is used in addition, as a back-up for sustained through faults. Earth fault protection is provided in addition to phase fault protection.

For small distribution transformers below 500 kVA, overcurrent protection may be provided simply by means of fuse on H.V. side, as such transformers are installed in unattended sub-stations, circuit breakers and relays are not provided. [Ref. Fig. 14.12(*c*)].

External short-circuits (Through Faults)

As per the various standards on distribution transformers, power transformers and regulating transformers, the transformer should be capable of withstanding the mechanical and thermal stresses caused by external short-circuits with following conditions.

— the magnitude of r.m.s. value of symmetrical current in any winding does not exceed 25 times the base current in that winding.

— the duration of external short-circuit is limited to time period indicated in the table.

(intermediate values obtained by interpolation)

Table 32.4*

R.M.S. Value of Symmetrical current in a winding (Times base current)	*Time period in seconds*	*Transformer % Impedance*
25	2	4
20	3	5
16.6	4	6
14.4	5	7

*Ref. ANSI C 57 12.00 — 1968.

Through faults are not detected by differential protection of transformer. If the through faults persist of longer duration, the transformer gets damaged by thermal stresses. The through faults are detected by overcurrent relays, overcurrent relays with undervoltage blocking, zero sequence protection, negative sequence protection.

The setting of overcurrent protection for through faults covers transformer, station busbar and portion of a transmission line. The overcurrent protection for through faults provides back-up protection to differential protection for internal faults.

The overcurrent due to faults are accompanied by voltage drop, negative phase sequence currents. Earth faults are accompanied by zero phase sequence currents.

32.13.1. Overload Protection

The permissible overload and their duration depends upon the type of cooling and insulation class of transformer. Higher overloads are permissible for a shorter duration (Table 32.5).

Table 32.5. Permissible Duration of Overload

Overload % :	125	150	175	200	300
Duration (Minutes) :	125	45	15	10	1

Hence for sub-station transformers, overload protection is generally arranged to initiate alarm. In unattended stations, overload protection is arranged to trip the breaker after a requisite time delay.

The transformers with utility equipment are prone to sudden overloads. (Furnace transformers, transformers for Motors). The overload protection for such transformers is also given requisite time delay.

While selecting the overcurrent protection of transformer, the following aspects need consideration.

— Magnetizing current inrush: IDMT relays are not affected by the current inrush as they have enough time lag. Instantaneous overcurrent relays should be high set to avoid maloperation.

— The fault currents on primary side and secondary side of power transformers are different for phase-phase faults. Lower value should be selected for setting of overcurrent relays.

— Primary full load current should be considered while setting the overcurrent relay.

— The setting of IDMT overcurrent relay is generally 125 per cent of transformer rating to take care of normal overloads. Enough time delay should be provided as per the application.

— The setting of instantaneous overcurrent relay on primary side should be more than asymmetrical value of fault current for 3 phase fault on secondary side of transformer. This setting is generally adequate to take care of magnetizing current inrush.

— Same set of current transformers should not be used for differential protection and overcurrent protection.

[Refer Sec. 27.5, 27.7 for connections of overcurrent protection and earth fault protection].

32.14. THERMAL OVER-HEATING PROTECTION OF LARGE TRANSFORMERS

Thermocouples or resistor temperature detectors are kept near each winding. These are connected to a bridge circuit. When temperature increases above safe value, an alarm is sounded. If measures are not taken, the circuit breaker is tripped after a certain temperature. Some typical settings for oil temperatures are as follows :

Switch on fans	:	60°C.
Alarm	:	95°C.
Trip	:	120°C.

Oil Temperature Indicator Thermometer

An oil thermometer, which is common with all oil-filled transformers, can be considered as a partially effective protective device when equipped with alarm contacts connected to give remote warning of abnormally high oil temperature. Its location is such that it naturally monitors the hottest fluid that exists in the transformer. The same thermometer is often used to start fan motors on transformers equipped with automatic air blast to increase the nameplate kVA rating.

The thermometer cannot be relied upon as a fault-detecting device. Transformer oil has a much longer time constant then the windings themselves, hence is many times more sluggish in response to changes in loading losses which directly affect winding temperature. Thus the thermometer's temperature warning will vary between being to conservative or too pessimistic, depending on the rate and direction of change in loading.

Alarm contacts used in conjunction with a oil thermometer are adjustable but are typically set in a sequence that brings on fans at a liquid temperature of 60°C and actuate a switch contact should the temperature reach 90°C. For a typical design in a 30°C ambient, the fans are brought into operation at about 90 per cent rated load whereas the alarm is given at about 130 per cent rated load. These percentages will vary with each manufacture for each design and are dependent upon the actual ambient temperature. The percent loadings will be somewhat lower at ambient above 30°C and higher at ambients under 30°C.

Switches are usually capable of readjustment through a range of ± 10°C, thus allowing compensation for some of the factors mentioned above.

Hot Spot Thermometer (Winding Temperature Device)

The thermometer bulb is located in a pocket near the winding. The bulb is surrounded by hot circulating oil. The bulb is also heated by a small heater connected across CT secondary. Thereby the heat given to the bulb is a function of load current as well as the temperature of oil near winding. The device is matched with heating curve of the transformer winding.

Th reading of hot spot thermometer is related to actual thermal condition of transformer than that of oil temperature indicator. However due to the necessity of closely matching its artificial bimetal gradient to the theoretically hottest spot winding gradient, a short time heavy overload will often register higher on the dial than a long-time light overload.

32.15. OVER-FLUXING PROTECTION

The flux density 'B' in transformer core is proportional to $V/f \cdot (B \propto V/f)$. Power transformers are designed to withstand $(V_n/f_n \times 1.1)$ continuously, where V_n is normal highest r.m.s. voltage and fn is standard frequency. Core design is such that higher V/f causes higher core loss and core heating. The capability for V/f for higher values is limited to a few minutes.

$\dfrac{v/f}{v_n/f_n}$	1.1	1.2	1.25	1.3	1.4
Duration of Withstand limit (minutes)	Continuous	2	1	0.5	0

High V/f can occur in Generator Transformers and Unit-auxiliary transformers if full excitation is applied to generator before full synchronous speed is reached. V/f relay (Volts/Hertz) relay is

provided in the automatic voltage regulator of generator. The relay blocks and prevents increasing excitation current before full speed and frequency is reached.

In V/f relay, a resistance and capacitance are connected to secondary of VT. The voltage drop across the resistance is a function of V/f, where V is the line to earth voltage and f is frequency. This voltage is fed to the volts 'per Hertz' relay.

The magnetic flux density in the transformer core is a function of V/f. Hence the relay senses magnetic flux condition. Overfluxing relay is provided with enough time lag. Overfluxing relay is not necessary for substation transformers. In substations, V/f relays are provided for load shedding (Sec. 45.7)

32.16. PROTECTION OF ARC FURNACE TRANSFORMERS

Furnace transformers are subjected to repeated short circuits during the melting process. Inverse time overcurrent relays are provided for both phase faults and earth faults.

Induction type inverse overcurrent-relays are used for short circuit and overcurrent protection of Furnace Transformer. The setting is such that for current of the order 300 to 400 per cent of full load current, faster tripping is obtained. For overcurrent of the order of 150 per cent, enough time delay provide so that the relay does not trip during normal current surges.

The time delay should be such that the relay should not operate during initial magnetizing current inrush. High speed overcurrent relays are provided on secondary side. These are set to pick up instantaneously for currents more than full load secondary current but slightly less than the corresponding setting on relays on HT side.

Backup breaker is provided in the main sub-station which is set to interrupt short circuits in the HT side of the furnace transformer.

Differential protection schemes have been developed for arc furnace transformers and have been used in several installation.

32.16.1. Power Supply Requirements of Arc Furnace Plants

While selecting the power supply for an arc furnace plant the fault level at the point of connection of the furnace should be adequate. Hence, the power line should be taken from the sub-station bus having adequate fault level. If the fault at a bus is inadequate the power should be taken from the bus of yet higher voltage level, having desired fault level. The expression given below can be taken as a guide rule.

$$Sa = K \cdot 80,\ T \text{ mva}$$

where Sa = Fault level at the point of connection of furnace transformer (MVA)

T mva = Nominal rating of furnace transformer (MVA)

K = Multiplying factor to take into account, the number of arc furnaces in the plant

K = 1 for one furnace

A = 1.2 for two furnaces

Choice of Voltage. The choice of voltage for feeding the arc furnace plant is determined by the voltage-levels of the buses in the sub-station and their fault levels. The fault level requirements of the supply are calculated as described above.

kVA Rating of Intermediate Step-down Transformer that feeds that arc furnace plant.

The furnace transformers are given a nominal kVA rating such that they can be safely overloaded by about 20% during the melt down periods. In other words :

$$(T \text{ mva}) \max = 1.2\ (T \text{ mva}) \quad \ldots(2)$$

where, $(T$ mva$)$ = Nominal MVA rating of the furnace transformer.

$(T$ mva$)$ max = The rated apparent power the furnace transformer can supply.

*Overvoltage relays should be provided in bus-bar protection to avoid transformer failure do to temporary overvoltage.

32.17. PROTECTION OF RECTIFIER TRANSFORMER

Protection of rectifier transformer depends upon type and class of rectifier *i.e.* whether diode or thyristor rectifier. Static relays having characteristics closely matching the overload characteristics of the rectifier are preferable. The general practice is as follows :

— Overload protection. Very inverse or extremely inverse over-current relay for protection of rectifier transformer.

— Faults in rectifier : (*a*) HRC fuses for protection of rectifier
(*b*) Overload relays on primary side of transformer as a backup.

32.18. PROTECTION OF GROUNDING TRANSFORMER

The CT secondaries are delta connected. An overcurrent relay with time lag is inserted in the delta. The zero sequence currents circulate in this delta. The time setting of this relay is selected to co-ordinate with thermal rating of the earthing resistor (if used) or with time setting of other earth fault relays. The earthing transformer is disconnected by opening the circuit-breaker, on a persistent earth fault.

The other three relays provide protection against faults in the grounding transformer. These are instantaneous relays, set between 25 to 50 per cent of continuous current-rating of grounding transformer. Buchholz relay is also used. Earth fault protection is provided by residually connected relay (not shown in the figure).

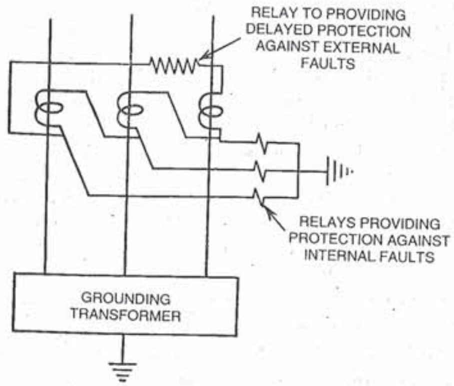


Fig. 32.18. Protection of grounding transformers.

SUMMARY

The protections provided for a transformer are summarised in Tables 32.1 and 32.2.

Buchholz relay is used transformers with conservators. It is connected in the pipe between the tank and the conservators. It gives an alarm on incipient faults below oil level.

Differential protection is used for phase to phase and phase to ground faults. Harmonic restraint is used for preventing the relay operation due to magnetizing current inrush during switching. Biased or percentage differential relaying is used to prevent wrong operation due to inaccuracies of CT ratios. The secondaries on star connected side are connected in delta. The secondaries on delta connected side are connected in star.

Restricted earth fault protection is provided to prevent operation on external earth faults and to give sensitive earth fault protection.

The overload protection is given by overcurrent relays and thermal relays. V/f relays are for overfluxing protection and surge arresters for protection against switching/lightning surges.

QUESTIONS

1. With the help of net sketches explain the protections of a star-delta power transformer, against the following abnormal conditions :
(*a*) Phase to phase fault (*b*) Earth fault (*c*) High voltage surges.

2. Describe the principle of Differential System of Protection applied to a power transformer. What are the difficulties experienced and how are they overcome?
3. Explain the meaning of percentage differential protection. Why is it necessary to provide a bias coil?
4. Explain why densensitizing of relay was not satisfactory process in transformer protection. What is the principle of Harmonic Restraint?
5. What is the meaning of restricted earth fault protection ? A 10,000 kVA, 11/6.6 kV transformer has 11 kV star connected side. The neutral point is earthed through an impedance. Calculate the impedance magnitude to provide protection to 90% winding from phase to earth fault.
6. A star-delta, 11kV/6.6kV transformer is protected by means of Differential Protection system. The 6.6 kV delta is connected side has CT of ratio 600/5. Calculate CT ratio of HT side.
7. Describe the principle of Differential Protection system applied to Delta-Star connected transformer.
8. Describe in brief the various protections to be provided to a 20 MVA transformer and a 250 kVA Transformer.
9. Explain the Buchholz relay with reference to
(*a*) Principle of operation (*b*) Installation
(*c*) Difficulties (*d*) Merits
(*e*) Limitations.
10. Distinguish between :
(*a*) Through faults and internal faults. (*b*) Incipient faults and serious faults.
11. Write notes on :
(*a*) Protection of Arc Furnace Transformer. (*b*) Harmonic Restraint
(*c*) Overfluxing Protection.
12. The bus bar voltage of a 220 kV substation shot-up to 280 kV while frequency was 48 Hz. Which protections would operate and protect the 220 kV/110 kV power transformers in the substation ?