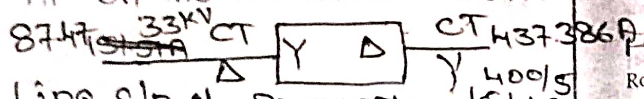
14. Discuss the basic setting and bias setting of percentage differential relay. What are the typical values of these settings for generator and transformer protection.

15. Describe the balanced (opposed) voltage differential protection scheme.

(1) A 3-ϕ T/F rated for 5MVA, 33kV/6.6kV is connected star/delta and the protecting current T/F on the low v/g side have a ratio of 400/5. Determine the ratio of the c/n T/F on the HV side.

Sol:-



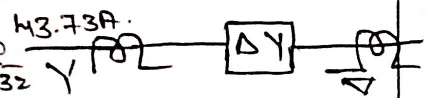
CT T/F ratio = Line c/n of Power T/F / CT connection of phase c/n

The current in the CT, secondary (phase current) is = $\frac{5.46}{\sqrt{3}}$

∴ The CT ratio on the H.T side will be = 87.47 : $\frac{5.46}{\sqrt{3}}$

=X=

(2) For a 10MVA, 132kV/6.6kV power T/F with Δ-Y connections, obtain the numbers of turns each c/n T/F should have, for the differential protection scheme to circulate a current of 5A in the pilot wires.



The line c/n on HV side = $\frac{10,000}{\sqrt{3} \times 132}$

" " " " LV side = $\frac{10,000}{\sqrt{3} \times 6.6}$ = 874.75 A.

The C.T on the delta side (HV side) are star connected.

∴ The ratio of CT on the LV side is 874.75 : $\frac{5}{\sqrt{3}}$

&

The C.T ratio on the H.V side will be = 43.73 : 5

9 Rotating Machines Protection

9.1 INTRODUCTION

Rotating machines include synchronous generators, synchronous motors, synchronous condensers and induction motors. The protection of rotating machines involves the consideration of more possible failures or abnormal operating conditions than any other system equipment. The protection scheme for any machine is influenced by the size of the machine and its importance in the system. The failures involving short circuits are usually detected by some type of overcurrent or differential relay. Electromechanical, static or microprocessor-based relays can be used stand-alone or in combination with one another to achieve the desired degree of security and dependability. The failures of mechanical nature use mechanical devices or depend upon the control circuits for removing the problem.

9.2 PROTECTION OF GENERATORS

A generator is the most important and costly equipment in a power system. As it is accompanied by prime mover, excitation system, voltage regulator, cooling system, etc., its protection becomes very complex and elaborate. It is subjected to more types of troubles than any other equipment. A modern generating set is generally provided with the following protective schemes.

(i) **Stator protection**
  (a) Percentage differential protection
  (b) Protection against stator inter-turn faults
  (c) Stator-overheating protection

(ii) **Rotor protection**
  (a) Field ground-fault protection
  (b) Loss of excitation protection
  (c) Protection against rotor overheating because of unbalanced three-phase stator currents

(iii) **Miscellaneous**
  (a) Overvoltage protection
  (b) Overspeed protection
  (c) Protection against motoring
  (d) Protection against vibration

(e) Bearing-overheating protection
(f) Protection against auxiliary failure
(g) Protection against voltage regulator failure

9.2.1 Stator Protection

(a) Percentage Differential Protection Figure 9.1(a) shows the schematic diagram of percentage differential protection. It is used for the protection of generators above 1 MW. It protects against winding faults, i.e. phase to phase and phase to ground faults. This is also called biased differential protection or longitudinal differential protection. The polarity of the secondary voltage of CTs at a particular moment for an external fault has been shown in the figure. In the operating coil, the current sent by the upper CT is cancelled by the current sent by the lower CT and the relay does not operate. For an internal fault, the polarity of the secondary voltage of the upper CT is reversed, as shown in Fig. 9.1(b). Now the operating coil carries the sum of the currents sent by the upper CT and the lower CT and it operates and trips the circuit breaker.

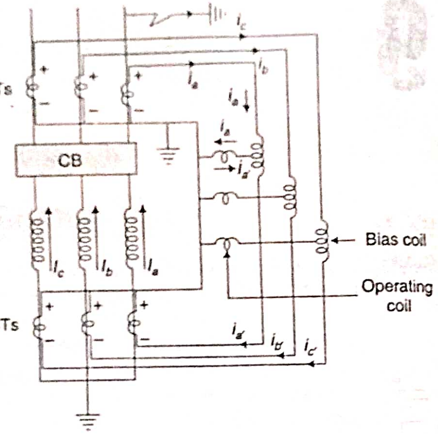


Fig. 9.1(a) *Percentage differential protection for external fault condition (instantaneous current directions shown for external fault condition)*

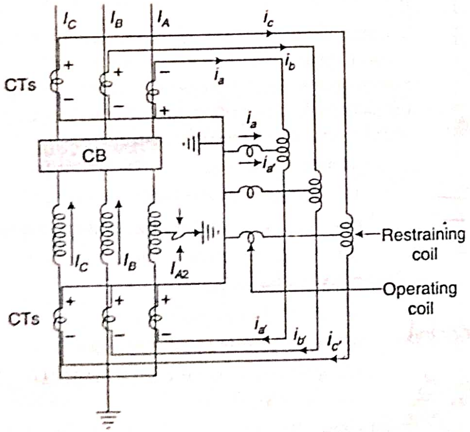


Fig. 9.1(b) *Percentage differential protection of generator (instantaneous current directions shown for internal fault condition)*

The percentage differential protection does not respond to external faults and overloads. It provides complete protection against phase to phase faults. It provides protection against ground faults to about 80 to 85 per cent of the generator wind- ings. It does not provide pro-tection to 100 per cent of the winding because it is influenced by the magnitude of the earth fault current which depends upon the method of neutral grounding. When the neutral is grounded through an impedance, the differential protection is supplemented by sensitive earth fault relays which will be described later.

Due to the difference in the magnetising currents of the upper and the lower CTs, the current through the operating coil will not be zero even under normal loading conditions or during external fault conditions. Therefore, to provide stability on external faults, bias coils (restraining coils) are provided. The relay is set to operate, not at a definite current but at a certain percentage of the through current. To obtain the required amount of biasing a suitable ratio of the restraining coil turns to operating coil turns is provided. High-speed percentage-differential relays having variable ratio or percentage slope characteristics are preferred. The setting of the bias coils varies from 5% to 50% and that of the relay coil (operating coil) from 10% to 100% of the full load current.

In case of stator faults, the tripping of circuit breaker to isolate the faulty generator is not sufficient to prevent further damage as the generator will still continue to supply power to the fault until its field excitation is suppressed. Therefore, the percentage differential relays initiate an auxiliary relay which in turn trips the main circuit breaker, trips the field circuit breaker, shuts down the prime mover, turns on CO_2 if provided and operates an alarm.

Restricted earth-fault protection by differential system

When the neutral is solidly grounded, it is possible to provide protection to complete winding of the generator against ground faults. However, the neutral is grounded through resistance to limit ground fault currents. With resistance grounding it is not possible to protect the complete winding against ground faults. The percentage of winding protected depends on the value of the neutral grounding resistor and the relay setting. The usual practice is to protect 80 to 85% of the generator winding against ground fault. The remaining 15-20% from neutral end is left unprotected. In Fig. 9.2 for phase to ground fault, it can be seen that the relay setting for the differential protection is determined by the value of the neutral grounding resistor and the percentage of winding to be protected.

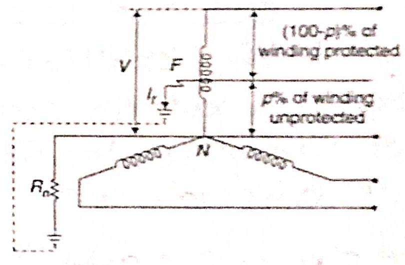


Fig. 9.2 *Percentage of unprotected winding against phase to ground fault*

If the ground fault occurs at the point F of the generator winding, the voltage V_{FN} is available to drive the ground-fault current I_f through the neutral to ground connection. If the fault point F is nearer to the neutral point N, the forcing voltage V_{FN} will be relatively less. Hence, ground fault current I_f will reduce. It is not practicable to keep the relay setting too sensitive to sense the ground fault currents of small magnitudes. Because, if the relay is made too sensitive, it may respond during through faults or other faults due to inaccuracies of CTs, saturation of CTs etc. Hence, a practice is to protect 80-85% of the generator winding against phase to ground faults and to leave the 15-20% portion of the winding from neutral end unprotected.

In Fig. 9.2, let p% of the winding from the neutral remains unprotected. Then $(100 - p)$% of the winding is protected. The ground fault current I_f is given by

$$I_f = \frac{p}{100}\frac{V}{R_n} \qquad (9.1)$$

where V is the line to neutral voltage and R_n is the neutral grounding resistance.

For the operation of the relay, the fault current must be greater than the relay pick-up current.

Percentage differential protection for a Y-connected generator with only four leads brought out

When the neutral connection is made within the generator and only the neutral terminal is brought out, the percentage differential protection can be provided, as shown in Fig. 9.3. This scheme protects the generator winding only against ground

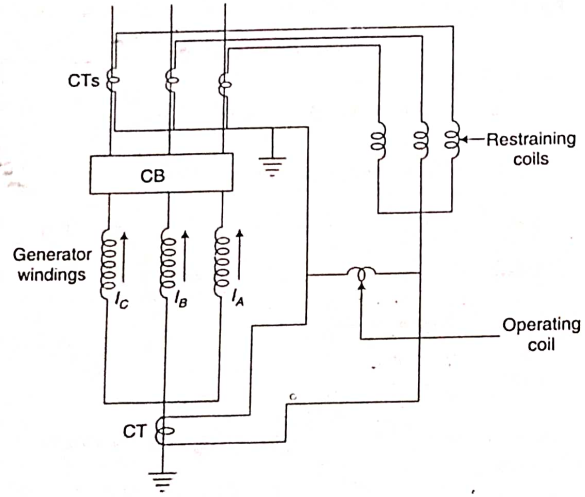


Fig. 9.3 *Percentage differential protection for Y connected generator with only four leads brought out*

faults. It does not protect it against phase faults. This is also called restricted earth fault protection because the relays operate only for ground faults within the protected windings.

Generator-transformer unit protection

In modern power systems, each generator is directly connected to the primary winding of a power transformer. The primary winding of the power transformer is

connected in delta configuration and the secondary winding in Y configuration. The secondary winding which is the H.V. winding is connected through a circuit breaker to the H.V. bus. The generator and transformer is considered as a single unit and the percentage differential protection is provided for the combined unit. This type of unit protection has been discussed later while discussing transformer protection.

Example 9.1 | An 11 kV, 100 MVA alternator is grounded through a resistance of 5 Ω. The CTs have a ratio 1000/5. The relay is set to operate when there is an out of balance current of 1 A. What percentage of the generator winding will be protected by the percentage differential scheme of protection?

Solution: Primary earth-fault current at which the relay operates

$$= \frac{1000}{5} \times 1 = 200 \text{ A}$$

Suppose p% of the winding from the neutral remains unprotected.

$$\text{The fault current} = \frac{p}{100} \times \frac{11 \times 10^3}{\sqrt{3} \times 5}$$

For the operation of the relay, the fault current must be greater than the relay pick-up current

$$\frac{p}{100} \times \frac{11 \times 10^3}{\sqrt{3} \times 5} > \frac{1000}{5} \times 1 \quad \text{or} \quad p > 15.75$$

This means that 15.75% of the winding from the neutral is not protected. In other words, $100 - p = 100 - 15.75 = 84.25\%$ of the winding from the terminal is protected.

Note: Near the neutral point voltage stress is less and therefore, phase to earth faults are not likely to occur.

Example 9.2 | An 11 kV, 100 MVA alternator is provided with differential protection. The percentage of winding to be protected against phase to ground fault is 85%. The relay is set to operate when there is 20% out of balance current. Determine the value of the resistance to be placed in the neutral to ground connection.

Solution: (a) Primary earth-fault current at which the relay operates

$$= \frac{100 \times 10^3}{\sqrt{3} \times 11} \times \frac{20}{100} = 1049.759 \text{ A}$$

15745 Vph = 6350.85

Suppose that the percentage of winding which remains unprotected is

$$p = 100 - 85 = 15\%.$$

$$\text{The fault current} = \frac{p}{100} \times \frac{11 \times 10^3}{\sqrt{3}\, R_n},$$

where R_n is the resistance in the neutral connection

$$\therefore \quad \frac{15}{100} \times \frac{11 \times 10^3}{\sqrt{3}\, R_n} = 1049.759$$

$$\therefore \quad R_n = \frac{15 \times 11 \times 10^3}{100 \times \sqrt{3} \times 1049.759} = 0.91\ \Omega$$

(b) Protection against Stator Interturn Faults Longitudinal percentage differential protection does not detect stator interturn faults. A transverse percentage differential protection, as shown in Fig. 9.4 is employed for the protection of the generator against stator interturn faults. This type of protection is used for generators having parallel windings separately brought out to the terminals. The coils of modern large steam turbine driven generators usually have only one turn per phase per slot and hence they do not need interturn fault protection. Hydro generators having parallel windings in each phase employ such protection which thus provides back-up protection and detects interturn faults. This scheme is also known as split-phase protection.

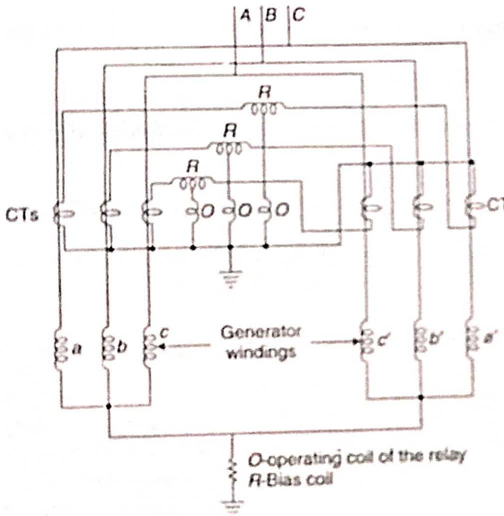


Fig. 9.4 *Transverse percentage differential protection for multi-winding generators*

A faster and more sensitive split-phase protection as shown in Fig. 9.5 can be employed. In this scheme, a single CT having double primary is used. No bias is necessary because a common CT is employed so that errors due to CT differences do not occur.

Interturn protection based on zero-sequence component

If generators do not have access to parallel windings, a method based on zero-sequence voltage measurment can be employed for the protection against stator interturn faults. This type of scheme will also be applicable to single winding generators having multi-turn per phase per slot to protect against interturn faults. Figure 9.6 shows the schematic diagram of interturn protection by zero-sequence voltage measurement across the machine.

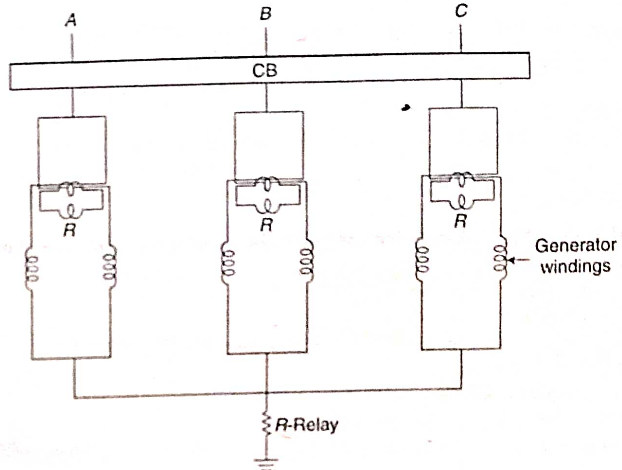


Fig. 9.5 *Split-phase protection of generator using double primary CTs*

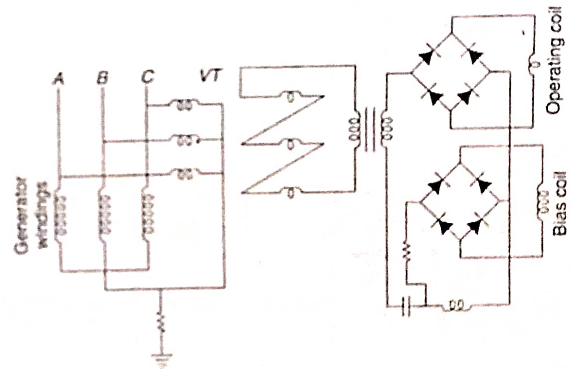


Fig. 9.6 *Interturn protection of generator using zero-sequence voltage*

The zero-sequence voltage does not exist during normal conditions. If one or more turns of a phase are short circuited, the generated emf contains zero-sequence component. A voltage transformer as shown in the figure is employed to extract zero-sequence component. The secondary winding of the voltage transformer is in open-delta connection to provide the zero-sequence component of the voltage to the protective relay. A filter is provided to extract a third harmonic component from the VT output and apply it as the relay bias.

The zero-sequence voltage is also produced in case of an external earth fault. But most of this voltage appears across the earthing resistor. A very small amount, 1 or 2 per cent, appears across the generator. Therefore, the zero-sequence voltage is measured across the generator windings at the line terminals rather than the zero-sequence voltage to the earth as shown in the figure to activate the relay on the occurrence of internal faults.

(c) *Stator-overheating Protection* Overheating of the stator may be caused by the failure of the cooling system, overloading or core faults like short-circuited laminations and failure of core bolt insulation. Modern generators employ two methods to detect overheating both being used in large generators (above 2 MW). In one method, the inlet and outlet temperatures of the cooling medium which may be hydrogen/water are compared for detecting overheating. In the other method, the temperature sensing elements are embedded in the stator slots to sense the temperature. Figure 9.7 shows a stator overheating relaying scheme. When the temperature exceeds a certain preset maximum temperature limit, the relay sounds an alarm. The scheme employs a temperature detector unit, relay and Wheatstone-bridge for the purpose. The temperature sensing elements may either be thermistors, thermocouples or resistance temperature indicators. They are embedded in the stator slots at different locations. These elements are connected to a multi-way selector switch which checks each one in turn for a period long enough to operate an alarm relay.

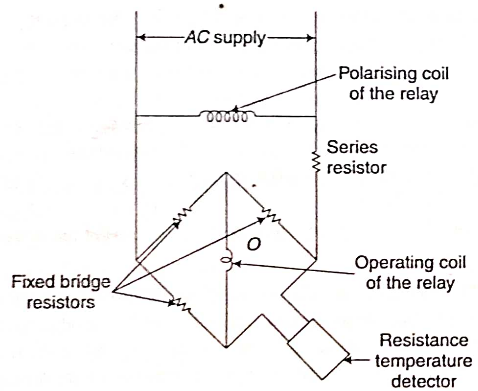


Fig. 9.7 *Stator-overheating protection*

For small generators, a bimetallic strip heated by the secondary current of the CT is placed in the stator circuit. This relay will not operate for the failure of the cooling system.

Thermocouples are not embedded in the rotor winding as this makes slip ring connections very complicated. Rotor temperature can be determined by measuring the winding resistance. An ohm-meter type instrument, energised by the rotor voltage and current and calibrated in temperature is employed for the purpose.

9.2.2 Rotor Protection

(a) *Field Ground-fault Protection* As the field circuit is operated ungrounded, a single ground fault does not affect the operation of the generator or cause any

damage. However, a single rotor fault to earth increases the stress to the ground in the field when stator transients induce an extra voltage in the field winding. Thus, the probability of the occurrence of the second ground fault is increased. In case a second ground fault occurs, a part of the field winding is bypassed, thereby increasing the current through the remaining portion of the field winding. This causes an unbalance in the air-gap fluxes, thereby creating an unbalance in the magnetic forces on opposite sides of the rotor. The unbalancing in magnetic forces makes the rotor shaft eccentric. This also causes vibrations. Even though the second ground fault may not bypass enough portion of the field winding to cause magnetic unbalance, the arcing at the fault causes local heating which slowly distorts the rotor producing eccentricity and vibration.

Figure 9.8 shows the schematic diagram of rotor earth protection. A dc voltage is impressed between the field circuit and earth through a polarised moving iron relay. It is not necessary to trip the machine when a single field earth fault occurs. Usually an alarm is sounded. Then immediate steps are taken to transfer the load from the faulty generator and to shut it down as quickly as possible to avoid further problems.

In case of brushless machines, the main field circuit is not accessible. If there is a partial field failure due to short-circuiting of turns in the main field winding, it is detected by the increase in level of the field current. A severe fault or short-circuiting of the diode is detected by a relay monitoring the current in the exciter control circuit.

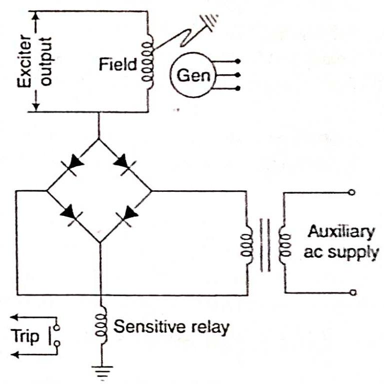


Fig. 9.8 *Earth fault protection*

(b) *Loss of Excitation* When the excitation of a generator is lost, it speeds up slightly and operates as an induction generator. Round-rotor generators do not have damper windings and hence they are not suitable for such an operation. The rotor is overheated quickly due to heavy induced currents in the rotor iron. The rotors of salient pole generators are not overheated because they have damper windings which carry induced currents. The stators of both salient and non-salient pole generators are overheated due to wattless current drawn by the machines as magnetising current from the system. The stator overheating does not occur as quickly as rotor overheating. A large machine may upset the system stability because it draws reactive power from the system when it runs as an induction generator whereas it supplies reactive power when it runs as a generator. A machine provided with a quick-acting automatic voltage regulator and connected to a very large system may run for several minutes as an induction generator without harm.

Field failure may be caused by the failure of excitation or mal-operation of a faulty field breaker. A protective scheme employing offset mho or directional impedance relay having a characteristic as shown in Fig. 9.9 is recommended for large modern generators. When a generator loses its excitation, the locus of the equivalent generator impedance moves from the first quadrant to the fourth quadrant, irrespective of initial conditions. This type of locus is not traced in any other conditions. The relay trips the field breaker and the generator is disconnected from the system.

(c) Protection against Rotor Overheating because of Unbalanced Three-phase Stator Currents The negative sequence component of unbalanced stator currents cause double frequency current to be induced in the rotor iron. If this component becomes high severe overheating of the rotor may be caused. The unbalanced condition may arise due to the following reasons:

(i) When a fault occurs in the stator winding
(ii) An unbalanced external fault which is not cleared quickly

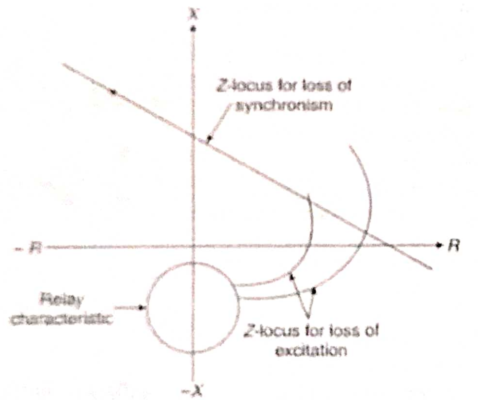


Fig. 9.9 Loss of excitation relay characteristic

(iii) Open-circuiting of a phase
(iv) Failure of one contact of the circuit breaker

The time for which the rotor can be allowed to withstand such a condition is related by the expression

$$I_2^2 t = K$$

where I_2 is the negative sequence component of the current, t = time, and K = a constant which depends on the type of generating set and its cooling system.

K = 7 for turbo-generator with direct cooling
= 60 for a salient-pole hydro generator.

Figure 9.10 shows a protective scheme using a negative sequence filter and relay. The overcurrent relay used in the negative phase sequence protection has a long operating time with a facility of range setting to permit its characteristic to be matched with $I_2^2 t$ characteristic of the machine. A typical time range of the relay is 0.2 to 2000 s. It has a typical construction with a special electromagnet. It has shaded pole construction with a mu-metal shunt. The negative sequence filter gives an output proportional to I_2. It actuates an alarm as well as the time-current relay which has a very inverse characteristic. The alarm unit also starts a timer which is adjustable from 8% to 40% of negative sequence component. The timer makes a delay in the alarm to prevent the alarm from sounding unnecessarily on unbalanced loads of short duration.

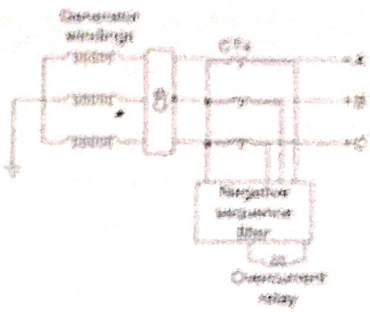


Fig. 9.10 Protection against unbalanced stator currents

9.2.3 Miscellaneous

(a) Overvoltage Protection Overvoltage may be caused by a defective voltage regulator or it may occur due to sudden loss of electrical load on generators. When a load is lost, there is an increase in speed and hence the voltage also increases. In case of a steam power station, it is possible to bypass the steam before the speed reaches a limit above which a dangerous overvoltage can be produced. In steam power stations, the automatic voltage regulator controls the overvoltages which is associated with overspeed. In hydro-stations it is not possible to stop or divert water flow so quickly and overspeed may occur. Therefore, overvoltage relays are provided with hydro and gas-turbine sets. But overvoltage relays are not commonly used with turbo-alternators.

(b) Overspeed Protection A turbo-generator is provided with a mechanical overspeed device. The spseed governor normally controls its speed. It is designed to prevent any speed rise even with a 100 per cent load rejection. An emergency centrifugal overspeed device is also incorporated to trip emergency steam valves when the speed exceeds 110 percent.

Large turbosets are sometimes provided with overspeed relays. In USA out of step tripping relays are used which cut off steam when the generator is 180° out of synchronism and has slipped one pole. In UK a sensitive fast power relay is used to determine whether the power output falls below a certain value or reversed.

Severe electrical faults also cause overspeed and hence HV circuit breakers, field circuit breakers and the steam turbine valves are tripped simultaneously. As water flow cannot be stopped quickly, hydrosets are provided with overspeed protection. The setting of overspeed relays for hydrosets is 140%. Overspeed relays are also provided with gas-turbine sets.

(c) Protection against Motoring When the steam supply is cut off, the generator runs as a motor. The steam turbine gets overheated because insufficient steam passes through the turbine to carry away the heat generated by windage loss. Therefore, a protective relay is required for the protection of the steam turbine. Generally, the relay operates when power output falls below 3%. A sensitive reverse power relay is available which has an operating setting of about 0.5% of the generator's output.

Hydrosets sometimes require protection against motoring. Cavitation problems arise in water turbines at low water flow. Protection is provided by reverse power relay having an operating setting of 0.2 to 2% of the rated power. A diesel set and gas turbine require 25% and 50% setting respectively.

(d) Protection against Vibration and Distortion of Rotor Vibration is caused by overheating of the rotor or some mechanical failure or abnormality. The overheating of the rotor is caused due to unbalanced stator currents or rotor ground faults. Overheating of the rotor distorts it, thereby causing eccentricity. Eccentric running produces vibration. Protection provided for unbalanced stator currents and rotor ground faults minimise vibration. A vibration measuring device is also used for steam turbine sets. Such a device detects the vibration which is caused either by electrical or mechanical causes. An alarm is actuated if vibration takes place. The vibration detector is mounted rigidly on one of the bearing pedestals of a horizontal shaft machine or on the upper guide-bearing of vertical shaft bearing. For details see Ref. 5.

(e) Bearing Overheating Protection Temperature of the bearing is detected by inserting a temperature sensing device in a hole in the bearing. For large machines where lubricating oil is circulated through the bearing, an oil flow device is used to detect the failure of oil cooling equipment. An alarm is actuated when the bearing is overheated or when the circulation of the lubricating oil fails.

(f) Protection against Auxiliary Failure The power plant auxiliaries are very important for the running of the generating sets. High grade protective equipment is employed for their reliable operation. For large generating sets, protection against loss of vacuum and loss of boiler pressure are provided. Such failures are due to the failure of the associated auxiliaries. So the protection provided for the loss of vacuum and loss of boiler pressure provides to some extent protection against the auxiliary failure. In the case of such failures generating sets are shut down. Protection against the failure of induced draught fans is also provided.

(g) Protection against Voltage Regulator Failure Modern quick response automatic voltage regulators are very complex. They are subject to component failures. Suitable protective devices are provided against their failure. A definite time dc overcurrent relay is provided which operates when there is overcurrent in the rotor circuit for a period longer than a prescribed limit. In such a situation, the excitation is switched to a predetermined value for manual control.

The supply for the regulator reference voltage is given from a separate voltage transformer. Protection is also required against the failure of the regulator reference voltage. An under voltage relay is used for this purpose. A better approach is to use a voltage balance relay which compares the voltage derived from the instrument transformer with the voltage derived from the voltage regulator transformer. If there is mal-operation of the voltage regulator due to the failure of the reference voltage, the relay operates and switches the excitation to a predetermined value for manual control.

(h) Protection against Pole Slipping In case of system disturbances after the operation of circuit breaker or when heavy load is thrown or switched on, the generator rotor may oscillate. Consequently, variations in current, voltage and power factor may take place. Such oscillations may disappear in a few seconds. Therefore, in such a situation, tripping is not desired. In some cases, angular displacement of the rotor exceeds the stability limit and the rotor slips a pole pitch. If the disturbance is over, the generator may regain synchronism. If it does not, it should be tripped.

An alternative approach is to trip the field switch and allow the machine to run as an asynchronous machine, thereby removing the oscillations from the machine. Then the load is reduced to a low value at which the machine can re-synchronise itself. If the machine does not re-synchronise, the field switch is reclosed at the minimum excitation setting. This will cause the machine to re-synchronise smoothly.

(i) Field Suppression When a fault occurs in the generator winding, the circuit breaker trips and the generator is isolated from the system. However, the generator still continues to feed the fault as long as the excitation is maintained, and the damage increases. Therefore, it is desirable to suppress the field as quickly as possible. The field cannot be destroyed immediately. The energy asssociated with the flux must be dissipated into an external device. To achieve this, the field winding is connected to a discharge resistor to absorb the stored energy. The discharge resistor is connected in parallel with the field winding before opening the field circuit breaker.

(j) Back-up Protection Overcurrent relays are used as back-up protection. As the synchronous impedance of a turbo-generator is more than 100%, the fault current, may fall below the normal load current. Therefore, standard time-overcurrent relays cannot be employed for back-up protection. A voltage controlled overcurrent can be employed for such a purpose. A better alternative is to use reactance or impedance type distance relays.

In addition to overcurrent relays, the stator protection is generally supplemented by sensitive earth fault relays. Relays having inverse time characteristic are used. An earth fault relay is connected to a CT placed in the neutral point earthing lead. This is an unrestricted protection and hence, it is to be graded with the feeder protection.

EXERCISES

1. Enumerate the relaying schemes which are employed for the protection of a modern alternator.

   Describe with a neat sketch, the percentage differential protection of a modern alternator.
2. What is transverse or split phase protection of an alternator? For what type of fault is this scheme of protection employed? With a neat sketch discuss the working principle of this scheme.
3. What type of protective device is used for the protection of an alternator against overheating of its (a) stator, (b) rotor? Discuss them in brief.
4. What type of a protective scheme is employed for the protection of the field winding of the alternator against ground faults?

5. Discuss the protection employed against loss of excitation of an alternator.
6. Are the protective devices employed for the protection of an alternator against (a) overvoltage, (b) overspeed, (c) motoring? Discuss them in brief.
7. Are the protective devices employed for the protection of an alternator against (a) vibration and distortion of the rotor, (b) bearing overheating, (c) auxiliary failure, (d) voltage regulator failure? Briefly describe them.
8. What is pole slipping phenomenon in case of an alternator? What measures are taken if pole slipping occurs?
9. What do you understand by field suppression of an alternator? How is it achieved?
10. Is any back-up protection employed for the protection of an alternator? If yes, discuss the scheme which is used for this purpose.
11. An 11 kV, 100 MVA generator is grounded through a resistance of 6 Ω. The CTs have a ratio of 1000/5. The relay is set to operate when there is an out of balance current of 1 A. What percentage of the generator winding will be protected by the percentage differential scheme of protection. (Ans. 14.1%)
12. An 11 kV, 100 MVA generator is provided with differential scheme of protection. The percentage of the generator winding to be protected against phase to ground fault is 80%. The relay is set to operate when there is 15% out of balance current. Determine the value of the resistance to be placed in the neutral to ground connection. (Ans. 1.61 Ω)
13. A 5 MVA, 6.6 kV Y (star) connected generator has resistance per phase of 0.5 Ω and synchronous reactance per phase of 2 Ω. It is protected by a differential relay which operates when the out of balance current exceeds 10% of the load current. Determine what proportion of the generator winding is unprotected if the star point is grounded through a resistor of 6.5 Ω. (Ans. 22.3%)

[Hint. If p % of the winding remains unprotected, the impedance of this portion of the winding $= \frac{p}{100}(0.5 + j2.0)$

$= p(0.005 + j0.02)$

Grounding resistance $= 6.5\ \Omega$

Total impedance in the fault circuit $= 6.5 + 0.005p + j0.02p$

$= (6.5 + 0.005p)$ very approx.

neglecting reactance portion which is small.

14. The neutral point of a 50 MVA, 11 kV generator is grounded through a resistance of 5 Ω, the relay is set to operate when there is an out of balance current of 1.5 A. The CTs have a ratio of 1000/5. What percentage of the winding is protected against a ground fault and what should be the minimum value of the grounding resistance to protect 90% of the winding. (Ans. 78.4%, 2.12 Ω)
15. Discuss the faults and various abnormal operating conditions of induction motors and protection provided against each.

16. Describe the protection of low voltage induction motor using conductor starter.
17. Explain the various methods of short circuit and ground fault protection of motors.
18. Discuss the causes of motor failure of both electrical and mechanical origin.
19. Explain the terms, 'single phasing' and 'phase reversal'. In what form protection is provided against single phasing and phase reversal.
20. Discuss the differential protection scheme for large motors.
21. What additional protection is required for synchronous motors?

10 Transformer and Buszone Protection

10.1 INTRODUCTION

The power transformer is a major and very important equipment in a power system. It requires highly reliable protective devices. The protective scheme depends on the size of the transformer. The rating of transformers used in transmission and distribution systems range from a few kVA to several hundred MVA. For small transformers, simple protective device such as fuses are employed. For transformers of medium size overcurrent relays are used. For large transformers differential protection is recommended.

Bus zone protection includes, besides the busbar itself, all the apparatus connected to the busbars such as circuit breakers, disconnecting switches, instrument transformers and bus sectionalizing reactors etc. Though the occurrence of bus zone faults are rare, but experience shows that bus zone protection is highly desirable in large and important stations. The clearing of a bus fault requires the opening of all the circuits branching from the faulted bus.

10.2 TRANSFORMER PROTECTION

10.2.1 Types of Faults Encountered in Transformers

The faults encountered in transformer can be placed in two main groups.

(a) External faults (or through faults)

(b) Internal faults

External Faults

In case of external faults, the transformer must be disconnected if other protective devices meant to operate for such faults, fail to operate within a predetermined time. For external faults, time graded overcurrent relays are employed as back-up protection. Also, in case of sustained overload conditions, the transformer should not be allowed to operate for long duration. Thermal relays are used to detect overload conditions and give an alarm.

Internal Faults

The primary protection of transformers is meant for internal faults. Internal faults are classified into two groups.

(i) *Short circuits in the transformer winding and connections* These are electrical faults of serious nature and are likely to cause immediate damage. Such faults are detectable at the winding terminals by unbalances in voltage or current. This type of faults include line to ground or line to line and interturn faults on H.V. and L.V. windings.

(ii) *Incipient faults* Initially, such faults are of minor nature but slowly might develop into major faults. Such faults are not detectable at the winding terminals by unbalance in voltage or current and hence, the protective devices meant to operate under short circuit conditions are not capable of detecting this type of faults. Such faults include poor electrical connections, core faults, failure of the coolant, regulator faults and bad load sharing between transformers.

10.2.2 Percentage Differential Protection

Percentage differential protection is used for the protection of large power transformers having ratings of 5 MVA and above. This scheme is employed for the protection of transformers against internal short circuits. It is not capable of detecting incipient faults. Figure 10.1 shows the schematic diagram of percentage differential protection for a $Y - \Delta$ transformer. The direction of current and the polarity of the CT voltage shown in the figure are for a particular instant. The convention for marking the polarity for upper and lower CTs is the same. The current entering end has been marked as positive. The end at which current is leaving has been marked negative.

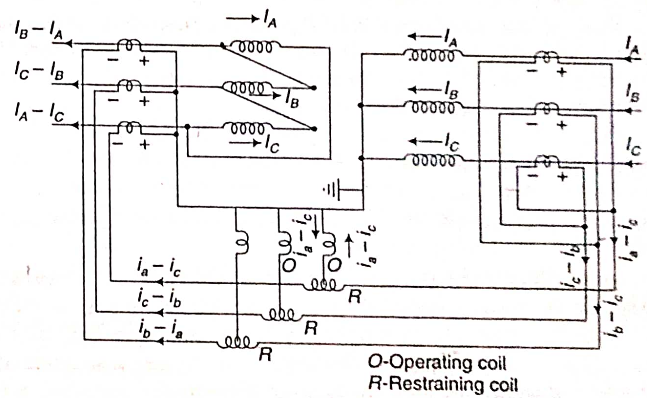


Fig. 10.1 *Percentage differential protection for $Y - \Delta$ connected transformer*

O and R are the operating and restraining coils of the relay, respectively. The connections are made in such a way that under normal conditions or in case of external faults the current flowing in the operating coil of the relay due to CTs of the primary side is in opposition to the current flowing due to the CTs of the secondary side. Consequently, the relay does not operate under such conditions. If a fault occurs on the winding, the polarity of the induced voltage of the CT of the secondary side is reversed. Now the currents in the operating coil from CTs of both primary and secondary side are in the same direction and cause the operation of

$X_C X_L$ allows only current of fundamental frequency to flow through the operating coil. The dc and harmonics, mostly second harmonics in case of magnetic inrush current, are diverted into the restraining coil. The relay is adjusted so as not to operate when the second harmonic (restraining) exceeds 15% of the fundamental current (operating). The minimum operating time is about 2 cycles.

The dc offset and harmonics are also present in the fault current, particularly if CT saturates. The harmonic restraint relay will fail to operate on the occurrence of an internal fault which contains considerable harmonics due to an arc or saturation of the CT. To overcome this difficulty, an instantaneous overcurrent relay (the high set unit) is also incorporated in the harmonic restraint scheme. This relay is set above the maximum inrush current. It will operate on heavy internal faults in less than one cycle.

In an alternative scheme, known as harmonic blocking scheme, a separate blocking relay whose contacts are in series with those of a biased differential relay, is employed. The blocking relay is set to operate when the second harmonic is less than 15% of the fundamental.

10.2.5 Buchholz Relay

It is a gas actuated relay. It is used to detect incipient faults which are initially minor faults but may cause major faults in due course of time. The Buchholz relay is used to supplement biased differential protection of the transformer because the Buchholz relay cannot necessarily detect short circuits within the transformer or at the terminals.

When a fault develops slowly, it produces heat, thereby decomposing solid or liquid insulating material in the transform. The decomposition of the insulating material produces inflammable gases. The operation of the Buchholz relay gives an alarm when a specified amount of gas is formed. The analysis of gas collected in the relay chamber indicates the type of the incipient fault. The presence of; (a) C_2H_2 and H_2 shows arcing in oil between constructional parts; (b) C_2H_2, CH_4 and H_2 shows arcing with some deterioration of phenolic insulation, e.g. fault in tap changer; (c) CH_4, C_2H_4 and H_2 indicates hot spot in core joints; (d) C_2H_4, C_3H_6, H_2 and CO_2 shows a hot spot in the winding.

There is a chamber to accommodate Buchholz relay, in between the transformer tank and the conservator as shown in Fig. 10.3 (a). A simple diagram to explain the operating principle of Buchholz relay is shown in Fig. 10.3 (b). When gas accumulates, the oil level falls down and thus the float also comes down. It causes an alarm to sound and alert the operator. For reliable operation, a mercury switch is attached with the float. Some manufacturers use open-topped bucket in place of a bob. When the oil level falls because of gas accumulation, the bucket is filled up with oil. Thus, the force available to operate the contacts is greater than with hollow floats. The accumulated gas can be drawn off through the petcock via a pipe for analysis to know the type of fault. If there is a severe fault, large volumes of gases are produced which cause the lower float to operate. It finally trips the circuit breakers of the transformer.

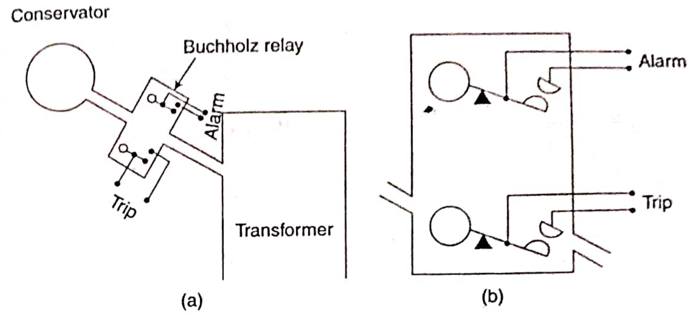


Fig. 10.3 *(a) Transformer tank, Buchholz relay and conservator (b) Buchholz relay*

The buchholz relay is a slow acting device, the minimum operating time is 0.1 s, the average time 0.2 s. Too sensitive settings of the mercury contacts are not desirable because they are subjected to false operation on shock and vibration caused by conditions like earthquakes, mechanical shock to the pipe, tap changer operation and heavy external faults. This can be reduced by improved design of the mercury contact tubes.

10.2.6 Oil Pressure Relief Devices

An oil pressure relief device is fitted at the top of the transformer tank. In its simplest form, it is a frangible disc located at the end of an oil relief pipe protruding from the top of the transformer tank. In case of a serious fault, a surge in the oil is developed, which bursts the disc, thereby allowing the oil to discharge rapidly. This avoids the explosive rupture of the tank and the risk of fire.

The drawback of the frangible disc is that the oil which remains in the tank after rupture is left exposed to the atmosphere. This drawback can be overcome by employing a more effective device: a spring controlled pressure relief valve. It operates when the pressure exceeds 10 psi but closes automatically when the pressure falls below the critical level. The discharged oil can be ducted to a catchment pit where random discharge of oil is to be avoided. The device is commonly employed for large power transformers of the rating 2 MVA and above but it can also be used for distribution transformers of 200 kVA and above.

10.2.7 Rate of Rise of Pressure Relay

This device is capable of detecting a rapid rise of pressure, rather than absolute pressure. Its operation is quicker than the pressure relief valve.

It is employed in transformers which are provided with gas cushions instead of conservators. Figure 10.4 shows a modern sudden pressure relay which contains a metallic bellows full of silicone oil. The bellows is placed in the transformer oil. The relay is placed at the bottom of the tank where maintenance jobs can be performed conveniently. It operates on the principle of rate or increase of pressure. It is usually designed to trip the transformer.

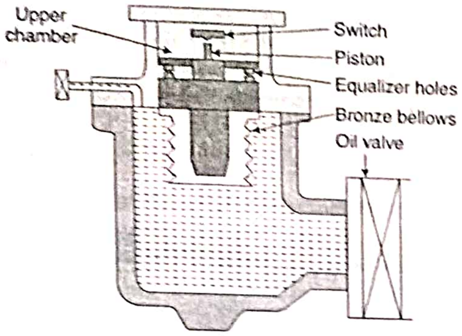


Fig. 10.4 *Sudden pressure relay*

10.2.8 Overcurrent Relays

Overcurrent relays are used for the protection of transformers of rating 100 kVA and below 5 MVA. An earth fault tripping element is also provided in addition to the overcurrent feature. Such relays are used as primary protection for transformers which are not provided with differential protection. Overcurrent relays are also used as back-up protection where differential protection is used as primary protection.

For small transformers, overcurrent relays are used for both overload and fault protection. An extremely inverse relay is desirable for overload and light faults, with instantaneous overcurrent relay for heavy faults. A very inverse residual current relay with instantaneous relay is suitable for ground faults.

10.2.9 Earth Fault Relays

A simple overcurrent and earth fault relay does not provide good protection for a star connected winding, particularly when the neutral point is earthed through an impedance. Restricted earth fault protection, as shown in Fig. 10.5 provides better protection. This scheme is used for the winding of the transformer connected in star where the neutral point is either solidly earthed or earthed through an impedance. The relay used is of high impedance type to make the scheme stable for external faults.

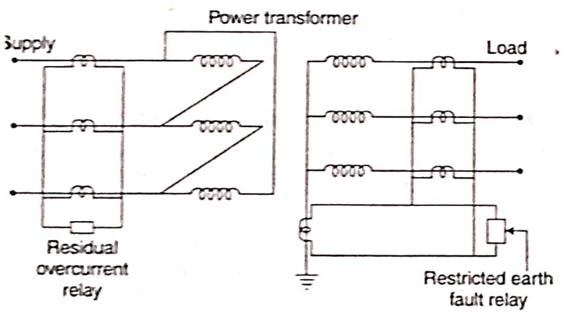


Fig. 10.5 *Earth fault protection of a power transformer*

For delta connection or ungrounded star winding of the transformer, residual overcurrent relay as shown in Fig. 10.5 is employed. The relay operates only for a ground fault in the transformer.

The differential protection of the transformer is supplemented by restricted earth fault protection in case of a transformer with its neutral grounded through resistance. For such a case only about 40% of the winding is protected with a differential relay pick-up setting as low as 20% of the CT rating.

10.2.10 Overfluxing Protection

The magnetic flux increases when voltage increases. This results in increased iron loss and magnetising current. The core and core bolts get heated and the lamination insulation is affected. Protection against overfluxing is required where overfluxing due to sustained overvoltage can occur. The reduction in frequency also increases the flux density and consequently, it has similar effects as those due to overvoltage. The expression of flux in a transformer is given by

$$\phi = K\frac{E}{f}$$

where, ϕ = flux, f = frequency, E = applied voltage and K = constant.

Therefore, to control flux, the ratio E/f is controlled. When E/f exceeds unity, it has to be detected. Electronic circuits with suitable relays are available to measure the E/f ratio. Usually 10% of overfluxing can be allowed without damage. If E/f exceeds 1.1, overfluxing protections operates. Overfluxing does not requires high speed tripping and hence instantaneous operation is undesirable when momentary disturbances occur. But the transformer should be isolated in one or two minutes at the most if overfluxing persists.

10.2.11 Protection of Earthing Transformer

The function of an earthing transformer is to provide a grounding point for the power system where machines have delta connection. An earthing transformer is connected either in star-delta or zig-zag fashion. When a fault occurs only zero sequence current flows from the earthing transformer to the grounding point. Positive or negative sequence currents can flow only towards the earthing transformer and not away from it. An earthing transformer can be protected by IDMT overcurrent relays fed by delta connected CTs, as shown in Fig. 10.6.

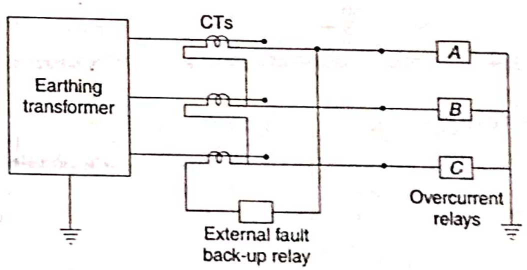


Fig. 10.6 *Protection of earthing transformer*

The CTs are connected in delta and zero sequence currents circulate in it. An over-current relay with time delay is inserted in this delta. The time setting of this relay is selected to coordinate with the time setting of the earth fault relays. This relay is used as a back-up relay for external faults.

10.2.12 Protection of Three-Winding Transformer

In a three-winding transformer, one of the three windings is connected to the source of supply. The other two windings feed loads at different voltages. One line diagram is shown in Fig. 10.7 for the protection of a three-winding transformer.

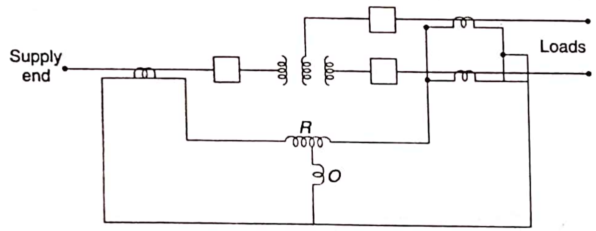


Fig. 10.7 *Protection of three-winding transformer with power source at one end*

When a three-winding transformer is connected to the source of supply at both primary and secondary side, the distribution of current cannot readily be predicted and there is a possibility of current circulation between two sets of paralleled CTs without producing any bias. Figure 10.8 shows protective scheme for such a situation. In this case, the restraint depends on the scalar sum of the currents in the various windings.

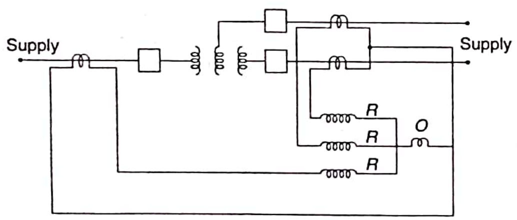


Fig. 10.8 *Protection of three-winding transformer with power source at both ends*

10.2.13 Generator-Transformer Unit Protection

In a modern system, each generator is directly connected to the delta connected primary winding of the power transformer. The star connected secondary winding is HV winding and it is connected to the HV bus through a circuit breaker. In addition to normal protection of the generator and transformer, an overall biased differential protection is provided to protect both the generator and transformer as one unit.

Figure 10.9 shows an overall differential protection. Usually harmonic restraint is not provided because the transformer is only connected to the busbar at full voltage. However, there is a possibility of a small inrush current when a fault near the busbar is cleared, suddenly restoring the voltage.

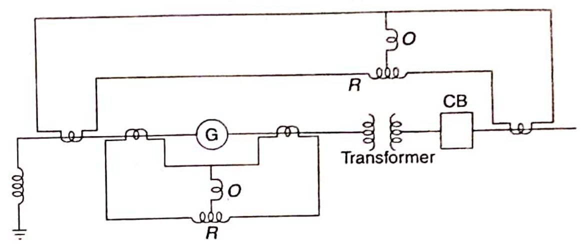


Fig. 10.9 *Differential protection of generator transformer unit*

10.2.14 Miscellaneous

Tank-earth Protection

If the transformer tank is nominally insulated from earth (an insulation resistance of 10 ohms being sufficient), the primary of a CT is connected between the tank and earth. A relay is connected to the secondary of the CT. This protection is similar to the frame earth scheme of protection for busbar discussed in the next section. This is also called Harward protection.

Neutral Displacement

In case of unearthed transformer, an earth fault elsewhere in the system may result in the displacement of the neutral. A neutral displacement detection scheme is shown in Fig. 10.10. The secondary of the potential transformer is connected in open delta. Its output which is applied to the relay is proportional to the zero sequence voltage of the line, i.e. any displacement of the neutral point. For details, see Ref. 5.

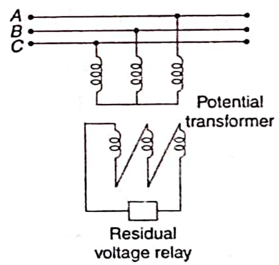


Fig. 10.10 *Neutral displacement detection*

Example 10.1 | A three-phase, 11 kV/132 kV, Δ-Y connected power transformer is protected by differential protection. The CT_s on the LV side have a current ratio of 500/5. What must be the current ratio of the CT_s on the HV side and how should they be connected.

Solution: In order that circulating currents in the relay are in phase opposition, the CT_s on the delta connected LV side of the transformer should be connected in star and the CT_s on the star connected HV side of the transformer should be connected in delta. Connections of CT_s on LV and HV sides are shown in Fig. 10.11

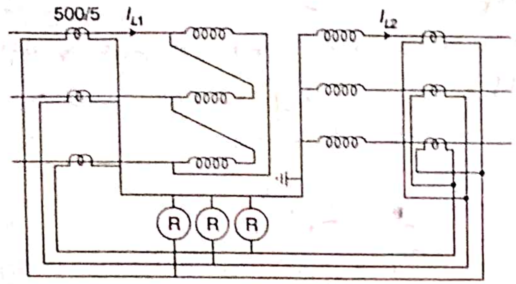


Fig. 10.11

Let the line currents on the primary and secondary sides of the transformer be I_{L1} and I_{L2} respectively. Then,

$$\sqrt{3} \times 11 \times I_{L1} = \sqrt{3} \times 132 \times I_{L2}$$

or

$$I_{L2} = \frac{11}{132} I_{L1}$$

For I_{L1} of 500 A, $I_{L2} = \frac{11}{132} \times 500 = 41.66$ A

Since the CT_s on the LV side are connected in star, the current through the secondary of the CT and the pilot wire will be 5 A. The CT_s on the HV side being delta connected will have a current of $5/\sqrt{3}$ A in the secondary.

Hence CT ratio on HV side

$$= 41.66/5/\sqrt{3}$$
$$= \sqrt{3} \times 41.66/5$$
$$= 72.15/5$$

Example 10.2 | A three-phase, 11 kV/33 kV, Y-Δ connected power transformer is protected by differential pratection. The CT_s on the LV side have a current ratio of 400/5. What must be the ratio of CT_s on the HV side. How the CT_s on both the sides of the transformer are connected.

Solution: The connections of the CT_s on both the sides of the transformer are shown in Fig. 10.12.

Let the line currents on the primary and secondary sides of the transformer be I_{L1} and I_{L2} respectively.

Then, $$\sqrt{3} \times 11 \times I_{L1} = \sqrt{3} \times 33 \times I_{L2}$$

or $$I_{L2} = \frac{11}{33} I_{L1}$$

For I_{L1} of 400 A, $I_{L2} = \frac{11}{33} \times 400 = 133.3$ A

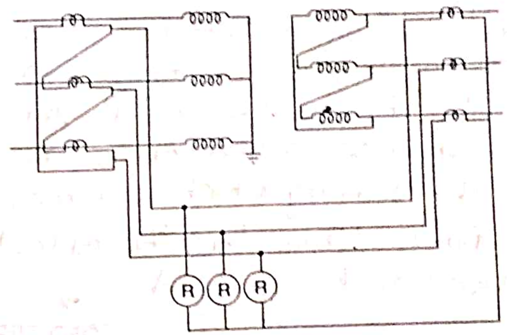


Fig. 10.12

The current through secondary of the CT on the primary side of the transformer will be 5A. Since the CT_s on the primary side are connected in delta, the current through its pilot wire will be 5 $\sqrt{3}$ A. The CT_s on the secondary side being star connected will have a current of 5 $\sqrt{3}$ in the secondary.

Hence CT ratio on HV side

$$= 133.3/5\sqrt{3}$$
$$= 76.7/5$$

10.3 BUSZONE PROTECTION

10.3.1 Differential Current Protection

Figure 10.13 shows a scheme of differential current protection of a buszone. The operating principle is based on Kirchhoff's law. The algebraic sum of all the currents entering and leaving the busbar zone must be zero, unless there is a fault therein. The relay is connected to trip all the circuit breakers. In case of a bus fault the algebraic sum of currents will not be zero and relay will operate.

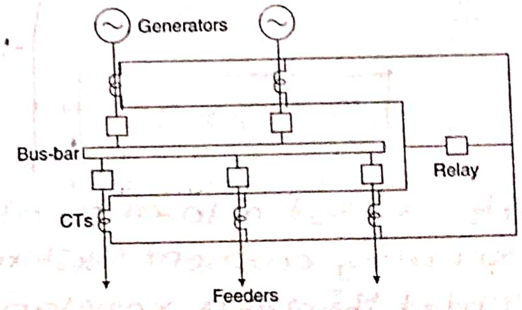
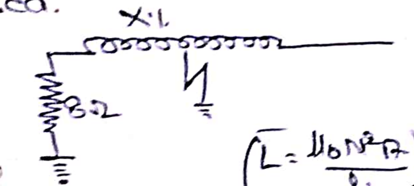


Fig. 10.13 *Differential current protection of bus-zone*

P) A 6.6kV, 5MVA star connected alternator has a reactance of 1.5 Ω per phase and negligible resistance. Merz-Price protection scheme is used which operates when the out of balance current exceeds 25% of the full load current. The neutral of the generator is grounded through a resistance of 8Ω. Determine the protection of the winding which remains unprotected against earth fault. Show that the effect of the alternator reactance can be ignored.



Ans:-

The phase voltage will be

$= \frac{6600}{\sqrt{3}} = 3810$

$\left(L = \frac{\mu_0 N^2 A}{l}\right)$

$L = N^2$

The voltage of the unprotected portion $= 3810 \times \frac{x}{100}$

The fault current $= 3810 \times \frac{x}{100} \times \frac{1}{8}$

The full load current $= \frac{5000}{\sqrt{3} \times 6.6} = 437.37A$.

The out of balance current required for the operation of the relay.

$= 437.37 \times 0.25 = 109.34A$.

$\frac{3810x}{800} = 109.34$

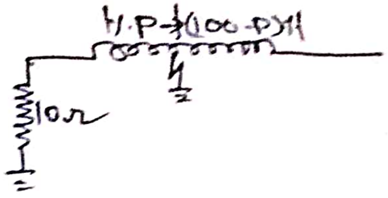
$x = 22.95\%$

$\%P = \frac{I_F(Z+R)}{V_{ph}} \times 100$

= X =

2) An alternator rated a 10kV protected by the balanced circulating current system has its neutral grounded through a resistance of 10Ω. The protective relay is set to operate when there is an out of balance current of 1.8A in the pilot wires, which are connected to the secondary windings of 1000/5 ratio current transformers. Determine (i) the percent winding which remains unprotected (ii) the minimum value of the earthing resistance required to protect 80% of the winding.

Ans:-



$I_{oc} = I_F \times \frac{5}{1000}$

$I_F = 1.8 \times \frac{1000}{5}$

$I_F = 360A$

$\%P = \frac{\frac{360 \times 10}{\sqrt{3}}(10)}{5773} = 0.6236 \times 100 = 62.36\%$

(ii) To protect 80% of the winding, the unprotected portion is 20%. The voltage of the unprotected portion.

$R = 3.118\,\Omega$.

= X =

3) The neutral point of a three-phase 20MVA 11kV alternator is earthed through a resistance of 5Ω, the relay is set to operate when there is an out-of-balance current of 1.5A. The CTs have a ratio of 1000/5A. What is the percentage of winding protected? Also calculate the earthing resistance required to protect 90% of the winding.

$\%x = 76.4\%$.

$R = 2.12\,\Omega$.