33

Protection of Generators

Introduction — Protection Chart — Faults on Generator — Differential Protection of Generator — Problems — Turn to turn Fault — Stator Overheating — Reverse Power — Rotor Earth Fault — Field Suppression — Unbalanced Loads — Back-up Protection — Overspeed — Bearing Insulation — Protection of Large Generator — Transformers Units — Protection of small standby Generators — Summary.

33.1. INTRODUCTION

Protection of turbo-generators is the most complex and elaborate. The reasons being the following :

— Generator is a large machine and is connected to busbars. It is accompanied by unit-transformers, auxiliary transformer and bus system.

— It is accompanied by excitation system, prime mover, voltage regulator, cooling system etc. Hence it is not a single equipment. The protection of generator should be co-ordinated with associated equipment.

— It is a costly and important equipment. It should not be shut off as far possible because that would result in power shortage and emergency.

Modern Turbo-generators have the following typical ratings.

60 MW	11.8 kV
120 MW	13.8 kV
500 MW	22 kV

Generator unit upto 500 MW have been installed in India.

1000 MW unit capacity Turbo-generators has been installed in U.K. during 1970's.

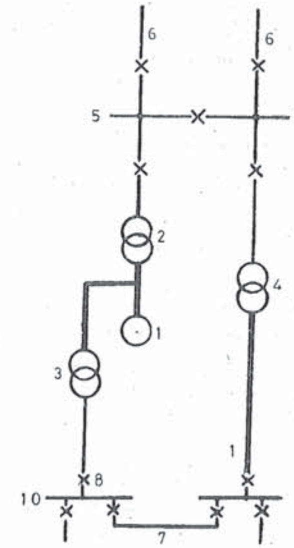
A generator is protected against several fault. Table 33.1 gives data about the present practice of alternator protection. Several other abnormal conditions give an alarm and indication. Static protection schemes have been developed for generator protection.

Table 33.1. Generator Protection

		Below 1 MW	*Above 1 MW*	*Above 10 MW*	*Above 100 MW*
1.	Differential			*	*
2.	Restricted earth fault			*	*
3.	Stator turn to turn fault				*
4.	Time over current	*	*		
5.	Temperature (Thermo-Detector)		*	*	*
6.	Negative sequence current		*	*	*
7.	Loss of load			*	*
8.	Loss of input-anti-motoring		*	*	*
9.	Loss of field			*	*
10.	Loss of synchronism			*	*
11.	Overspeed	*		Only for hydro-generators	
12.	Over-voltage	*		Only for hydro-generators	
13.	Rotor-earth Faults			*	*
14.	Back-up overcurrent	*	*	*	*
15.	Bearing temperature			*	*
16.	Bearing insulation		*	*	*

In unit system of generator connection, generator is connected to LV side of the main step-up transformer and H.V. side of unit auxiliary step-down transformer (Fig. 33.1). The H.V. side of the main transformer is connected to bus *via* switchgear, from where power is transmitted into the Grid. The unit auxiliary transformer feeds the power to the auxiliaries directly, concerned with the unit. The generator and main transformer form a 'unit' and each unit has a boiler, turbine, condenser and other auxiliary systems.

While selecting the scheme for generator protection, the protection of the complete unit and the stability of the system due to disturbance, in the generator should be considered in addition to the protection of the generator itself.



1. Generator (Indoor)
2. Main Transformer (Outdoor)
3. Unit auxiliary transformer (Usually outdoor)
4. Station Service Transformer. (Usually outdoor)
5. H.V. bus. (Outdoor)
6. Transmission line. (Outdoor, overhead)
7. Inter-connection between the Unit Auxiliary Switchgear and Station Service Switchgear.
8. Circuit Breaker. (Indoor)
9. Station Service Switchgear. (Indoor)
10. Unit Auxiliary Switchgear. (Indoor)

Fig. 33.1. Generator connections in unit system. (Refer Table 33.2).

The protection of generator-transformer unit can be divided into three groups :

— Protective relays to detect faults or abnormal conditions external to the unit.

— Protective relays to detect faults internal to the unit.

— Devices associated with the unit *e.g.*, over-speed safeguards, temperature measuring devices for bearings, windings etc. Some of these wound an alarm and some cause tripping.

The protection of a large Generator-Transformer unit can be grouped as follows :

— Preventive measures forming part of the generator protection scheme, indicating systems and alarms.

— Protective systems for generator-transformers together.

— Protective system for generator.

— Protective systems for main transformer.

— Protective systems for unit-auxiliary transformer.

(Refer Table 33.1, 33.2). (Refer Sec. 17.5).

33.2. ABNORMAL CONDITIONS AND PROTECTION SYSTEMS (Ref. Table 33.3).

Table 32.2. Protection of Large Generator-Transformer Unit

Protection of Generator Transformer together	*Generator-transformer overall differential protection*
Generator protection	Generator differential protection* Stator earth fault protection** Negative phase sequence protection Against-unbalanced loading*** Inter-turn fault protection Reverse power protection** Field failure protection* Rotor earth fault protection*** Temperature sensors in slots Overcurrent relays in stator and rotor circuits Surge arresters for surge overvoltage R-C Surge suppressors
Protection of unit auxiliary transformer	Differential protection* Restricted earth fault protection* Buchholz relay Overcurrent protection, overvoltage protection Winding and oil temperature sensors
Protection of main transformer	HV Overcurrent Protection*, overfluxing protection HV Restricted earth fault protection* Buchholz relay Winding and oil temperature sensors Surge arresters on HV side
Preventive measures — Sound alarm on control panel	Continuous monitoring of outlet temperature of gaseous of liquid coolants Flow monitors Low boiler pressure alarm/trip Lubrication oil failure Emergency trip Low vacuum

* Trip generator c.b. close throttle valves, opened field c.b., one auxiliary c.b.

** Close emergency throttle valves main c.b. opened only after operation of interlock reverse power relay.

*** Trip main circuit breaker only. (Refer Fig. 33.1).

33.2.1. External Faults.

During external faults with large short-circuit currents, severe mechanical stress will be imposed on the stator windings. If any mechanical defects already exist in the winding, these may be further aggravated. The temperature rise is however, relatively slow and a dangerous temperature level may be obtained after about 10 seconds. With asymmetrical faults, severe vibrations and overheating of the rotor may occur.

The external faults such as faults on bus-bars are not covered by generators protection zone. Hence differential protection of generator does not responds to external fault.

The *overcurrent and earth fault protection of generator* provides back-up protection to external faults, while the primary protection as provided by the protective system of respective equipment (*e.g.* bus-bars, transmission lines).

33.2.2. Thermal overloading.

Continued overloading may increase the winding temperature to such an extent that the insulation will be damaged and its useful life reduced.

Temperature rise can also be caused by failure of cooling system. In large machines thermal elements (thermo-couples or resistance thermometers) are embedded in the stator slots and cooling system.

The electrical overcurrent protection is generally set at higher value for responding the excessive overloads. Hence it cannot sense the continuous overloads of less value. Neither can it sense the failure of cooling system.

33.2.3. Unbalanced loading.

Continued unbalanced loads, equal to or more than 10 per cent of the rated current cause dangerous heating of the cylindrical rotor in turbo-generators. Salient pole rotors in hydro-generators often include damper windings and are, therefore, much less affected by unbalance loading (negative phase-sequence currents).

Unbalanced loading on generator can be due to

— unsymmetrical faults in the system near the generating station.

— mal-operation of a circuit-breaker near generating station, the three phases not being cleared.

Negative sequence protection senses unbalanced loading of generators.

33.2.4. Stator Winding Faults.

Stator winding faults involve armature winding and must therefore be cleared quickly by complete shutdown of the generator. Only opening the circuit does not help since the e.m.f. is induced in the stator winding itself. The field is opened and de-energized by "Field Suppression" (Ref. Sec. 33.16).

The stator faults include.

(1) Phase-to-phase faults. (2) Phase-to-earth faults. (3) Stator inter-turn faults.

Phase to phase faults and phase inter-turn faults are less common. Inter turn faults are more difficult to be detected.

Phase to Earth faults. These faults normally occur in the armature slots. The damage at the point of fault is directly related to the selected neutral earthing resistor. With fault currents less than 20 A, negligible burning of the iron core will result if the machine is tripped within some seconds. The repair work than amounts to changing the damaged coil without restacking of core laminations.

If, however, the earthing resistor is selected to pass a much larger earth-fault current (> 200 A) severe burning of the stator core will take place, necessitating restacking of laminations. Even when a high speed earth-fault differential protection is used, severe damage may be caused owing to the large time constant of the field-circuit and the relatively long time required to completely suppress the field flux. In the case of high earth-fault currents it is therefore normal practice to install a circuit breaker in the neutral of the generator in order to reduce the total fault-clearance time.

Circulating current biased differential protection provides the earth fault protection. However the sensitivity of such a protection for earth faults depends upon the resistance in neutral to earth connection and the position of earth fault in the winding.

A separate and *sensitive earth fault protection* is generally necessary for generators with resistance earthing.

Phase to phase faults. Short circuits between the stator windings very rarely occur because the insulation in a slot between coils of differents phases is at least twice as large as the insulation between one coil and the iron core. However a phase to earth fault may cause a phase-to-phase fault within the slots. If a phase-to-phase fault should occur, this is most likely to be located at the end-connections of the armature windings, i.e. in the overhanging parts outside the slots. A fault of this nature causes severe arcing with high temperatures, melting of copper and risk of fire if the insulation is not made of fire-resistant, non-flammable material. Since the short-circuit currents in this case do not pass *via* the stator core, the limitations will not be particularly damaged. The repair work may therefore be limited to replacing the affected coil and mechanical parts of the end-structure.

With acknowledgements to ASEA Sweden ; Brown Boveri, Switzerland.

Circulating current biased differential protection gives adequate and fast protection against phase-to-phase faults in the generator zone. (Ref. Sec. 33.3).

— **Stator Inter-turn faults.** Short circuits between the burns of one coil may occur if the stator winding is made up of multiturn coils. Such faults may develop owing to incoming current surges with a steep wave-front which may cause a high voltage *(L di/dt)* across the turns at the entrance of the stator winding.

If, however, the stator winding is made up of single-turn coils, with only one coil per slot, it is, of course, impossible to have an inter-turn fault. If there are two coils per slot the insulation between the coils is of such dimensions that an inter-turn fault is not likely to occur.

For large machines (> 50 MVA), it is the normal practice in some countries to use single-turn coils whereas in the U.S.A. and Canada multi-turn coils are used. In the latter countries, therefore, the inter-turn, or split-phase, protection has become very popular.

Differential protection and overcurrent protection does not sense inter-turn faults. *Stator interturn fault protection detects the inter-turn faults.*

33.2.5. Field Winding Faults.

Rotor faults include rotor inter-turn fault and conductor-to-earth faults. These are caused by mechanical and temperature stresses.

The field system is normally not connected to the earth so that a single earth fault does not give rise to any fault current. A second earth fault will short circuit part of the winding and may thereby produce an unsymmetrical field system, giving unbalanced force on the rotor. Such a force will cause, excess pressure on bearing and shaft distortion, if not cleared quickly.

The unbalanced loading on generator gives rise to negative sequence currents which cause negative sequence component of magnetic field. The negative sequence field to rotates in opposite direction of the main field and induces e.m.f.'s. in rotor winding. Thus the unbalanced loading causes rotor heating.

Reduced excitation may occur due to short circuit or an open circuit in field or exciter circuits or a fault in automatic voltage regulator. If the field circuit breaker opens by mistake, the fully loaded generator falls out of step within 1 second, and continues to run as an induction generator drawing reactive power from the bus. To avoid this, a tripping scheme is so arranged that opening of field circuit breaker causes the tripping of generator unit breaker.

'Rotor earth fault protection' is provided for large generators.

Rotor temperature indicators are used with large sets for detecting rotor overheating due to unbalanced loading of generator.

33.2.6. Overvoltages (Ref. Sec. 18.11)

Atmospheric surge-voltages are caused by direct lightning strokes to the aerial lines in the H.V. system. Induced and capacitively transferred voltage surges can, however, reach the generator *via* the unit transformer. The amplitude and the duration of the surge on the generator side depends on the type of lightning arresters used on the H.V. side and also on the actual configuration of the H.V. busbar.

To protect generators from severe voltage surges, surge arresters and surge capacitors and often used. In the case of smaller machines directly connected to a distribution network comprising overhead lines, such protective devices are of prime importance.

Switching Surges. Switching operations may cause relatively high transient overvoltage if restriking occurs across the contacts of the circuit-breakers. These transients are similar to those obtained during intermittent earth faults (arcing grounds) and may be limited by using modern circuit-breakers.

Arcing Grounds. The amplitude of the transient voltages during arcing grounds may theoretically, under the most unfavourable conditions of arc-restriking, reach a value of 5 times normal line to neutral peak voltage. By means of the resistance earthing of the generator neutral these over-voltages will be reduced to a maximum value of about 2.5 times the rated peak voltage. In the case of generator-transformer units, stray voltages may appear at the generator neutral during an earth fault in the HV network. This is due to the capacitive coupling between the HV and LV windings of the step up transformer. The magnitude of these stray voltages depends on : (*a*) the method of neutral earthing of the HV network, *i.e.*, effectively earthed or reactance earthed (Petersen-coil)

and (*b*) the step up transformer inter-winding capacitance, and (*c*) the ohmic value of the generator neutral earth resistor.

When the HV system is directly earthed, the voltage across the generator earthing resistor, during an HV earth fault will be small and can normally be disregarded. However, if the HV network is Petersen coil earthed, the neutral displacement voltage of the generator can reach the normal setting of the earth fault protection. This problem must therefore be investigated for each particular installation, and can be solved by either increasing the earth-fault relay setting or reducing the ohmic value of the generator earthing resistor.

Surge arresters and R-C surge suppressors installed between the generator circuit-breaker and the generator may also assist in reducing some of the highest switching surges. (Ref. Sec. 18.12)

Specially developed indoor type surge arresters are connected near generator terminals. These comprise three star connected unit plus another unit between star point and earth and thus provide overvoltage protection for all phases and between phases. Capacitors rated about 0.1 μF to earth are fitted to absorb surge voltages.

33.2.7. Other Abnormal Conditions.

Loss of excitation results in loss of synchronism and slightly increased speed. The machine continues to run as an induction generator, drawing excitation current from bus bars, the damper winding acts like a squirrel cage. The currents are taken at a high lagging power factor and magnitude is of the order of full load current. This causes overheating of stator winding and rotor winding. This condition should not be allowed to persist for a long time. The field should be either restored or the machine should be shut off, before system stability is lost.

Field-failure protection or loss of field protection is provided for generators. (Ref. sec. 33.13).

In addition to the above mentioned electrical faults, the running of a machine can be endangered by relatively minor mechanical defects in any of the auxiliary apparatus associated with the prime mover.

Loss of Synchronism. If the machine losses synchronism with respect to the network after a short circuit has been interrupted, a certain amount of slip is generally permissible, providing that the stator current does not exceed 85% of the maximum asymmetric short current with a solid short-circuit at the terminals.

Wrong Synchronization. Present day requirements stipulate that a generator must be short-circuit proof. However, with low reactance of the network and at the unit-connected transformer, in the event of wrong synchronization the current can be higher than under short-circuit conditions. This is not permissible. In other words wrong synchronization must not occur. Preventive measures must therefore be taken. In particular, uncontrolled reclosure after complete isolation of the generator from the network must be avoided because this quickly results in an excessive phase angle. In this connection it must also be noted that the recovery voltage in the network following interruption of a short circuit can lead to considerable stresses.

Asynchronous Running without Excitation. If asynchronous running is permitted by the manufacturer and requested by the operator for emergency conditions, it must be monitored. It must be decided whether asynchronous running is to be carried out with open or short-circulated rotor. Slip and stator current must not be allowed to exceed the specified limits.

Local Overheating. Local overheating can occur in generators for various reasons and it is often a difficult matter to locate these with the usual protection equipment. Normally, emission products, in the form of gas, mist or smoke escape and these can be used for tripping a signal. An analysis of these products provides a basis for decision.

Leakage in Hydrogen Circuit. Hydrogen losses are predetermined on the basis of gas consumption. However, continuous direct display is not recommended because temperature fluctuations in the generator cause variations in pressure and therefore gas make up is not directly related to losses. Consequently, long term monitoring is more suitable. It is only hydrogen leakage into the pure water system which is detected separately by the gas blow-off device in the pure water tank. Other points of leakage are not directly detected. It is essential for adequate ventilation to be provided in the vicinity of the generator and terminal box. Special attention must be paid to the cooling water circuit because any hydrogen carried along by the water is a danger factor and must therefore be prevented.

Moisture in the Generator Winding. Moisture is the generator is to be avoided. Moisture detectors and drains must be provided at all points where liquids can collect. The situation can arise where the make up hydrogen is moist and can thus introduce moisture into the generator even if the cooling water circuits are absolutely leakproof. This can be overcome by a gas drying plant which must be kept operational by the staff.

Oxygen in Pure Water Circuit. Dissolved oxygen in the pure water circuit leads to wear at the copper of the hollow conductors of windings with direct cooling. At hydrogen cushion of adequate pressure in the pure water compensating tank reduces the oxygen content to a minimum Continuous supervision of oxygen content thus becomes superfluous.

Overspeeding may occur as a result of a fault in the turbine governor or its associated equipment. If the main generator circuit-breaker is tripped while full electrical power is being delivered to the network, dangerous overspeeding is prevented by the normal actions of the governor. It is essential, therefore, that the normal working of the governor be supervised by some additional protective devices. Over-frequency and Under-frequency Protection : Ref. Ch. 45.

Motoring of generator will occur if the driving torque of the prime mover is reduced below the total losses of the turbo-generator unit. Active power will then be drawn from the network in order to maintain synchronous running, and the generator will work as a synchronous motor. If this is allowed to persist (> 20 seconds), serious over-heating of the steam turbine blades may occurs, depending on the type turbine and the design limits imposed by the manufacturer.

Table 33.3. Some Abnormal Conditions and Protection Systems

S.No.	*Abnormal Condition*	*Effect*	*Protection*
1.	Thermal overloading — continuous overloading — failure of cooling system	Overheating of stator winding and insulation failure.	Thermocouples of resistance thermometer imbedded in stator slots and cooling system. Stator over-load protection with overcurrent relays.
2.	External fault fed by generator	Unbalanced loading stresses on winding and shaft, excessive heating for prolonged short-circuit.	Negative phase sequence protection for large machines. Overload protection for small generators.
3.	Stator faults — phase to phase — phase to earth — inter-turn	Winding burn-out, welding of core laminations, shut down.	Biased differential protection, sensitive earth-fault protection, interturn fault protection.
4.	Rotor earth faults	Single fault does not harm second fault causes unbalanced magnetic forces causing damage to shaft, bearings.	Rotor earth-fault protection.
5.	Loss of field — Tripping of field circuit-breaker.	Generator runs as induction generator deriving excitation currents from bus-bar. Speed increases slightly.	'Loss of field' or 'Field failure' protection.
6.	Motoring of generator. When input to prime mover stops, the generator draws power from bus-bars and runs a synchronous motor in the same direction.	Effect depends upon type of prime mover and the power drawn from the bus during motoring.	Reverse power protection by Directional power relays direct the reversal of power.
7.	Over-voltages.	Insulation failure	Lightning arresters connected near generator terminals.
8.	Over-fluxing of Generator Transformer and Auxiliary Transformer	Heating of core	*V/f* relay. Connected in voltage regulator circuit generator.
9.	Under-frequency	Failure of blades of steam turbines	Frequency Relays (Ref. Ch. 45)

Reverse-power protection achieved by directional power relays are incorporated in the generator protection scheme. (Ref. Sec. 26.16).

Vibrations may occur owing to unbalanced loads or certain types of mechanical faults. Vibration detectors are usually mounted on the generator bearing pedestal.

Excessive bearing temperature may arise due to mechanical faults, impurities in the lubricating oil or defects in the oil circulation system. These fault may be detected by means of a temperature monitoring device embedded in the bearing.

Bearing Current. An induced e.m.f. of some volts may be developed in shaft of a generator owing to certain magnetic dissimilarities in the armature field. If the bearing pedestals at each side of the generator are earthed, the induced e.m.f. will be impressed across the thin oil films of the bearings. A breakdown of the oil-film insulation in the two bearings can give rise to heavy bearing currents owing to the very small resistance of the shaft and the external circuit thus developed.

Consequently, the bearing pedestal farthest from the prime mover is usually insulated from earth and the insulation supervised by a suitable relay. Further, to prevent the rotor and the shaft from being electrostatically charged, the shaft is usually earthed *via* a slipring and a 200 ohm resistor. This resistor also contributes by taking the injected a.c. leakage current of the field circuit earth-fault protective scheme.

33.3. PERCENTAGE DIFFERENTIAL PROTECTION OF ALTERNATOR STATOR WINDINGS

(Also called Biased Differential Protection or Merz-Price Protection) (Ref. Ch. 28).

(*a*) **Principle.** The differential protection is that which responds to the vector difference between two or more similar electrical quantities. In generator protection, the current transformers are provided at each end of the generator armature windings. When there is no fault in the windings and for through faults, the currents in the pilot wires fed from CT connections are equal. The differential current $I_1—I_2$ is zero. When fault occurs inside the protected winding, the balance is disturbed and the differential current $I_1—I_2$ flows through the operating coil of relays causing relay operation. Thereby the generator circuit-breaker is tripped. The field is disconnected and discharged through a suitable impedance (Ref. Ch. 28).

(*b*) **Connections of CT's for differential protection of generator.** Fig. 33.2 illustrates connection of CT's for a star-connected generator. Fig. 33.3 illustrates connections for a delta connected generator.

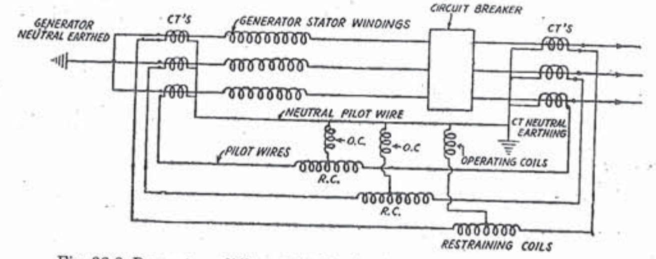


Fig. 33.2. Percentage differential relaying of a star connected generator, for phase-phase faults.

The percentage differential relay has an operating coil and a restraining coil, one for each phase. The restraining coil is connected centrally in pilot wires. The operating coil is connected between mid-point of restrains coil neutral pilot wire (Ref. Sec. 28.4).

The CT connections are as shown in Fig. 33.3.

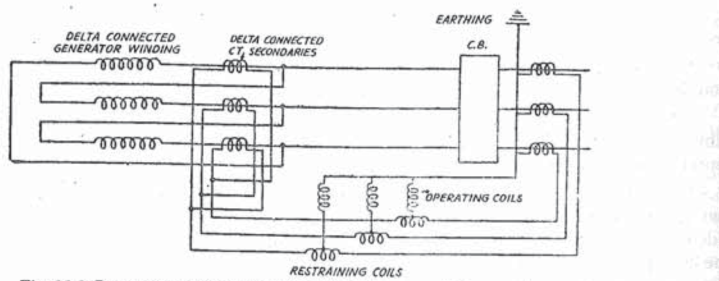


Fig. 33.3. Percentage differential relay of a delta connected generator, for phase-phase fault.

Typical protective arrangement of a generator connected to bus bars is shown in Fig. 33.4.

Differential relay provides fast protection to the stator winding against phase to phase faults and phase to ground faults. If neutral is not grounded or is grounded through impedance, additional sensitive ground fault relaying should be provided. Differential protection is recommended for generators above 2 MVA rating. Separate sets of CT's are used for each protection. Desirable features of generator differential protection are :

- high speed operation, about 15 ms. with static protection
- low setting
- full stability on external faults.

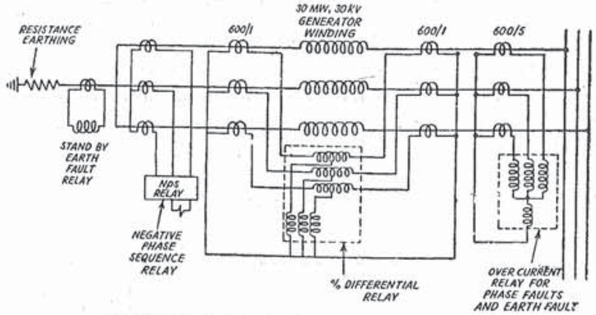


Fig. 33.4. Protection of a direct connected generator.

Differential protection which protects only generator is arranged to trip main circuit breaker and to suppress the field.

Differential protection does not respond to through faults and overloads.

Differential protection gives a complete protection to generator windings against phase to phase faults.

The biasing of the differential relay eliminates the problems associated with CT's. (Ref. Sec. 28.6).

The protection against earth faults by differential is influenced by the magnitude of earth-fault current. The magnitude of earth-fault current depends upon value of the reactance/reactance connected between neutral and earth; and the position of earth fault in generator winding. When the generator winding is earthed through impedance, a separate additional earth fault protection is necessary in addition to differential protection. The differential protection provides earth-fault protection to about 85% of generator winding.

33.4. RESTRICTED EARTH-FAULT PROTECTION BY DIFFERENTIAL SYSTEM

When neutral is solidly grounded, it is possible to protect complete alternator of transformer winding against phase to ground fault.

However, neutral is earthed through resistance to limit earth-fault currents.

With resistance earthing, it is not possible to protect complete winding from earth-fault and the % of winding protected depends on the value of neutral earthing resistor and the relay setting. While selecting the value of resistor and earth-fault relay setting, the following aspects should be kept in mind :

- The current rating of resistor, resistance value, relay setting, etc. should be selected carefully.
- Setting should be such that the protection does not operate for earth-faults on EHV side. Earth faults are not likely to occur near the neutral point due to less voltage w.r.t. earth. It is a usual practice to protect about 80 to 85% of generator winding against earth-faults. The remaining 20 to 15% winding from neutral side left unprotected by the differential protection. In additional to differential protection, a separate earth-fault protection is provided to take care of the complete winding against earth faults. (Ref. Sec. 33.6 (*b*)).

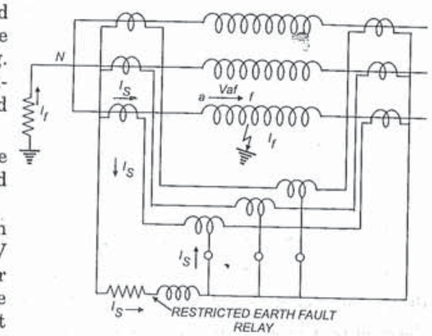


Fig. 33.5. Percentage Differential with protection Restricted Earth fault relay.

The restricted earth-fault relays in the differential protection is explained here. During earth-fault I_f in the alternator winding, the current, I_f flows through a part of the generator winding and neutral to ground circuit. The corresponding secondary current I_s flows through the operating coil and restricted earth-fault coil of the differential protection. The setting of the restricted earth fault relay can be selected independent of the setting of the overcurrent relay.

If the earth-fault I_f occurs at point f of alternator winding V_{af} is available to drive earth-fault current I_f through the neutral to ground connection. If point is nearer to terminal a (nearer to the neutral point) the forcing voltage V_{af} will be relatively less. Hence earth fault current I_f will reduce. It is not practicable to keep the relay setting too sensitive to sense the earth-fault currents of small magnitudes. Because, if too sensitive, the relay may respond during through faults of other faults due to inaccuracies of CT's, saturation of CT's etc. Hence a practice is to protect about 85% of the generator winding against phase to earth fault and to leave the 15% portion unprotected by the differential protection against earth-faults. A separate earth-fault protection covers the entire winding against earth-faults. [Sec. 33.6 (*b*)].

The resistance R limits the earth-fault current. If R is too small (solid earthing) earth fault currents are too large. Hence such a method is not used for large machines. Solid earthing is limited to machines upto 3.3 kV.

For low resistance earthing the resistance R is such that full load current passes through neutral, for a full line to neutral voltage.

Medium resistance earthing is commonly used on generator transformer units. The earth-fault current is restricted to about 200 A for full line to neutral voltage, for a 60 MW unit.

In high resistance earthing maximum earth-fault current is of the order of 10 A. Such earthing is used for distribution transformers and generator transformer units.

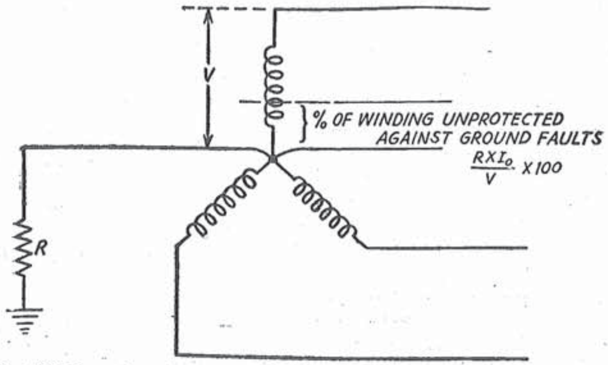


Fig. 33.6. Percentage of unprotected winding against phase to ground faults.

With higher neutral resistance, the earth faults current is reduced, hence lesser percentage of winding is protected by the restricted earth fault protection.

Assuming R is the resistance in neutral connection to the earth and the fault current for line to ground fault is equal to full load current of the generator or transformer, the value of impedance to be inserted in neutral to earth connections is given by,

$$R = \frac{V}{I}$$

where R = impedance in ohms between neutral and ground
V = line to neutral voltage
I = full load current of largest machine or transformer.

If a relay setting of 15% is chosen this affords protection of 85% of the winding of **largest machine** while a greater percentage of windings of smaller machines running in parallel with the large machine.

$$\boxed{\% \text{ of winding unprotected} = \frac{R \times I_0 \times 100}{V}}$$

R = ohmic value of impedance
I_0 = minimum operating current in primary of CT
V = line to neutral voltage.

If 15% of relay setting is used, I_0 is 15% of full load current of the machine.

Example 33.1. *A generator is provided with restricted earth-fault protection. The ratings are 11 kV, 5000 kVA. The percentage of winding protected against phase to ground fault is 80%. The relay setting such that it trips for 25% out of balance. Calculate the resistance to be added in neutral to ground connection.*

Solution. $$V = \frac{11}{\sqrt{3}} \times 1000 = 6340 \text{ V}$$

$$I = \frac{5000}{\sqrt{3} \times 11} = 262 \text{ A}$$

$$I_0 = 262 \times \frac{25}{100} = 65.5 \text{ A}$$

% of winding unprotected

$$= \frac{R \times I_0}{V} \times 100$$

$$\therefore \quad 20 = \frac{R \times 65.5}{6340} \times 100$$

Hence resistance to be added in the neutral connections is

$$R = \frac{20 \times 6340}{65.5 \times 100} = \mathbf{1.94 \text{ ohms.}} \quad \textbf{Ans.}$$

Example 33.2. *The neutral point of a 10,000 V alternator is earthed through a resistance of 10 ohms, the relay is set to operate when there is an out of balance current of 1A. The CT's have a ratio of 1000/5. What percentage of the winding is protected against fault to earth and what must be minimum value of earthing resistance to give 90% protection to each phase winding ?*

Solution. Out of balance current in pilot wires is 1 Amp. Corresponding current in CT primary will be

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

Hence current I_0 for which the relay operates in 200 A.

% of winding unprotected

$$= \frac{R \times I_0}{V} \times 100 = \frac{10 \times 200}{\frac{10{,}000}{\sqrt{3}}} \times 100 = \frac{20 \times \sqrt{3}}{14} = 34.8\%$$

% of winding protected $= 100 - 34.8 = \mathbf{65.2\%}$. **Ans.**

Resistance to get 90% of winding protection

$$10 = \frac{R \times 200 \times 100}{\frac{10{,}000}{\sqrt{3}}}$$

$$R = \frac{10 \times 10{,}000}{200 \times \sqrt{3} \times 100} = \mathbf{2.88 \text{ ohms.}} \quad \textbf{Ans.}$$

In these problems, remember, for largest machine :

$$\boxed{\% \text{ of winding unprotected} = \frac{R \times I_0}{V} \times 100}$$

R = Resistance in neutral connection,
I_0 = Primary current for relay operation,
V = Phase voltage.

Example 33.3. *A 3 phase, 2 pole, 11 kV, 10,000 kVA alternator has neutral earthed through a resistance of 7 ohms. The machine has current balance protection which operates upon out of balance current exceed 20% of full load. Determine % of winding protected against earth fault.*

Solution. $$kVA = \sqrt{3} \text{ kV } I$$

$$I = \frac{10{,}000}{\sqrt{3} \times 11} = 525 \text{ A.}$$

Out of balance current for which relay operates I_0

$$= \frac{20}{100} \times 525 = 105 \text{ A}$$

Voltage V line to neutral $= \frac{11}{\sqrt{3}} = 6.35$ kV

% of winding unprotected against earth fault

$$= \frac{R \times I_0}{V} \times 100 = \frac{7 \times 105 \times 100}{6.35 \times 1000} = \mathbf{11.6\%.}$$

Note : % reactance of generator winding was not considered.

Example 33.4. *Fig 33.7 shows percentage differential relay applied to the protection of an alternator winding. The Relay has a 1% slope of characteristic $I_1 - I_2$ vs. $(I_1 + I_2)/2$.*

A high resistance ground fault occurred near the grounded neutral end of the generator winding while generator is carrying load. As a consequence, the currents in amperes flowing at each end of the winding are shown in Fig. 33.7. Assuming CT ratio of 400/5 amperes will the relay operate the trip of the breaker.

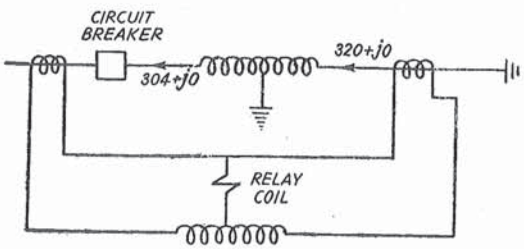


Fig. 37.7 (a)

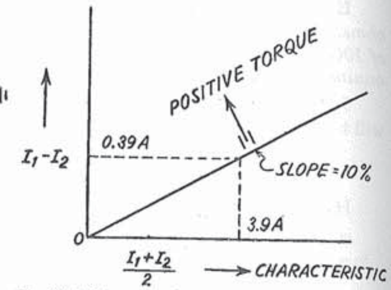


Fig. 33.7 (b)

Solution. CT ratio 400 : 5

Secondary current of CT_1

$$I_1 = \frac{304 + j0}{400} \times 5 = 3.8 + j0 \text{ A}$$

Secondary current of CT_2

$$I_2 = \frac{320 \times 5}{400} = 4 + j0 \text{ A}$$

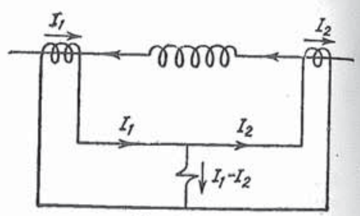


Fig. 33.8.

Directions of current are as shown in Fig. 33.8.
Out of balance current $I_1 - I_2$ flows through the relay coil. *i.e.*

$$3.8 - 4.0 = - 0.2 \text{ A}$$

$$\frac{I_1 + I_2}{2} = \frac{3.8 + 4}{2} = 3.9 \text{ A.}$$

Corresponding point on $I_1 - I_2$ *vs.* $\frac{I_1 + I_2}{2}$ characteristic is 0.39 A [from the known slope]. The relay operates if out of balance current is above the characteristic. In this problems out of balance current is 0.2 A and therefore in negative torque region. Hence the relay does not operate. **Ans.**

Examples 33.5. *A 11 kV, 3 phase Alternator has full load rated current of 200 A. Reactance of armature winding is 15 per cent. The differential protection system is set to operate on earth fault currents of more than 200 A. Find the neutral earthing resistance, which gives earth fault protection to 90% of stator winding.*

Solution. In this problem, the alternator reactance should be considered in calculations.

Full load current 200 A.

Let resistance in neutral connection be r ohms. Let reactance per phase be X ohms.

$$\frac{IX}{V} \times 100 = \%X \quad \begin{array}{|l} I = \text{rated current} \\ X = \text{reactance per phase in ohms} \\ V = \text{phase voltage.} \end{array}$$

$$\frac{200 \times X}{11/\sqrt{3} \times 100} \times 100 = 15$$

$$X = \frac{15 \times 11\sqrt{3}}{20} = 4.75 \text{ [ohms]}$$

Reactance of unprotected winding $= 4.75 \times 0.1 = 0.475$ [ohms]

Voltage induced in 10% unprotected winding

$$= \frac{11000}{\sqrt{3}} \times 0.1 = 635 \text{ volts.}$$

If the voltage is say v and impedance is say Z, then fault current in the loop is $i = v/Z$

$$Z = \sqrt{r^2 + x^2}$$

where r = resistance in neutral connection
x = reactance of 10% winding
v = voltage of 10% winding

Given $i = 200$ A
$v = 635$ (calculated value)
$x = 0.475$ (calculated above)

$$200 = \frac{635}{\sqrt{r + (0.475)^2}}$$

$$r^2 + (0.475)^2 = (3.18)^2 = 10.2$$

$$r = 3.145 \text{ ohms.} \qquad \textbf{Ans.}$$

Or

Neglecting the impedance of alternator winding, % of unprotected winding

$$= \frac{R \times I_0 \times 100}{V}$$

where R = resistance in neutral circuit
I_0 = minimum operating current in generator winding.
V = line to neutral voltage.

In this problem : R is to be determined

$$V = \frac{11{,}000}{\sqrt{3}} = 6350 \text{ V}$$

$$I_0 = 200 \text{ A}$$

% of unprotected winding = 100 – 90 = 10

Hence
$$10 = \frac{R \times 200 \times 100}{6350}$$

$$R = \frac{63{,}500}{20{,}000} = 3.175 \text{ ohms.}$$

Hence resistance in neutral connection = 3.175 ohms.

33.5. OVERCURRENT AND EARTH-FAULT PROTECTION FOR GENERATOR BACK-UP

For generators above 1 MW, where primary protection to stator winding is provided by Differential Protection, the overcurrent and earth-fault protection gives back-up protection for external phase to phase faults and earth-faults (Ref. Fig. 33.9).

Induction type inverse definite minimum time relays may be used for generator back-up protection for external faults.

Since the faults in stator winding are fed by the stator winding itself, their influence on current in the outgoing terminals of generator depends upon fault level of the main bus (Ref. Fig. 33.10).

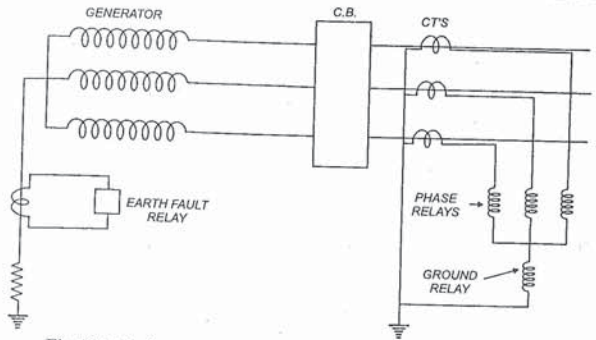
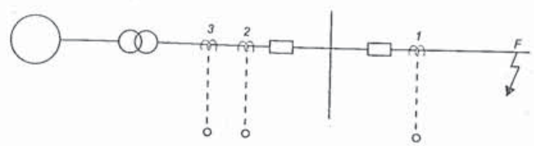


Fig. 33.9. Back-up protection by overcurrent protection.



Sequence of operation = 1, 2, 3

1. Line protection.
2. Bus bar protection.
3. The generator back-up overcurrent, earth-fault protection.

Fig. 33.10. The generator back-up protection should be the last to operate for external faults.

Hence overcurrent and earth-fault relays *do not* provide satisfactory protection against internal faults.

However the overcurrent and earth-fault relays provide back-up protection to generator against external faults (*e.g.* faults in bus zone, transmission zone).

The setting is selected that the generator overcurrent and earth-fault protection *does not* normally operate for external faults such as *F*.

However, if fault *F* continues for a long time due to failure of line protection (1), the fault will be fed by the generator. Hence the over-current and earth-fault protection of generator (3) may be set to operate with due time lag for higher values of external fault currents. Hence high set, definite minimum time, induction type, inverse over-current, earth fault relays are recommended for generator back-up.

33.6. (a) SENSITIVE STATOR EARTH-FAULT PROTECTION

When generator neutral is earthed through a high impedance, differential protection does not protect the complete alternator stator winding against earth faults, hence a separate sensitive earth-faults protection is necessary. The method for sensitive earth-fault protection depends upon the generator connection.

Two alternative methods are employed for neutral connection.

— The neutral connected through resistor which limits the maximum earth-fault current to much lower value than full load current, Fig. 33.11 (*a*). This method is preferred for large units.

— The neutral connected through a voltage transformer. The earth- fault current is limited to the magnetising current of the voltage transformer plus the zero-sequence current of generator, Fig. 33.11 (*b*).

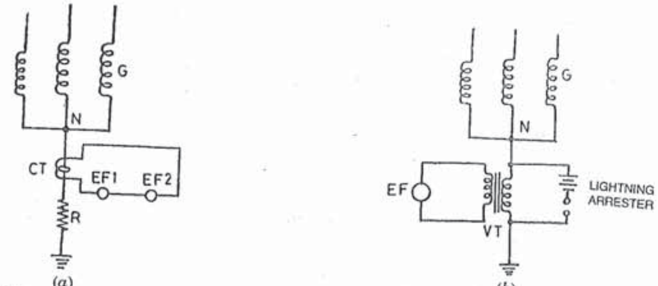


Fig. 33.11. Sensitive earth-fault protection of generator-transformer unit.

With resistance earthing (Fig. 33.11) two earth-fault relays may be provided on the secondary side of neutral CT. The First EF relay is set at 10 per cent and is instantaneous type. The second EF relay is inverse definite minimum time (IDMT) and is set at 5 per cent. (The relay pick-up when earth fault current is 5 per cent of full load current of generator).

Depending upon sensitivity, the first relay would protect about 90 per cent of stator winding and the second winding about 95 per cent. For such sensitive settings, it is necessary to provide a time delay, otherwise the relays may respond to transient neutral currents during external faults.

When neutral is connected through VT (Fig. 33.11), the rated primary voltage of VT is generally equal to phase to neutral voltage of generator. The EF relay is connected to the secondary of VT with a setting of 10% of rated secondary voltage of VT. When the voltage between neutral and earth reaches 10% of phase to neutral voltage of generator, the earth-fault relay operates.

The VT for neutral connection is specially designed. It should not saturate for twice the maximum neutral to earth voltage. The VT is protected from high voltage surges by Lightning Arrester connected in parallel with the primary. (Fig. 33.11(*b*)).

33.6. (*b*) 100% STATOR EARTH-FAULT PROTECTION

The earth-fault protection by differential relays or by residually connected relay can give effective protection to about 80 to 85% of generator winding. 100% stator earth-fault protection is provided in recent installations.

A coupling transformer is connected in neutral to ground circuit. A coded signal current is continuously injected into stator winding through the coupling transformer. The frequency of coded signal is 12.5 Hz. During normal condition the signal fed into stator winding flows only into stray capacitance of generator and directly connected system. In case of earth-fault, the capacitance is by-passed and the monitoring current increases. The increase in monitoring current (of 12.5 Hz) is sensed by the measuring system.

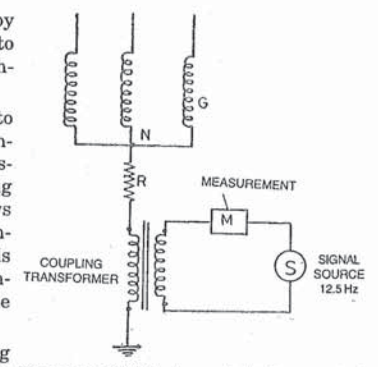


Fig. 33.11. 100% Stator earth fault protection by signals through neutral.

This protection covers 5 to 20% of stator winding from the neutral end. The remaining 80% winding is protected by differential protection or earth fault protection discussed in Sec. 33.6 (*a*).

33.7. PROTECTION AGAINST TURN-TO-TURN FAULT ON STATOR WINDING

The incidence of turn to turn fault in alternator is rare. One method of detecting inter-turn faults is by employing five limb voltage transformer with tertiary connected to watt hour meter type induction relay. The inter-turn faults are detected by measuring the residual voltage of generator terminals. This voltage appears across the tertiary winding which is connected to operating winding of a three element directional relay. The quadratic winding is operated from secondary side of the voltage transformer (Fig. 33.12).

During normal condition, the residual voltage is zero, *i.e.*,

$$V_{RES} = V_{RN} + V_{YN} + V_{BN} = 0.$$

This balance is disturbed during inter-turn fault on any of the single windings. And the residual voltage is fed to the relay coil.

When the generator is with single winding per phase, the Residual Voltage Detection method is employed for inter-turn fault protection.

Another method is to connect main voltage transformers in star-delta and connect an auxiliary VT in the delta circuit (Fig. 33.13). A voltage V_{res} proportional to the residual voltage

$$V_{RES} = V_{RN} + V_{YN} + V_{BN}$$

flow through the secondary delta connected winding of the VT. The relay is connected in this circuit *via* an auxiliary VT. The short circuit between turns gives residual voltage of fundamental frequency

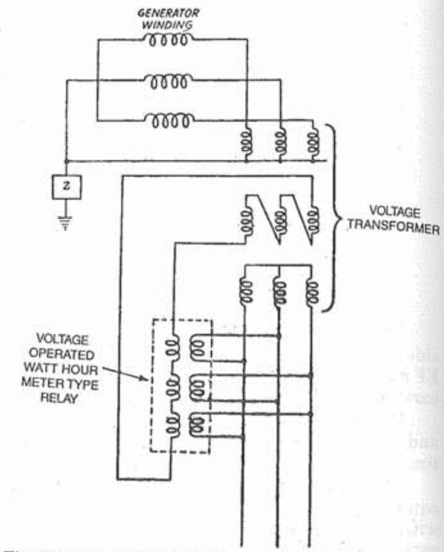


Fig. 33.12. Generator protection against inter-turn faults by residual voltage direction.

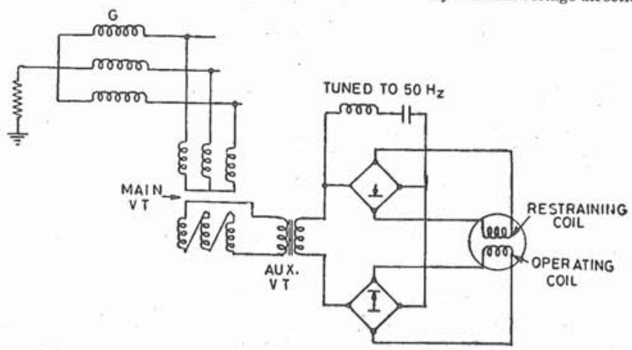
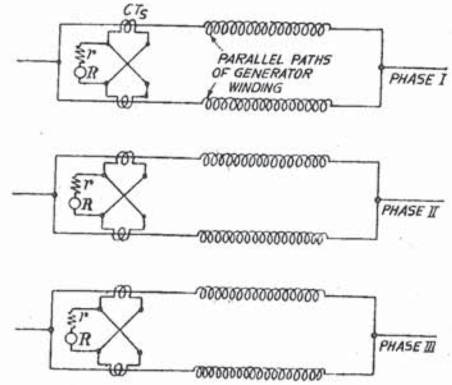


Fig. 33.13. Residual voltage inter-turn fault protection using main VT.

which should operate the relay. The relay should not operate for earth fault. Earth fault also causes residual voltage. Hence the zero-sequence voltages of third harmonic are fed to the restraining coil of the relay. The *LC* circuit tuned to fundamental frequency offers low resistance path to power frequency voltages appearing due to inter-turn faults. Hence for inter-turn faults the restraining current does not flow and relay operates only for inter-turn fault.

Another method of inter-turn fault protection is based on cross-differential principal (Fig. 33.14). In this case, the stator winding has two separate parallel paths. The current transformer primaries are inserted in these paths and the secondaries are cross-connected. During inter-turn fault in the phase winding, the out-of balance current CT secondaries flows through the relay. Such a protection can be extremely sensitive. However it can be employed to generators with parallel winding for each phase. (Ref. Fig. 33.14).

The fault between turns does not disturb the current balance of CT's for differential protection, hence differential protection does not detect inter-turn fault.



r = Stabilizing resistor R = Relay

Fig. 33.14. Generator inter-turn fault protection based on cross-differential principle.

33.8. ROTOR EARTH FAULT PROTECTION

A single ground fault does not cause flow of current since the rotor circuit is ungrounded. When the second ground fault occurs part of the rotor winding is by-passed and the currents in the remaining portion may increase. This causes unbalance in rotor and may cause mechanical as well as thermal stresses resulting in damage to the rotor. In some cases the vibrations have caused damage to bearings and bending of rotor shaft. Such failures have caused extensive damage.

One method of detecting earth fault on rotor circuit is described below. A high resistance is connected across the rotor circuit. The centre point of this is connected to earth through a sensitive relay. The relay detects the earth faults for most of the rotor circuit (Fig. 23.15) except the centre point of rotor.

Other methods of rotor earth fault protection include d.c. injection method and a.c. injection method, (Fig. 33.16). A single earth fault in the rotor circuit completes the circuit comprising voltage source *S*, sensitive relay earth fault. Thereby the earth fault is sensed by the voltage relay. D.C. injection method is simple and has no problems of leakage currents.

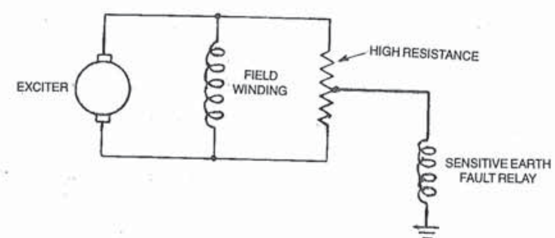


Fig. 33.15. Schematic diagram of rotor e.f. protection.

33.9. ROTOR TEMPERATURE ALARM

This protection is employed only to large sets and indicates the level of temperature and not the actual hot spot temperature. It is not practicable to embed thermocouples in rotor winding since the slip ring connections would be complicated. Resistance measurement is adopted. The rotor voltage and current are compared by a moving coil relay. The voltage coil of the relay is connected across the slip ring brushes. The current coil is connected across the shunt in the field circuit. Double actuating quantity moving coil relay is used, the restraining coil being circuit coil and the operating coil is the voltage coil (Fig. 33.17). Resistance increases with temperature.

The relay measures the ratio

$V/I = R$ (which gives a measure of rotor temperature).

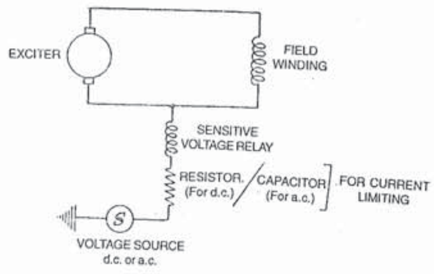


Fig. 33.16. Principle of d.c./a.c. injection method for rotor earth fault protection.

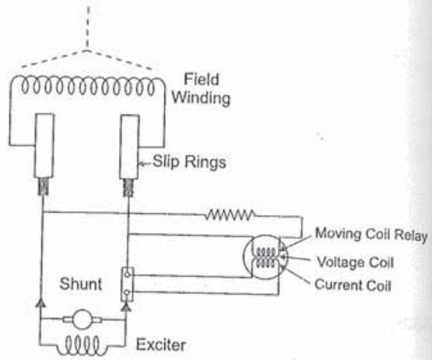


Fig. 33.17. Rotor temperature protection by measuring V/I.

33.10. NEGATIVE SEQUENCE PROTECTION OF GENERATORS AGAINST UNBALANCED LOADS

The unbalanced 3-phase stator currents cause double frequency currents to be induced in rotor. They cause heating of rotor and damage the rotor. Unbalanced stator currents also cause severe vibrations and heating of stator. From the theory of symmetrical components, we know that unbalance three-phase currents have a negative sequence components. This component rotates at synchronous speed in a direction opposite to the direction of rotation of rotor. Therefore double frequency currents are induced in the rotor.

Negative sequence current filter with overcurrent relay provides protection against unbalanced loads (Fig. 33.18).

The relative asymmetry of a three-phase generator is defined as the ratio of negative sequence current (I_2) to rated current $(I_n)_i$ *i.e.*,

$$\%S = \frac{I_2}{I_n} \times 100$$

In case of loss of one phase the relative asymmetry $\%S$ is equal to 58%.

The time for which the machine can be allowed to operate for various amounts of relative asymmetries depends on type of machine. The additional heat caused by negative sequence currents in rotor is proportional to $I_2^2 t$. The product $I_2^2 t$ is a machine characteristic.

$I_2^2 t = 30$ is a generally accepted figure as per ASA, (I_2 in per unit, t in sec.) for would rotor machines and 40 for salient pole machine.

It is generally necessary to install negative sequence relays that match with the $I_2^2 t$ characteristic of the machine. (Ref. Fig. 33.18 (*b*)).

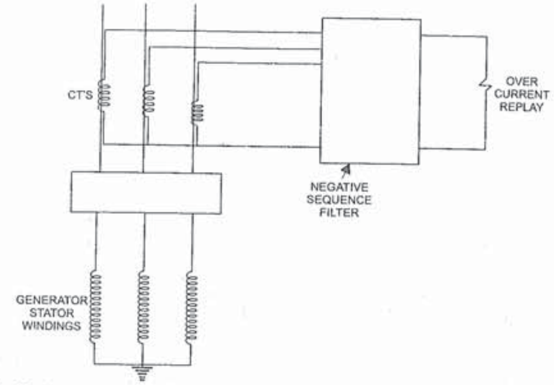


Fig. 33.18. (*a*) Protection against unbalanced load using negative sequence filter.

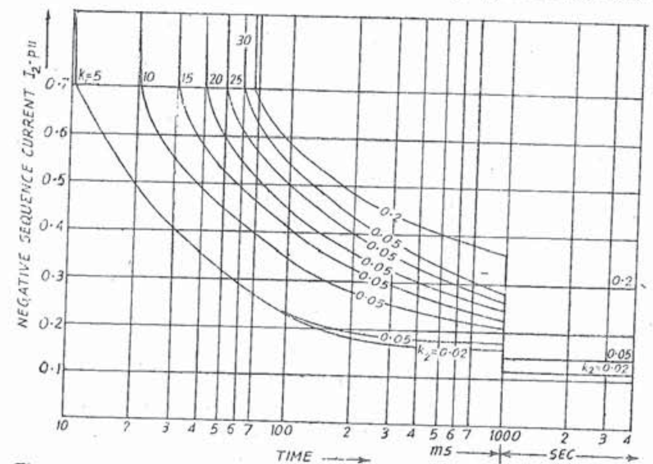


Fig. 33.18. (*b*) Current time characteristics of a static negative phase sequence relay.
Courtesy : Brŏwn Boveri, Switzerland.

Negative sequence filter circuit comprises resistors and inductors connected in the secondary circuit in such a way that negative sequence component flows through the relay coil, Z_L (Ref. Fig. 33.19).

The overcurrent relay (Z_L) of negative phase sequence protection is with inverse characteristics matching with the $I_2^2 t$ rating curve of the machine and is arranged to trip the unit.

33.11. NEGATIVE PHASE SEQUENCE CIRCUIT

Fig. 33.19 illustrates the principle of the negative phase sequence circuit. The twin windings of the two auxiliary current-transformers are so connected to the line current-transformers that under normal balanced-load condition, currents I_a, I_b and I_c flow in the direction shown. Impedance

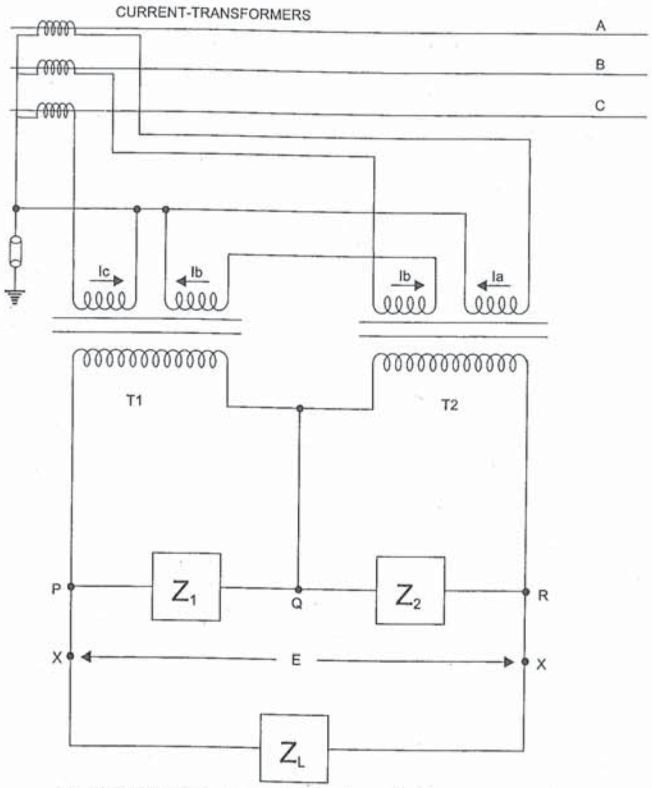


Fig. 33.19. Circuit showing principle of negative phase-sequence circuit.
Courtesy. Reyrolle Parsons Ltd. England.

Z_1 and Z_2 are connected across auxiliary current-transformers T_1 and T_2, and a load impedance Z_L is connected across the terminals *XX*.

When primary load current flows, the current through T_1 will be $(I_b - I_c)$ and that through T_2 will be $(I_a - I_b)$. For a given value of load impedance Z_L, (over-current relay) the impedance Z_1 and Z_2 are chosen such that points *P* and *R* remain at the same potential, *i.e.*, the voltages across *QR* and *QP* are equal and opposite. Under unbalanced conditions these voltages differ, and an output is produced proportional to the negative-phase sequence across *XX* (voltage *E*) so as to operate the relay. The protection remains stable on symmetrical overloads up to about three times rated full load.

As the output is instantaneous in operation, it is necessary to operate the equipment in conjunction with a time-lag relay.

Negative phase sequence relays are used for protection against unbalanced loads.

33.12. STATOR-HEATING PROTECTION

Generator overheating can be caused by failure cooling system or by sustained overloads.

Embedded resistance detectors or thermocouples are provided in the slots among with the stator coils for large generators. These give an alarm if temperature rises above safe value. The protection is provided for generators above 1 MW.

It is not practicable to provide overload protection by back-up stator-fault over-current protection. Because back-up over-current protection is generally set for sensing fault currents and should not trip for overloads. Electrical over-current relays cannot sense the winding temperature accurately because temperature rise depends on I^2Rt and also on cooling. Electrical protection cannot detect a cooling system failure.

33.13. LOSS OF FIELD PROTECTION

A 'loss of field' or 'field failure' can be caused by opening of field switch or field circuit-breaker. The behaviour of the generator depends upon whether the generator connected singly to a load or whether the generator is connected in parallel with other units or the system.

If it is a single unit supplying a local load, the loss of field causes loss of terminal voltage and subsequently loss of synchronism depending upon the load conditions.

If the generator is connected in parallel with other units it can draw the magnetizing currents from the bus-bars and continue to runs as induction generator. The magnetising currents are large and are to be supplied by other units. Hence the stability of the other units is affected.

The power-output of the generator is reduced while running as induction generator. The slip frequency e.m.f. is induced in the rotor.

In wound rotor generators, the e.m.f. induced in the rotor gives rise to circulating currents in the rotor body and slot wedges resulting in overheating. In salient pole machines there are no rotor slots and the rotor body is formed of laminations. Hence salient pole machines can endure the condition for a longer duration.

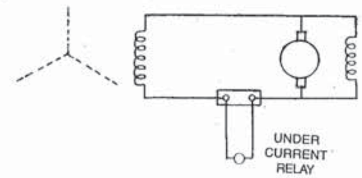


Fig. 33.20. Loss of field protection.

The stator currents may increase above normal current rating of generator during the run as induction generator. High currents may cause voltage drop and overheating of generator bus-bars, stator winding, etc.

Fig. 33.20 illustrating the loss of field protection by means of an under-current relay connected across a shunt in series with the field winding.

33.14.REVERSE POWER PROTECTION (Ref. Sec. 26.16 Directional Power Relay)

When the input to the turbine is stopped the generator continues to rotate as a synchronous motor, taking power from the bus bars. It then rotates as synchronous motor and the turbine acts as a load. Such incidents have occurred in old stations.

Motoring protection is mainly for the benefit of the prime-mover, and load coming on generator bus while motoring. Reverse power protection measures the power flow from bus-bars to the generator running as a motor. Normally the power taken in most cases is low of the order of 2 to 10% of the rated power. Power factor and current depends on excitation level.

During the motoring action of the generator, the power flows from the bus-bars to the machine and the conditions in the three phases are balanced. Hence a single-element directional power relay (reverse power relay, Sec. 26.6 sensing the direction of power flow in any one phase is sufficient. The CT's for reverse-power protection may be either at the neutral end or the bus-bar and of the generator winding. The setting depends on the type of prime-mover. Intentional time lag is provided in the reverse power protection so that the protection does not operate during system disturbances and power swings.

1. **Steam Turbine.** Time delay sensitive directional relays, set to operate on somewhat less than 3% of rated power.

Back-pressure steam turbine sets should be protected with sensitive reverse power protection. The blades of such steam turbine get overheated quickly as the stem gets trapped if rotated in opposite direction due to windage.

In steam turbines the steam acts like a coolant of the turbine blades and maintain them at constant temperature. If the steam flow stops, the blades get overheated due to windage (friction with air).

In condensing type steam turbine, the heating of blades is slower hence reverse power protection may not be necessary.

For large turbo-generators with back-pressure type, non-condensing steam turbines, sensitive reverse power protection with sensitivity of the order of 0.5% of rated power is preferred. The relay should have directional stability for the entire relay operating zone (Fig. 33.21).

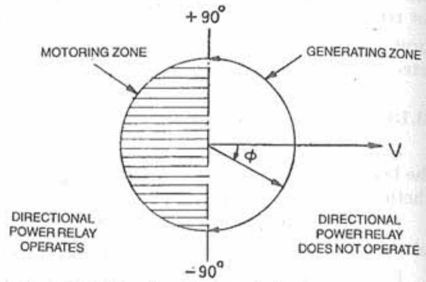


Fig. 33.21. Operating characteristics of reverse power protection.

2. **Reciprocating Engine.** Motoring is harmful to the engine. Hence the reverse power protection should be sensitive and the engine must be disconnected from generator shaft during motoring.

3. **Hydraulic Turbines.** The water-turbine is generally fitted with mechanical devices which detect the low water flow because such a flow causes cavitation. However reverse power protection may be provided to operate for motoring power less than 3 per cent of rated power.

4. **Gas Turbine.** The gas turbine driven generator should not be permitted to operate as a motor because the gas turbine offers a load of 10 to 50% of full load during motoring.

The factors to be considered are :

1. Capability of prime-mover to run as a load.
2. Load current drawn while motoring.

The reverse power protection is generally set for 10% rated power in reverse direction.

33.15. OVER-SPEED PROTECTION

It is essential to incorporate safety device in turbine governing system to prevent overspeeding.

Overspeeding can occur due to sudden loss of electrical load on generator due to tripping of generator circuit-breaker, before disconnection of prime-mover.

The speed of the generator should be maintained by the governor.

The overspeeding results in over voltages and increase in frequency.

Hydro-generators.* Overspeeds are prevented by centrifugal governors. Sensitive frequency relays operated from an auxiliary permanent magnet alternator fitted on the shaft sense the overspeed.

Steam turbines.* The generator responds to the over-speed caused by load rejection. However, the steam beyond governor keeps on expending causing further increase in speed. The steam beyond governor should be bypassed by some other path quickly so that input to steam turbine is bypassed

* Blades of steam turbine have tendency to vibrate at speeds other than rated speed. Frequency Relays are used. Ref. Sec. 45.8.1.

quickly and increase in speed is checked. This is achieved by sensing overspeeding by electrical measurements on generator side and by steam measurement on turbine side.

The emergency valve is closed momentarily so as to stop the steam supply more rapidly. The value opens again automatically, meanwhile the governor responds to changed conditions and regulates the speed.

With gradual reduction in load the emergency valve does not operate.

33.16. FIELD SUPPRESSION

When a fault develops in an alternator winding even though the generator circuit-breaker is tripped, the fault continues to be fed because e.m.f. is induced in the generator itself. Hence the field circuit-breaker is opened and the stored energy in the field winding is discharged through another resistor. This method is known as field suppression.

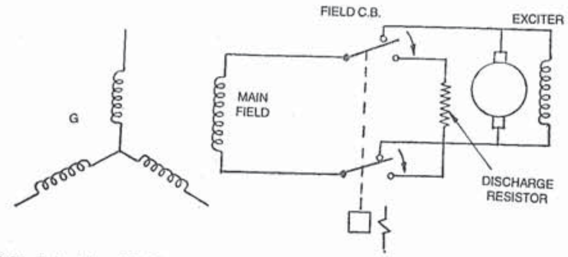


Fig. 33.22. Principle of field suppression (The energy in main field is discharged through resistor by closing C.B. on to the discharge resistor).

33.17. OTHER PROTECTIONS

Bearing Insulation. In case of large generators, the voltage generated in the shaft due to leakage fluxes can circulate currents through the shaft. These currents flow through the bearings and foundation and cause pitting of bearing. To prevent the circulating shaft currents one of the bearings and its auxiliary piping should be insulated from ground.

Vibration Protection. A vibration detector may be mounted on one of the bearing pedestals in the case of a horizontal shaft machine, or on the upper guide-bearing of a vertical shaft machine. It may be set to trip the machine or initiate an alarm when the radial deflections of a certain duration exceed a pre-selected value. Stepped Underfrequency Relays are also used. (Ref. Ch. 45)

Bearing overheating protection. Temperature detectors are inserted in the bearings which are connected to temperature indicator and alarm circuits.

Mechanical conditions. These are related with prime mover, cooling systems and other auxiliaries. Sometimes these abnormal conditions are serious enough to bring about the complete shut-down. But generally an alarm is provided for less serious abnormal conditions.

Loss of vacuum. Failure of vacuum plant associated with steam turbine gives rise to very high temperature and pressure at exhaust end. The loss of vacuum protection is in two stages :

— In the first stage, the unloading gear operates and the control valves start to close the input to steam turbine. If loss of vacuum is a temporary, the valve opens again and original condition is restored.

— The second stage operates when the vacuum is too low, the vacuum trip operates the emergency control and the generator unit is tripped open.

33.18. PROTECTION OF SMALL, STANDBY GENERATORS*

Small generators and standby generators require simple but reliable protective equipment. Basically the following operating conditions and fault conditions should be considered while selecting a protection scheme. (Also, refer Sec. 43.9).

Overcurrent. The generator of the standby set and the consumers must be protected against the effects of short circuit currents. Fuses are inaccurate in their rupturing characteristics and are not available for high currents. Also, the rupturing of a fuse cannot be indicated at a central display. It is advisable therefore, to use a time-lag over-current relay operating direct on the generator breaker, even at relatively modest overcurrents.

Overvoltage. Dangerous overvoltages, such as can occur due to a fault at the controller or due to sudden load shedding can be monitored with a time-lag overvoltage relay.

Overload. The winding insulation of an electrical machine can sustain damage at excessive bar temperatures and this will shorten its service life. Stator winding temperatures must therefore be monitored. If a given permissible limit is exceeded, an alarm must be given or the machine switched off. Monitoring is mostly carried out by a thermal replica of the machine; a thermal relay. (Ref. Sec. 31.6).

Frequency. Certain installations, such as transmitters, depend on a constant frequency and consequently the frequency must be monitored. If there is an excessive drop in frequency the generator breaker of the standby set must be opened or an alarm given. If the relay acts on the generator breaker there is no need to throttle-back the diesel engine.

In other cases the frequency relay prevents feedback into the supply system. During storms or under other conditions which can be dangerous as far as the supply system is concerned, the standby set is often run in the parallel with the system before being separated. If, under these conditions, the supply voltage fails, relay must respond to the drop in frequency due to the overloading of the machine and cause the line switch to open; the standby set thus continues to operate without interruption.

Depending on the plant and the design of the protection system, it may be necessary to use two frequency relays with staggered time gradings, arranged such that the first one opens the line switch and the second opens the generator breaker. In many cases, however, the trip command of only one of the relays is passed from the control system to one or the other breaker. In parallel operation with the system the frequency relay operates on the line switch, and in isolated operation on the generator breaker. To give the standby generator drive time to accelerate again after disconnection from the supply, the command to the generator breaker must be delayed.

Forward power. The rated power output of a standby generator set is adequate to cover the total installed power of the installation. To this end a part of the load, which is classified according to certain priorities for this purpose, is switched off during standby operation. This can be carried out the control system or by a power relay with several load-shedding stages.

A power directional relay can be used in place of the frequency relay to prevent feedback from the standby set into the system. As soon as the maximum power feedback permissible in normal service is exceeded, the relay issues a trip command to the line switch.

Reverse power. If the drive for the generator fails in parallel operation, the generator is driven by the system and operates as a motor. To prevent damage to the machine a power directional relay must be used to monitor the direction of the active power flow. Under such conditions the generator must be decoupled from the system as quickly as possible. The shortest response time depends on the degree of hunting to be expected in the system.

* Acknowledgements to Brown Bovery and Co. Ltd., Switzerland Ref. "Protection Equipment for Stand by Generating Plant and Small Generators".

Table 33.4.
Protection Chart for Generator-Transformer Unit (Ref. Table 33.2)

	Protection	*Equipment covered*
1.	Generator differential protection.	Generator
2.	Main transformer differential protection.	Main transformer
3.	Unit auxiliary transformer differential protection.	Unit auxiliary transformer
4.	Overall differential protection.	Generator main transformer
5.	Generator protection.	Ref. Table 33.1
6.	Unit auxiliary transformer protections.	Ref. Table 32.1, 32.2
7.	Main transformer protection.	Ref. Table 32.1, 32.2

33.19. Generator Transformer Unit Protection

The scheme of Generator transformer Unit Protection comprises the following (Ref. Table 33.2).

— Primary Protection and back-up protection of generator
— Primary and back-up protection of main transformer
— Primary and back-up protection of unit auxiliary transformer (service transformer)
— Combined protection for generator and main transformer. The basic layout of generator connections has been illustrated in Fig. 33.1.

33.19.1. COMBINED DIFFERENTIAL PROTECTION FOR GENERATOR MAIN TRANSFORMER

In the protection scheme the differential protection generally covers the generator and main step-up transformer. Separate differential protections are provided for generator and for unit auxiliary transformers (Ref. Table 33.4).

The zone of combined differential protection may include generator stator winding, main step-up transformer and the bus-bar connections. A separate set of CT's is provided for this protection. The CT's at neutral side are star connected and CT's on HT side of main step-up transformer are delta connected. A third set of CT's is provided on the Teed-off to unit-auxiliary transformer. The CT's on Teed-off connection are necessary to compensate for the load current in Teed-off connection. These CT's are connected in parallel with the CT's of combined differential protection (Fig. 33.23).

Generally it is not practicable to cover the unit auxiliary transformer in the generator main transformer differential protection due to following reasons :

— Zone of protection should not be too large.
— Burden on CT's increases.
— Rating of unit auxiliary transformer is 1/10th main generator and it is difficult to select relay setting.

33.20. STATIC PROTECTION OF LARGE TURBOGENERATORS AND MAIN TRANSFORMER

The static protection equipment for protecting generator-comprises solid state relays in form of plug in assemblies, associated auxiliaries, intermediate transformers, tripping programmes and testing facilities for circuits. As compared with conventional electrons mechanical relays, the static protection has many superior features which make the use of static relays, a must. The reasons being :

— Complex generator protection requirements.

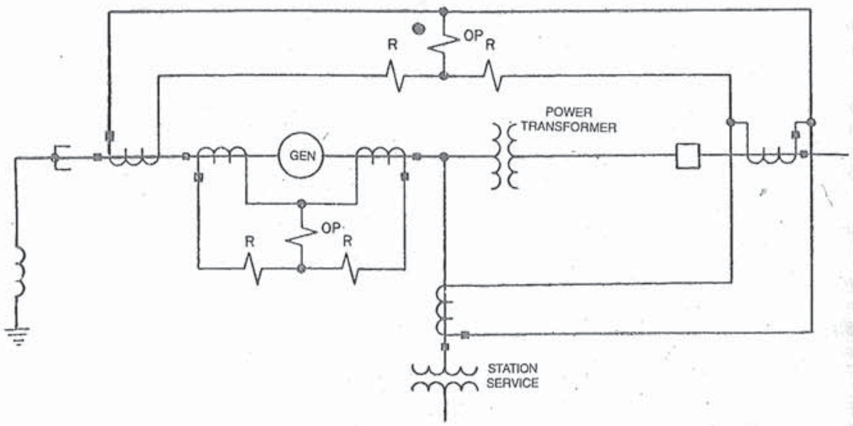
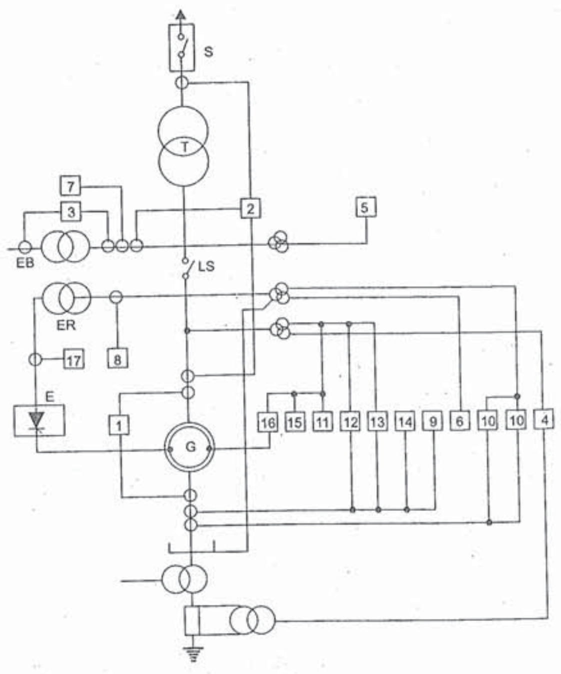


Fig. 33.23. Differential Protection of unit type Generator-Transformer systems. (Single line diagram)
(*Courtesy* : Westinghouse Electric Corporation, U.S.A.)



R = Restraining Coil
O = Operating coil.
G — Generator Unit transformer
EB — Service transformer
T — Unit transformer
ER — Exciter transformer
S — Circuit breaker
E — Excitation system
LS — Load switch ; (which can switch normal load currents)
Relay :
1 — Differential protection
2 — Differential protection, unit transformer generator,
3 — Differential protection, service transformer
4 — Stator earth-fault protection
5 — Earth-fault protection
6 — Inter-turn-fault protection
7 — Overcurrent protection, service transformer
8 — Overcurrents protection exciter transformer
9 — Stator overload protection
10 — Reverse power protection (duplicated)
11 — Overvoltage protection
12 — Minimum impedance or maximum current/minimum voltage back-up protection
13 — Asynchronous running protection
14 — Asymmetrical load protection
15 — Minimum frequency protection
16 — Rotor earth-fault protection
17 — Rotor overload protection

Fig. 33.24. Protection scheme for a large generator in unit connection*
(*Courtesy* : Brown Boveri, Switzerland)

— large number of protective systems resulting in large CT burdens and complex set-up.
— CT saturation problems.
— stability requirements of protective relaying.
— large power concentration near generator-transformer bus.
— several protections needed.

The conventional protective relaying, therefore, becomes too complicated and unacceptable for generators of 500 MVA and above, as superior static-relays are now available.

33.21. STATIC, DIGITAL, PROGRAMMABLE PROTECTION SYSTEM FOR GENERATOR AND GENERATOR-TRANSFORMER UNIT

The static protection equipment for protecting generator-comprises solid state relays in form of plug in assemblies, associated auxiliaries, intermediate transformers, tripping programmes and testing facilities for circuits.

The Programmable, Numerical (digital) Microprocessor based Protection Systems have been introduced during 1990s. Table 32.6 gives a list of protections incorporated in the schemes for various sizes of generator-transformer units.

The major features and merits of such protection systems are :

A real-time microprocessor system utilizes sampled or preprocessed power system waveform data.

Digital filtering and numerical calculations take place on the bases of a continuous stream of data from the power system.

Programs, algorithms and settings are stored in the memory used by the microprocessor.

Extensive hardware and software monitoring ensures high availability.

The protection system can communicate with the Station Control System (SCS) and the Station Monitoring System (SMS), SCADA.

Event and disturbance recording on printouts, with time tagging is initiated by abnormal power system conditions, being afterwards available on request.

The interface for the man-machine communication (MMC) is either a personal computer, a mounted terminal or a remote terminal (with modem). Communication via the personal computer is menu-driven, highly structured, and provides full documentation of all the settings and recorded information.

The implementation of suitable algorithms allows an adaptive response by the protection functions to changing power system conditions and changed system parameters.

Protective Functions in two Groups

Two independent protective systems are provided for *Redundancy*.* In one of the protection system fails, the other operates, Table 32.6 gives a list of protective systems. The division in two groups (*A* and *B*) is given in Table 33.5.

* Redundant Protection : Additional, independent, duplicate protection, which is superfluous, can be avoided but is provided in important protection scheme.

Table 33.5
Two Independent Protection Schemes for Higher Availability

Type of fault	*ANSI No.*	*Protection function*	*System*	
Generator stator				
Short circuits	87 G	Generator differential	A	
	87 T	Overall differential		B
	21	Minimum impedance or as alternative	A	
	51/27	Overcurrent/undervoltage (for thyristor excitation) or as option		B
	51	Overcurrent		B
Asymmetry	46	Negative sequence	A	
Stator overload	49	Thermal	A	
Earth fault, stator	59	Stator earth fault (90%)		
Earth fault, stator	64	Stator earth fault (100%)	A	B
Loss of excitation	40	Minimum reactance		B
Out of step	78/21	Pole slip	A	
Motoring	32	Reverse power (dual protection for large generators)	A	
Overspeed	81	Maximum frequency		B
Blade fatigue	81	Minimum frequency		B
Interturn fault	59	Overvoltage or overcurrent	A	
Lower voltages	27	Undervoltage		B
Increased magnetization	24	Overexcitation (U/f)		B
Higher voltage	59	Overvoltage	A	
Generator rotor				
Rotor overload	49	Thermal		B
Earth fault, rotor	64 R	Overvoltage	A	
Step-up transformer				
Short circuits	87 T	Transformer differential	A	
	50/51	Overcurrent		B
Earth fault	51 N	Earth fault overcurrent	A	
	87 N	Restricted earth fault		B
Unit transformer				
Short circuits	87 T	Transformer differential	A	
	50/51	Overcurrent		B
	49	Overload	A	
Earth fault	(51 N)	Residual overcurrent (option)	A	
	(87 N)	Restricted earth fault (option)		B

Summary

Alternator protection is complex. Most of the alternators are provided with % differential protection of phase to phase and phase to ground faults.

Differential relaying responds to vector difference between the current entering in the winding and current leaving the winding.

Bias of restraining coil is providing to prevent faulty tripping due to inaccuracies of CT's during through fault currents.

Unbalanced load cause rotor heating. Loss of input to turbine causes motoring action. (Ref. Tables 33.1, 33.2 and 33.3).

Loss of excitation causes generator to run as induction generator. The back-up protection against external faults is given by over-current and earth fault relays.

QUESTIONS

1. Show in detail, the protection arrangement of a 60 MW generator provided with :
   (*a*) Differential protection
   (*b*) Back-up over-current protection through faults.
   (*c*) Standby earth fault protection in neutral connection.

[**Hint.** Refer Fig. 33.2 to 33.4 and 33.9].

2. Explain, with the aid of neat diagram of connections, the principle of operation of current balance type differential protection of generator against earth and interphase faults.
   A 3-phase, 11 kV, 15,000 kVA star connected alternator has differential protection. The neutral is earthed through a resistance of 8 ohms. The relay operates for out of balance of 18% full load. Calculate percentage of winding unprotected against ground fault.
3. Fig. Q. 3 shows a differential protection system. The fault current for an earth fault on the winding are indicated. The CT ratio is 400/5. The relay is set to operate for current of 0.1 Amp. in its coil. Under the indicated conditions, will the relay operate? Relay is without bias.

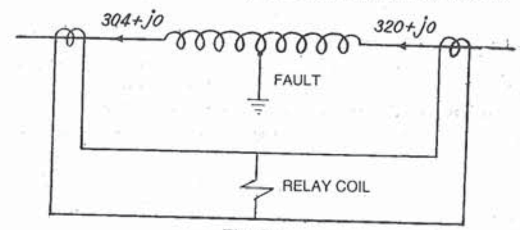


Fig. Q.3.

4. What is differential protection ? What is percentage differential protection ? Why it is superior to simple differential protection. Explain the characteristic.
5. What are the difficulties experienced in differential relay in generator protection ? How are they overcome?
6. What is the effect of balance load on the generator ? Which part is damaged due to sustained unbalanced currents?
7. Why field suppression is necessary?
8. State the protections provided for a 100 MW generator.
9. Why restricted earth fault protection is provided to alternators though it leaves a portion of winding unprotected against earth fault. Can it be justified ?
10. State effect of unbalanced load on the generator. What are the permissible durations of unbalance ?
11. State the effect of providing full excitation current to synchronous generator at 70% of synchronous speed. Which equipment in the generator-transformer unit will fail ? which protection prevents such a failure.